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Surveillance Alternatives: Cost Estimates and Technical Considerations for the En Route Domain

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13. ABSTRACT (Maximum 200 words)
This report presents cost estimates and technical performance projections for ten aircraft surveillance architectures. The architectures are intended for use in the en route flight domain, and are comprised of various combinations of Automatic Dependent Surveillance – Broadcast (ADS-B), Monopulse Secondary Surveillance Radar (MSSR), and multilateration systems. Cost estimates are developed for use in comparing technologies (rather than specific programs). Technical performance information is presented in the areas of coverage, accuracy, and capacity.

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PREFACE

The work described in this report was performed for the Federal Aviation Administration, Surveillance System Engineering Group (AND-402). The work was performed by the Department of Transportation/Research and Special Projects Administration/Volpe National Transportation Systems Center, Surveillance and Sensors Division, under Project Planning Agreement FA83E.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

°C=5/9(°F - 32)

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

°F=9/5(°C) + 32

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0			1		2			3		4			5
CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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Executive Summary

Background and Objective

The National Airspace System (NAS) architecture is evolving as operational requirements increase and technology progresses. To address the on-going need for architecture optimization and cost reduction, the Surveillance System Engineering Group (AND-402), in coordination with the Architecture and Investment Analysis Division (ASD-140), initiated a joint program with the DOT/Volpe Center and MIT Lincoln Laboratory to evaluate surveillance architecture alternatives based upon mixes of Automatic Dependent Surveillance – Broadcast (ADS-B), secondary surveillance radar (SSR), and multilateration system technologies.

There is a consensus within the aviation community that — for the en route flight domain especially — the NAS surveillance architecture should move away from the use of primary radar and toward greater reliance on cooperative and dependent surveillance systems. The *NAS Architecture* Version 3.0 now being coordinated within the FAA, is consistent with this consensus and calls for: (1) removal of long-range primary radars within the interior of CONUS, except where other government agencies have a requirement, beginning in June 2000; (2) installation, also beginning in 2000, of the new ATCBI-6 Monopulse SSR (MSSR) in place of 25+ year-old ATCBI-5 systems; (3) deployment of 116 new ADS-B ground stations over the period 2006-2010; and (4) research of surveillance systems that can serve as the necessary future complement and backup to ADS-B.

The objective of this report is to present cost estimates and supporting technical information for ten en route surveillance architecture alternatives. The architectures emphasize ADS-B, MSSR, and multilateration systems that use aircraft transponder emissions. Cost estimates are used for comparing technologies rather than evaluating programs. Costs germane to individual programs — e.g., effect of procurement schedule and time value of money — are neglected.

Architecture Descriptions

Table ES-1 provides an overview of the ten surveillance architecture alternatives considered. The table begins with the simplest form of ADS-B ground system — i.e., Alternative 1, involving a passive ground station with no method for validation — and builds on that base. Extensions to the simplest ADS-B system include: including techniques for validating the GPS information in ADS-B messages (Alternatives 2 and 3); adding fixed-antenna range-azimuth measuring systems (Alternatives 4 and 5); adding passive and active multilateration capabilities (Alternatives 6 and 7); and adding MSSR with Selective Interrogation (SI) and Ground-Initiated Communications Mode B (GIC-B) capabilities (Alternative 8). Alternatives 9 and 10 include MSSR but do not have an ADS-B ground station. An MSSR with SI and GIC-B can obtain surveillance information both by measuring aircraft range and azimuth and by (for Mode S equipped aircraft) downloading GPS-derived information from the aircraft transponder.

Table ES-1. En Route Surveillance Architecture Alternatives

#	Principal Surveillance System	Complementary Surveillance System	Complementary System Implementation
1	ADS-B	None (no validation)	Not applicable
2	ADS-B	None (partial validation)	Not applicable
3	ADS-B	None (Full validation)	Not applicable
4	ADS-B	Range-Azimuth-Altitude Surveillance	Integrated into ADS-B station
5	ADS-B	Range-Azimuth-Altitude surveillance	Separate station
6	ADS-B	Passive Multilateration	Integrated into ADS-B station
7	ADS-B	Active Multilateration	Integrated into ADS-B station
8	ADS-B	MSSR SI/GIC-B, MSSR interog-response	Separate ATCBI
9	MSSR SI & GIC-B	MSSR interog-response	Same ATCBI provides dual capabilities
10	MSSR SI & GIC-B	MSSR interog-response	Same ATCBI provides dual capabilities

☐ Designates architecture in *NAS Architecture v3.0* document

Operational Capabilities

Alternatives 4 through 8 include ADS-B and a complementary surveillance system which also uses the aircraft transponder. In each case, the complementary system performs three functions: ADS-B backup (particularly against GPS failures), ATCRBS aircraft surveillance, and ADS-B validation.

In assessing the capability of the alternatives to support ATC operations, it was determined that Alternatives 6-10 can support full radar separation while Alternatives 1-5 cannot. Alternatives 1-5 are most suitable for use in remote areas and as gap-fillers, because they either lack the ability to determine the location of ATCRBS-equipped aircraft (the case for Alternatives 1-3) or can only poorly determine their location (the case for Alternatives 4-5). In contrast, Alternatives 6-10 can perform accurate surveillance on ATCRBS, Mode S or ADS-B-equipped aircraft.

Cost Estimates

A major impetus for this study is to compare the costs of Alternatives 6 and 7 with those for Alternative 9, as these alternatives are most comparable. Alternatives 6 and 7 have separate subsystems devoted to ADS-B and ATCRBS-equipped aircraft (ADS-B ground stations and multilateration, respectively), while Alternative 9 uses the MSSR for both user classes. Alternative 8 has three methods for performing surveillance (ADS-B ground sites, GIC-B, and ATCRBS/Mode S capabilities). Alternative 10 does not support ADS-B, but can work with ADS-B-equipped aircraft if the transponder has an SSR mode of operation.

Figure ES-1 compares the life-cycle costs of the alternatives for a 20-year-period. It is assumed that all new equipment is installed at every site, and the cost of land is omitted. As might be expected, Alternatives 1-5 have significantly lower costs than the other five. In contrast, Alternative 8, having the highest capability, has the highest cost. Costs for Alternative 9 are approximately 17% higher than those for Alternatives 6 and 7. While the SSR cost is larger, when consideration is given to (1) the risk involved in instituting a fundamental change surveillance technology, and (2) the degree of uncertainty in the cost estimating process, this difference does not constitute a strong argument for substituting ADS-B and multilateration for secondary radar.

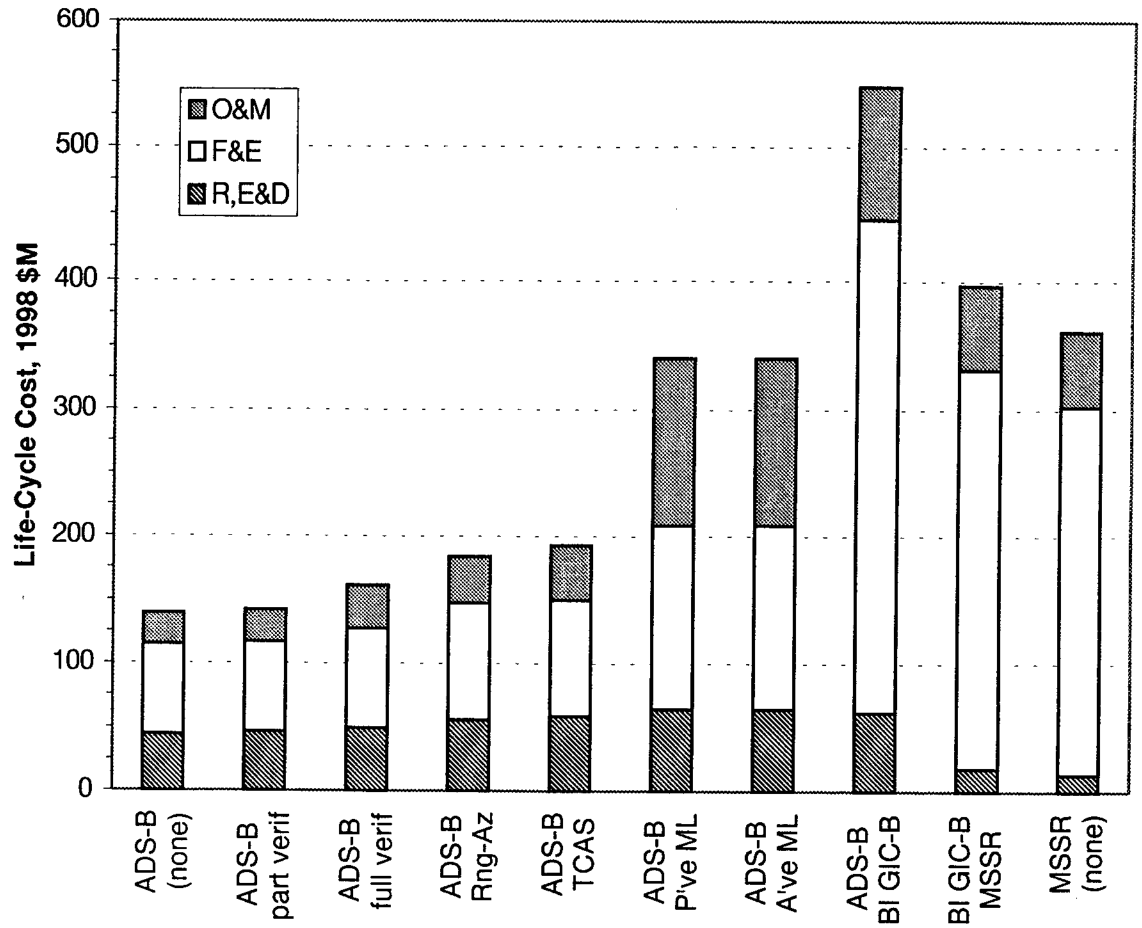

Figure ES-1. Total Costs, without Land, Existing Radar Site Equipment Utilized

Many radar sites have equipment items available which could be used with new radar electronics without degrading performance. These items include the tower, antenna, rotary joint, beacon video reconstituter, shelter, engine-generator, and beacon parrot. To bound the cost savings which could be realized by utilizing at existing sites or in depot storage equipment, the cost estimate was recomputed neglecting these items. The result is that Alternative 9 costs are 5% less than those for Alternatives 6 and 7. In an implementation program, it is likely that a portion of the existing equipment will not be re-usable, so the costs of Alternatives 6/7 and 9 will be even closer together. In these circumstances, it would not be prudent to implement a large change in surveillance technologies.

1. Objectives and Approach

1.1 Background

The *NAS Architecture,* Version 3.0 (Reference 1), is currently the most authoritative description of the future National Airspace System (NAS) equipment mix and functionality. It envisions a future Air Traffic Management (ATM) system which implements free flight operations. Automatic Dependent Surveillance-Broadcast (ADS-B) is specified as the principal surveillance system, supported by a mix of radars, and possibly one or more developing surveillance technologies such as multilateration when they are cost effective and operationally beneficial. However, the future NAS architecture is evolving, and operational requirements and cost and benefit estimates are still being refined. To address the need for continuing architecture optimization and cost reductions, the Federal Aviation Administration (FAA) Surveillance System Engineering Group (SSEG) (AND-402), in coordination with the Architecture and Investment Analysis Division (ASD-140), initiated a joint program with the DOT/Volpe Center and MIT Lincoln Laboratory to evaluate surveillance system/architecture alternatives based upon ADS-B, secondary surveillance radar, and multilateration system mixes.

Both the Volpe Center and Lincoln Laboratory have performed extensive studies and development work to improve the NAS surveillance infrastructure. The Volpe Center has supported the Federal Aviation Administration Surveillance Integrated Product Team (AND-400) over the past eight years, with emphasis on architecture development and assessment (e.g., References 2-4). Lincoln Laboratory developed Mode S Secondary Surveillance Radar (SSR), Traffic Collision and Avoidance System (TCAS), and formulated Mode S extended squitter.

1.2 Surveillance Trend

There is a consensus within the FAA and the broader aviation community that — for the en route flight domain especially — the NAS surveillance architecture should move away from the use of primary radar and toward greater reliance on cooperative and dependent surveillance systems. The *NAS Architecture* Version 3.0 now being coordinated within the FAA is consistent with this consensus and calls for: (1) removal of long-range primary radars within the interior of CONUS, except where other government agencies have a requirement, beginning in June 2000; (2) installation, also beginning in 2000, of a new secondary surveillance radar, termed Air Traffic Control Beacon Interrogator, Model 6 (ATCBI-6), to replace the aging ATCBI-5 systems now in place; (3) installation of 116 new Automatic Dependent Surveillance – Broadcast ground stations over the period 2006-2010; and (4) "mid-term research" of alternative surveillance systems that will serve as the required complement and backup to ADS-B.

While the trend toward cooperative[1] and dependent[2] surveillance is clear, full agreement has not been reached regarding the relative roles of these two modes, nor have specific system characteristics and capabilities been determined. For example:

- There is uncertainty as to whether the ADS-B ground stations called for in the *NAS Architecture* document should be totally passive or should include an active capability
- Beacon multilateration is being developed as a surveillance system on the airport surface for use with ATCRBS aircraft and as a backup to ADS-B, but has not been fully evaluated for the en route and terminal domains
- Range and azimuth measuring systems using a fixed ground station antenna have also been suggested for ATCRBS aircraft surveillance and ADS-B backup, but also have not been fully evaluated.

There is a need for quantitative, verifiable cost and technical data to help resolve questions associated with the configuration of ADS-B and possible alternative ground stations. Such information is needed for defining cooperative/dependent surveillance ground stations for the Flight 2000 program, the Gulf of Mexico, and the future CONUS surveillance architecture.

1.3 Objectives

The primary objective of this report is to present cost estimates for ten surveillance system alternatives. The architectures emphasize ADS-B, Air Traffic Control Beacon Interrogator (ATCBI),[3] and multilateration systems. Cost estimates presented herein are developed for use in

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[1] Cooperative surveillance makes use of replies from the aircraft transponder to interrogations from ground-based radars to measure aircraft range and azimuth.

[2] Dependent surveillance uses position and other information which is collected by the aircraft GPS navigation system and sent to the ground via the aircraft transponder.

[3] The terms ATCBI (without model number) and Monopulse SSR (MSSR) are used interchangeably herein. Selective Interrogation (SI) and Ground Initiated Communication Mode B (GIC-B) capabilities, when implemented, are explicitly stated.

comparing technologies, rather than programs. Certain specific costs germane to a program — e.g., effect of procurement schedule and time value of money — are neglected. This report also presents technical information on the performance of systems, particularly those employing multilateration.

1.4 Approach

If the architecture described in Reference 1 — with ADS-B as the end-state principal surveillance system — is adopted, a second surveillance system will be needed to work in parallel with ADS-B, for the following reasons:

- It is standard practice that, in IFR airspace, both primary and backup surveillance systems be deployed
- GPS will serve as the principal source of aircraft position information for both ADS-B surveillance and navigation, and thus will be a common point of failure for these two major functions
- A surveillance system is needed that will serve non-ADS equipped aircraft during transition
- ADS-B can be easily spoofed — an ADS transponder simply relays to the ground any purported GPS information provided to it.

The ADS-B complementary system can either be an extension of the ADS-B system (i.e., uses the same sites and equipment to a significant extent), or can be an entirely separate system.

Table 1-1 provides an overview of the ten alternatives that are considered. The approach to identifying ADS-B and complementary surveillance system configurations is to start with the simplest form of an ADS-B ground system — i.e., Alternative 1, involving a passive ground station with no method for validation — and to build on that base. Extensions to the simplest ADS-B system include: employing techniques for validating GPS information provided via ADS-B (Alternatives 2 and 3); adding fixed-antenna range-azimuth measuring systems (Alternatives 4 and 5); adding passive and active multilateration capability to the ADS-B stations (Alternatives 6 and 7); and employing a monopulse secondary surveillance radar (MSSR) along with ADS-B (Alternative 8). Additionally, Alternatives 9 and 10 include an MSSR but not an ADS-B ground station.

Table 1-1. En Route Surveillance System Alternatives

#	Principal Surveillance System	Complementary Surveillance System	Complementary System Implementation
1	ADS-B	None (no validation)	Not applicable
2	ADS-B	None (partial validation)	Not applicable
3	ADS-B	None (Full validation)	Not applicable
4	ADS-B	Range-Azimuth-Altitude Surveillance	Integrated into ADS-B station
5	ADS-B	Range-Azimuth-Altitude surveillance	Separate station
6	ADS-B	Passive Multilateration	Integrated into ADS-B station
7	ADS-B	Active Multilateration	Integrated into ADS-B station
8	ADS-B	ATCBI ADS/GIC-B & ATCBI MSSR	Separate ATCBI
9	ATCBI ADS/GIC-B	ATCBI MSSR	Same ATCBI provides dual capabilities
10	ATCBI MSSR	None	Not applicable

Alternatives 4 through 8 have a surveillance system which is complementary to ADS-B and utilizes the aircraft transponder. In each case, the complementary system performs the functions itemized at the beginning of this section: ADS-B backup (particularly against GPS failures), ATCRBS aircraft surveillance, and ADS-B validation.

1.5 Report Overview

Chapter 2 presents technical background and performance considerations for the systems considered herein. Chapter 3 describes the alternatives shown in Table 1-1 in greater detail. Chapter 4 presents estimates of FAA costs for each alternative. Appendix A contains technical material on multilateration system's dilution of precision (DOP), which is a major determinant of their accuracy. Appendix B describes beacon multilateration system capacity projections. Appendix C presents detailed descriptions of the elements of the cost breakdown structure used for estimating costs.

2. System Performance Considerations

2.1 Overview of Concepts

A summary of the ten alternative en route surveillance architecture concepts investigated is provided in Table 2-1.

- Column 1 is a numerical identifier.
- Column 2 contains a brief description of each concept.
- Column 3 details the way in which the 1090 MHz surveillance frequency is used — i.e., mode and method of initiating aircraft transmissions. Both passive (squitter only) and active (interrogate-respond) techniques are employed, and Mode A/C/S formats are used.
- Column 4 describes the nature of the cooperative information available at the ground station — i.e., the "axes" involved and whether the information quality is sufficient for surveillance or can only be used for validating ADS information from the aircraft navigation system.
- Column 5 identifies the principal and complementary surveillance systems. The principal system is the one with the highest accuracy and update rate capabilities.
- Column 6 describes the equipment at the ADS-B ground station.
- Column 7 describes the equipment at the non-ADS-B station, for those architectures having a separate ground station for the complementary system.
- Column 8 identifies the type of aircraft transponder required for the alternative being considered. For example, for architectures that require Mode S extended squitter to perform surveillance (see Alternatives 1, 2, 3) all aircraft must carry a Mode S extended squitter transponder.
- Column 9 depicts the type of air traffic services that may be provided for each alternative. These service capabilities range from simple VFR flight following to full radar separation services.

The equipment for the ground station associated with each alternative is described in Chapter 3. This chapter presents material on the performance (coverage, accuracy and capacity) of the concepts; these influence equipment characteristics and the number of systems.

Table 2-1. En Route Surveillance Architecture Alternatives

#	Surveillance System Description	Operating Modes	Cooperative Surveillance Information§	Principal / Comple'ry Systems	ADS-B Station Equipment†	Separate Station Equipm't‡	Aircraft Trans-ponder	ATC Operational Services
1	ADS-B* without verification	Mode S extended squitter	None	ADS-B / None	Sectored ant., 1090 Mode S Rcvr, Computer	None	Mode S w/ extended squitter	VFR flight follow; IFR non-radar proc w/ auto pos reports
2	ADS-B* with coarse azimuth & altitude verification	Mode S extended squitter	Altitude and azimuth validation	ADS-B / None	Same as #1	None	Mode S w/ extended squitter	VFR flight follow; IFR services pseudo radar
3	ADS-B* with active range & coarse az-alt verification	Mode S ext squitter + Mode S interrog-respond	Range, azimuth, and altitude validation	ADS-B / None	Same as #1 + integral 1030 Mode S Xmtr	None	Mode S w/ extended squitter	VFR flight follow; IFR services pseudo radar
4	ADS-B* + range-az-alt surveil with same antenna	Mode S ext squitter + Mode A/C/S interrog-respond	Range, azimuth, and altitude surveillance	ADS-B / range-az-alt	Like #3, ex Xtr/ Rvr Mode A/C/S & monopulse	None	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services pseudo radar
5	ADS-B* + range-az-alt surveil w/TCAS-like system	Mode S ext squitter + Mode A/C/S interrog-respond	Range, azimuth, and altitude surveillance	ADS-B / range-az-alt	Same as #1	TCAS on ground	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services pseudo radar
6	ADS-B* + passive multilatat surveil w/ same station	Mode A/C and Mode S short/ext squitter	x, y, and altitude surveillance	ADS-B / Multilat-eration	Like #1, ex Rcvr Mode A/C/S + Clock + 2d Comp	None	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services full radar
7	ADS-B* + active multilat surveil w/ same station	Mode S ext squitter + Mode A/C/S squit & interrog-resp	x, y, and altitude surveillance	ADS-B / Multilat-eration	Like #3, ex Xtr/ Rvr Mode A/C/S + 2d Comp	None	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services full radar
8	ADS-B* + ATCBI GIC-B* & range-az-alt surveil	Mode S ext squit + Mode S/GIC-B + Mode A/C/S int-resp	Range, azimuth, and altitude surveillance	ADS-B / GIC-B / SSR	Same as #1	ATCBI w/ SI & GIC-B	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services full radar
9	ATCBI GIC-B* & range-az-alt surveil	Mode S/GIC-B + Mode A/C/S interrogate-respond	Range, azimuth, altitude	GIC-B / SSR	None	ATCBI w/ SI & GIC-B	Ext squit for ADS-B, or Mode A/C/S	VFR advisories; IFR services full radar
1 0	ATCBI range-az-alt surveillance	Mode A/C interrogate-respond	Range, azimuth, altitude	SSR / None	None	ATCBI without SI & GIC-B	Mode A/C/S	VFR advisories; IFR services full radar

* ADS-B and GIC-B Information — ID, position, velocity, and intent; derived from aircraft navigation system or flight management system
§ Cooperative Surveillance Information — Not derived from aircraft navigation system or flight management system
† ADS-B Station Equipment — Includes enhancements to perform ADS-B validation and backup surveillance
‡ Separate Station Equipment — Equipment at a ground station separate from ADS-B facility, but possibly colocated with it

2.2 ADS-B Equipment and Performance

2.2.1 Concept Description

In its basic form, ADS-B is a ground-passive, air-to-air traffic avoidance and ground surveillance system based on aircraft broadcast of information obtained from the GPS satellite navigation system. The basic ADS-B system consists of a fixed ground antenna-receiver and avionics capable of broadcasting Mode S extended squitter messages (112 bits) on the 1090 MHz surveillance channel. ADS-B messages are defined in References 5 and 6, and contain aircraft identity, GPS position and velocity, barometric altitude, and intent information (e.g., next waypoints). The *NAS Architecture* (Reference 1) describes an ADS-B ground network comprising: approximately 20 gap filler sites in non-radar areas; approximately 96 other en route sites; 200 sites for covering 150 terminal areas; and, 600 sites for covering 150 airport surfaces.

2.2.2 Basic ADS-B Ground Station Equipment

Alternatives 1 through 8 include an ADS-B ground station. While each alternative involves some variation in the ADS-B ground station equipment capabilities and/or redundancy, the constituent elements of the basic ground station are identified here for reference purposes:

- A multi-sector antenna, to provide sufficient gain for the receiver to detect and decode squitters from aircraft at the station's maximum range of 100 nmi or more; 6 sectors is used for most alternatives
- A 1090 MHz Mode S receiver having a hardware channel for each antenna element and the capability to detect and decode, at a minimum, Mode S extended squitter messages
- A computer processor for data management and limited processing
- Modems for communication with one or more off-site surveillance servers or ARTCCs
- An uninterruptible power supply.

The basic 1090 MHz receiver only decodes Mode S signals. It does not decode Mode A/C formats, measure time-of-arrival of aircraft emissions, or harmonize its operation with a collocated transmitter. The RF hardware is assumed to have a minimum threshold level of -82.5 dBm, which is well within the current state-of-the-art. Link budgets for the receiver (Table 2-2) reveal margins of 11 dB for an aircraft at 100 nmi and 7.4 dB at 150 nmi.

Table 2-2. ADS-B Air-to-Ground Link Budgets

Link Element	Value (100 nmi)	Value (150 nmi)
Transmitter Power, 250 W	54.0 dBm	54.0 dBm
Aircraft Antenna Gain	0.0 dB	0.0 dB
Path Loss, 1090 MHz	-138.5 dB	-142.1 dB
Ground Antenna Gain, 6 sectors	13.0 dB	13.0 dB
Received Power	-71.5 dBm	-75.1 dBm
Receiver MTL*	-82.5 dBm	-82.5 dBm
Link Margin	11 dB	7.4 dB

* Minimum Triggering Level

2.2.3 Ground Station Coverage

En route ADS-B ground stations are assumed to be sited to provide coverage of aircraft above 6,000 feet in altitude. Figure 2-1 shows the visible range of aircraft, using a four-thirds earth propagation model, for various signal elevation angles at the ground antenna. If the antenna can

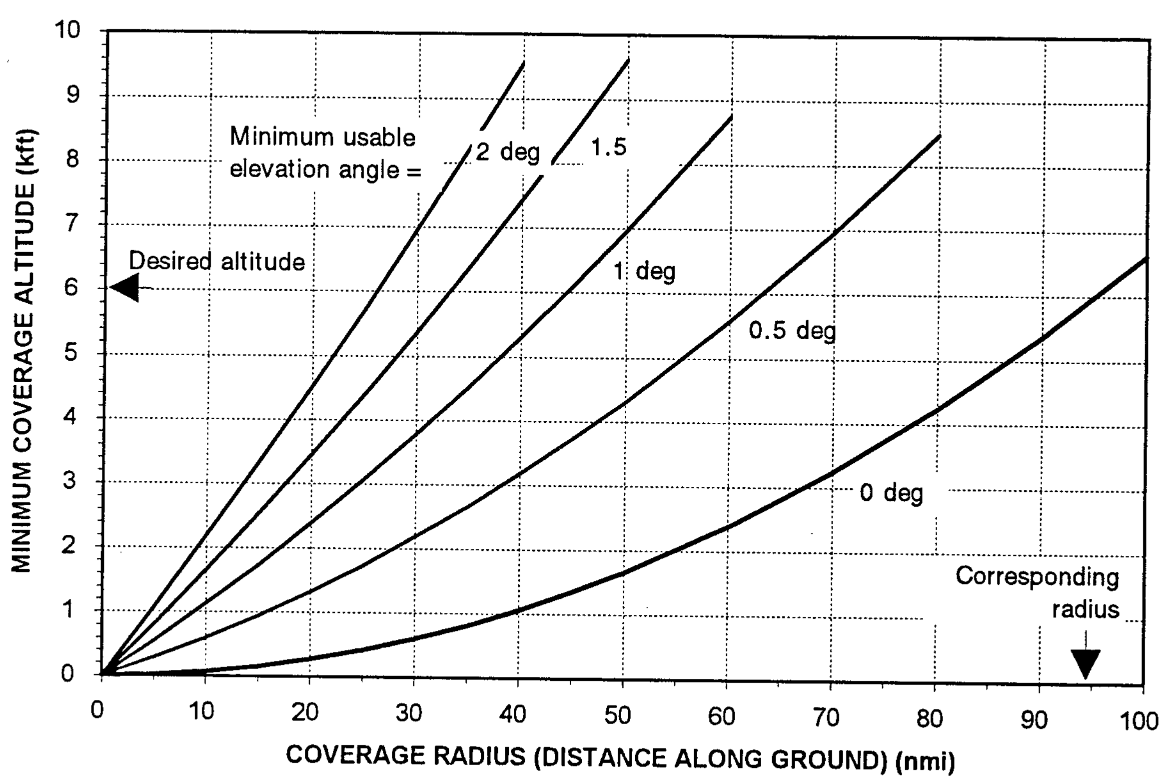


Figure 2-1. ADS-B Coverage Radius vs. Minimum Aircraft Altitude

"see" the horizon (i.e., 0 degrees elevation is applicable), the coverage radius for aircraft 6,000 ft and above is 95 nmi along the ground.

With their coverage radius specified, a rough estimate of the number and arrangement of the ground station can be calculated by neglecting terrain masking. Figure 2-2 shows the optimal ground stations arrangement: a hexagonal pattern with stations separated from their nearest neighbors by 164.5 nmi.

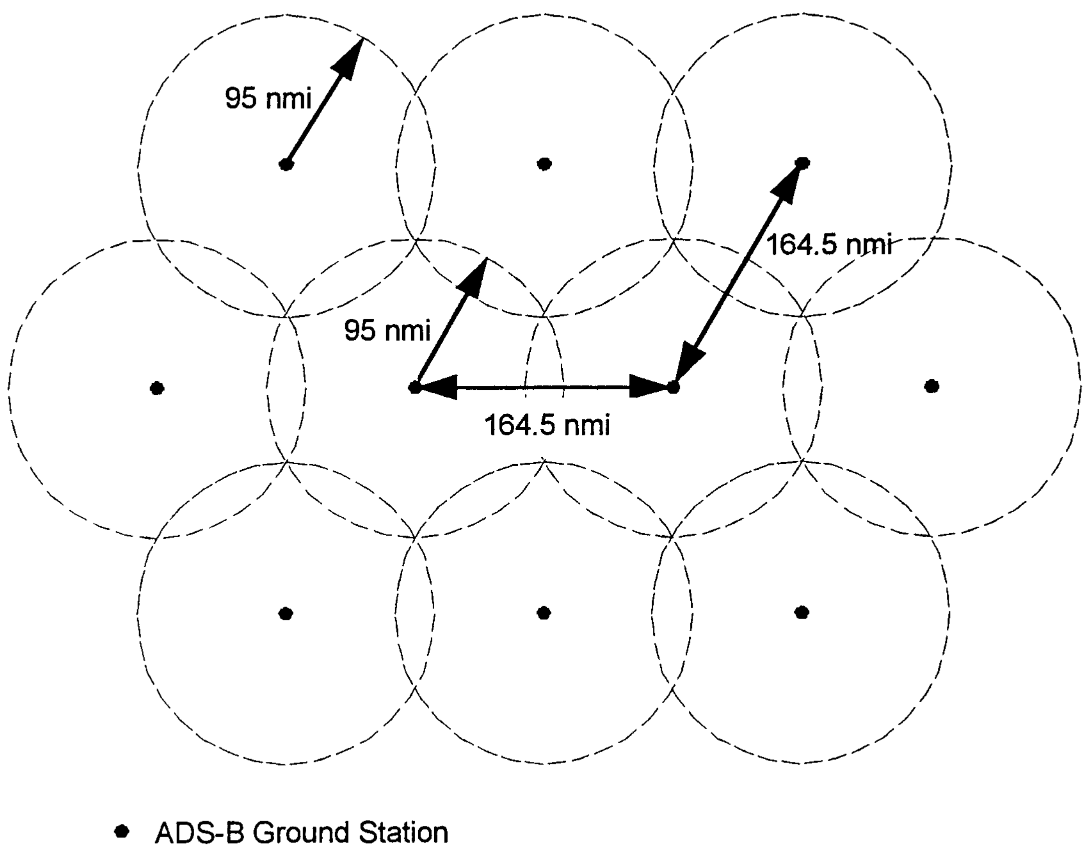


Figure 2-2. ADS-B Ground Station Grid and Coverage Regions for 6,000 feet Altitude

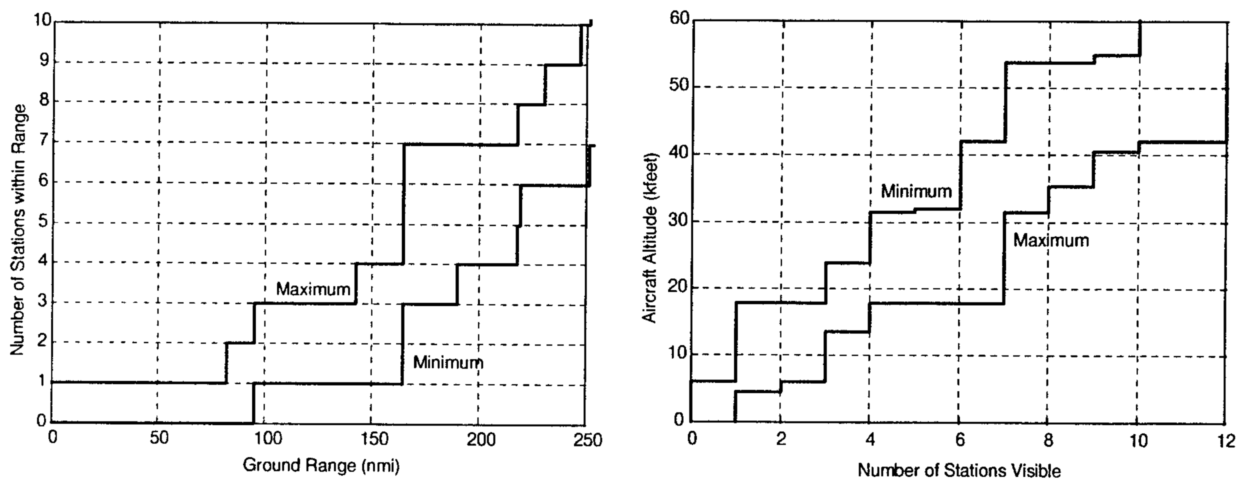
The station grid is assumed to be overlaid on CONUS, which is approximated by a rectangle with dimensions 3,000 smi by 1,000 smi. The number of stations along straight lines in the east-west and north-south directions, respectively, are approximately

$$N_{ew} = \frac{1}{2} + \left(3000 \times \frac{5280}{6076}\right) / 164.5 = 16.3 \qquad \textbf{Eq. 2-1}$$

$$N_{ns} = 1 + \frac{\left(1000 \times \frac{5280}{6076}\right)}{\left(164.5 \times \frac{\sqrt{3}}{2}\right)} = 6.9 \qquad \textbf{Eq. 2-2}$$

The product of N_{ew} and N_{ns} is 112.5. Cost estimates herein are based on 116 ADS-B ground stations, the planning number in the *NAS Architecture* document (Reference 1).

The number of ground stations visible to an aircraft depends upon its altitude and location relative to the station grid. Figure 2-3 shows the minimum and maximum number of stations (a) within a circle on the ground of a given radius centered at the aircraft location, and (b) visible to the aircraft as a function of its altitude. Redundant coverage is ensured above 18,000 ft.



(a) Versus. Horizontal Distance (b) Versus Altitude

Figure 2-3. ADS-B Ground Station Coverage Redundancy

2.2.4 ADS-B Accuracy

ADS-B does not perform a measurement of aircraft position which is independent of the information obtained from GPS. Therefore, ADS-B accuracy is that of the GPS system used by the aircraft. Three GPS variants may provide data to ADS-B:

- Unaugmented GPS — Only C/A code signals from the 24 satellite GPS constellation installed and maintained by the Department of Defense are utilized. Currently, these signals are intentionally degraded by the Selective Availability (SA) mechanism.
- GPS/WAAS — GPS signals are augmented by signals from FAA Wide Area Augmentation System (WAAS) satellites.
- GPS/LAAS — GPS signals are augmented by signals from the FAA Local Area Augmentation System (LAAS).

WAAS will consist of 2 to 5 geostationary satellites broadcasting on the GPS L1 frequency and a ground infrastructure of Reference Stations, Master Stations, and Uplink Stations. WAAS satellites will broadcast additional ranging signals (similar to those from the GPS satellites), differential corrections to errors which degrade GPS, and information concerning the integrity of GPS/WAAS navigation. WAAS signals will be available throughout the U.S., and may be extended to other counties. WAAS is now under contract for development; it is scheduled to be placed in service between mid-1999 (phase 1) and late-2001 (phase 3).

LAAS will be installed at airports, and will be usable within a radius of 20 to 30 nmi. A LAAS system consists of several GPS receivers on the airport, processing capabilities, a VHF transmitter which broadcasts differential corrections, and a variable number of pseudolites (ground-based transmitters of GPS-like signals). LAAS is scheduled to be introduced between 2003 (Initial Operational Capability, IOC) and 2006 (Full Operational Capability, FOC).

Accuracy figures for GPS and its augmented versions may be found in many places, and vary depending upon the conditions and applications. Table 2-3 presents figures from official sources, with the exception of GPS Unaugmented with SA (Selective Availability) deactivated, for which official figures are not available. Official accuracies for WAAS and LAAS are based on the requirements for specific operations, and may overstate the errors most user will experience. For example, the geometry of the GPS satellites favors the horizontal axes over the vertical by approximately the 1.6:1 ratio seen in the table for GPS Unaugmented. A similar ratio is expected to apply to the WAAS, which also only involves signals from satellites. Assuming

Table 2-3. Official GPS Accuracies

GPS Variant	Accuracy (95%)		Information Source
	Horizontal	Vertical	
GPS Unaugmented, SA on*	328 ft	515 ft	Ref. 7
GPS Unaugmented, SA off*	98 ft	154 ft	Ref. 8
GPS/WAAS	25 ft	25 ft	Ref. 9
GPS/LAAS, Facility Type 1	30 ft	13 ft	Ref. 10
GPS/LAAS, Facility Type 2	23 ft	7 ft	Ref. 10
GPS/LAAS, Facility Type 3	20 ft	7 ft	Ref. 10

* SA = Selective Availability, the intentional degradation of GPS C/A code accuracy; will be phased out by 2006, per Presidential Decision Directive in 1996.

the vertical specification to be correct, this ratio would result in a horizontal accuracy of 16 ft.

2.3 Multilateration Performance

2.3.1 Concept Description

Beacon multilateration is the determination, on the ground, of aircraft position based on the reception of 1090 MHz transmissions from the aircraft at multiple ground stations. ATCRBS (Modes A and C), Mode S short or extended, and ADS-B formats may be used. Each station measures aircraft range or the time of arrival (TOA) of an aircraft signal; aircraft position is determined by joint processing of the measurements (not by decoding information in the received signals). Table 2-4 summarizes the "pros" and "cons" of multilateration surveillance, with entries listed in approximate decreasing order of importance.

Passive Multilateration — Passive multilateration is implemented by measuring the TOA of the same aircraft transmission at multiple ground stations. Three ground station systems enable determination of the aircraft's horizontal position based on the intersection of two hyperbolas (Reference 15). Altitude must be obtained by decoding aircraft Mode C transmissions. Four or more ground stations allow the aircraft's three-dimension position to be determined, although vertical accuracy is generally significantly poorer than horizontal. The basic passive concept discussed herein employs decoded Mode C altitude information.

Transmissions from ATCRBS aircraft can be replies to SSR interrogations or unelicited squitters. However, not all current transponders can be relied upon to squitter in the absence of interrogations. Thus, in the near term, passive multilateration processing would likely require ground stations with 1030 MHz interrogation capability.

Ground stations whose TOA measurements are processed jointly must have closely synchronized clocks. For the surface domain, relatively low-accuracy clocks can be used if they are regularly (e.g., several times a minute) re-synchronized using a fixed transponder in view of all ground stations. However, due to the distances involved, a common fixed site cannot be used in the en route domain. High accuracy clocks must be placed at each station. In this analysis it is assumed that a GPS receiver which is optimized for time-keeping forms part of the equipment

Table 2-4. Multilateration "Pros" and "Cons"

"Pros"	"Cons"
• Use of range-like measurements exclusively results in high accuracy • Absence of large, scanning ground antenna – Reduces cost – Improves reliability – Reduces siting difficulties • Provides aircraft identification • Ground stations are passive for some variants – Can site near populated areas – Transponder turn-around variations do not cause position errors • Ground station equipment has ADS-B capability – Triple ADS-B en route coverage for 6,000 ft altitude (no terrain) – Single ADS-B coverage at 2,000 ft altitude (no terrain) • Serves all aircraft with ATCRBS, Mode S or ADS-B transponder – Active ground station — No transponder modification – Passive ground station — new or modified ATCRBS transponder may be needed • High capacity • Robust – Tolerates failure of some ground stations or inter-station communications links – Not spoofable	• Three-to-one increase in number of ground stations – Increased equipment cost, partially offset by reduced need for redundancy at stations – Increased site acquisition and maintenance costs • Significant inter-station communications • Less mature than radar technology

complement at each station. An associated Rubidum standard, which enables coasting through satellite outages, is also used.

Active Multilateration —Active multilateration involves the use of at least some ground stations with transmit and receive capabilities similar to TCAS avionics — i.e., interrogation of aircraft on 1030 MHz, and reception of replies on 1090 MHz. In the most straightforward approach, each station separately interrogates an aircraft to obtain a range measurement. Joint processing of the measurements enables the aircraft position to be determined. Two active stations can determine aircraft horizontal position based on the intersection of two circles. The solution is accurate in the regions on either side of the baseline joining the stations. However, position errors approach infinity along the baseline. To provide coverage without restrictions on flight paths, three stations must be visible to an aircraft. A fourth station allows determination of both horizontal and vertical position, but vertical accuracy is generally inferior to barometric altitude information.

An alternative active concept has one active and two passive stations as its basic "building block." The basic measurements are the elapsed time between the active station interrogation and reception of the aircraft response at the three stations. Joint processing determines the aircraft location based on the intersection of either a sphere and two ellipsoids (three-dimensional solution) or the intersection of a circle and two ellipses (two-dimensional solution).

2.3.2 Multilateration Coverage

Figure 2-4 illustrates the ground station arrangement which, for a smooth earth, provides multilateration coverage for all aircraft above 6,000 ft and also provides triple ADS-B coverage. The station configuration may be thought of as a grid of equilateral triangles. The triangle side length is the distance that will provide coverage from a given station of the airspace above each adjacent station. For a minimum coverage altitude of 6,000 ft, the station separation is 95 nmi. Using calculations similar to Eqs. 2-1 and 2-2 (with 95 in place of 164.5), the total number of ground stations is found to be 348.

The number of ADS-B/multilateration ground stations visible to an aircraft depends upon its altitude and location relative to the station grid. Figure 2-5 shows the minimum and maximum number of stations (a) within a given distance along the ground from the aircraft location, and (b) visible to the aircraft as a function of altitude. Highly redundant ADS-B and multilateration coverage is available

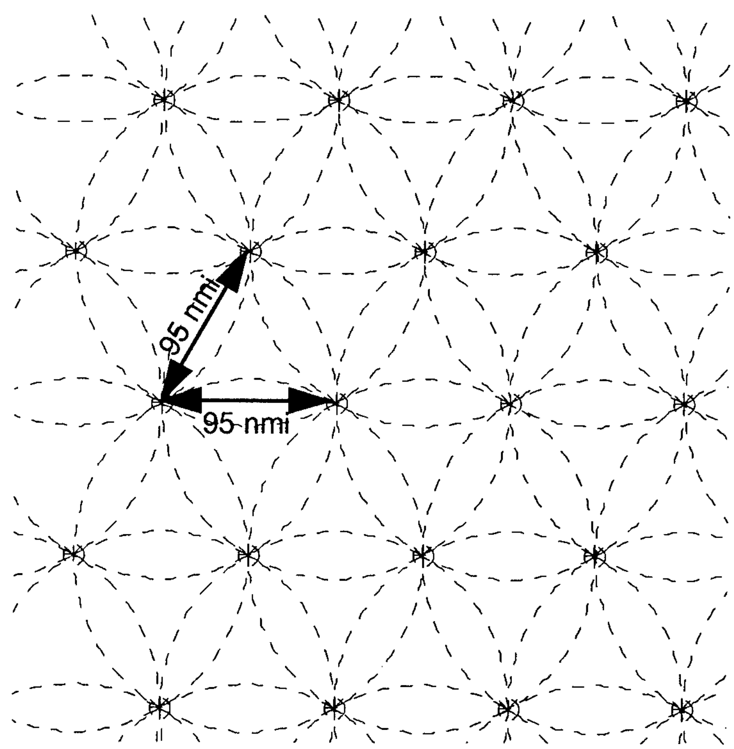
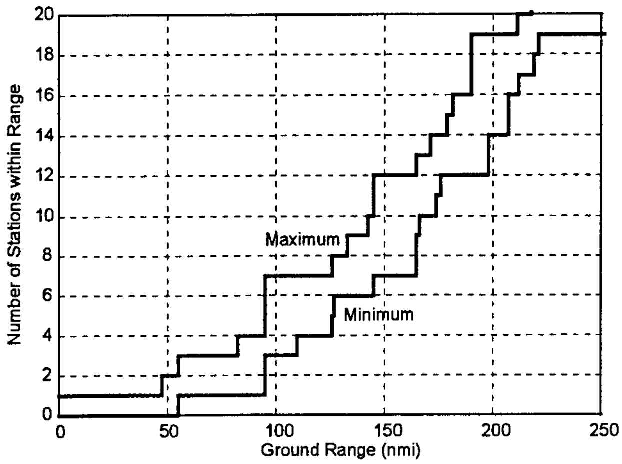
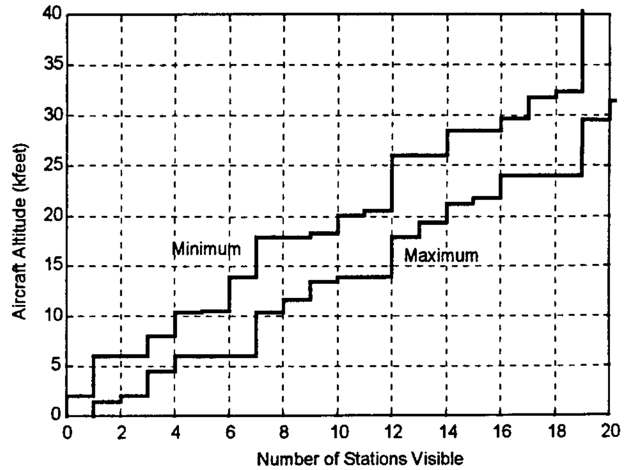


Figure 2-4. ADS-B/Multilateration Ground Station Grid and Station Coverage Regions for 6000 feet



(a) Horizontal



(b) Vertical

Figure 2-5. ADS-B/Multilateration Ground Station Coverage Redundancy

at altitudes above 6,000 ft — e.g., 4 to 7 stations are visible at 10,000 ft; 7 to 12 stations are visible at 15,000 ft; and 10 to 14 stations are visible at 20,000 ft.

2.3.3 Multilateration Accuracy

The accuracy of a multilateration system is, to a good approximation, given by

Horizontal error = HDOP x range measurement error **Eq. 2-3**

Vertical error = VDOP x range measurement error **Eq. 2-4**

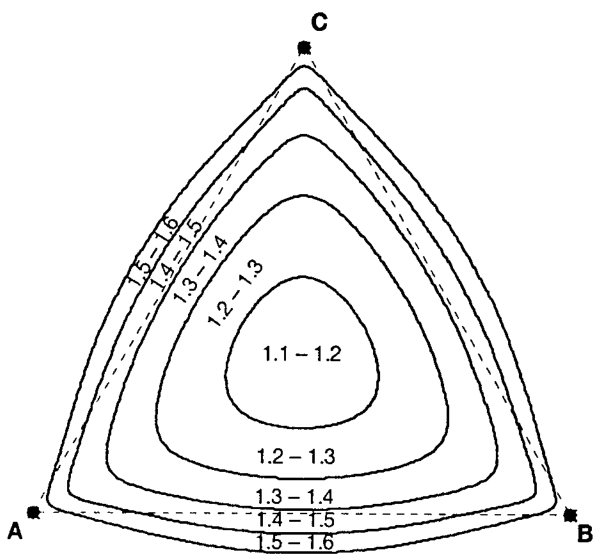
where DOP stands for dilution of precision. Only Eq. 2-3 is applicable for a system which determines altitude by decoding Mode C barometric altitude messages. The range measurement error defines the basic system capability. HDOP and VDOP, which are almost always greater than 1, amplify the range measurement error.

For a passive multilateration system, range measurement error is almost entirely attributable to the ground station clock, and is 79 ft. (95%) when a GPS/Rubidum combination is used (Reference 11). Active multilateration range measurement error depends on whether ATCRBS or Mode S equipment is used on the ground and in the aircraft. Table 2-5 gives figures for various combinations of SSR equipment. ATCRBS transponder turn-around error is approximately 4.5 times that of a GPS/Rubidum clock, and is a major reason for the FAA's ATIDS program choosing the passive multilateration technique.

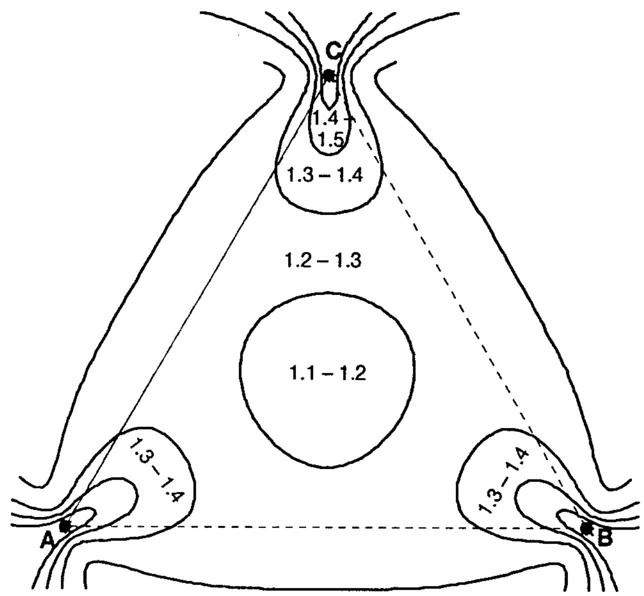
Table 2-5. SSR Range Measurement Errors (95%)

Ground Interrogator	Aircraft Transponder	
	ATCRBS	Mode S
ATCRBS	379 ft	91 ft
Mode S	372 ft	50 ft

HDOP and VDOP only depend upon: (1) whether the active or passive technique is employed, (2) the number of stations visible to the aircraft, and (3) aircraft position relative to the station grid. Figure 2-6 shows HDOP contours when consideration is limited to only three stations; within the triangle, these are the HDOPs that an aircraft at 6,000 ft would experience. HDOPs for the passive and active techniques are comparable, although those for the active technique are slightly better. Both are considered good.



(a) Passive



(b) Active

Figure 2-6. Three-Station Multilateration HDOPs (Altitude Obtained via Mode C)

A detailed analysis of passive multilateration DOPs was conducted during this effort. Results of that analysis are presented in Appendix A; their consequences for position accuracy are summarized in Table 2-6. In the absence of ground station failures, maximum horizontal error at 6,000 ft is 119 ft (95%), considerating all possible aircraft locations relative to the stations. Smaller errors are incurred at higher altitudes, where more stations are visible. Redundant ground stations also enable multilateration to be used when some stations fail.

Table 2-6. Passive Multilateration System Position Errors*

Maximum Reception Range	Minimum Aircraft Altitude	Minimum No. Visible Stations	Ground Station Failure Status: 0 Failures	1 Failure	2 Failure
			Maximum† Horizontal Error (95%)		
95 nmi	6,000 ft	3	119 feet	—	—
110 nmi	8,000 ft	4	87 feet	198 feet	—
126 nmi	11,500 ft	5	79 feet	103 feet	316 feet
			Maximum† Vertical Error (95%)		
110 nmi	8,000 ft	4	2,607 feet	—	—
126 nmi	11,500 ft	5	2,133 feet	—	—

*TOA measurement error = 79 nsec (95%) (VDOP is infinite directly over a station)
†Maximum considering all aircraft positions within coverage region

A comparable DOP analysis was not performed for active multilateration. However, since active DOPs will always be smaller than passive DOPs, an upper (i.e., pessimistic) bound on active system errors can be computed by multiplying the passive errors by the ratio of the range measurement errors. For example, with no station failures and 8,000 ft of altitude, the maximum horizontal error for an ATCRBS-equipped aircraft would be no greater than 87 ft x (372/79) = 410 ft (95%).

2.3.4 Multilateration System Capacity

Estimates of the capacity of the 1090 MHz frequency to support multilateration were generated using a Poisson model for interfering FRUIT (False Replies Unsynchronized In Time, see Reference 12). Only ATCRBS emissions are considered herein; a more thorough analysis that includes Mode S short and extended messages is presented in Appendix B.

ATCRBS multilateration capacity is defined herein as the number of aircraft that can be accommodated by a set of three ground stations, based on a 99% probability that at least one

Mode C transmission is successfully received at all three stations within the update interval specified for the flight regime involved. The calculations assume that ATCRBS emissions are divided equally among Mode A and Mode C formats; thus, there is also a 99% probability of receiving a Mode A transmission at the three stations. Three update intervals are considered: surface, 1 sec; terminal, 5 sec; and en route, 10 sec. Coverage redundancy, which is ensured for aircraft above 8,000 ft, increases the probability that an aircraft transmission is received by at least three stations but is not taken into account.

Table 2-7 lists the two 1090 MHz environments considered herein: Near-Term Worst Case, representative of the highest activity observed in major metropolitan areas prior to widespread installation of Mode S SSRs; and Post 2015, which assumes that all ground-based ATCRBS radars are phased out. These scenarios were employed in conjunction with both omni-directional and six-sector ground station antennas. Results are shown in Figures 2-7 (Near-Term Worst Case) and Figure 2-8 (Post 2015 Case), and provide reasonable limits on beacon multilateration capacity. In these figures, the bottom axis pertains to an omni-directional ground station antenna, and the top to a six-sector antenna.

Table 2-7. 1090 MHz Environments (transmissions/second/aircraft)

Near-Term Worst-Case
120 ATCRBS (100 replies to ground radars; 20 replies to TCAS)
8 Mode S Short (2 replies to ground radars; 5 replies to TCAS; 1 squitter)
8 Mode S Extended (4 replies to a ground system; 4 ADS-B squitters)
Post 2015 Case
20 ATCRBS (20 replies to TCAS and ADS-B/multilateration ground stations)
8 Mode S Short (2 replies to ground radars; 5 replies to TCAS; 1 squitter)
8 Mode S Extended (4 replies to a ground system; 4 ADS-B squitters)

Mode C multilateration capacity for the Near-Term scenario with six-sector antenna ground stations — 524 aircraft in the surface regime, 795 in the terminal area, and 903 in the en route regime — appears to be sufficient for virtually all locations. Post 2015 capacities are larger for en route and terminal regimes, but is lower (399 aircraft, for six-sector antennas) for the surface regime.

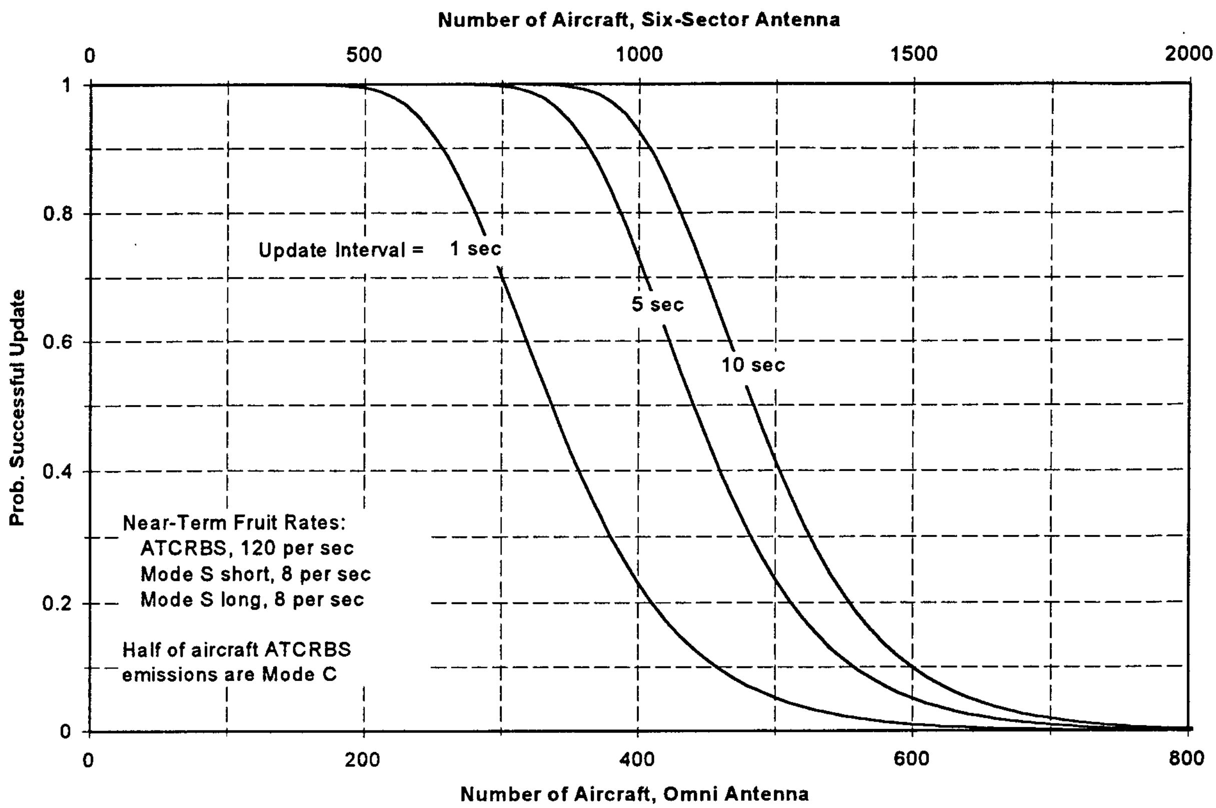


Figure 2-7. Mode C Multilateration Update Probability: Near-Term Case

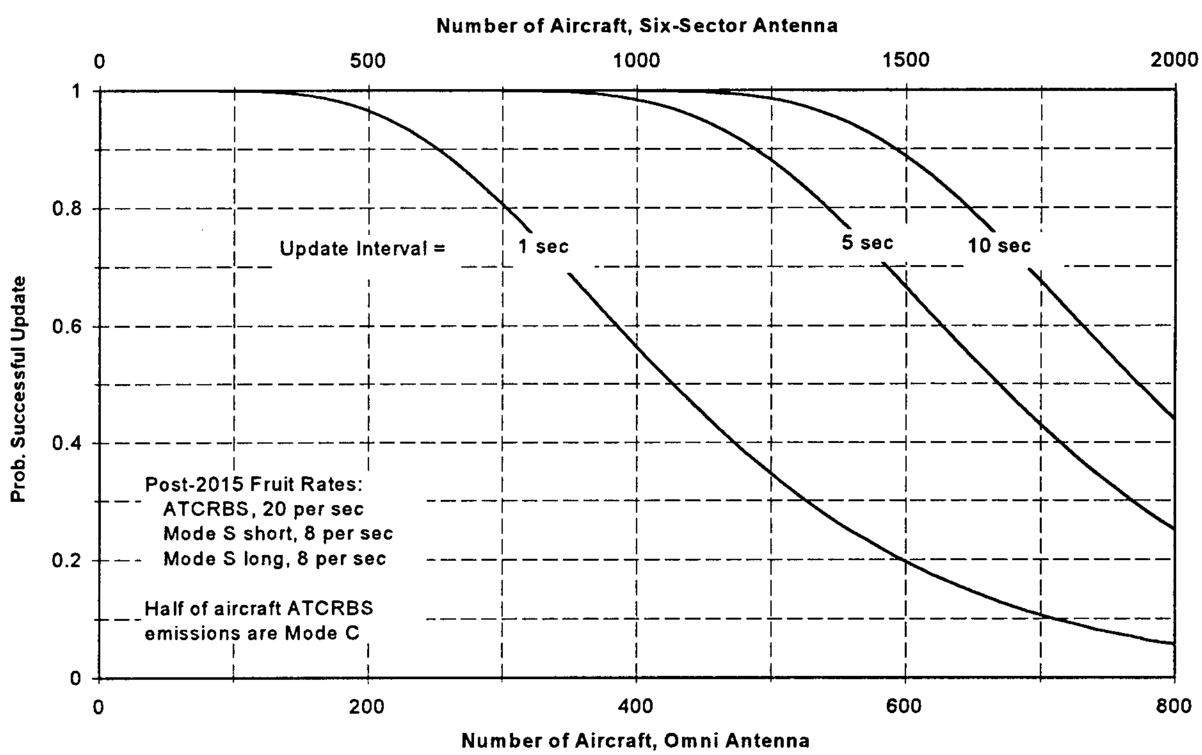


Figure 2-8. Mode C Multilateration Update Probability: Post 2015 Case

Changing the 1090 MHz ATCRBS emission rate has two conflicting effects. For example, reducing the rate decreases the amount of interference from other aircraft, but also decreases the number of opportunities for obtaining an emission in the clear from the desired aircraft. This phenomenon is quantified in Figure 2-9, which displays Mode C multilateration capacity versus aircraft ATCRBS 1090 MHz emission rate for update intervals of 1, 5, and 10 sec. The left-hand axis pertains to an omni-directional antenna, and the right-hand axis to a six-sector antenna. Peak capacities are given in Table 2-8, and correspond to emissions rates between 30 and 64 per second, with higher rates corresponding to shorter update intervals.

For the Near-Term scenario, Mode C multilateration capacity is limited by the high emissions rates caused by ground radar interrogations. In the Post-2015 scenario analyzed, capacity is limited by insufficient aircraft emissions. The later result provides guidance for setting emissions rates for new ATCRBS transponders with squittering capability and/or for setting ADS-B/multilateration ground station interrogation rates.

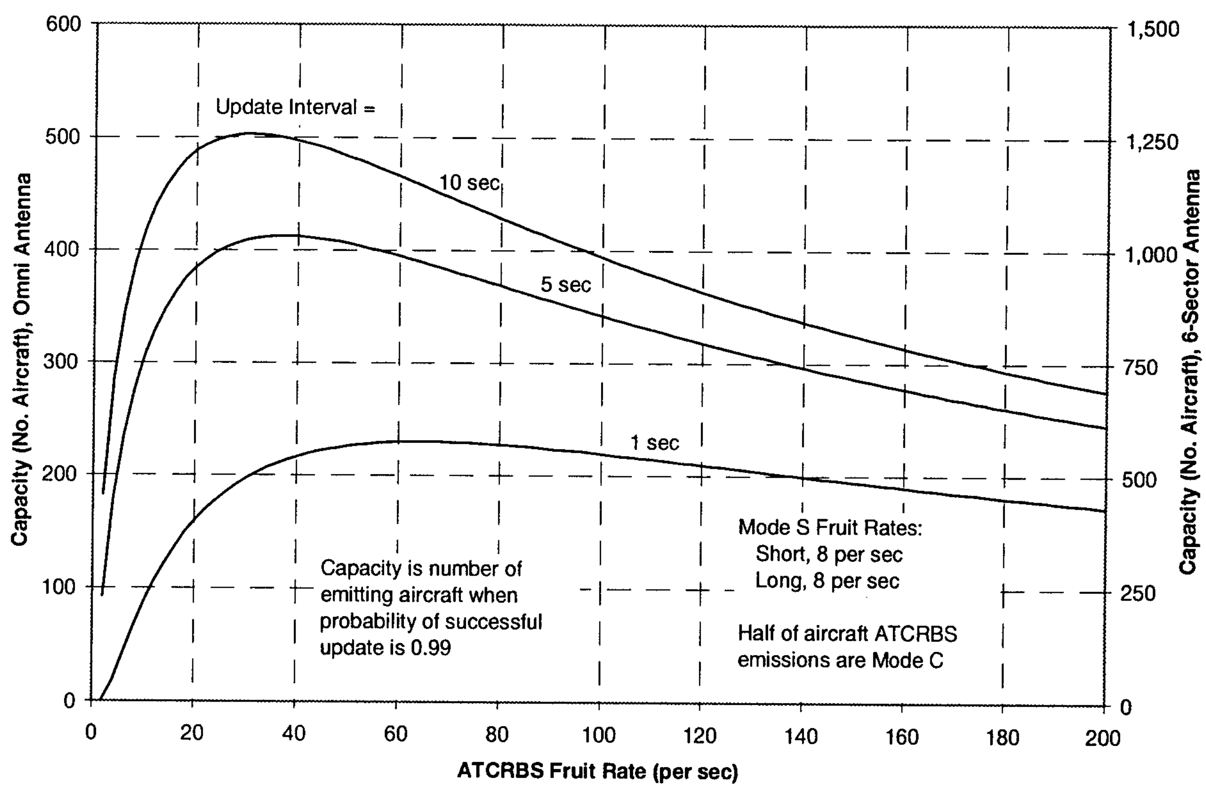


Figure 2-9. Mode C Multilateration Capacity vs. ATCRBS Fruit Rate

Table 2-8. Mode C Multilateration Peak Capacities and Emissions Rates*

Update Interval	ATCRBS Emissions	Capacity, Omni Antenna	Capacity, 6-Sector Antenna
1 sec	64 / sec	230	576
5 sec	38 / sec	412	1,031
10 sec	30 / sec	503	1,257

* Half of ATCRBS emissions are Mode C; Mode S Extended emissions are 8 per second

3. Description of Alternatives

3.1 Alternative 1: ADS-B without Validation

This is the simplest ADS-B configuration (Figure 3-1): Surveillance information is only obtained from an unelicited broadcast of ADS Mode S messages from the aircraft on 1090 MHz. The ground station equipment is similar to that for the basic station described in Section 2.2, except that there is a redundant copy of the active electronics (1090 MHz receiver, computer and modem). User aircraft are required to be equipped with Mode S transponders with extended

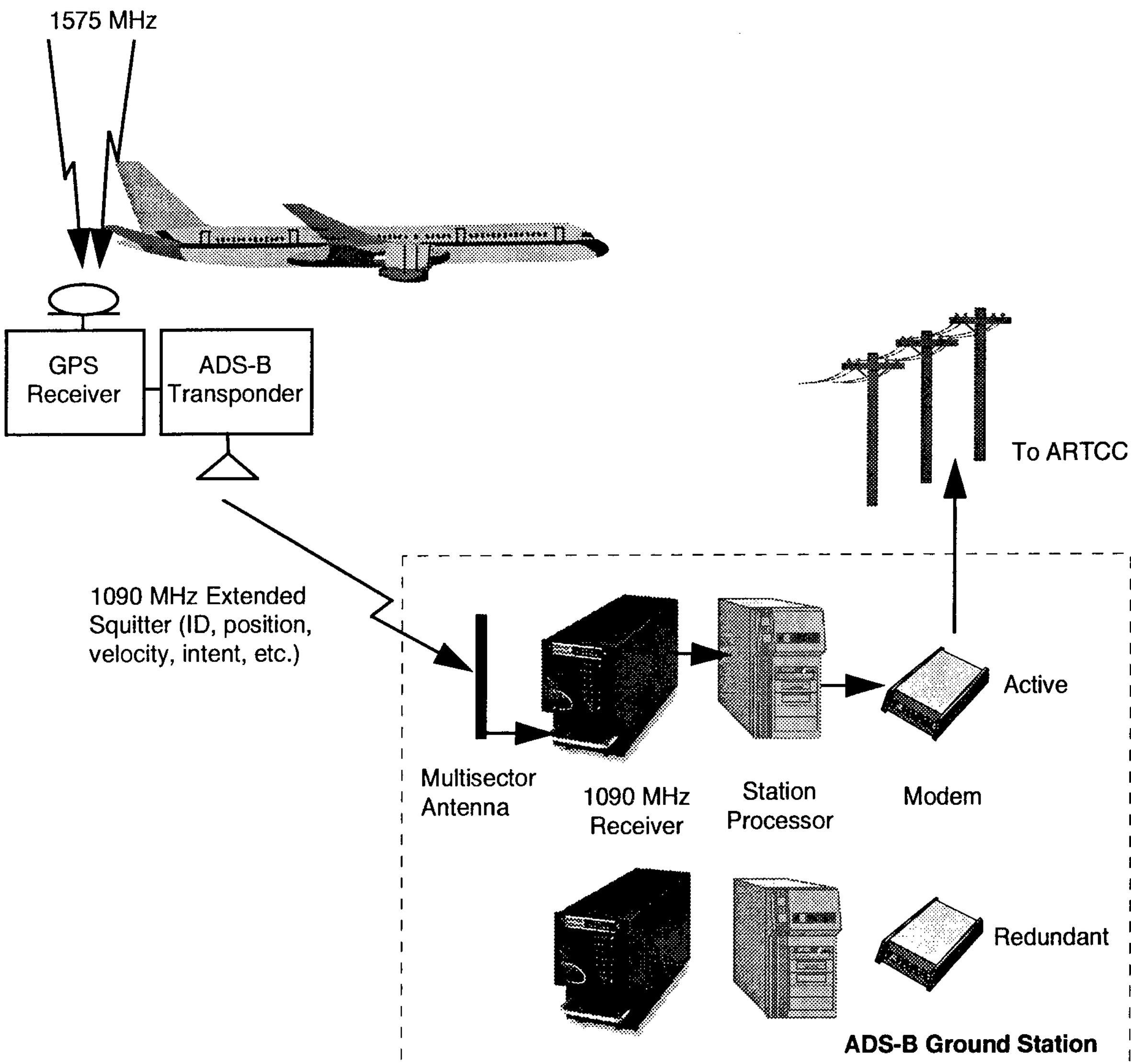


Figure 3-1. Alternative 1: ADS-B without Validation

squitter capability. There is no validation of the GPS information provided to the surveillance system, and there is no complementary surveillance capability for obtaining data independent of the GPS-derived information. In terms of Air Traffic Control services, Alternative 1 ADS-B reports can support VFR flight following and IFR non-radar procedures.

3.2 Alternative 2: ADS-B with Partial Validation

Alternative 2 (Figure 3-2) is identical to Alternative 1, except it has the additional capability of partially validating the ADS-B information. Crude partial validation is accomplished by comparing: (1) the aircraft azimuth calculated from the GPS position data with the antenna sector(s) on which the squitter was received, and (2) the GPS-derived altitude with the aircraft's barometric altitude. Since the receiver has a channel for each ground station antenna element, crude azimuth determination can be done by simply noting the channel(s) on which a target is observed.

For altitude validation, the aircraft must transmit both GPS and barometric altitude information in Mode S extended squitter messages. Azimuth validation provides partial protection against both GPS blunders (e.g., "stuck bit" in the avionics processing) and spoofing, while altitude validation only provides protection against GPS blunders. Alternative 2 ground station equipment is virtually identical to that for Alternative 1. In terms of Air Traffic Control services, Alternative 2 ADS-B reports can support VFR flight following and IFR pseudoradar procedures.

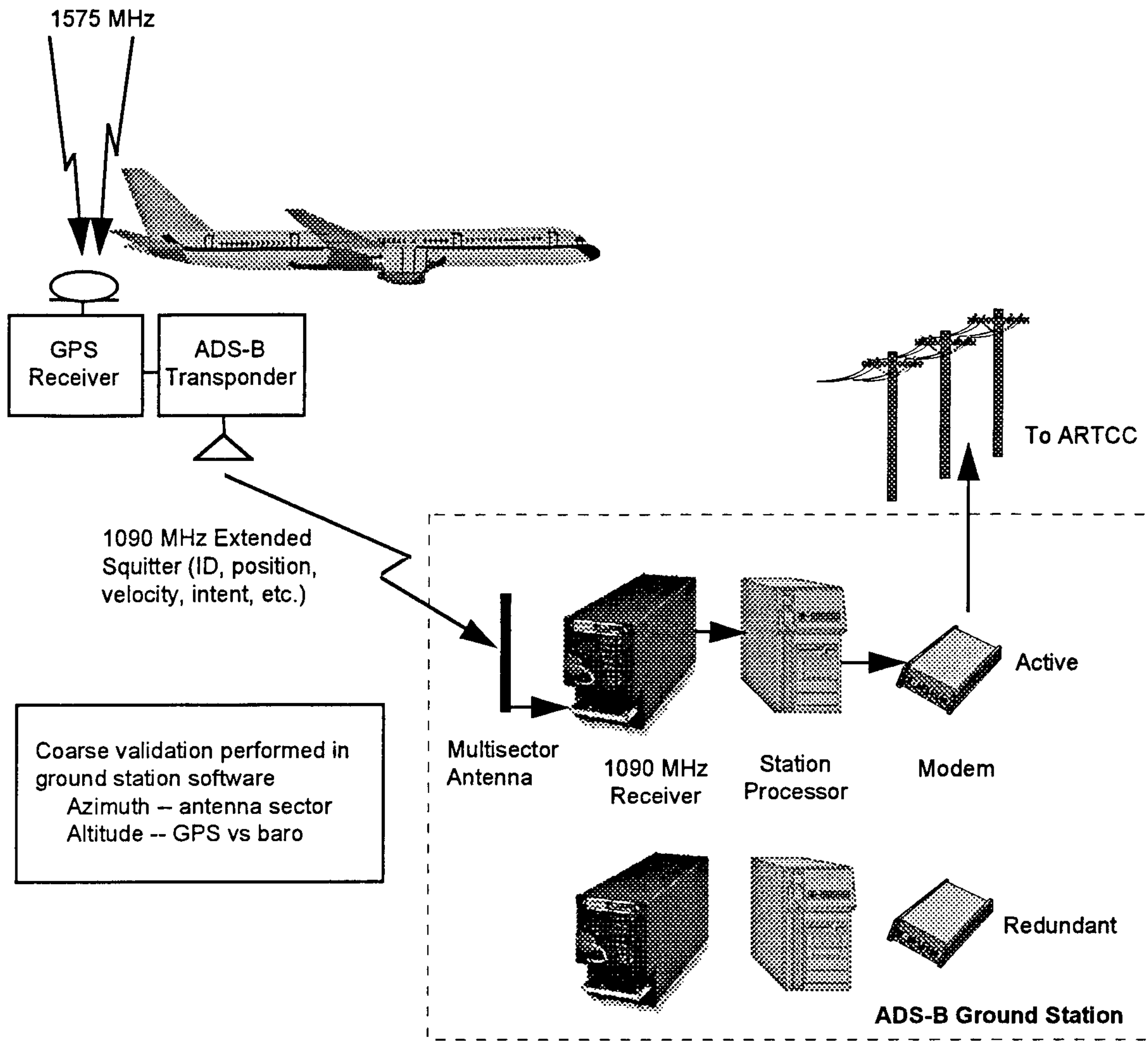


Figure 3-2. Alternative 2: ADS-B with Partial Validation

3.3 Alternative 3: ADS-B with Full Validation

Alternative 3 (Figure 3-3) is functionally identical to Alternative 2, except that, an additional validation of the ADS-B information is achieved by comparing the distance between the aircraft and the ground station as derived from the ADS-B information with an active range measurement. A Mode S 1030 MHz transmitter is integrated with the 1090 MHz ground station receiver, and the receiver is enhanced to measure the time-of-arrival of aircraft emissions and harmonize operations with the transmitter.

Each target aircraft is occasionally interrogated (e.g., once per 10 seconds) in order to obtain an independent measure of its range. Like the azimuth check, the ranging measurement protects against both GPS data blunders and spoofing. However, ranging accuracy is much more accurate than azimuth determination, so a greater level of assurance is provided. In terms of Air Traffic Control services, Alternative 3 can support VFR flight following and IFR pseudo-radar procedures.

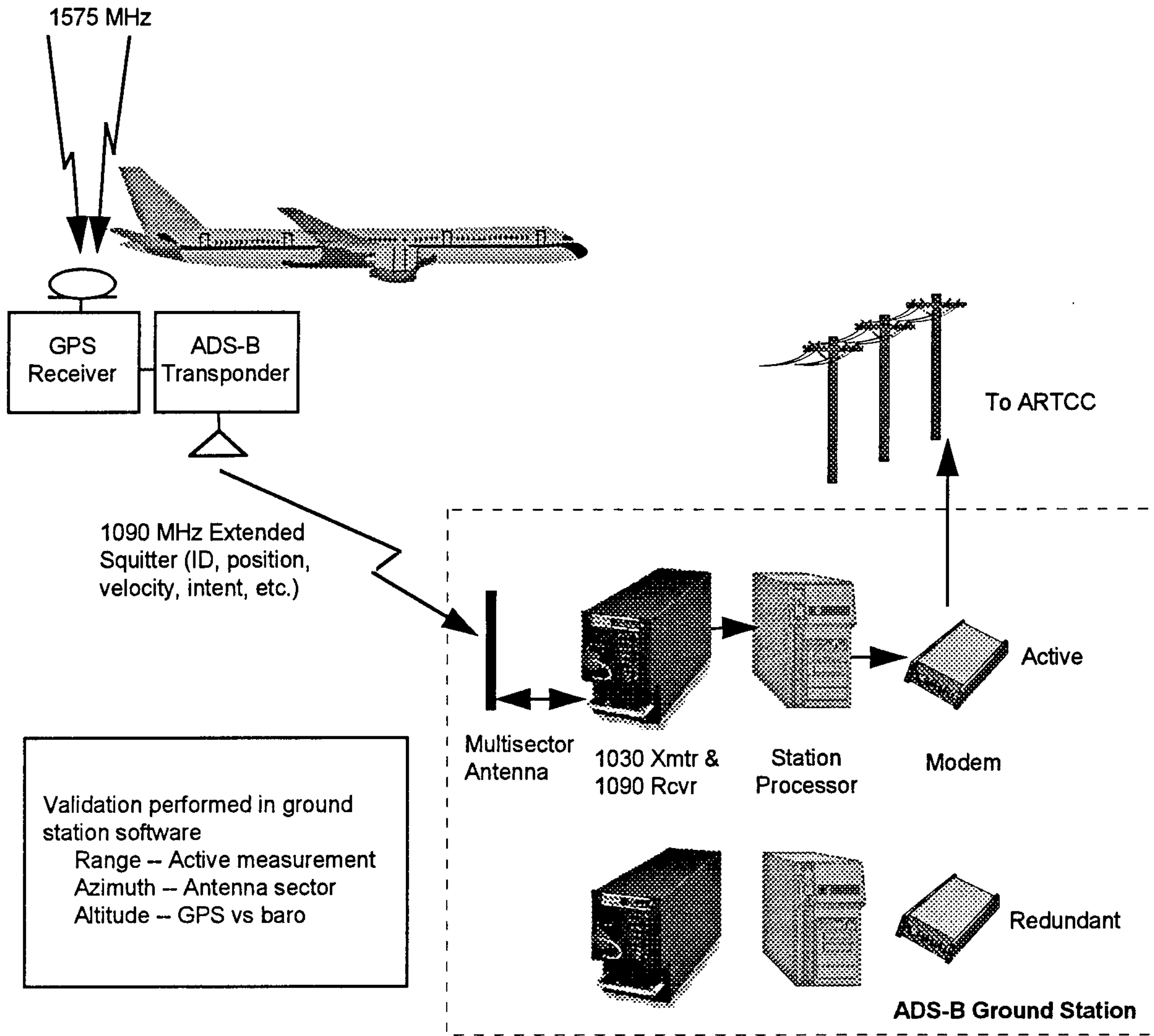


Figure 3-3. Alternative 3: ADS-B with Full Validation

3.4 Alternative 4: ADS-B and Range-Azimuth Surveillance with Same Station

Alternative 4 (Figure 3-4) is an enhancement of Alternative 3. Azimuth measurement accuracy is improved by increasing the number of ADS-B ground station antenna sectors and employing monopulse processing in the 1090 MHz receiver. For example, a 12-sector antenna could be employed, yielding approximately 30-degree coverage per sector; with monopulse processing, the azimuth accuracy could be approximately 1 degree. Monopulse processing necessitates that the 1090 MHz receiver have two channels for each antenna element (e.g., 24 channels for a 12-sector antenna). Additionally, the ground station 1030 MHz transmitter and 1090 MHz receiver would interrogate and decode messages from ATCRBS Mode A and C equipped aircraft.

By interrogating frequently (e.g., 10 to 100 times per second), Alternative 4 implements a crude cooperative range-azimuth measurement system which may be suitable for use in low traffic density areas against ATCRBS or Mode S short squitter equipped aircraft. For ADS-B equipped aircraft, the range and azimuth surveillance data would be used for validating the GPS-derived ADS-B data during normal operations and would also be the backup system for use when GPS fails. Alternative 4 can support VFR flight following and IFR pseudo-radar procedures.

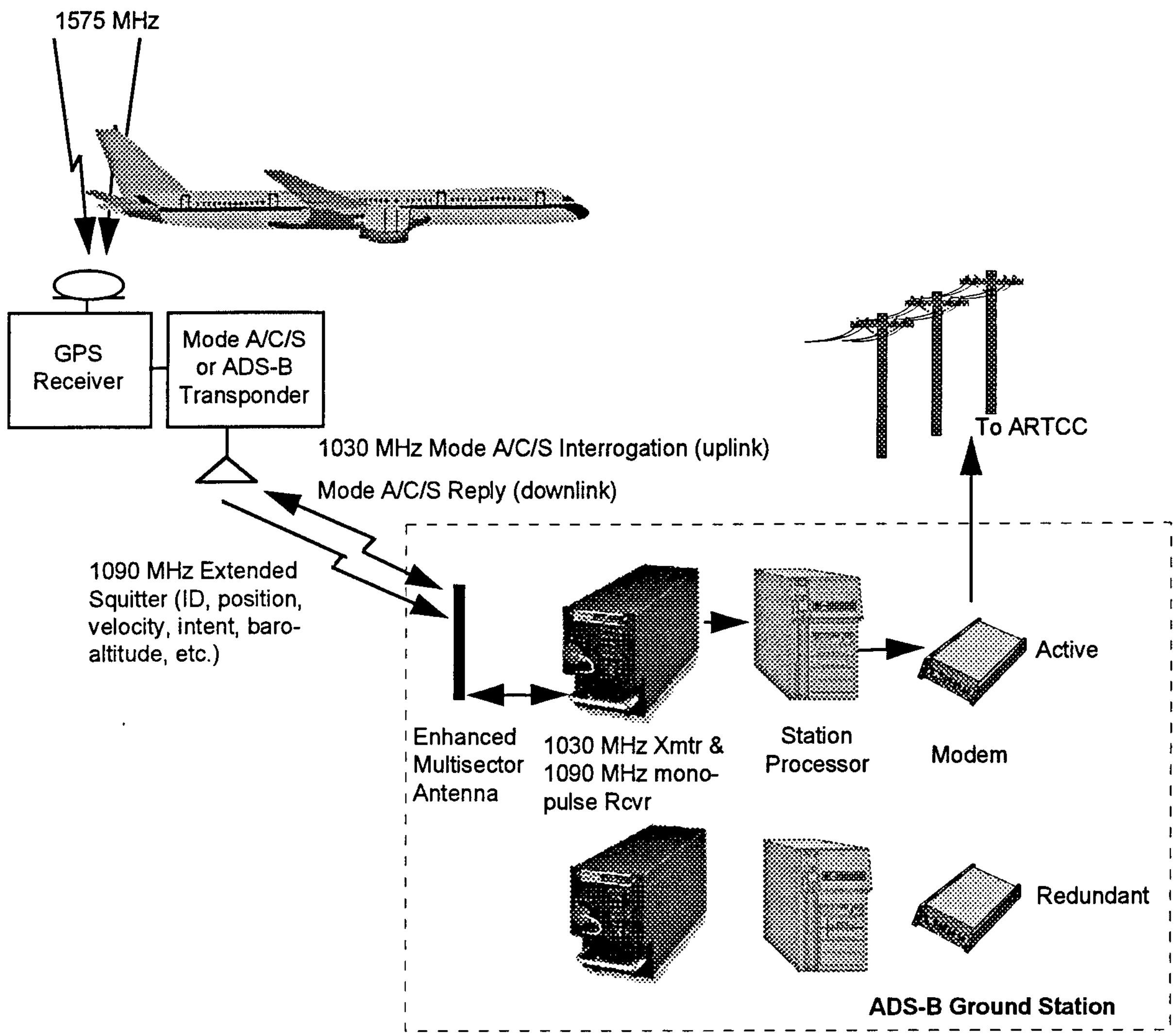


Figure 3-4. Alternative 4: ADS-B and Range-Azimuth Surveillance Using Same Station

3.5 Alternative 5: ADS-B plus TCAS-like Ground Station

For this alternative (Figure 3-5), each ground station consists of two separate stations:

- A passive ADS-B station without redundant equipment or mechanism for validating the GPS information embedded in an ADS-B message.
- A separate ground station which actively measures the aircraft's range and bearing using a fixed (non-scanning) antenna.

The ground station transmitter/receiver could be based on a TCAS system. An inexpensive primary radar could also be used for this purpose, but would only be applicable in an all Mode S environment, since the Mode C information from ATCRBS transponders would not be available. Alternative 5 can support VFR flight following and IFR pseudo-radar procedures.

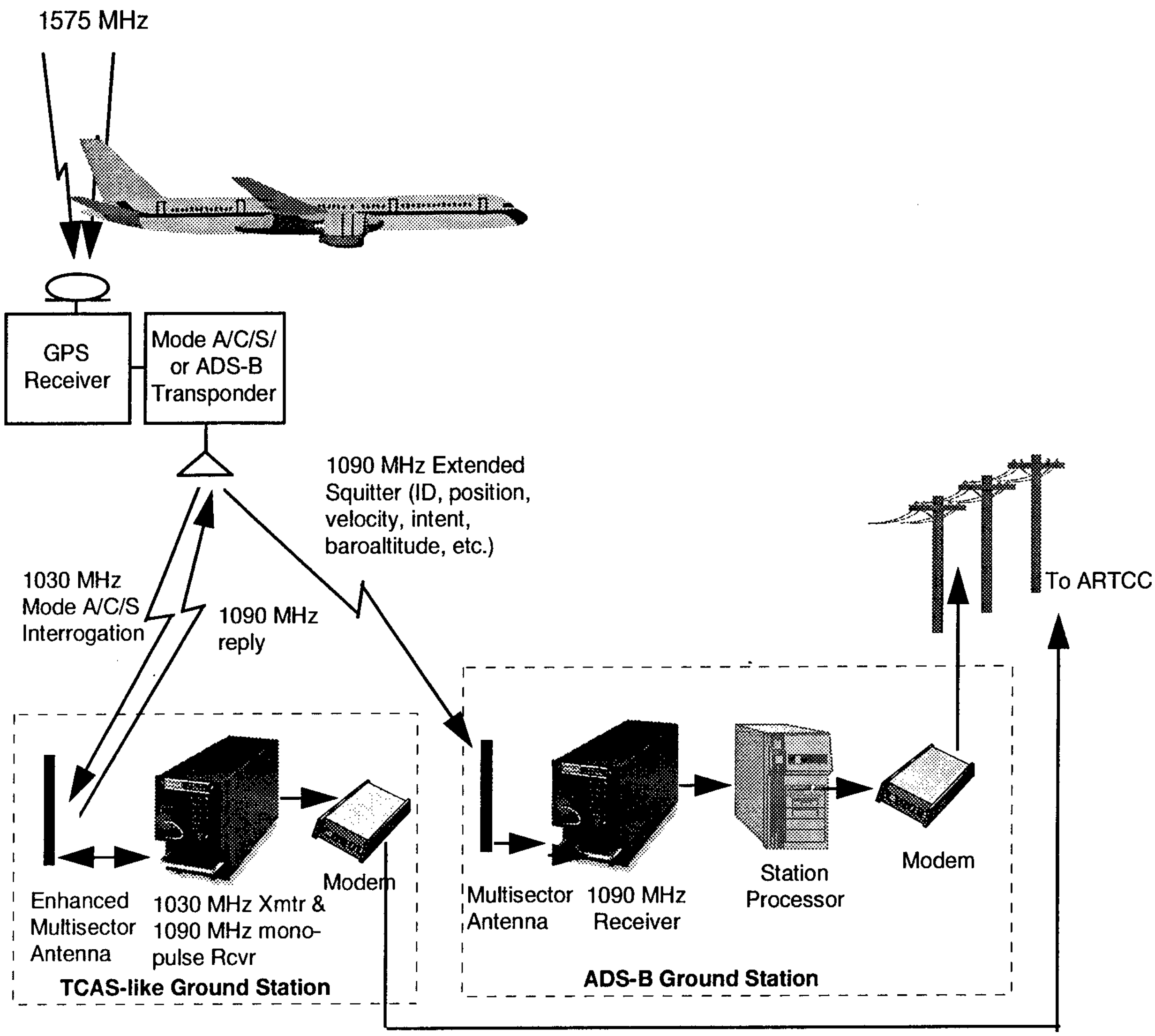


Figure 3-5. Alternative 5: ADS-B plus TCAS-like Ground Station

3.6 Alternative 6: ADS-B plus Passive Multilateration

This alternative (Figure 3-6) requires that all aircraft have a 1090 MHz transponder which emits unelicited squitters — either Mode S extended, Mode S short, or Modes A and C. The ground station listens to the squitters and determines the aircraft position from the ADS-B message (equipped aircraft only) and via a multilateration calculation based on the squitter time-of-arrival (TOA) at three ground stations (all aircraft). A minimum of triple ground site coverage of the airspace served is required for passive multilateration, so three times as many ground stations are needed than for non-multilateration techniques. Moreover, each station must communicate with its six nearest neighbors (Figure 2-4). However, with triple coverage redundancy, there is little need for redundant equipment at individual stations. Being passive and relatively small (all equipment fits on a hand cart), the ground stations could be sited in populated areas.

Passive ADS-B/multilateration ground station equipment consists of single copies of the basic ADS-B station equipment (Section 2.2) with the following additions/enhancements:

- The 1090 MHz receiver must have the capability to detect and decode messages in the ATCRBS Mode A/C, Mode S short squitter, and Mode S extended squitter formats, and to time-stamp the time-of-arrival
- A GPS timing receiver with integrated rubidium clock is included for time-stamping the squitter TOAs when GPS is operating and up to several hours after GPS has failed
- An additional computer processor, with capability equivalent to a Pentium, is added to perform the multilateration calculations
- Modems for communicating with the six nearest ground stations (Figure 2-4), in order to perform multilateration calculations.

Technical information concerning the envisioned en route passive multilateration system are provided in Appendix A (station geometry) and Appendix B (aircraft capacity). As shown in Appendix A, tripling the number of ground stations provides both triple (i.e., dual redundant) ADS-B coverage above the 6,000 ft altitude minimum assumed herein, and single (i.e., non-redundant) ADS-B coverage above 2,000 ft. For aircraft above 8,000 ft, multilateration coverage is retained even if one of the visible ground stations fails, and for aircraft above 11,500 ft, multilateration coverage is retained even if two visible ground stations fail.

Expected en route multilateration horizontal position accuracy (see Table 2-6) is superior to ADS-B without WAAS but poorer than ADS-B with WAAS. Multilateration position accuracy is primarily governed by the accuracy of the ground station clock used to time-stamp the squitter arrivals. In the current 1090 MHz RF environment, to achieve an update every 5 seconds with 99% assurance, the capacity of a multilateration system is approximately 903 ATCRBS aircraft, 374 Mode S long squitter aircraft, and 237 Mode S long squitter aircraft. Capacity will rise as ATCRBS interrogators are phased out.

For this alternative, ADS-B is the principal source of surveillance information for aircraft equipped with a transponder capable of Mode S long squitters. For these users, multilateration provides validation of the ADS-B information as well as surveillance backup in the event of a GPS failure. For Mode S short squitter and ATCRBS Mode C equipped aircraft, the principal surveillance information is provided by the multilateration solution, and there is no backup surveillance system. It is expected that full IFR services superior to those provided in today's system will be possible for Mode S equipped aircraft. For ATCRBS-equipped aircraft, surveillance would be equivalent or superior to current beacon-only radar sites, thereby also supporting full IFR services.

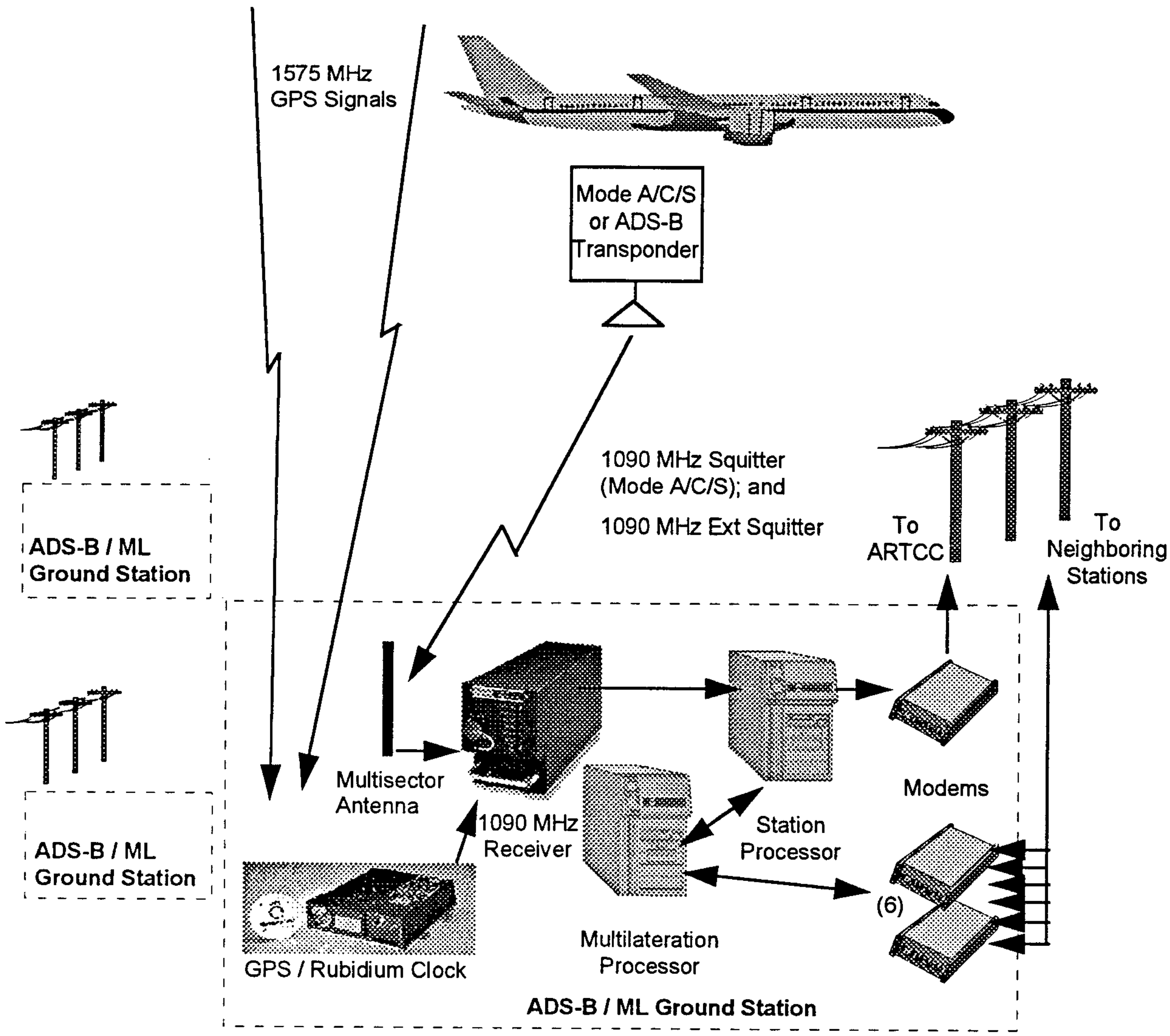


Figure 3-6. Alternative 6: ADS-B plus Passive Multilateration

3.7 Alternative 7: ADS-B plus Active Multilateration

This alternative (Figure 3-7) provides the capability to perform surveillance using both ADS-B and active multilateration with a set of ground stations that have both capabilities. Alternative 7 differs from Alternative 6 in that multilateration is based on active measurements of the range of the aircraft from three or more ground stations, rather than the time-of-arrival of a common aircraft squitter. In most other aspects, Alternatives 6 and 7 are very similar; in particular, triple ground station coverage and inter-station communications are needed for both.

For this alternative, the ground station equipment consists of single copies of the basic ADS-B station equipment (Section 2.2) with the following additions/enhancements:

- The 1090 MHz receiver must have the capability to detect and decode messages in the ATCRBS Mode A/C, Mode S short squitter, and Mode S extended squitter formats and to operate in concert with the 1030 MHz transmitter to measure round-trip travel time to an aircraft
- A 1030 MHz transmitter capable of interrogating at least Modes A and C, and preferably in Mode S also
- An additional computer processor, with capability equivalent to a Pentium, is added to perform the multilateration calculations
- Modems for communicating with six nearby ground stations, in order to perform multilateration calculations.

The primary advantage of active multilateration is that it guarantees that no aircraft modifications would be necessary for surveillance of all current ATCBRS aircraft. The primary disadvantage is that, because the stations radiate, they would be more difficult to site. In terms of accuracy, active systems suffer significant degradation from variations in transponder turn-around time. The result is that active system horizontal errors are expected to be a factor of 4.5 larger than passive errors. Active multilateration measurement of altitude is better than is passive; however, it is generally not as good as barometric data.

As for Alternative 6, for ADS-B equipped aircraft, multilateration provides complete validation of the ADS-B aircraft position and provides a backup in the event of GPS failure. For aircraft with a Mode S short squitter or a Mode A/C squitter, active multilateration provides the primary surveillance data. Because of this independent position determination capability, it is expected that full IFR services equivalent or superior to those provided in today's system will be possible for ADS-B aircraft. FOR ATCRBS Mode C aircraft, full IFR services would also be supported as they are by current beacon-only en route radar sites.

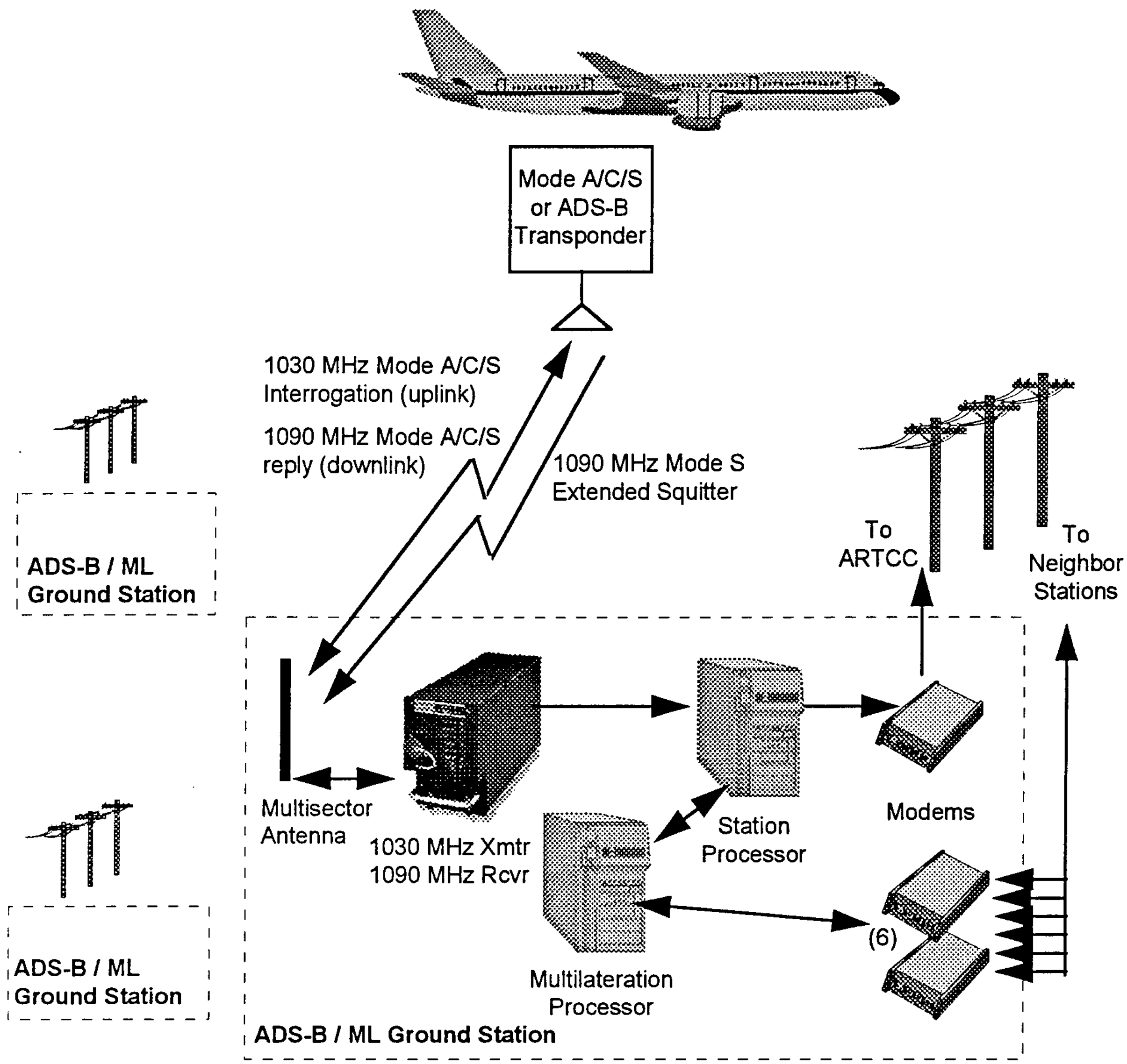


Figure 3-7. Alternative 7: ADS-B plus Active Multilateration

3.8 Alternative 8: ADS-B plus ATCBI with SI and GIC-B

This alternative (Figure 3-8) has ground facilities for separate ADS-B and ATCBI with SI and GIC-B. It is similar to the en route surveillance architecture set forth in the *NAS Architecture* V3.0 (Reference 1). Surveillance of aircraft with Mode S extended squitter transponders is accomplished by ADS-B ground stations, and is fully backed-up by the GIC-B feature of the ATCBI. Validation of both information derived via ADS-B and GIC-B is accomplished by the ATCBI/SI range/azimuth measurement functionality, which provides backup capability in the event of GPS failures. Surveillance of aircraft having Mode S short squitter transponders is accomplished using the ATCBI/SI capability and there is no validation or backup for these aircraft. Surveillance of aircraft with Mode A/C transponders is accomplished using the ATCBI beacon capability, and there no validation or surveillance backup for these aircraft either.

This alternative supports full VFR and IFR services for all Mode S and Mode C equipped aircraft.

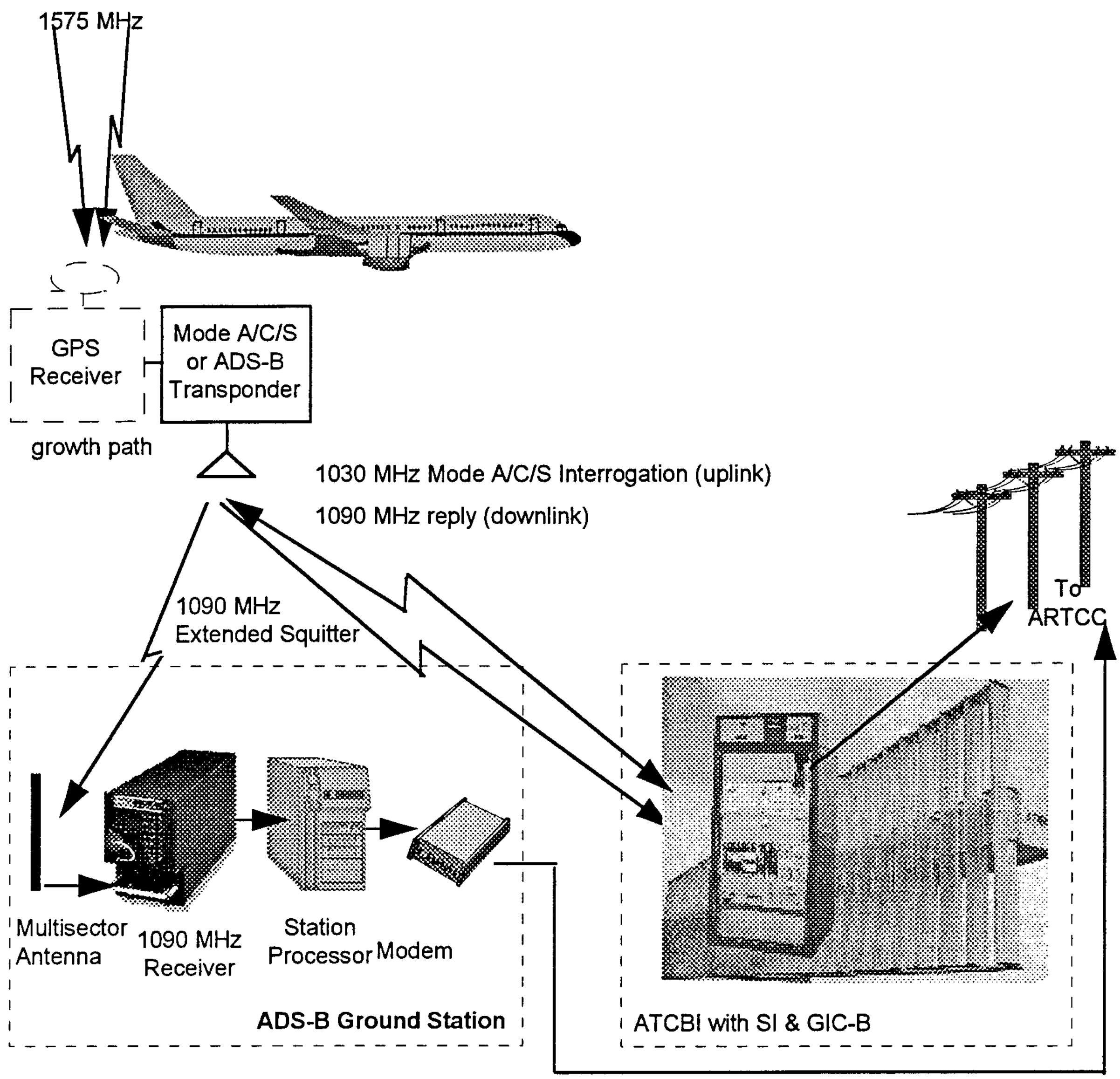


Figure 3-8. Alternative 8: ADS-B plus ATCBI with SI and GIC-B

3.9 Alternative 9: ATCBI with SI and GIC-B

This alternative (Figure 3-9) consists of an ATCBI secondary surveillance radar with SI and GIC-B capability. ADS-B ground stations are not included. Surveillance of aircraft carrying Mode S transponders with long squitter capability is accomplished by the GIC-B feature of the ATCBI. Validation of the GIC-B provided information is accomplished by the beacon range/azimuth capability of the ATCBI/SI, which also provides backup surveillance capability in the event of GPS failure. Surveillance of Mode S short squitter aircraft is accomplished using the ATCBI/SI functionality, and there is no validation or backup for these aircraft. Surveillance of Mode A/C transponders is accomplished using the ATCBI beacon capability and again there is no validation or surveillance backup for these aircraft.

Current VFR and IFR services are supported by this alternative, just as they are by current beacon-only en route radar sites.

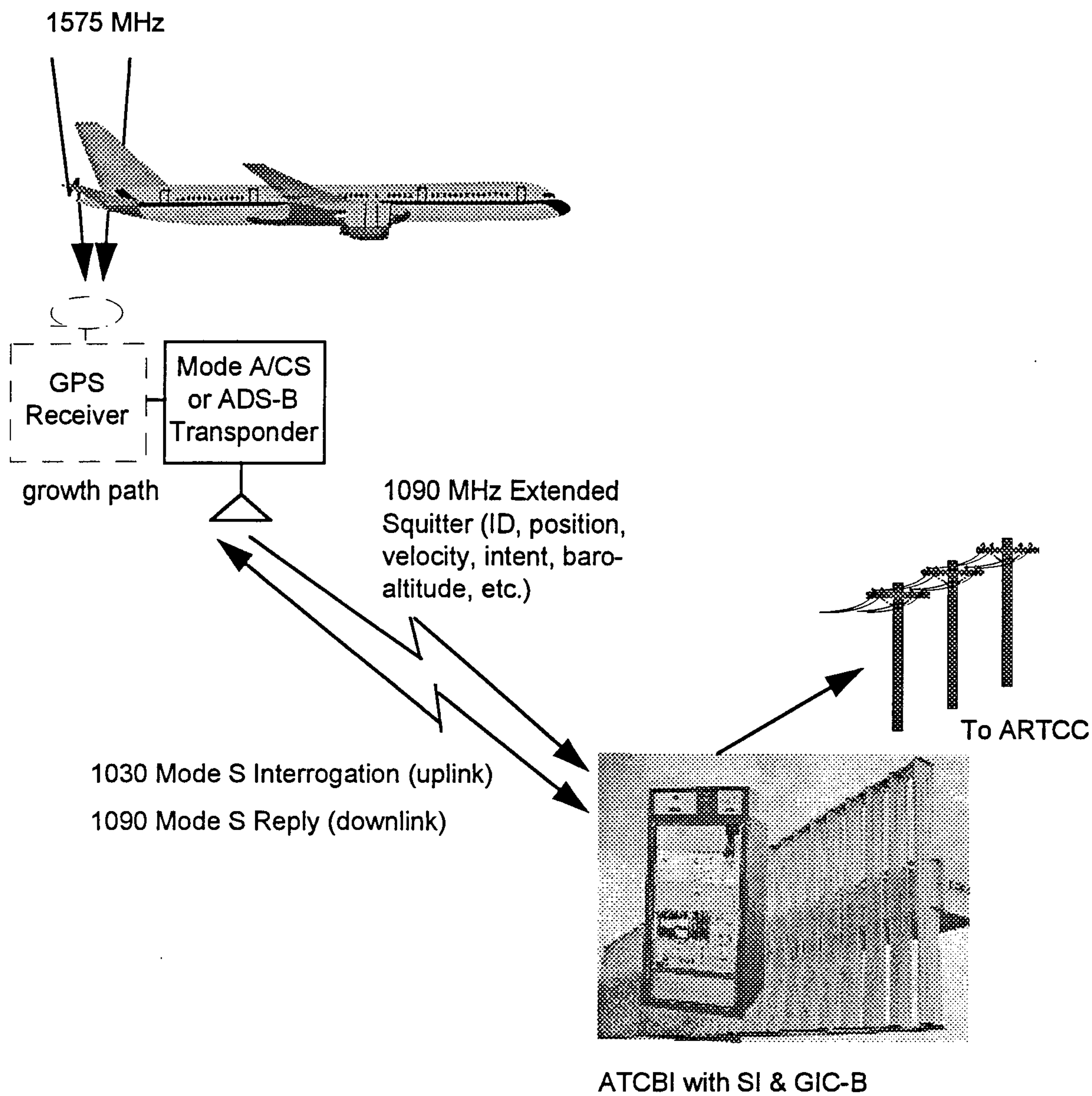


Figure 3-9. Alternative 9: ATCBI with SI and GIC-B

3.10 Alternative 10: ATCBI without SI and GIC-B

This alternative (Figure 3-10) consists of an ATCBI secondary surveillance radar. The SSR does not have SI or GIC-B capability, and there are no ADS-B ground stations. Surveillance of all transponder-equipped aircraft is accomplished using the ATCRBS Modes A and C of the ATCBI. This is identical to the existing surveillance architecture, with the major exception that primary radar is not available to provide a position backup for transponder equipped aircraft.

Current system VFR and IFR services are supported by this alternative, just as they are by current beacon-only en route radar sites.

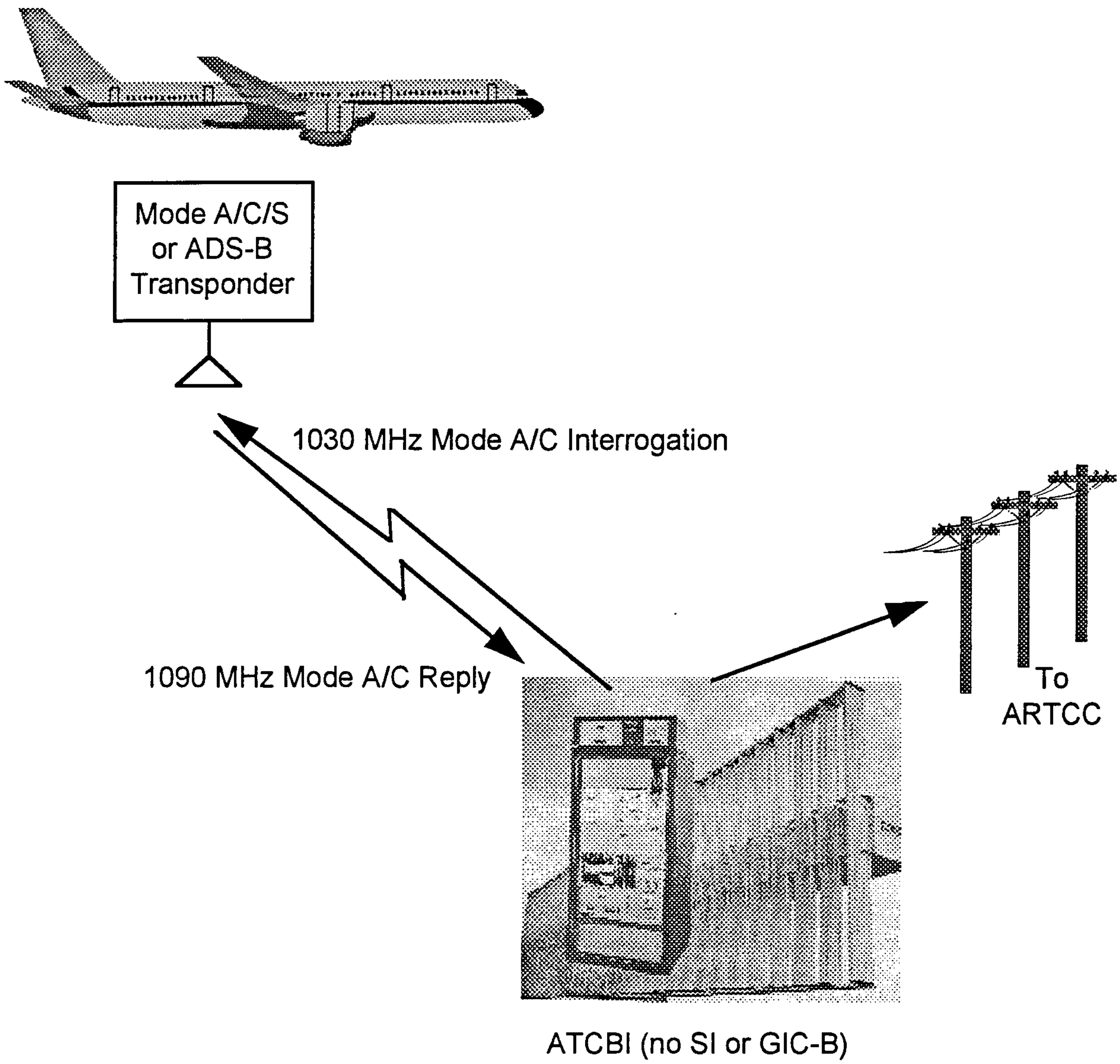


Figure 3-10. Alternative 10: ATCBI without SI and GIC-B

4. Cost Estimates

4.1 Approach and Methodology

This chapter presents cost estimates for the ten en route surveillance architectures shown in Tables 1-1 and 2-1 and described in Chapter 3. These estimates are generated for the purposes of comparing technologies, in order to identify those which merit more throrough investigation as candidates for inclusion in future NAS plans. This long-term, technology-oriented viewpoint is somewhat different than that taken when generating cost estimates for a specific program — for example:

1. Each cost element is either fully included or omitted herein. In contrast, specific programs may be able to delay or avoid a portion of the costs for certain elements by taking advantage of units in depot storage or at existing sites.
2. The time value of money (discount rate) is ignored herein. This is logically equivalent to performing all activities (acquisition, training, maintenance, etc.) within one year. Estimates for a specific program must account for changes in the value of money over the applicable schedules for procurement, deployment, and operational use.

Consequently, cost figures presented herein, while providing an equitable basis for comparing alternative surveillance technologies, cannot be fairly compared with estimates for specific programs.

Costs for the ten architectures are estimated based on a common cost breakdown structure. The structure was derived from the costing effort for the ATCBI-6 program (Reference 15), and is presented in Table 4-1. Costs are intially broken down into the three major budgetary categories used by the FAA — Research, Engineering and Development (R,E&D), Facilities and Equipment (F&E), and Operations and Maintenance (O&M). These categories are further broken down into a total of 30 cost elements — 5 R,E&D, 14 F&E, and 11 O&M — which include all the cost of development, procuring, operating and maintaining a system.

Cost estimates summaries for the ten alternatives are presented in Section 4.2 (for the case of all new equipment) and Section 4.3 (for the case where certain existing equipment at radar sites can be re-used). Appendix C provides details of the methodology used for each element in the cost breakdown structure in Table 4-1.

Table 4-1. Cost Breakdown Structure

RESEARCH, ENGINEERING AND DEVELOPMENT (R,E&D)
System Engineering
Non-Recurring Engineering -- Hardware
Non-Recurring Engineering -- Software
Pre-Production Systems
Development Test and Evaluation (DT&E)
FACILITIES AND EQUIPMENT (F&E)
Program Office Support
Contractor Program Management
Contractor Systems Engineering
Civil Works (Real Property Improvements)
Prime Mission Equipment (PME)
Support Equipment
Site Activation
Equipment Installation and Test
Initial Spares
Documentation
Freight and Inspection
Engineering Change Orders (ECOs)
Initial Operations Training
Initial Maintenance Training
OPERATIONS AND MAINTENANCE (O&M)
Consumables
Rent
Energy
Operations Personnel
Operations Travel
Operations Training
Telecommunications
Hardware Maintenance
Maintenance Training
Software Maintenance
Replenishment Spares

4.2 Cost Estimates: All New Equipment

The distinguishing conditions for this scenario are: (1) all new equipment is installed at every site and (2) the cost of land (real property improvements and rent) is omitted. Land costs are omitted because — since they can be large and vary widely (e.g., depending upon whether an existing site is available or a new site must be built) — they can distort comparisons between technologies. Figure 4-1 and Table 4-2 present life-cycle costs for each alternative.

For Alternatives 1 – 5, costs increase from $139M (Alternative 1) to $193M (Alternative 5) as additional verification and independent surveillance capabilities are added to the basic ADS-B ground station. Referring to the far right-hand column of Table 2-1, none of these alternatives can support radar separation services currently available in most of the NAS. They are suitable for use as gapfillers or for deployment in areas which do not now have surveillance coverage.

Alternatives 6-10 have better capabilities than Alternatives 1-5 and similar or better capabilities than current SSRs. Their costs are all higher than those for Alternatives 1-5. Alternatives 6 (ADS-B and passive multilateration) and 7 (ADS-B and active multilateration) are most directly compared to Alternatives 9 (SSR with SI and GIC-B capability). Each provides surveillance of both ADS-B and ATCRBS equipped aircraft. In contrast, Alternative 10 lacks the SI/GIC-B capability necessary to receive ADS-B extended squitter messages. Alternative 8, the architecture described in Reference 1, includes both ADS-B and SSR with SI/GIC-B. It is the most capable and most expensive.

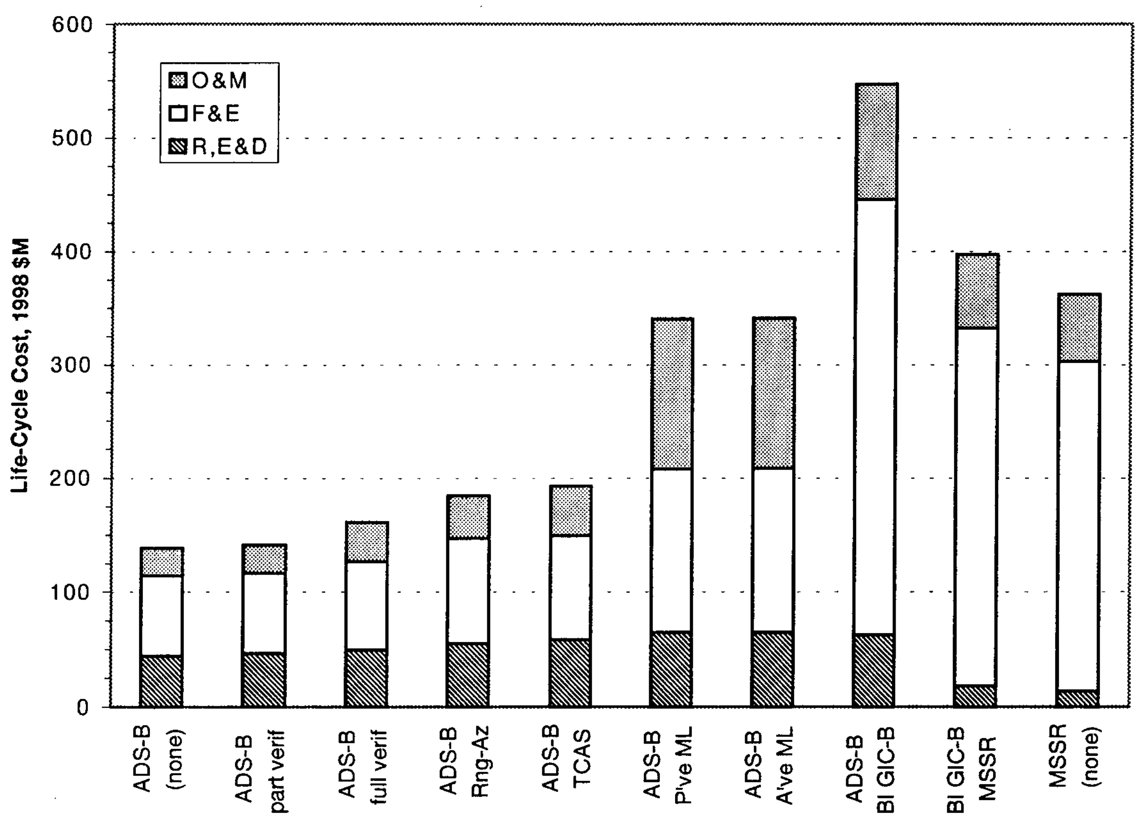


Figure 4-1. Total Costs, without Land, All New Equipment

Table 4-2. Total Costs (1998 $M), without Land, All New Equipment

	ARCHITECTURE ALTERNATIVE									
DESCRIPTION	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Principal Surveillance System	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**GIC-B**	**MSSR**
Complementary System	**(none)**	**part ver**	**full ver**	**Rng-Az**	**TCAS**	**P ML**	**A ML**	**GIC-B**	**MSSR**	**(none)**
BASIC PARAMETERS										
Number of sites	116	116	116	116	116	348	348	116	116	116
System life (years)	20	20	20	20	20	20	20	20	20	20
RESEARCH, ENGINEERING AND DEVELOPMENT (R,E&D) COSTS										
System Engineering	5.0	5.5	6.0	6.0	6.0	7.5	7.5	6.0	1.5	1.0
Non-Recurring Eng'ring -- H/W	17.8	17.8	18.7	21.4	22.8	20.8	20.8	20.8	3.0	0.0
Non-Recurring Eng'ring -- S/W	15.1	16.6	17.4	18.1	18.1	25.1	25.1	15.9	0.7	0.0
Pre-Production Systems	1.2	1.2	1.4	1.7	1.5	0.9	0.9	9.2	8.0	7.3
Devel. Test and Eval (DT&E)	5.0	5.2	6.0	8.0	10.0	10.0	10.0	10.0	5.0	5.0
TOTALS	*44.2*	*46.4*	*49.5*	*55.2*	*58.5*	*64.3*	*64.3*	*61.9*	*18.2*	*13.3*
FACILITIES AND EQUIPMENT (F&E) COSTS										
Program Office Support	14.3	14.3	15.8	17.2	21.5	21.5	21.5	28.7	14.3	14.3
Contractor Prog. Mgmt.	1.9	1.9	2.1	2.6	2.3	4.0	4.0	13.9	12.1	11.1
Contractor Systems Eng'ring	1.9	1.9	2.2	2.7	2.4	4.2	4.2	14.6	12.6	11.6
Real Property Improvements	-	-	-	-	-	-	-	-	-	-
Prime Mission Equipment	28.6	28.6	32.1	40.2	35.1	61.0	61.2	214.2	185.6	170.1
Support Equipment	1.7	1.7	1.9	2.4	2.1	3.7	3.7	12.9	11.1	10.2
Site Activation	4.8	4.8	4.8	4.8	5.1	14.4	14.4	9.9	5.1	5.1
Equipment Installation & Test	1.2	1.2	1.2	1.2	2.3	5.5	5.5	8.6	7.5	7.5
Initial Spares	2.0	2.0	2.2	2.8	2.5	4.3	4.3	15.0	13.0	11.9
Documentation	1.3	1.3	1.5	1.9	1.6	2.8	2.8	9.9	8.5	7.8
Freight & Inspection	0.9	0.9	1.0	1.2	1.1	1.8	1.8	6.4	5.6	5.1
Engineering Change Orders	8.8	9.0	9.8	11.6	11.4	15.3	15.3	35.1	26.3	23.7
Initial Operations Training	1.0	1.0	1.0	1.1	2.0	1.5	1.5	3.0	2.0	1.8
Initial Maintenance Training	1.7	1.7	1.8	2.3	2.0	3.8	3.8	11.2	9.5	8.8
TOTALS	*70.2*	*70.4*	*77.5*	*92.1*	*91.4*	*143.8*	*144.1*	*383.4*	*313.3*	*289.0*
OPERATIONS AND MAINTENANCE (O&M) COSTS										
Consumables	2.4	2.4	2.4	2.4	3.7	7.3	7.3	3.7	3.7	3.7
Rent	-	-	-	-	-	-	-	-	-	-
Energy	2.2	2.2	3.5	3.5	4.8	8.5	8.5	12.6	10.4	10.4
Operations Personnel	5.5	5.5	8.2	8.2	11.0	21.9	21.9	18.3	11.0	9.9
Operations Travel	0.2	0.2	0.2	0.2	0.2	0.7	0.7	0.2	0.2	0.2
Operations Training	0.7	0.7	1.0	1.0	1.8	2.7	2.7	2.1	1.4	1.2
Telecommunications	1.1	1.1	1.1	1.1	1.1	66.1	66.1	1.1	1.1	1.1
Hardware Maintenance	5.4	5.4	6.0	7.5	6.6	11.4	11.5	30.1	17.4	16.0
Maintenance Training	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.5	0.3	0.3
Software Maintenance	2.9	2.9	6.7	6.7	9.6	4.4	4.4	9.6	6.7	4.4
Replenishment Spares	4.1	4.1	4.6	5.8	3.8	8.8	8.8	23.1	13.3	12.2
TOTALS	*24.8*	*24.8*	*34.2*	*36.9*	*43.1*	*132.1*	*132.1*	*101.4*	*65.6*	*59.4*
GRAND TOTALS	***139.1***	***141.5***	***161.1***	***184.2***	***193.0***	***340.2***	***340.5***	***546.7***	***397.1***	***361.8***

ADS-B/multilateration architecture costs (Alternatives 6 and 7) are each estimated to be approximately $340M over 20 years. The increase over that for the basic ADS-B architectures can be attributed primarily to two reasons: (1) a tripling of the number of ground stations, which (when decreased per-site redundancy is taken into account) essentially causes the F&E costs to be twice those for Alternative 1 ($143M vs. $70M); and (2) an additional $66M in operational cost for inter-site communications.

Estimated costs for Alternative 9 are $397.1M, which are approximately 17% higher than those for Alternative 6. One impetus for this effort was to estimate the cost of an ADS-B/multilateration architecture relative to that for SSR with SI/GIC-B. While the SSR cost is larger, when consideration is given to (1) the risk involved in instituting a fundamental change surveillance technology, and (2) the degree of uncertainty in the cost estimating process, this difference does not constitute a strong argument for substituting ADS-B and multilateration for secondary radar.

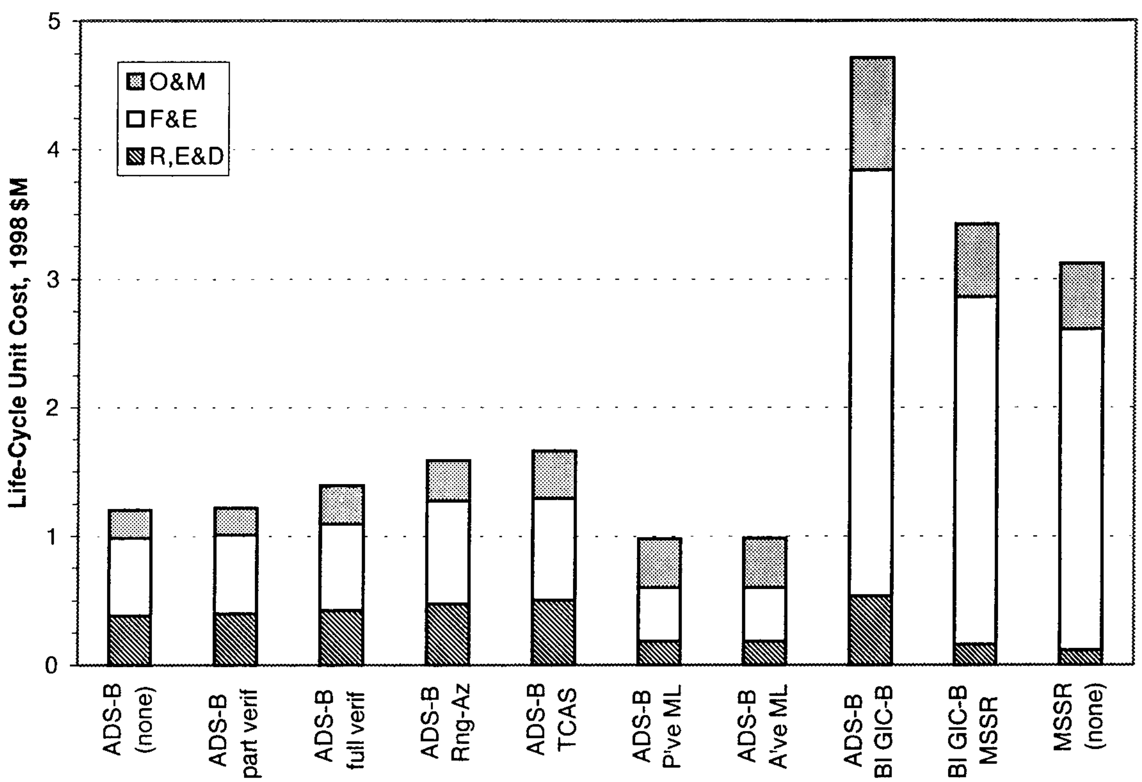


Figure 4-2. Per-Site Costs, without Land, All New Equipment

Figure 4-2 present cost for a single site. Per-site costs for all Alternatives except 6 and 7 have the same ratios as in Figure 4-1, because the same number of ground stations are involved. Per site costs for Alternatives 6 and 7 are smaller because these ground stations have little redundant equipment (which is permissible when the ground stations provide redundant coverage). Per-site costs are important when considering the addition or deletion of a few locations. However, they are not of high interest when deciding whether or not to proceed with an architecture.

4.3 Cost Estimates: Existing Radar Site Equipment Utilized

This scenario is similar to the previous one (Section 4.2), except that certain cost elements are ignored in Alternatives 8-10, on the assumption that existing equipment is available at depots or at current radar sites that can be utilized. These elements are: tower, antenna, rotary joint, beacon video reconstituter, shelter, engine-generator, and beacon parrot. Figure 4-3 and Table 4-3 present the estimated total life cycle cost for each alternative, with the cost of land (real property improvements and rent) ignored, for a 20-year service life.

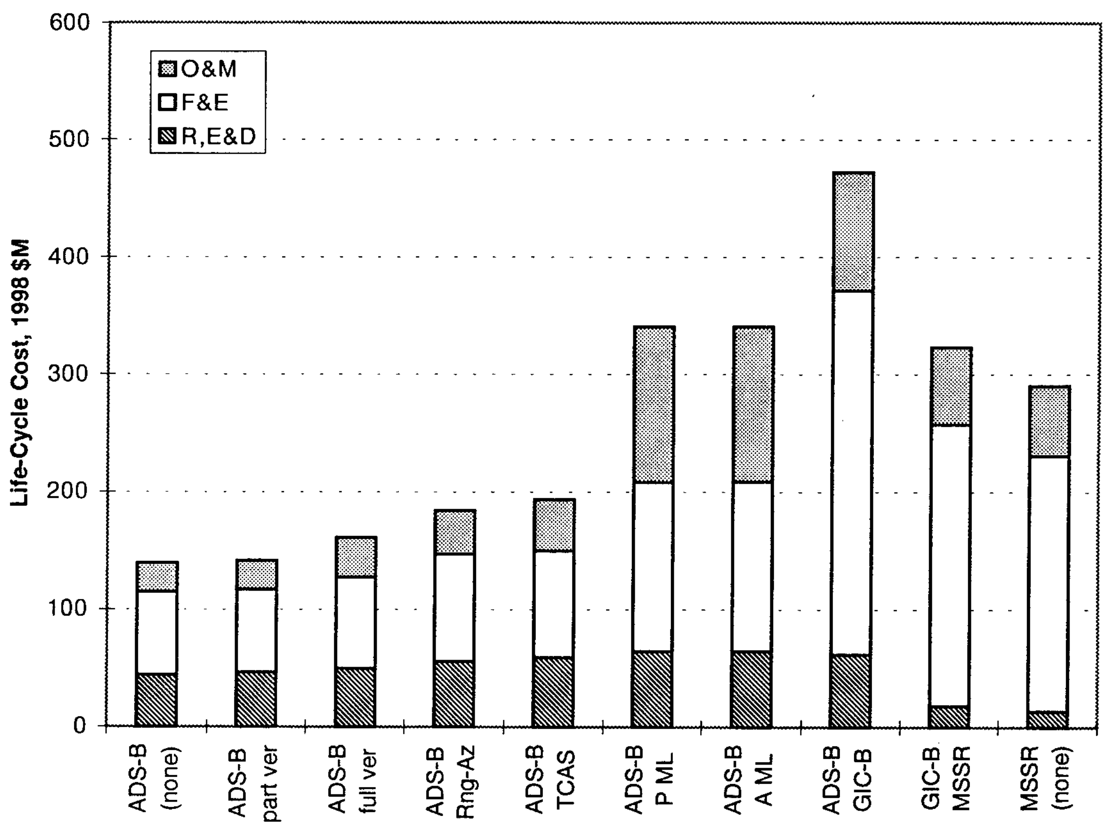


Figure 4-3. Total Costs, without Land, Existing Radar Site Equipment Utilized

Table 4-3. Total Costs (1998 $M), without Land, Existing Radar Site Equipment Utilized

	ARCHITECTURE ALTERNATIVES									
DESCRIPTION	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Principal Surveillance System	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**ADS-B**	**GIC-B**	**MSSR**
Complementary System	**(none)**	**part ver**	**full ver**	**Rng-Az**	**TCAS**	**P ML**	**A ML**	**GIC-B**	**MSSR**	**(none)**
BASIC PARAMETERS										
Number of sites	116	116	116	116	116	348	348	116	116	116
System life (years)	20	20	20	20	20	20	20	20	20	20
RESEARCH, ENGINEERING AND DEVELOPMENT (R,E&D) COSTS										
System Engineering	5.0	5.5	6.0	6.0	6.0	7.5	7.5	6.0	1.5	1.0
Non-Recurring Eng'ring -- H/W	17.8	17.8	18.7	21.4	22.8	20.8	20.8	20.8	3.0	0.0
Non-Recurring Eng'ring -- S/W	15.1	16.6	17.4	18.1	18.1	25.1	25.1	15.9	0.7	0.0
Pre-Production Systems	1.2	1.2	1.4	1.7	1.5	0.9	0.9	9.2	8.0	7.3
Devel. Test and Eval (DT&E)	5.0	5.2	6.0	8.0	10.0	10.0	10.0	10.0	5.0	5.0
TOTALS	*44.2*	*46.4*	*49.5*	*55.2*	*58.5*	*64.3*	*64.3*	*61.9*	*18.2*	*13.3*
FACILITIES AND EQUIPMENT (F&E) COSTS										
Program Office Support	14.3	14.3	15.8	17.2	21.5	21.5	21.5	28.7	14.3	14.3
Contractor Prog. Mgmt.	1.9	1.9	2.1	2.6	2.3	4.0	4.0	13.9	12.1	11.1
Contractor Systems Eng'ring	1.9	1.9	2.2	2.7	2.4	4.2	4.2	14.6	12.6	11.6
Real Property Improvements	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prime Mission Equipment	28.6	28.6	32.1	40.2	35.1	61.0	61.2	140.1	111.5	98.3
Support Equipment	1.7	1.7	1.9	2.4	2.1	3.7	3.7	12.9	11.1	10.2
Site Activation	4.8	4.8	4.8	4.8	5.1	14.4	14.4	9.9	5.1	5.1
Equipment Installation & Test	1.2	1.2	1.2	1.2	2.3	5.5	5.5	8.6	7.5	7.5
Initial Spares	2.0	2.0	2.2	2.8	2.5	4.3	4.3	15.0	13.0	11.9
Documentation	1.3	1.3	1.5	1.9	1.6	2.8	2.8	9.9	8.5	7.8
Freight and Inspection	0.9	0.9	1.0	1.2	1.1	1.8	1.8	6.4	5.6	5.1
Engineering Change Orders	8.8	9.0	9.8	11.6	11.4	15.3	15.3	35.1	26.3	23.7
Initial Operations Training	1.0	1.0	1.0	1.1	2.0	1.5	1.5	3.0	2.0	1.8
Initial Maintenance Training	1.7	1.7	1.8	2.3	2.0	3.8	3.8	11.2	9.5	8.8
TOTALS	*70.2*	*70.4*	*77.5*	*92.1*	*91.4*	*143.8*	*144.1*	*309.3*	*239.2*	*217.2*
OPERATIONS AND MAINTENANCE (O&M) COSTS										
Consumables	2.4	2.4	2.4	2.4	3.7	7.3	7.3	3.7	3.7	3.7
Rent	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy	2.2	2.2	3.5	3.5	4.8	8.5	8.5	12.6	10.4	10.4
Operations Personnel	5.5	5.5	8.2	8.2	11.0	21.9	21.9	18.3	11.0	9.9
Operations Travel	0.2	0.2	0.2	0.2	0.2	0.7	0.7	0.2	0.2	0.2
Operations Training	0.7	0.7	1.0	1.0	1.8	2.7	2.7	2.1	1.4	1.2
Telecommunications	1.1	1.1	1.1	1.1	1.1	66.1	66.1	1.1	1.1	1.1
Hardware Maintenance	5.4	5.4	6.0	7.5	6.6	11.4	11.5	30.1	17.4	16.0
Maintenance Training	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.5	0.3	0.3
Software Maintenance	2.9	2.9	6.7	6.7	9.6	4.4	4.4	9.6	6.7	4.4
Replenishment Spares	4.1	4.1	4.6	5.8	3.8	8.8	8.8	23.1	13.3	12.2
TOTALS	*24.8*	*24.8*	*34.2*	*36.9*	*43.1*	*132.1*	*132.1*	*101.4*	*65.6*	*59.4*
GRAND TOTAL	***139.1***	***141.5***	***161.1***	***184.2***	***193.0***	***340.2***	***340.5***	***472.6***	***323.0***	***290.0***

The omission of the costs of certain radar equipment reduces the total costs of Alternatives 8-10. An important consequence is that Alternative 9 becomes less costly than Alternatives 6 and 7. That is, the costs of MSSR with SI/GIC-B is reduced from 17% greater than that for ADS-B/multilateration (Section 4.2 and Table 4-2) to 5% less than that for ADS-B/multilateration. Any implementation program is likely to encounter conditions between the assumptions used in Sections 4.2 and 4.3. That is, some of the equipment listed previously will be available at existing sites or at depots. Thus the costs of MSSR with SI/GIC-B and multilateration are likely to be comparable, with the scenarios of Sections 4.2 and 4.3 serving as bounds.

Appendix A En Route Passive Multilateration DOPs

The idealized grid of en route ADS-B/multilateration stations used for this investigation is shown in Figure A-1. Each station has six nearest neighbors 95 nmi away, and communicates aircraft emission time-of-arrival information with these neighbors. The grid structure can be thought of as being generated by replicating either of two basic elements: (1) a triangle of stations; or (2) the hexagonal area surrounding a single station. The triangular viewpoint is simpler in that it has the minimum number of sides and involves the minimum number of stations needed to perform passive multilateration. The hexagonal viewpoint has the advantages that it more naturally fits the inter-station connectivity and it attributes a coverage area to a station.

Horizontal and Vertical Dilution of Precision (HDOP and VDOP) diagrams are shown in this appendix. The DOP computations were made based on the following conditions:

- Time-difference of arrival (hyperbolic) processing is performed at each station using aircraft emissions time-of-arrival (TOA) data collected at its own site and the six nearest ground stations

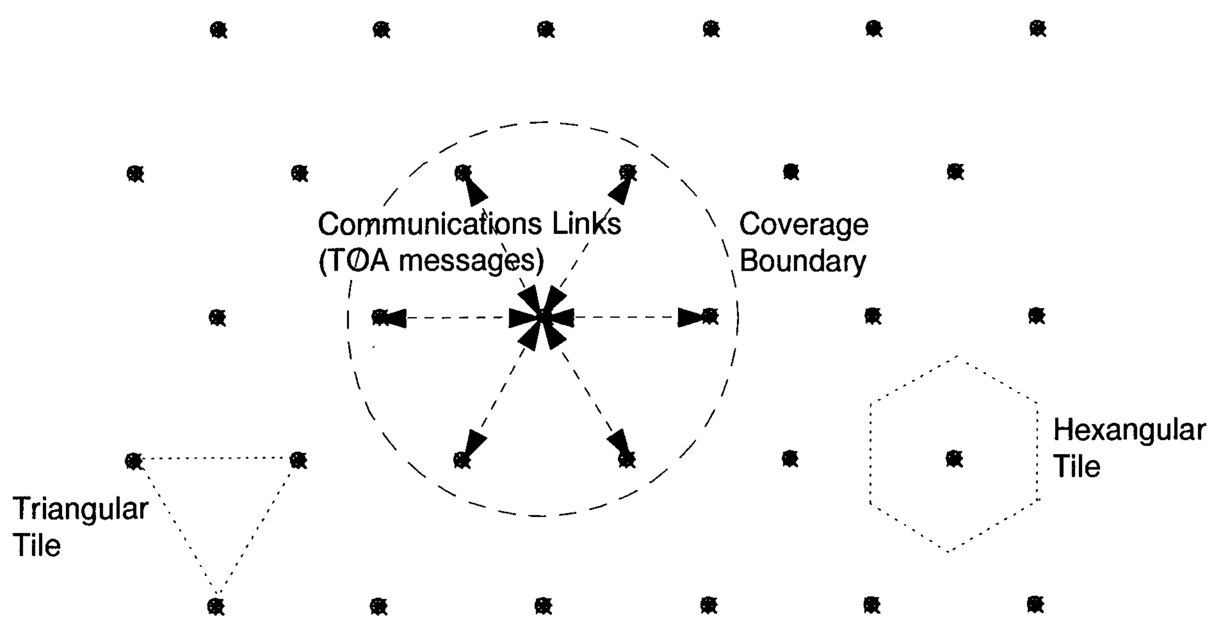
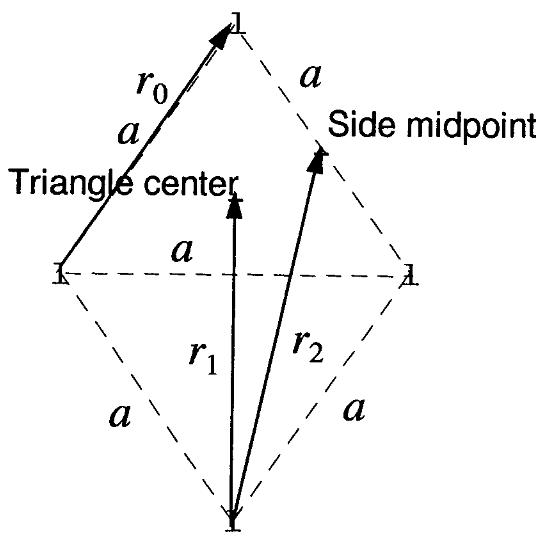


Figure A-1. Plan View of Network of En Route ADS-B/Multilateration Stations

- Horizontal or vertical position rms or 95% errors are found by multiplying HDOP or VDOP by the corresponding TOA (rather than TOA difference) measurement error
- All emissions received by any of the seven stations are used in forming the solution
- HDOP calculations assume that the aircraft vertical position is known by decoding barometric altitude information transmitted either in either a Mode C or extended squitter message
- The range of ground stations is limited by the earth's curvature and the antenna gain and receiver sensitivity, and emissions from aircraft outside of a station's range are not usable
- There is a cone-of-silence with a 60 degree half-angle above each ground station.

For the station grid structure used herein, Figure A-2 illustrates the basic relationship between the maximum range at which a station can reliably receive aircraft emissions and the minimum number of stations which will receive each emission, presuming the aircraft has sufficient altitude. DOPs are computed for three ground station reception ranges:

1. Range = 95 nmi, the minimum value which ensures that each aircraft is within range of at least three stations provided that its altitude is greater that 6,000 ft; this condition is termed redundancy 0



a = Station separation
r = Reception radius

- No redundancy — 3 or more signals received at all locations above 6,000 ft
  $r > r_0 = a = 95$ nmi
  Need $r > a$ to account for cone of silence
- Single redundancy — 4 or more signals received at all locations above 8,000 ft
  $r > r_1 = 1.155\,a = 110$ nmi
- Dual redundancy — 5 or more signals received at all locations above 11,500 ft
  $r > r_2 = 1.323\,a = 126$ nmi
- Quadruple redundancy — 7 or more signals received at all locations above 14,000 ft
  $r > r_3 = r_4 = 1.528\,a = 145$ nmi

Figure A-2. Multilateration Redundant Coverage Considerations

2. Range = 1.155 x 95 nmi = 110 nmi, the minimum value which ensures that each aircraft is within range of at least four stations, provided that its altitude is greater that 8,000 ft; this condition is termed single redundancy or redundancy 1
3. Range = 1.323 x 95 nmi = 126 nmi, the minimum value which ensures that each aircraft is within range of at least five stations, provided that its altitude is greater that 8,000 ft; this condition is termed dual redundancy or redundancy 2.

Figures A-3 through A-14 are diagrams of multilateration system HDOP and VDOP values for station ranges corresponding to redundancy 0, 1 and 2 conditions. The horizontal and vertical axes represent east-west and north-south distances quantified in nautical miles. Figures are provided for situations where 0, 1 or 2 stations have failed, and show the hexagonal region surrounding a station. DOP behavior outside the hexagon should be ignored. Table A-1 summarizes the worst-case DOP values for these figures.

Table A-1. Passive Multilateration Maximum DOPs

SIGNAL RECEPTION RANGE	MINIMUM AIRCRAFT ALTITUDE	MINIMUM NUMBER OF STATIONS	MAXIMUM HDOP		
			0 Failures	1 in 7 Failures	2 in 7 Failures
95 nmi	6,000 ft	3	1.5	—	—
110 nmi	8,000 ft	4	1.1	2.5	—
126 nmi	11,500 ft	5	1.0	1.3	4.0
SIGNAL RECEPTION RANGE	**MINIMUM AIRCRAFT ALTITUDE**	**MINIMUM NUMBER OF STATIONS**	**MAXIMUM VDOP**		
			0 Failures	**1 in 7 Failures**	**2 in 7 Failures**
110 nmi	8,000 ft	4	33	—	—
126 nmi	11,500 ft	5	27	—	—
(VDOP is infinite directly over station)					

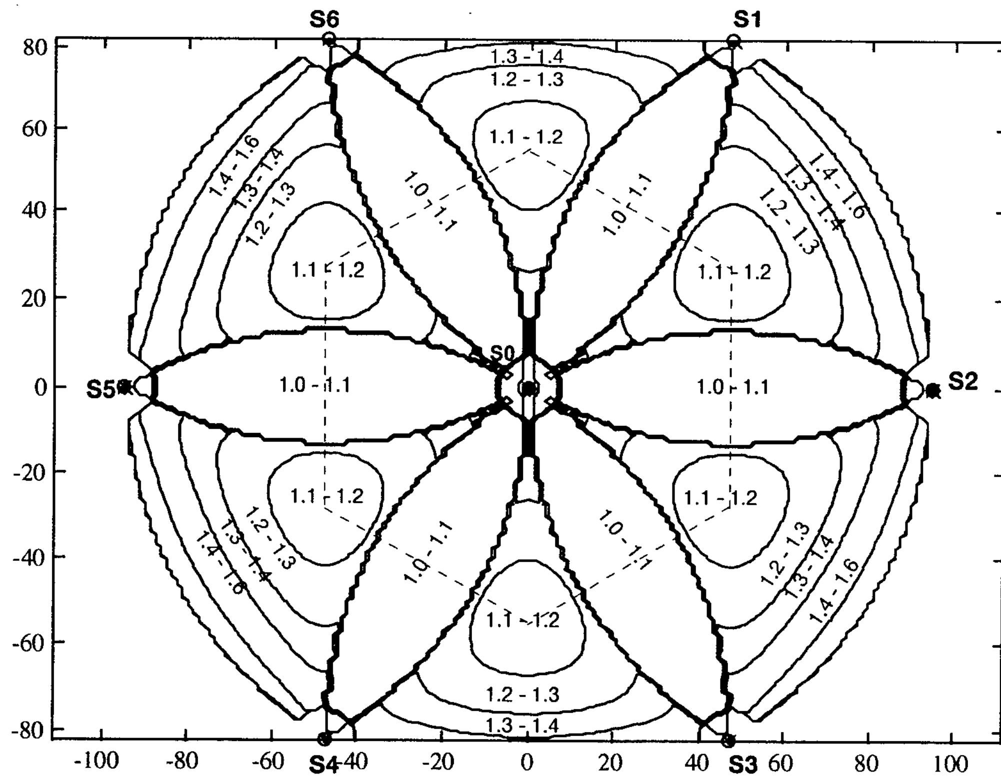


Figure A-3. Multilateration HDOP Ranges: Redundancy 0, Failures 0

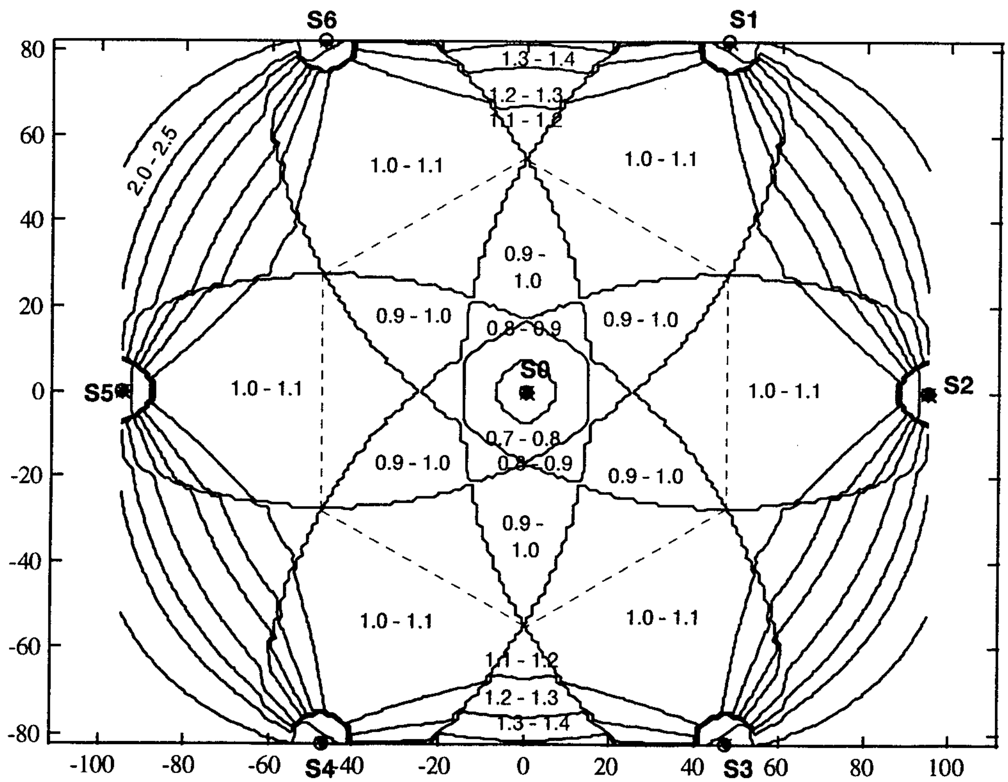


Figure A-4. Multilateration HDOP Ranges: Redundancy 1, Failures 0

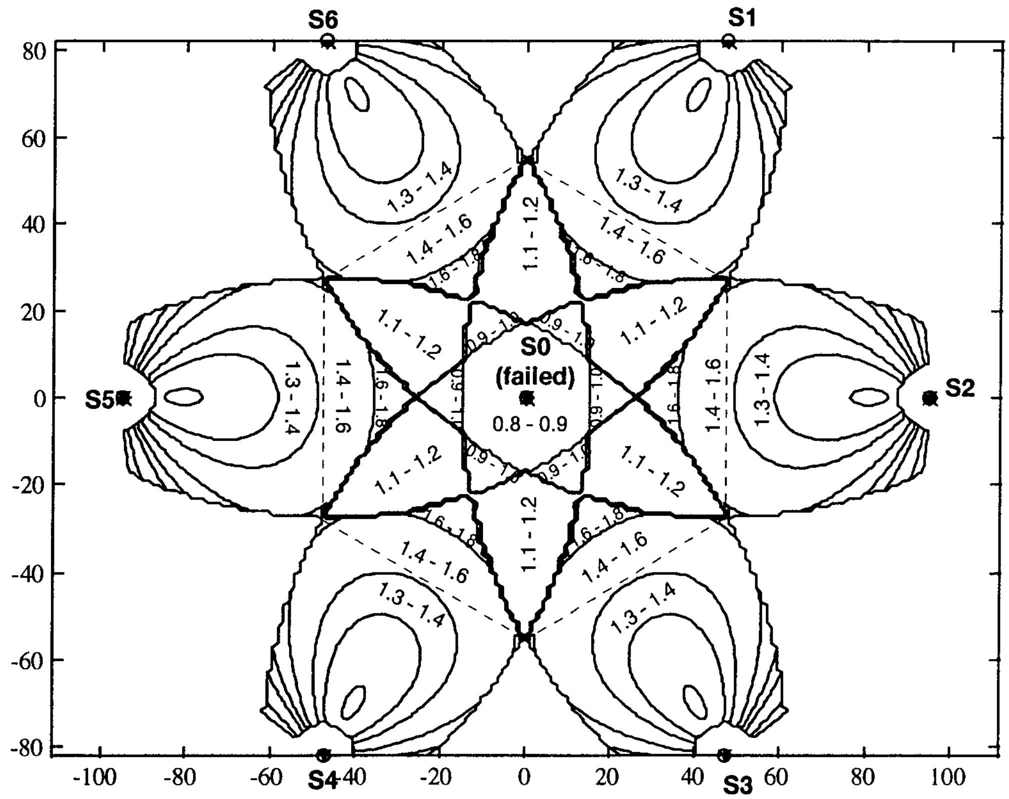


Figure A-5. Multilateration HDOP Ranges: Redundancy 1, Failures 1

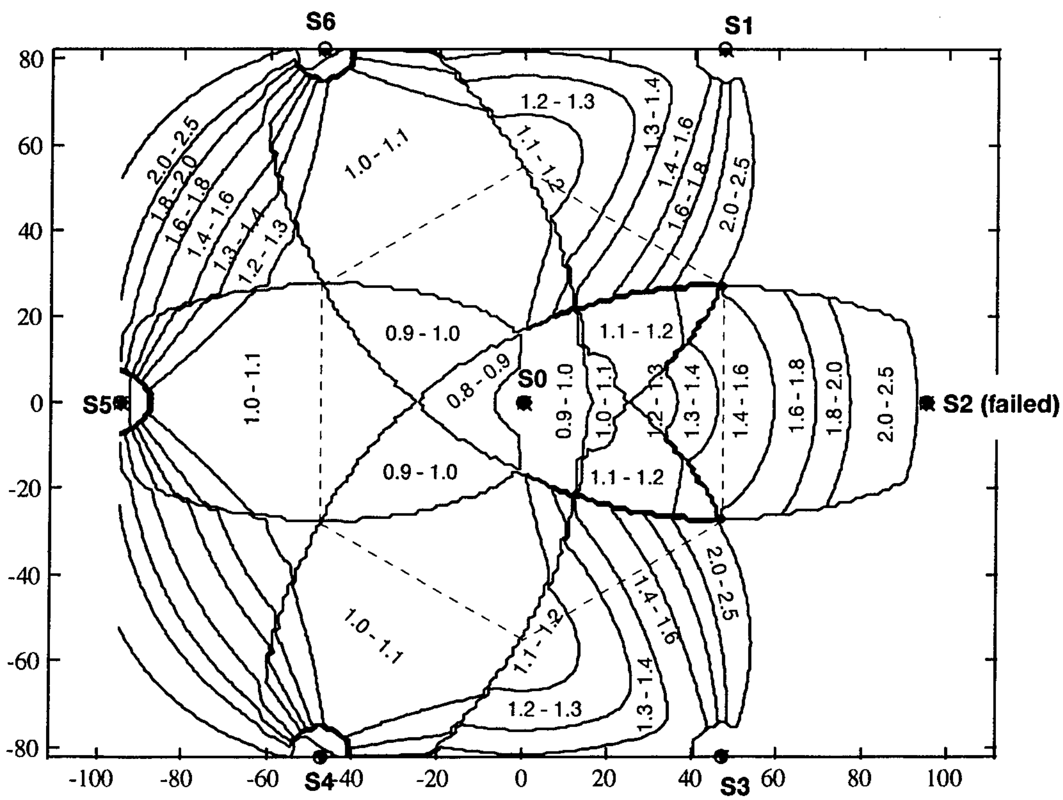


Figure A-6. Multilateration HDOP Ranges: Redundancy 1, Failures 1

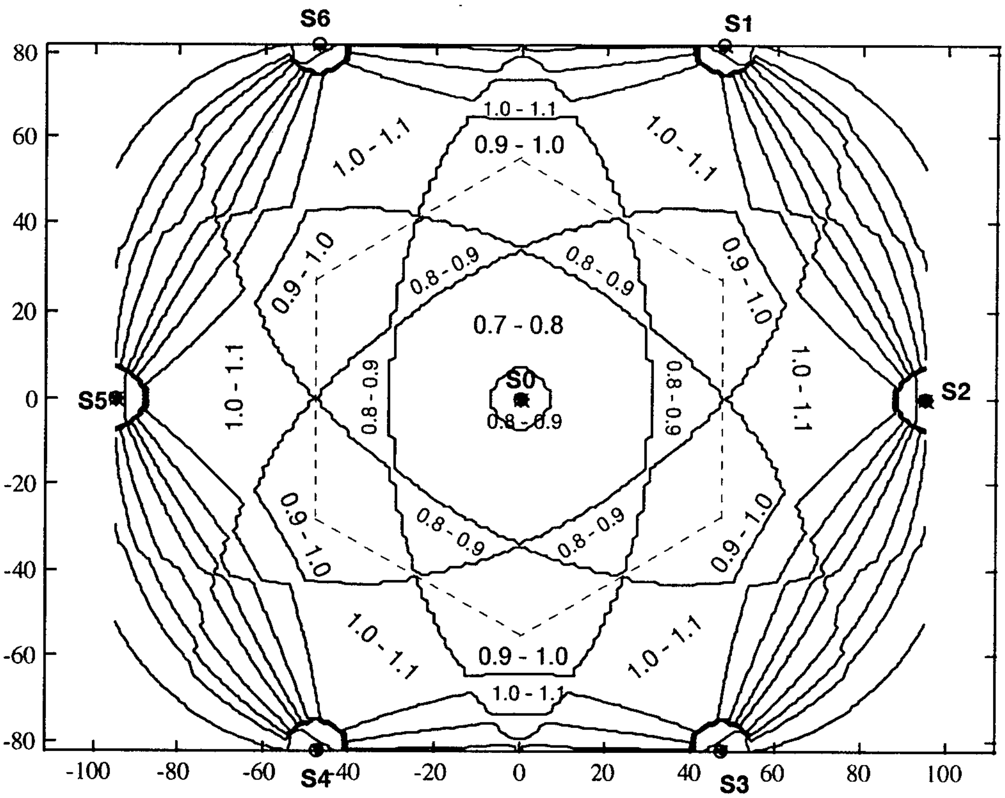


Figure A-7. Multilateration HDOP Ranges: Redundancy 2, Failures 0

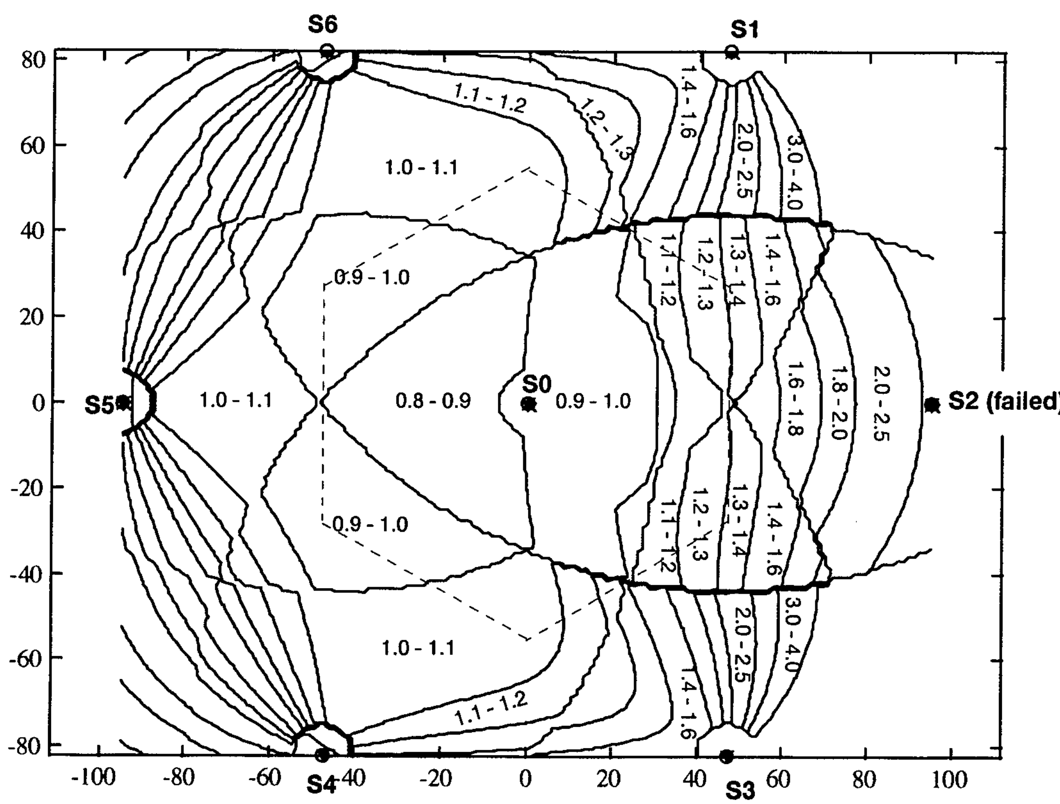


Figure A-8. Multilateration HDOP Ranges: Redundancy 2, Failures 1

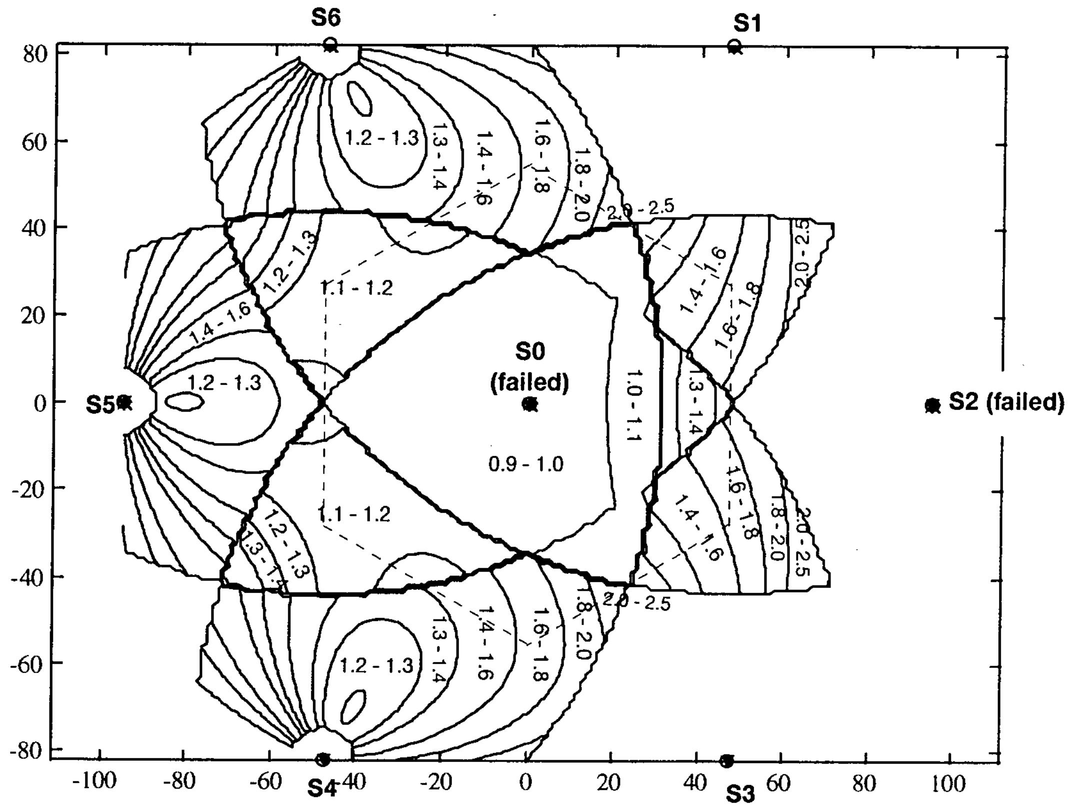


Figure A-9. Multilateration HDOP Ranges: Redundancy 2, Failures 2

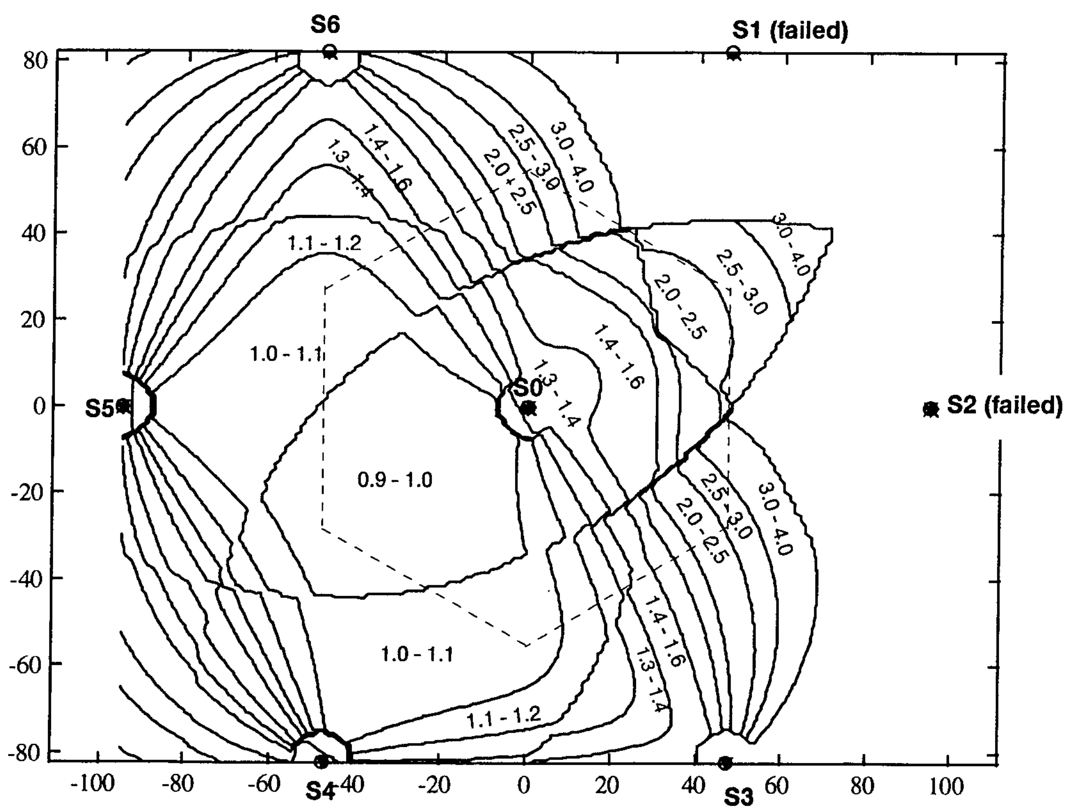


Figure A-10. Multilateration HDOP Ranges: Redundancy 2, Failures 2

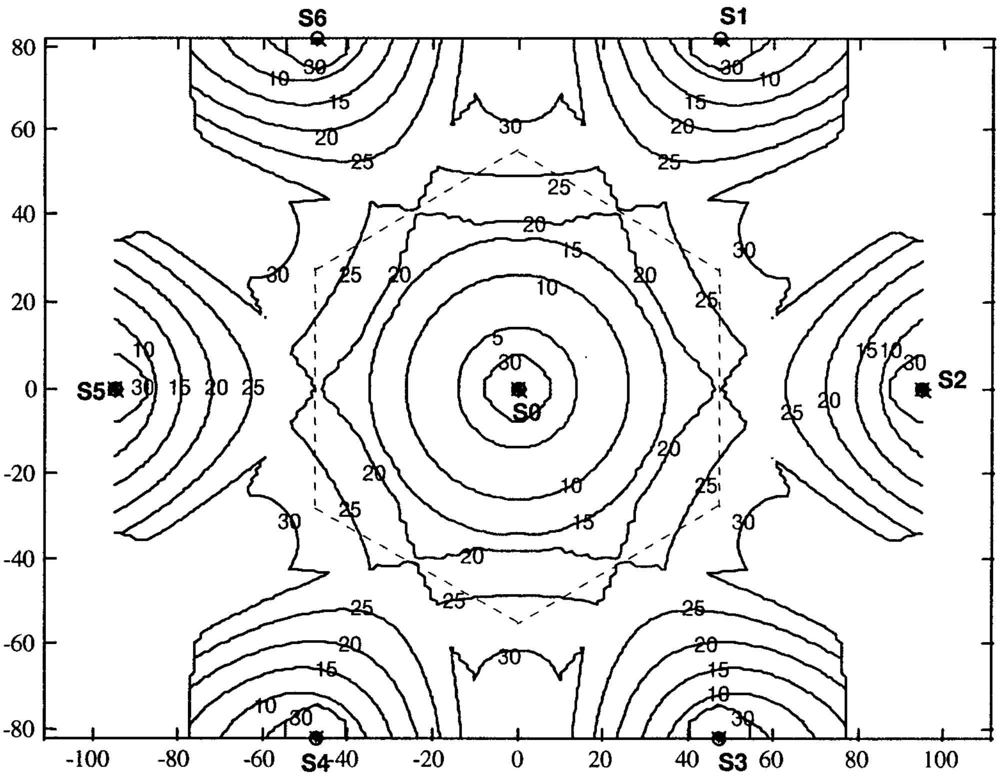


Figure A-11. Multilateration VDOP Ranges: Redundancy 1, Failures 0

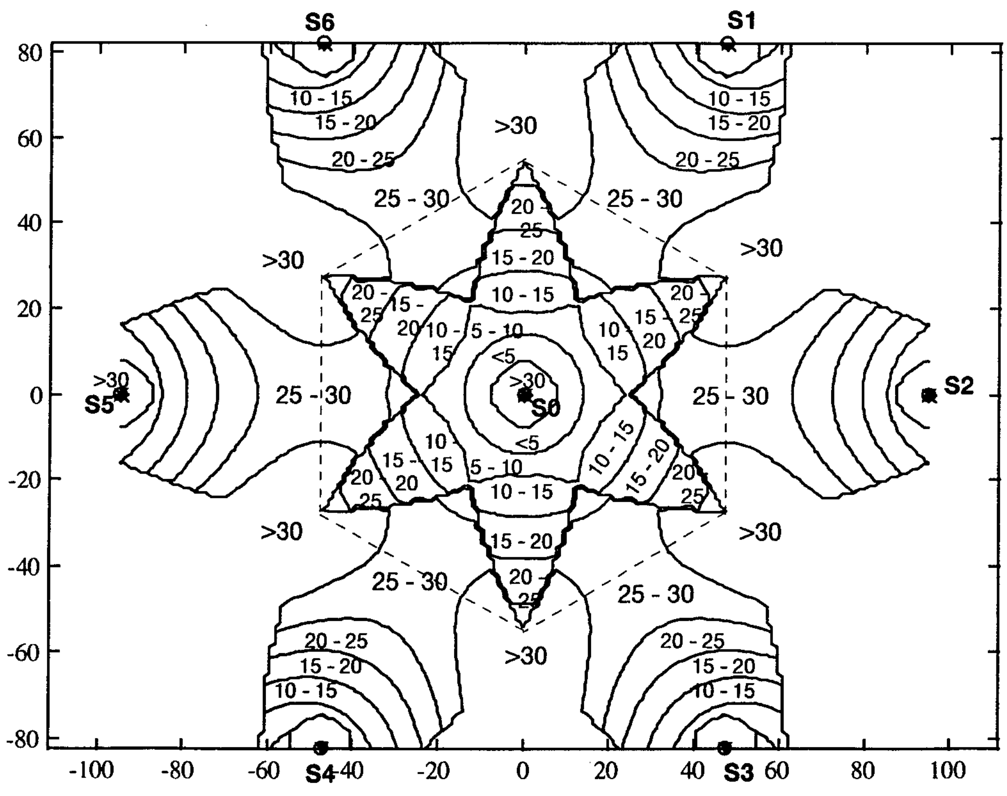


Figure A-12. Multilateration VDOP Ranges: Redundancy 1, Failures 0

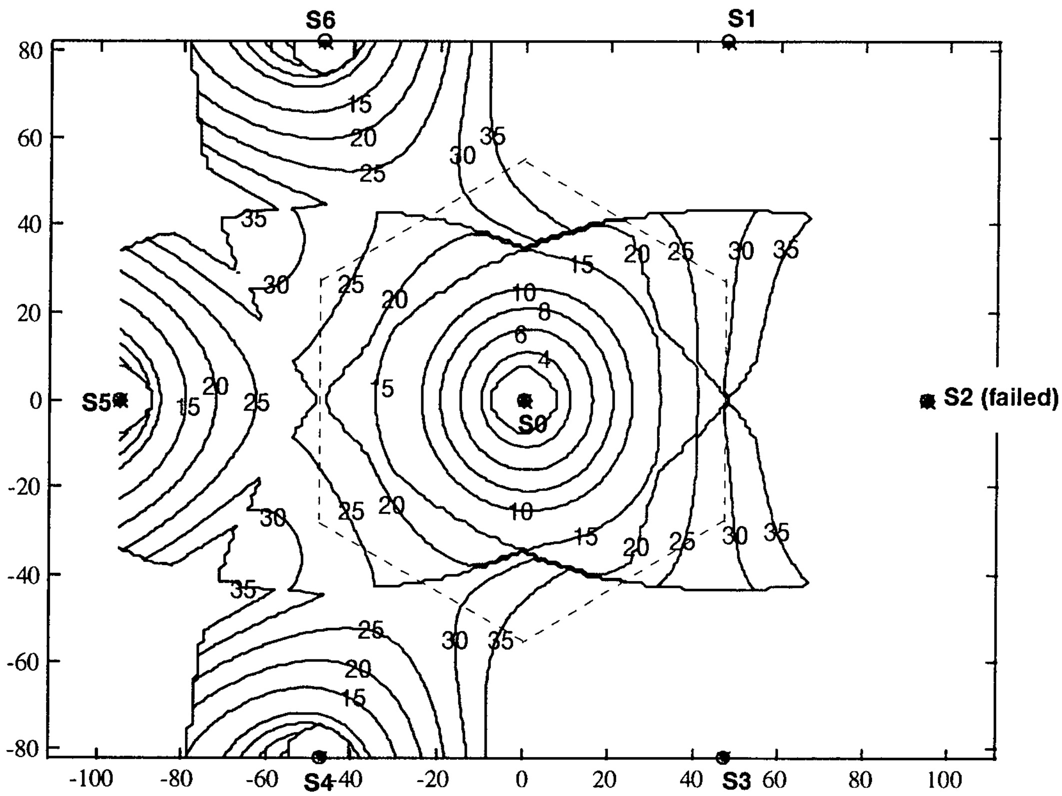


Figure A-13. Multilateration VDOP Contours: Redundancy 2, Failures 1

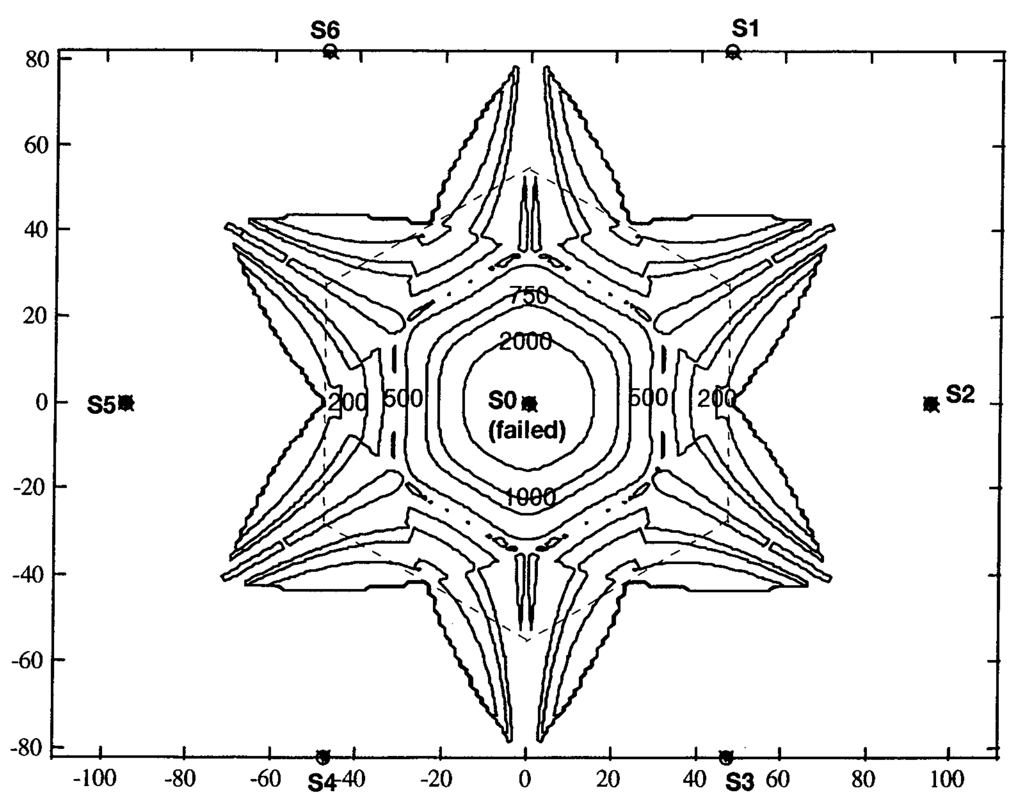


Figure A-14. Multilateration VDOP Contours: Redundancy 2, Failures 1

Appendix B Beacon Multilateration Capacity

B.1 1090 MHz Channel Interference Model

A model was used to estimate multilateration system probability of clear reception of the same aircraft's transponder signal at three ground sites as a function of ADS-B squitter rate, trilateration update rate, and interference environment (Reference 12). The model was based on a Poisson Model published by MIT/Lincoln Laboratory (Reference 13). Using this model it was possible to determine multilateration system sensitivities to the RF environment during transition from the existing system to an end state as a function of ground station antenna type, numbers of aircraft, and the type of transponder signal (i.e., Mode S short, Mode S extended, and Mode C) used as the multilateration signal.

According to the model, the probability of a single reply colliding with exactly n interfering transmissions is given by

$$p(n) = (\lambda t)^n e^{-\lambda t} / n!$$

where

- λ is the total number of fruit replies per aircraft per second,
- t is the sum of the desired message length plus the interfering message length, and
- n is the number of overlaps of the desired message.

When n = 0 (i.e., no transmissions from other aircraft overlap the desired signal) the probability of correct detection of the desired transmission is unity. When n = 2 or greater, the probability of correct detection is zero. When n = 1, the situation is more complicated. If the desired message is a Mode C reply, the probability of correct detection in the presence of an interfering ATCRBS message is either 2/3 or 0, depending upon whether or not the ground station receiver has de-interleaving capability, respectively. If an ATCRBS message is interfered with by a short or long Mode S message, the probability of correct detection is zero. If the desired message is a short or long Mode S message, the probability of correct detection in the presence of ATCRBS interference is either 1 or 0, depending upon whether or not the receiver error has error correction. When the desired message is a short or long Mode S message and a Mode S signal interferes, the probability of correct detection is 0.

For the case of a six-sector ADS-B ground station antenna, the value of λ is a factor of 2.5 smaller than for an omni-directional antenna.

The overall probability of correctly receiving an aircraft transmission p_r is the product of the individual probabilities attributable to each source of interference, i.e., ATCRBS, Mode S short messages and Mode S long messages, so that

$$p_r = p_a * p_{ss} * p_{sl}$$

Multilateration further requires that the same message be received at "k" different ground stations — k = 3 for the minimum number of sites. Thus, the probability of successfully receiving the same signal at k different ground stations is given by

$$P_k = (p_r)^k$$

Next, consider that for an update interval of "T" and K desired messages broadcast per second, there are KT opportunities to receive a message in the clear. The probability of successfully receiving the same message in the clear at least once at three different stations given m = KT opportunities is

$$P_r(T) = 1 - (1 - P_k)^m$$

Several aircraft densities and RF environments were examined by varying the values of λ for ATCRBS and Mode S interference. The specific scenarios investigated are described below:

B.2 Scenarios and Channel Congestion

Three scenarios were investigated.

Near Term

- 120 ATCRBS emissions/second/aircraft (100 replies to ground interrogations; 20 replies to TCAS)
- 8 Mode S Short emissions/second/aircraft (2 replies to ground interrogations; 1 squitter; 5 TCAS)
- 6 to 8 Mode S Long emissions/second/aircraft (4 replies to the ground system; 2, 3, or 4 ADS-B squitter)

Transition Case

- 60 ATCRBS emissions/second/aircraft (40 replies to ground interrogations; 20 replies to TCAS)
- 8 Mode S Short emissions/second/aircraft (2 replies to ground interrogations; 1 squitter; 5 TCAS)
- 6 to 8 Mode S Long emissions/second/aircraft (4 replies to the ground system; 2, 3, or 4 ADS-B squitter)

Post-2015 Case

- 20 ATCRBS emissions/second/aircraft (20 replies to TCAS & ADS-B sites; SSRs being phased out)
- 8 Mode S Short emissions/second/aircraft (2 replies to ground interrogations; 1 squitter; 5 TCAS)
- 6 to 8 Mode S Long emissions/second/aircraft (4 replies to the ground system; 2, 3, or 4 ADS-B squitter)

Each of these scenarios was applied to multilateration on a Mode C, a Mode S short, and a Mode S long message in the presence of simultaneous interference from ATCRBS and Mode S emissions. The three basic scenarios were employed in conjunction with both omni-directional and six-sector ground station antennas. The most interesting results are for the Near-Term and the Post-2015 cases, since these provide reasonable operational limits on beacon multilateration system performance.

The governing assumptions for this analysis are:

1. Half of the total ATCRBS replies will be Mode C and are candidates for trilateration;
2. Three ground stations and aircraft altitude information are required;
3. Mode C to Mode C receptions at different sites are correlated based on altitude and TOA; Mode C to Mode C receptions at one site are correlated based on position. Mode S reports are correlated based on identity;
4. Aircraft replying in more than one mode will be subjected to track-to-track correlation to eliminate duplicate tracks; and,
5. Ground receivers have Mode C de-interleaving and Mode S error correction capabilities.

Results for the Near-Term (Figure B-1) and for the Post-2015 (Figure B-2) environments with four ADS-B squitters per second are provided for multilateration on an ATCRBS Mode C message.

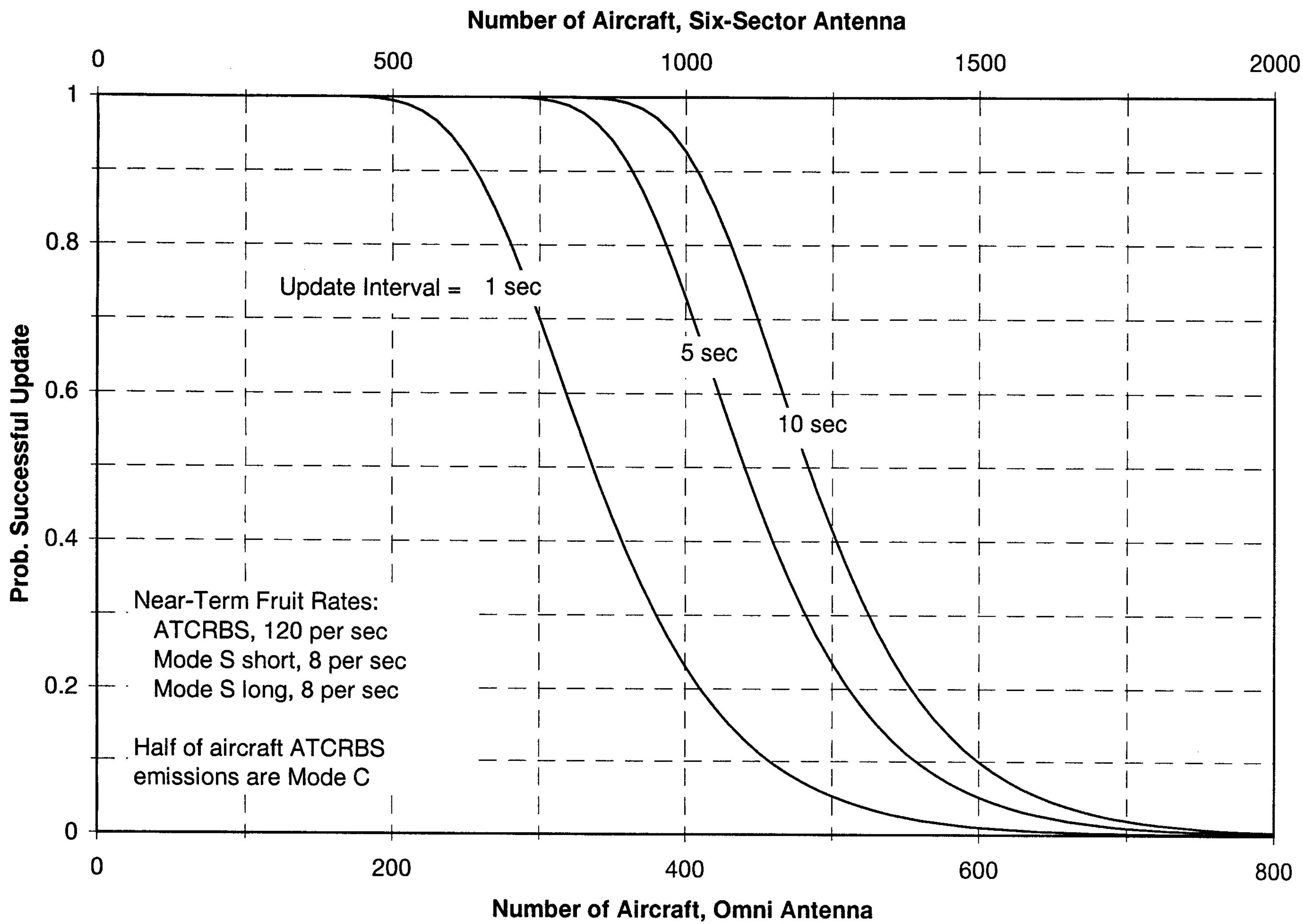


Figure B-1. Mode C Multilateration Update Probability — Near-Term Fruit Rate

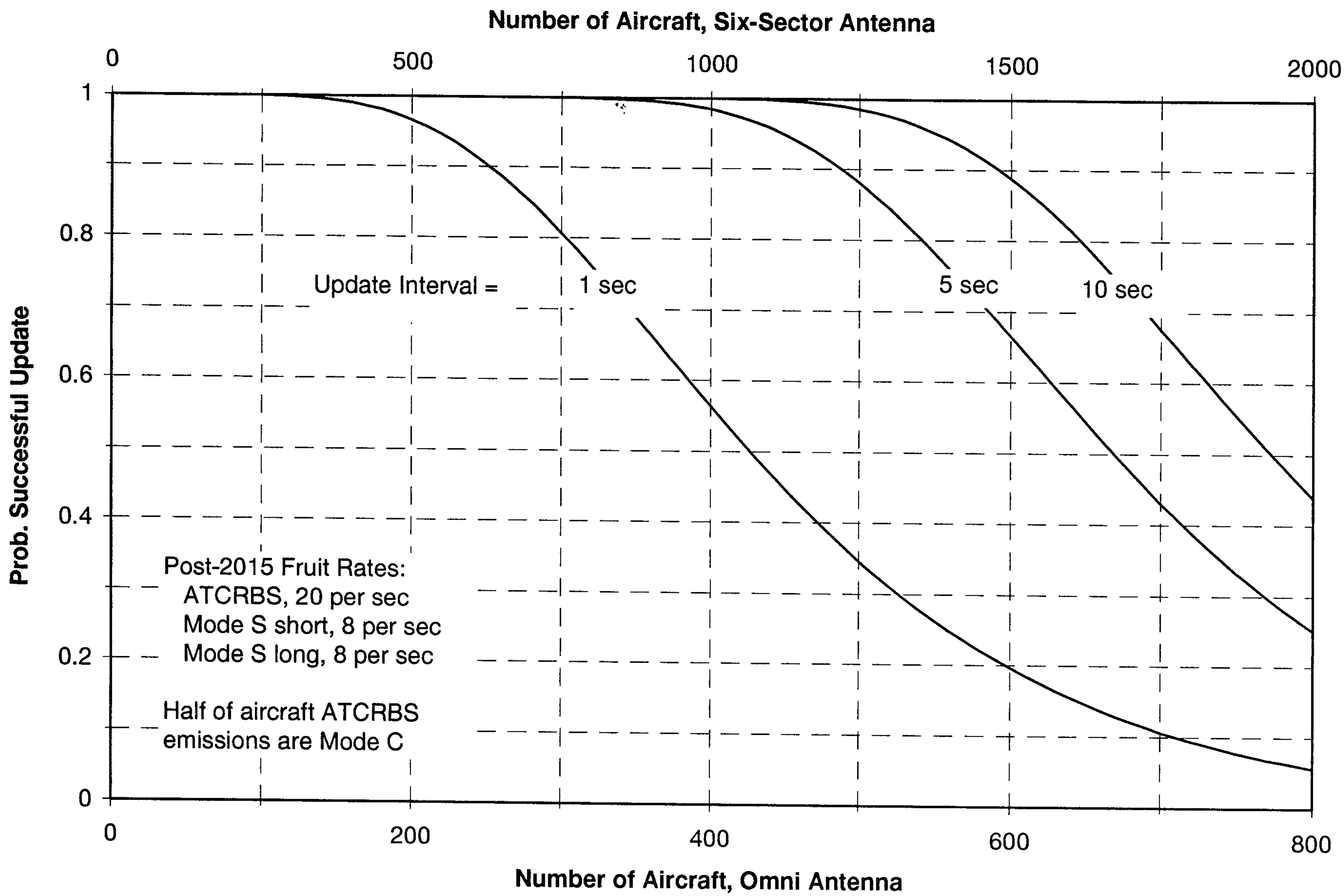


Figure B-2. Mode C Multilateration Update Probability — Post 2015 Fruit Rates

In Figures B-1 and B-2, the bottom axis pertains to an omni-directional ground station antenna and the top axis pertains to a six-sector antenna.

B.3 Capacity

The data developed by the multilateration probability model was used to determine beacon multilateration system capacity. For purposes of this report, multilateration system capacity is defined as the number of aircraft that can be accommodated by the system with a 99% probability of three ground stations successfully receiving at least one of an aircraft's transponder signals in the specified update interval. Table B-2 summarizes the beacon multilateration system capacities in the three environments for: update rates of 1, 5, and 10 seconds (i.e., existing update intervals for surface, terminal and en route domains respectively); ADS-B squitter rates of 2, 3, and 4 squitters/second; and, for two antenna types.

Examination of Table B-2 shows that multilateration is more robust with Mode C signals than with Mode S signals. This is because — since there are more Mode C signals per second than Mode S — the chances of getting the same emission in the clear at three stations is higher. In addition, the message length of the Mode C is significantly shorter than the Mode S messages which contributes to higher reception probabilities and therefore to higher capacities.

It is also worthwhile to note a phenomenon that is not immediately obvious: Diminishing returns are associated with increasing the message rate in order to increase the number of chances of obtaining a message in the clear, because at the same time the amount of interference from other aircraft is increased. This phenomenon is illustrated in Figure B-3, which displays Mode C multilateration capacity versus aircraft Mode C emission rate for update intervals of 1, 5, and 10 seconds. The left-hand axis pertains to an omni-directional antenna and the right-hand axis to a six-sector antenna.

Peak capacities are given in Table B-1. It is clear that for the Near-Term scenario, Mode C multilateration capacity is limited by the high rates of emissions due to ground radars. In the Post-2015 scenario, capacity is limited by insufficient aircraft emissions. This may necessitate remedial action such as retaining ground-based interrogators in high-density areas.

Table B-1. ATCRBS Multilateration Peak Capacity

Update Interval	ATCRBS Rate*	Omni Capacity	6-Sector Capacity
1 sec	64 / sec	230	576
5 sec	38 / sec	412	1,031
10 sec	30 / sec	503	1,257

* Half of ATCRBS emissions are Mode C; Mode S are 8 per second

Table B-2. Beacon Multilateration System Aircraft Capacities

Multilateration Signal	ATCRBS Multilateration									Mode S Short Multilateration									Mode S Long Multilateration								
Update Interval	1 second			5 seconds			10 seconds			1 second			5 seconds			10 seconds			1 second			5 seconds			10 seconds		
ADS-B Squitters/second	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4
ENVIRONMENT	**OMNI ANTENNA**																										
Near-Term Worst Case	223	216	210	337	327	318	384	374	363	63	61	59	129	126	123	156	153	150	33	36	38	74	76	78	91	93	95
Transition Case	253	241	230	433	413	395	509	486	466	91	87	83	201	193	186	247	238	230	49	53	56	119	121	123	148	150	151
Post-2015 Case	184	171	160	442	411	385	560	522	488	121	112	105	302	283	265	383	359	338	66	72	75	188	188	188	243	241	238
ENVIRONMENT	**SIX SECTOR ANTENNA**																										
Near-Term Worst Case	557	540	524	824	818	795	961	934	903	157	152	148	322	314	307	390	382	374	82	89	95	185	191	195	228	233	237
Transition Case	633	602	574	1081	1033	988	1272	1216	1164	228	217	207	502	483	465	617	595	574	122	132	140	296	303	307	371	375	377
Post-2015 Case	461	428	399	1105	1028	961	1400	1304	1220	302	281	262	755	706	663	957	897	844	165	179	189	469	471	469	607	602	594

* Based on the criterion that with 99% or greater probability, at least one and the same aircraft transmission will be received and correctly decoded at three ground stations during the specified update interval.

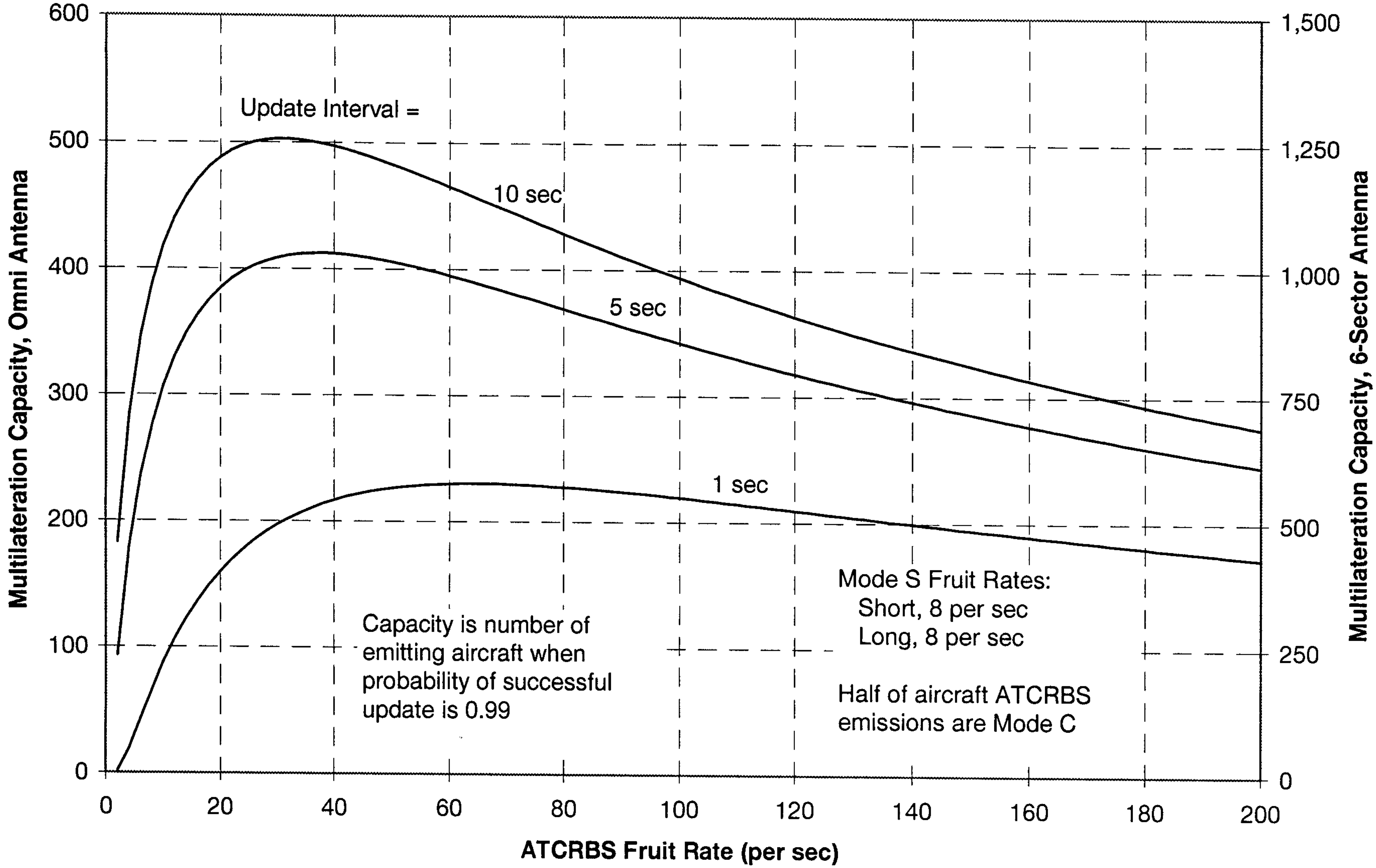


Figure B-3. Mode C Multilateration Capacity

Appendix C Cost Breakdown Structure Detailed Development

This appendix presents numerical values and associated rationale for each element in the cost breakdown structure employed in this investigation (Table C-1).

Table C-1. Cost Breakdown Structure

RESEARCH, ENGINEERING AND DEVELOPMENT (R,E&D)
System Engineering
Non-Recurring Engineering -- Hardware
Non-Recurring Engineering -- Software
Pre-Production Systems
Development Test and Evaluation (DT&E)
FACILITIES AND EQUIPMENT (F&E)
Program Office Support
Contractor Program Management
Contractor Systems Engineering
Civil Works (Real Property Improvements)
Prime Mission Equipment (PME)
Support Equipment
Site Activation
Equipment Installation and Test
Initial Spares
Documentation
Freight and Inspection
Engineering Change Orders (ECOs)
Initial Operations Training
Initial Maintenance Training
OPERATIONS AND MAINTENANCE (O&M)
Consumables
Rent
Energy
Operations Personnel
Operations Travel
Operations Training
Telecommunications
Hardware Maintenance
Maintenance Training
Software Maintenance
Replenishment Spares

MAJOR CATEGORY	**Research, Engineering and Development (R,E&D)**
SUBCATEGORY	**System Engineering**

DESCRIPTION

Analysis and planning efforts by FAA and support contracts to fully define system. Includes the following activities:

- Requirements Analysis
- Functional Allocation
- System Analysis
  - Trade Studies
  - Cost Benefit
  - Risk
- System Synthesis
- Validation and Verification

METHODOLOGY

Engineering judgment.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	5.0
2	ADS-B squitter	Az-Alt verify	5.5
3	ADS-B squitter	Range-az-alt verify	6.0
4	ADS-B squitter	Range-az-alt surveil	6.0
5	ADS-B squitter	TCAS range-az-alt	6.0
6	ADS-B squitter	Passive ML	7.5
7	ADS-B squitter	Active ML	7.5
8	ADS-B squitter	ATCBI GIC-B / MSSR	6.0
9	ATCBI GIC-B	ATCBI MSSR	1.5
10	ATCBI MSSR	(none)	1.0

MAJOR CATEGORY	**Research, Engineering and Development (R,E&D)**
SUBCATEGORY	**Non-Recurring Engineering (NRE) -- Hardware (HW)**

DESCRIPTION

Enineering efforts to develop ground station hardware. For ADS-B, the fusion tracker is also included.

- Ground station hardware
- Fusion tracker hardware
- Other hardware
- Acceleration/risk factor

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	17.8
2	ADS-B squitter	Az-Alt verify	17.8
3	ADS-B squitter	Range-az-alt verify	18.7
4	ADS-B squitter	Range-az-alt surveil	21.4
5	ADS-B squitter	TCAS range-az-alt	22.8
6	ADS-B squitter	Passive ML	20.8
7	ADS-B squitter	Active ML	20.8
8	ADS-B squitter	ATCBI GIC-B / MSSR	20.8
9	ATCBI GIC-B	ATCBI MSSR	3.0
10	ATCBI MSSR	(none)	0.0

ADS-B

In 1993, FAA estimated cost for ADS-B system comrised of ground station and fusion tracker. The estimate was: 15.0

Inflating by 5 years, to 1998 dollars 17.8

Multilateration

Relative to Alt. 1, additional hardware is: GPS receivers at all sites, computer at primary site at least, modems at all sites. All are off-the-shelf items. The only NRE cost foreseen is for paper design and analysis. The following nominal value is used (equivalent to approx 15 labor years): 3.0

ATCBI-6

MSSR systems are commercially available, so NRE would be zero if such system were purchased and used without alteration. However, some interface changes may be necessary (e.g., digital output in ASTERIX format). A nominal value is used (equivalent to 15 labor years): 3.0

ALT. NO. 6

Relative to Alt. 1, additional hardware is: GPS receivers at all sites, computer at primary site at least, microwave electronics and antennas at all sites. All are off-the-shelf items. The only NRE cost foreseen is for paper design and analysis. The following nominal value is used (equivalent to approx. 25 labor years): 5.0

ALT. NO. 5

Relative to Alt. 6, additional hardware is a transmitter at each ground site. This is an off-the-shelf item (TCAS). However, use of TCAS on the ground is essentially untested. The following nominal value is used (equivalent to approx 15 labor years): 3.0

MAJOR CATEGORY	**Research, Engineering and Development (R,E&D)**
SUBCATEGORY	**Non-Recurring Engineering (NRE) -- Software (SW)**

DESCRIPTION
Enineering efforts to develop software which performs all intended functions, as part of establishing that the system which will satisfy all performance requirements. Includes the following:

- Ground station software
- Fusion tracker software
- Other software
- Acceleration/risk factor

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	15.1
2	ADS-B squitter	Az-Alt verify	16.6
3	ADS-B squitter	Range-az-alt verify	17.4
4	ADS-B squitter	Range-az-alt surveil	18.1
5	ADS-B squitter	TCAS range-az-alt	18.1
6	ADS-B squitter	Passive ML	25.1
7	ADS-B squitter	Active ML	25.1
8	ADS-B squitter	ATCBI GIC-B / MSSR	15.9
9	ATCBI GIC-B	ATCBI MSSR	0.7
10	ATCBI MSSR	(none)	0.0

ALT. NO. 1

Estimated total cost (FY93$M)		24.9
Expended for Gulf of Mexico Program (FY93$M)		14.3
Difference (FY93$M)		10.6
Inflated by 5 years (FY98$M)		12.6
Risk	20.0%	15.1

NOTE: ADS-B requires ASTERIX format. Software development of the ASTERIX formatting within the ADS-B site computer is included in this cost.

ALT NO. 6 & 7
These systems have about the same complexity, so the same value is used. Two equipment manufacturers have already developed multilateration software at costs believed to be less than $1M. Added cost of multilateration (FY98$M): 10.0

MAJOR CATEGORY	**Research, Engineering and Development (R,E&D)**
SUBCATEGORY	**Pre-Production Systems**

DESCRIPTION

Development of two pre-production systems, to establish the production system design.

METHODOLOGY

Multiple cost of PME for one system by the following factor

Number systems	2
Premium for low volume	250%
PRODUCT	5.0

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME ($M)	PreProd ($M)
1	ADS-B squitter	(none)	0.25	1.23
2	ADS-B squitter	Az-Alt verify	0.25	1.23
3	ADS-B squitter	Range-az-alt verify	0.28	1.38
4	ADS-B squitter	Range-az-alt surveil	0.35	1.73
5	ADS-B squitter	TCAS range-az-alt	0.30	1.51
6	ADS-B squitter	Passive ML	0.18	0.88
7	ADS-B squitter	Active ML	0.18	0.88
8	ADS-B squitter	ATCBI GIC-B / MSSR	1.85	9.23
9	ATCBI GIC-B	ATCBI MSSR	1.60	8.00
10	ATCBI MSSR	(none)	1.47	7.33

MAJOR CATEGORY	**Research, Engineering and Development (R,E&D)**
SUBCATEGORY	**Development Test and Evaluation**

DESCRIPTION

Testing of the preproduction systems

METHODOLOGY

Engineering judgment.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	5.0
2	ADS-B squitter	Az-Alt verify	5.2
3	ADS-B squitter	Range-az-alt verify	6.0
4	ADS-B squitter	Range-az-alt surveil	8.0
5	ADS-B squitter	TCAS range-az-alt	10.0
6	ADS-B squitter	Passive ML	10.0
7	ADS-B squitter	Active ML	10.0
8	ADS-B squitter	ATCBI GIC-B / MSSR	10.0
9	ATCBI GIC-B	ATCBI MSSR	5.0
10	ATCBI MSSR	(none)	5.0

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Program Office Support**

DESCRIPTION
Technical and administrative efforts to plan, manage and implement the program, Includes the following:

- Government personnel
- Contractor personnel

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)	RATIONALE
1	ADS-B squitter	(none)	14.3	Same as BI-6 study
2	ADS-B squitter	Az-Alt verify	14.3	Same as BI-6 study
3	ADS-B squitter	Range-az-alt verify	15.8	1.1 times BI-6 study
4	ADS-B squitter	Range-az-alt surveil	17.2	1.2 times BI-6 study
5	ADS-B squitter	TCAS range-az-alt	21.5	1.5 times BI-6 study
6	ADS-B squitter	Passive ML	21.5	1.5 times BI-6 study
7	ADS-B squitter	Active ML	21.5	1.5 times BI-6 study
8	ADS-B squitter	ATCBI GIC-B / MSSR	28.7	2 times BI-6 study
9	ATCBI GIC-B	ATCBI MSSR	14.3	BI-6 Cost Study
10	ATCBI MSSR	(none)	14.3	0.9 times BI-6 study

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Contractor Program Management**

DESCRIPTION
Business and administrative planning, organizing, and managing designed to accomplish overall program objectives which are not associated with specific system elements and are not included in system engineering.

METHODOLOGY
Use fixed fraction of PME cost. Factor = 6.5%
Factor taken from ATCBI-6 study.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	1.9
2	ADS-B squitter	Az-Alt verify	1.9
3	ADS-B squitter	Range-az-alt verify	2.1
4	ADS-B squitter	Range-az-alt surveil	2.6
5	ADS-B squitter	TCAS range-az-alt	2.3
6	ADS-B squitter	Passive ML	4.0
7	ADS-B squitter	Active ML	4.0
8	ADS-B squitter	ATCBI GIC-B / MSSR	13.9
9	ATCBI GIC-B	ATCBI MSSR	12.1
10	ATCBI MSSR	(none)	11.1

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Contractor System Engineering**

DESCRIPTION
Technical and management efforts of directing and controlling an integrated engineering program.

METHODOLOGY
Use fixed fraction of PME cost. Factor = 6.8%
Factor taken from ATCBI-6 study.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST($M)
1	ADS-B squitter	(none)	1.9
2	ADS-B squitter	Az-Alt verify	1.9
3	ADS-B squitter	Range-az-alt verify	2.2
4	ADS-B squitter	Range-az-alt surveil	2.7
5	ADS-B squitter	TCAS range-az-alt	2.4
6	ADS-B squitter	Passive ML	4.2
7	ADS-B squitter	Active ML	4.2
8	ADS-B squitter	ATCBI GIC-B / MSSR	14.6
9	ATCBI GIC-B	ATCBI MSSR	12.6
10	ATCBI MSSR	(none)	11.6

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Real Property Improvments**

DESCRIPTION

Development of a new facility or improvement of an existing facility to accomodate Prime Mission Equipment (PME). Includes the following:

- Access road(s)
- AC power lines, generation or conditioning
- Building structure(s)
- Heating, ventilation and Cooling (HVAC)
- Building interior(s) (kitchen, bath, etc.)
- Water supply system
- Sewage system
- Security system
- Fire suppression system
- Fence(s)

METHODOLOGY

Based on Cost-Benefit Analysis by MCR Federal for AND-440, January 1997.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	WEIGHTED COST ($K)	NUMBER SITES	COST($M)
1	ADS-B squitter	(none)	39.0	116	4.5
2	ADS-B squitter	Az-Alt verify	39.0	116	4.5
3	ADS-B squitter	Range-az-alt verify	39.0	116	4.5
4	ADS-B squitter	Range-az-alt surveil	39.0	116	4.5
5	ADS-B squitter	TCAS range-az-alt	39.0	116	4.5
6	ADS-B squitter	Passive ML	39.0	348	13.6
7	ADS-B squitter	Active ML	39.0	348	13.6
8	ADS-B squitter	ATCBI GIC-B / MSSR	390.5	116	45.3
9	ATCBI GIC-B	ATCBI MSSR	390.5	116	45.3
10	ATCBI MSSR	(none)	390.5	116	45.3

ALTERNATIVES 1-7

Category	Fraction	Cost per Site ($K)
New sites	10%	205.5
Modified existing sites	90%	20.6
Weighted Average		39.0

ALTERNATIVES 8-10

Category	Fraction	Cost per Site ($K)
New sites	10%	2,055.0
Modified existing sites	90%	205.5
		390.5

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Prime Mission Equipment (PME)**

DESCRIPTION
Purchase of production operational system ground station equipment hardware. Note that: (1) NRE cost addressed separately, and (2) production software addressed separately.

METHODOLOGY
ATCBI-6 cost study used as starting point, modified as appropriate.

COST SUMMARY

			SITE	TOTAL COST ($M)	
ALT. NO.	PRINCIPAL SYSTEM	COMPLEMENTARY	COST ($K)	All New	Existing
1	ADS-B squitter	(none)	246.9	28.6	28.6
2	ADS-B squitter	Az-Alt verify	246.9	28.6	28.6
3	ADS-B squitter	Range-az-alt verify	276.9	32.1	32.1
4	ADS-B squitter	Range-az-alt surveil	346.9	40.2	40.2
5	ADS-B squitter	TCAS range-az-alt	302.9	35.1	35.1
6	ADS-B squitter	Passive ML	175.4	61.0	61.0
7	ADS-B squitter	Active ML	175.9	61.2	61.2
8	ADS-B squitter	ATCBI GIC-B / MSSR	1,846.9	214.2	140.1
9	ATCBI GIC-B	ATCBI MSSR	1,600.0	185.6	111.5
10	ATCBI MSSR	(none)	1,466.8	170.1	98.3

ALT. 1, ADS-B
SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K paid by MIT/LL
1090 MHz Receiver	2	75.0	150.0	6 channel set, decode long squit
Site Processor	2	20.0	40.0	Sun Sparc
Modem	4	0.5	2.0	Interface to two ARTCCs
UPS, 2kw	1	2.0	2.0	Cost approx $1/W
Shelter	1	15.0	15.0	
Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			246.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			28.6	

ALT. 2, ADS-B
SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K paid by MIT/LL
1090 MHz Receiver	2	75.0	150.0	6 channel set, decode long squit
Site Processor	2	20.0	40.0	Sun Sparc
Modem	4	0.5	2.0	Interface to two ARTCCs
UPS, 2kw	1	2.0	2.0	Cost approx $1/W

Shelter	1	15.0	15.0
Tower	1	10.0	10.0
TOTAL PER SITE ($K)			246.9
NUMBER OF SITES			116
TOTAL COST ($M)			28.6

ALT. 3, ADS-B

SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K paid by MIT/LL
1030 MHz Transmitter	2	15.0	30.0	TCAS unit, interrogate Mode S
1090 MHz Receiver	2	75.0	150.0	6 channel set, decode long squit
Site Processor	2	20.0	40.0	Sun Sparc
Modem	4	0.5	2.0	Interface to two ARTCCs
UPS, 2kw	1	2.0	2.0	Cost approx $1/W
Shelter	1	15.0	15.0	
Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			276.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			32.1	

ALT. 4, ADS-B w/ Active Range/Azimuth

SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K
1030 MHz Transmitter	2	15.0	30.0	TCAS unit, int'gate Mode A/C/S
1090 MHz Receiver	2	110.0	220.0	See Note
Site Processor	2	20.0	40.0	Sun Sparc
Modem	4	0.5	2.0	Interface to two ARTCCs
UPS, 2kw	1	2.0	2.0	Cost approx $1/W
Shelter	1	15.0	15.0	
Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			346.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			40.2	

Note: Receiver interfaces to 6 antenna elements, has monopulse processing (hence 12 channels),
decodes Mode A/C/S short & long decode emissions

ALT. 5, ADS-B + TCAS

SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K
1090 MHz Receiver	1	75.0	75.0	6 channel set, decode long squit
Site Processor	1	20.0	20.0	Sun Sparc
TCAS Xmtr/Rcvr	1	90.0	90.0	Commercial price
Antenna for TCAS	1	60.0	60.0	???
Modem	2	0.5	1.0	Interface to two ARTCCs
UPS, 4 kw	1	4.0	4.0	Cost approx $1/W
Shelter	1	15.0	15.0	

Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			302.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			35.1	

Note: Receiver interfaces to 6 antenna elements, has monopulse processing (hence 12 channels), decodes Mode A/C/S short & long emissions

ALT. 6, ADS-B / Passive Multilateration

SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	90% of $31K
1090 MHz Receiver	1	80.0	80.0	See Note
GPS/Rb Clock	1	7.0	7.0	GPS Rcvr w/Rubidium clock
Site Processor	1	20.0	20.0	Sun Sparc
Modem	7	0.5	3.5	
Multilateration Processor	1	10.0	10.0	
UPS, 2kw	1	2.0	2.0	
Shelter	1	15.0	15.0	
Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			175.4	
NUMBER OF SITES			348	
TOTAL COST ($M)			61.0	

Note: Receiver 1090 MHz: 6 channels, decode Mode A/C/S short/S extended, insert TOA mark

ALT. NO. 7, ADS-B / Active Multilateration

SINGLE SITE COMPONENT COSTS

Item	Number	Unit ($K)	Site ($K)	Rationale
Six-Sector Antenna	1	27.9	27.9	
1030 MHz Transmitter	1	15.0	15.0	TCAS unit, int'gate Mode A/C/S
1090 MHz Receiver	1	75.0	75.0	See Note
Signal Processor	1	20.0	20.0	
Multilat. Computer	1	10.0	10.0	
UPS, 2kw	1	2.0	2.0	
Modem	2	0.5	1.0	
Shelter	1	15.0	15.0	
Tower	1	10.0	10.0	
TOTAL PER SITE ($K)			175.9	
NUMBER OF SITES			348	
TOTAL COST ($M)			61.2	

Note: Receiver 1090 MHz: 6 channels, decode Mode A/C/S short/S extended, insert TOA mark

ALT. 9, ATCBI-6 w/SI/GIC-B

SINGLE SITE COMPONENT COSTS ($K)

Item	Unit ($K)	Site ($K)	Rationale
Antenna	123.2		ATCBI-6 study, Alt 5
Rotary Joint	98.0		ATCBI-6 study, Alt 5
MSSR (incl. SI & IISLS)	790.9		ATCBI-6 study, Alt 5
Test Set	45.1		ATCBI-6 study, Alt 5
Beacon Video Reconstituter	42.0		ATCBI-6 study, Alt 5
I/O Ports (2)	3.1		ATCBI-6 study, Alt 5
Interface Cards (2)	2.5		ATCBI-6 study, Alt 5
1996 COST per SITE ($K)		1,104.8	
Inflation Factor for two years		1.07	
1998 COST per SITE ($K)		1,183.5	
Tower	166.0		1993 Mode S Second Buy Study
Engine Generator	93.0		1993 Mode S Second Buy Study
Shelter	58.0		1993 Mode S Second Buy Study
1993 COST per SITE ($K)		317.0	
Inflation Factor for five years		1.19	
1998 COST per SITE ($K)		376.5	
Beacon Parrot		40.0	Mode S transponder
TOTAL COST PER SITE ($K)		1,600.0	
Number of Units		116	
TOTAL COST ALL UNITS ($M)		185.6	

Available at Existing Site

Antenna	123.2	
Rotary Joint	98.0	
Beacon Video Reconstituter	42.0	
1996 COST per SITE ($K)		263.2
Inflation Factor for two years		1.07
1998 COST per SITE ($K)		282.0
Tower	166.0	
Engine Generator	93.0	
Shelter	58.0	
1993 COST per SITE ($K)		317.0
Inflation Factor for five years		1.19
1998 COST per SITE ($K)		376.5
Beacon Parrot		40.0
TOTAL EXISTING ($K)		639.0
NEW COSTS ($K)		961.0
Number of Units		116
NEW COST, ALL UNITS ($M)		111.5

ALT. 10, ATCBI-6 w/o SI/GIC-B

SINGLE SITE COMPONENT COSTS ($K)

Item	Unit ($K)	Site ($K)	Rationale
Antenna	123.2		ATCBI-6 study, Alt 5
Rotary Joint	98.0		ATCBI-6 study, Alt 5
MSSR	579.5		ATCBI-6 study, Alt 5
IISLS	105.7		

Test Set	45.1		ATCBI-6 study, Alt 5
Beacon Video Reconstituter	42.0		ATCBI-6 study, Alt 5
I/O Ports (2)	3.1		ATCBI-6 study, Alt 5
Interface Cards (2)	2.5		ATCBI-6 study, Alt 5
1996 COST per SITE ($K)		999.1	
Inflation Factor for two years		1.07	
1998 COST per SITE ($K)		1,070.3	
Tower	166.0		1993 Mode S Second Buy Study
Engine Generator	93.0		1993 Mode S Second Buy Study
Shelter	58.0		1993 Mode S Second Buy Study
1993 COST per SITE ($K)		317.0	
Inflation Factor for five years		1.19	
1998 COST per SITE ($K)		376.5	
Beacon Parrot		20.0	Mode A/C transponder
TOTAL COST PER SITE ($K)		1,466.8	
Number of Units		116	
TOTAL COST ALL UNITS ($M)		170.1	

Available at Existing Site		
Antenna	123.2	
Rotary Joint	98.0	
Beacon Video Reconstituter	42.0	
1996 COST per SITE ($K)		263.2
Inflation Factor for two years		1.07
1998 COST per SITE ($K)		282.0
Tower	166.0	
Engine Generator	93.0	
Shelter	58.0	
1993 COST per SITE ($K)		317.0
Inflation Factor for five years		1.19
1998 COST per SITE ($K)		376.5
Beacon Parrot		20.0
TOTAL EXISTING ($K)		619.0
NEW COSTS ($K)		847.8
Number of Units		116
NEW COST, ALL UNITS ($M)		98.3

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Support Equipment**

DESCRIPTION

Equipment required to support the PME. Includes both common support equipment (purchasable on the open market) and peculiar support equipment.

METHODOLOGY

Follows the ATCBI-6 Cost Study. It estimates support equipment costs as a fraction of PME hardware costs

Peculiar Support Equipment Factor	0.0%
Common Support Equipment Factor	6.0%

COST

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME ($M)	SUP EQ ($M)
1	ADS-B squitter	(none)	28.6	1.7
2	ADS-B squitter	Az-Alt verify	28.6	1.7
3	ADS-B squitter	Range-az-alt verify	32.1	1.9
4	ADS-B squitter	Range-az-alt surveil	40.2	2.4
5	ADS-B squitter	TCAS range-az-alt	35.1	2.1
6	ADS-B squitter	Passive ML	61.0	3.7
7	ADS-B squitter	Active ML	61.2	3.7
8	ADS-B squitter	ATCBI GIC-B / MSSR	214.2	12.9
9	ATCBI GIC-B	ATCBI MSSR	185.6	11.1
10	ATCBI MSSR	(none)	170.1	10.2

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Site Activation**

DESCRIPTION

Site preparation costs. Note that when civil works are non-zero, these categories can easily overlap and effort must be made to ensure they don't. Site activation includes

- Survey
- Power line routing on site
- Trenching for cables
- Erection of towers
- Laying/pulling cables
- Miscellaneous

In the ATCBI-6 Cost Study, this category also includes the cost of relocating 25 Mode S systems scheduled to be replaced as part of the integrated ASR-11/MSSR program. Those costs ($250K/site) are ignored here; if applicable, they are very likely to be the same for all alternatives.

Power line relocation cost has been estimated as $10K/km or higher for rugged terrain, so cost will be significant where it is necessary. The issue is: how much relocation will be needed. In any event this should be an average cost. ATCBI-6 Study used 54K for ADS-B.

METHODOLOGY

ATCBI-6 cost study used plus other data used.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	
1	ADS-B squitter	(none)	4.8
2	ADS-B squitter	Az-Alt verify	4.8
3	ADS-B squitter	Range-az-alt verify	4.8
4	ADS-B squitter	Range-az-alt surveil	4.8
5	ADS-B squitter	TCAS range-az-alt	5.1
6	ADS-B squitter	Passive ML	14.4
7	ADS-B squitter	Active ML	14.4
8	ADS-B squitter	ATCBI GIC-B / MSSR	9.9
9	ATCBI GIC-B	ATCBI MSSR	5.1
10	ATCBI MSSR	(none)	5.1

ALT. NO. 1

PER-SITE COMPONENT COSTS ($K)			COMMENTS
PERSONNEL			
Salary, 2 peo, 3 da	2.8		
Travel, 1 trip each	1.0		
Per Diem, 3 da@150	0.9		
TOTAL PER SITE ($K)		4.7	
Power		0.0	See above
Cables		10.8	ATCBI-6 Study
Mounts		10.8	ATCBI-6 Study
Miscellaneous		15.1	ATCBI-6 Study

TOTAL ($K)			41.4	
NUMBER OF SITES			116	
TOTAL COST ($M)			4.8	

ALT. NO. 5

PER-SITE COMPONENT COSTS ($K)				
PERSONNEL				
Salary, 2 peo, 5 da	4.7			
Travel, 1 trip each	1.0			
Per Diem, 5 da@150	1.5			
TOTAL PER SITE ($K)		7.2		
Power		0.0		
Cables		10.8		
Mounts		10.8		
Miscellaneous		15.1		
TOTAL ($K)			43.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			5.1	

ALT. NO. 6

PER-SITE COMPONENT COSTS ($K)				
Salary, 2 peo, 3 da	2.8			
Travel, 1 trip each	1.0			
Per Diem, 3 da@150	0.9			
TOTAL PER SITE ($K)		4.7		
Power		0.0		
Cables		10.8		ATCBI-6 Study
Mounts		10.8		ATCBI-6 Study
Miscellaneous		15.1		ATCBI-6 Study
TOTAL			41.4	
NUMBER OF SITES			348	
TOTAL COST ($M)			14.4	

ALT. NO. 9

PER-SITE COMPONENT COSTS ($K)				
Salary, 1 peo, 1 wk	4.7			
Travel, 1 trip each	1.0			
Per Diem	1.5			
TOTAL PER SITE ($K)		7.2		
Cables		10.8		
Mounts		10.8		
Miscellaneous		15.1		
TOTAL ($K)			43.9	
NUMBER OF SITES			116	
TOTAL COST ($M)			5.1	

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Equipment Installation and Test**

DESCRIPTION

Assembly, installation and checkout at the sites. Includes hardware and software, both materials and services.

METHODOLOGY

ATCBI-6 Cost Study figures for a secondary radar used, modified for: length of effort (reduced from 7); number of trips (reduced from 3); and Mode S leapfrog costs ignored.

ALT. NO.	PRINCIPAL	COMPLEMENTARY		RATIONALE
1	ADS-B squitter	(none)	1.2	See below
2	ADS-B squitter	Az-Alt verify	1.2	See below
3	ADS-B squitter	Range-az-alt verify	1.2	See below
4	ADS-B squitter	Range-az-alt surveil	1.2	See below
5	ADS-B squitter	TCAS range-az-alt	2.3	Double for two systems
6	ADS-B squitter	Passive ML	5.5	See below
7	ADS-B squitter	Active ML	5.5	See below
8	ADS-B squitter	ATCBI GIC-B / MSSR	8.6	Sum of Alts. 1 and 9
9	ATCBI GIC-B	ATCBI MSSR	7.5	See below
10	ATCBI MSSR	(none)	7.5	See below

ALTs. NO. 1-4

Element	Cost ($K)	
Salary, 3 peo, 1 wk	7.0	
Travel, 1 trip each	1.5	
Per Diem, 1 wk	1.5	
TOTAL PER SITE ($K)		10.1
NUMBER OF SITES		116
TOTAL COST ($M)		1.2

ALTs. NO. 6-7

Element	Cost ($K)	
Salary, 3 peo, 1.5 wks	10.5	
Travel, 2 trips each	3.1	
Per Diem, 1.5 wks	2.3	
TOTAL PER SITE ($K)		15.9
NUMBER OF SITES		348
TOTAL COST ($M)		5.5

ALTs. NO. 9-10

Element	Cost ($K)	
Salary, 3 peo, 7 wks	49.2	
Travel, 3 trips each	4.6	
Per Diem, 7 wks	10.5	
TOTAL PER SITE ($K)		64.3
NUMBER OF SITES		116
TOTAL COST ($M)		7.5

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Initial Spares**

DESCRIPTION
Initial inventory of spares and consumables.

METHODOLOGY
Estimated as a percentage of the sum of PME costs.

Factor	7.0%

Factor taken from ATCBI-6 cost study.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME ($M)	Initial Spares ($M)
1	ADS-B squitter	(none)	28.6	2.0
2	ADS-B squitter	Az-Alt verify	28.6	2.0
3	ADS-B squitter	Range-az-alt verify	32.1	2.2
4	ADS-B squitter	Range-az-alt surveil	40.2	2.8
5	ADS-B squitter	TCAS range-az-alt	35.1	2.5
6	ADS-B squitter	Passive ML	61.0	4.3
7	ADS-B squitter	Active ML	61.2	4.3
8	ADS-B squitter	ATCBI GIC-B / MSSR	214.2	15.0
9	ATCBI GIC-B	ATCBI MSSR	185.6	13.0
10	ATCBI MSSR	(none)	170.1	11.9

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Documentation**

DESCRIPTION

Cost of preparing and producing and shipping system technical, engineering, management and support data.

METHODOLOGY

Estimated as a percentage of the sum of PME costs.

Factor 4.6%

Factor taken from ATCBI-6 cost study.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME ($M)	Initial Spares ($M)
1	ADS-B squitter	(none)	28.6	1.3
2	ADS-B squitter	Az-Alt verify	28.6	1.3
3	ADS-B squitter	Range-az-alt verify	32.1	1.5
4	ADS-B squitter	Range-az-alt surveil	40.2	1.9
5	ADS-B squitter	TCAS range-az-alt	35.1	1.6
6	ADS-B squitter	Passive ML	61.0	2.8
7	ADS-B squitter	Active ML	61.2	2.8
8	ADS-B squitter	ATCBI GIC-B / MSSR	214.2	9.9
9	ATCBI GIC-B	ATCBI MSSR	185.6	8.5
10	ATCBI MSSR	(none)	170.1	7.8

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Freight and Inspection**

DESCRIPTION

Consists of packing, inspecting and shipping the delivered systems.

METHODOLOGY

Estimated as a percentage of the PME costs.

Factor	3%

Factor taken from ATCBI-6 cost study.

NOTE: FAA Order 1810.6 uses 1.5% as the factor.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME ($M)	Initial Spares ($M)
1	ADS-B squitter	(none)	28.6	0.9
2	ADS-B squitter	Az-Alt verify	28.6	0.9
3	ADS-B squitter	Range-az-alt verify	32.1	1.0
4	ADS-B squitter	Range-az-alt surveil	40.2	1.2
5	ADS-B squitter	TCAS range-az-alt	35.1	1.1
6	ADS-B squitter	Passive ML	61.0	1.8
7	ADS-B squitter	Active ML	61.2	1.8
8	ADS-B squitter	ATCBI GIC-B / MSSR	214.2	6.4
9	ATCBI GIC-B	ATCBI MSSR	185.6	5.6
10	ATCBI MSSR	(none)	170.1	5.1

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Engineering Change Orders**

DESCRIPTION
Cost of implementing changes to system design. Actually constitutes cost adjustment for program and technical risk.

METHODOLOGY
ATCBI-6 Cost Study followed. Cost estimated as a fixed fraction of total R,E&D and F&E costs, with management-oriented items excluded.

Factor 13.0%

Factor taken from ATCBI-6 cost study.

NO.	PRINCIPAL	COMPLEMENTARY	NRE-HW	NRE-SW	PreProd	DT&E	PME
1	ADS-B squitter	(none)	17.8	15.1	1.2	5.0	28.6
2	ADS-B squitter	Az-Alt verify	17.8	16.6	1.2	5.2	28.6
3	ADS-B squitter	Range-az-alt verify	18.7	17.4	1.4	6.0	32.1
4	ADS-B squitter	Range-az-alt surveil	21.4	18.1	1.7	8.0	40.2
5	ADS-B squitter	TCAS range-az-alt	22.8	18.1	1.5	10.0	35.1
6	ADS-B squitter	Passive ML	20.8	25.1	0.9	10.0	61.0
7	ADS-B squitter	Active ML	20.8	25.1	0.9	10.0	61.2
8	ADS-B squitter	ATCBI GIC-B / MSSR	20.8	15.9	9.2	10.0	214.2
9	ATCBI GIC-B	ATCBI MSSR	3.0	0.7	8.0	5.0	185.6
10	ATCBI MSSR	(none)	0.0	0.0	7.3	5.0	170.1

MAJOR CATEGORY **Facilities and Equipment (F&E)**
SUBCATEGORY **Initial Operations Training**

DESCRIPTION
Consists of the development and conduct of courses to train the initial cadre of operators.

METHODOLOGY
Estimated MSSR (Alt. 9) from ATCBI-6 study. Estimated other alternative based engineering judgment of relative complexity.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	RELATIVE COMPLEXITY	COST ($M)
1	ADS-B squitter	(none)	50%	1.01
2	ADS-B squitter	Az-Alt verify	50%	1.01
3	ADS-B squitter	Range-az-alt verify	52%	1.05
4	ADS-B squitter	Range-az-alt surveil	55%	1.11
5	ADS-B squitter	TCAS range-az-alt	100%	2.02
6	ADS-B squitter	Passive ML	75%	1.51
7	ADS-B squitter	Active ML	75%	1.51
8	ADS-B squitter	ATCBI GIC-B / MSSR	150%	3.03
9	ATCBI GIC-B	ATCBI MSSR	100%	2.02
10	ATCBI MSSR	(none)	90%	1.82

ATCBI-6 Cost estimate ($M) 2.019

MAJOR CATEGORY	**Facilities and Equipment (F&E)**
SUBCATEGORY	**Initial Maintenance Training**

DESCRIPTION

Consists of the development and procurement of courses, materials and devices used to train the initial core of maintenance technicians.

METHODOLOGY

Estimated as a percentage of the sum of PME and Site Activation costs.

Factor	5%

COSTS ($M)

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME	Site Act	Init Maint Train
1	ADS-B squitter	(none)	28.6	4.8	1.7
2	ADS-B squitter	Az-Alt verify	28.6	4.8	1.7
3	ADS-B squitter	Range-az-alt verify	32.1	4.8	1.8
4	ADS-B squitter	Range-az-alt surveil	40.2	4.8	2.3
5	ADS-B squitter	TCAS range-az-alt	35.1	5.1	2.0
6	ADS-B squitter	Passive ML	61.0	14.4	3.8
7	ADS-B squitter	Active ML	61.2	14.4	3.8
8	ADS-B squitter	ATCBI GIC-B / MSSR	214.2	9.9	11.2
9	ATCBI GIC-B	ATCBI MSSR	185.6	5.1	9.5
10	ATCBI MSSR	(none)	170.1	5.1	8.8

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Consumables**

DESCRIPTION
Items consumed on a regular basis, such as filters, paper. Does not include energy or utilities.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	# Purch/ Year	Cost / Purchase	Ship Charge	# Sites	# Years	COST ($M)
1	ADS-B squitter	(none)	36.9	$22.81	25.0%	116	20	2.4
2	ADS-B squitter	Az-Alt verify	36.9	$22.81	25.0%	116	20	2.4
3	ADS-B squitter	Range-az-alt verify	36.9	$22.81	25.0%	116	20	2.4
4	ADS-B squitter	Range-az-alt surveil	36.9	$22.81	25.0%	116	20	2.4
5	ADS-B squitter	TCAS range-az-alt	55.4	$22.81	25.0%	116	20	3.7
6	ADS-B squitter	Passive ML	36.9	$22.81	25.0%	348	20	7.3
7	ADS-B squitter	Active ML	36.9	$22.81	25.0%	348	20	7.3
8	ADS-B squitter	ATCBI GIC-B / MSSR	55.4	$22.81	25.0%	116	20	3.7
9	ATCBI GIC-B	ATCBI MSSR	55.4	$22.81	25.0%	116	20	3.7
10	ATCBI MSSR	(none)	55.4	$22.81	25.0%	116	20	3.7

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Rent**

DESCRIPTION
Site rent. (Note that description in ATCBI-6 study is confusing; it indicates that depot and personnel costs are included.)

METHODOLOGY
Assume

ALT 1-5 All go into FAA-owned facilities (most existing); no rent

ALT 6-7 * 50% go into FAA-owned facilities (most existing); no rent.
* 45% go to sites with $250/month rent (typically rent for cellular sites in rural areas;
* 5% go to with $1500/month rent (typical cullular site rent in metropolitan areas quoted in Boston Globe 3/19/98, is $1200 to $5000 per month; ADS-B facilities far smaller/shorter than cellular)

ALT 8-10 All go into FAA-owned facilities (most existing); no rent

ALT. NO.	PRINCIPAL	COMPLEMENTARY	weighted cost/mo	Number Sites	Number Months	COST ($M)
1	ADS-B squitter	(none)	0.0	116	240	0.0
2	ADS-B squitter	Az-Alt verify	0.0	116	240	0.0
3	ADS-B squitter	Range-az-alt verify	0.0	116	240	0.0
4	ADS-B squitter	Range-az-alt surveil	0.0	116	240	0.0
5	ADS-B squitter	TCAS range-az-alt	0.0	116	240	0.0
6	ADS-B squitter	Passive ML	187.5	348	240	15.7
7	ADS-B squitter	Active ML	187.5	348	240	15.7
8	ADS-B squitter	ATCBI GIC-B / MSSR	0.0	116	240	0.0
9	ATCBI GIC-B	ATCBI MSSR	0.0	116	240	0.0
10	ATCBI MSSR	(none)	0.0	116	240	0.0

MAJOR CATEGORY	**Operations and Maintenance (O&M)**
SUBCATEGORY	**Energy**

DESCRIPTION
Electric power cost

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST ($M)
1	ADS-B squitter	(none)	2.2
2	ADS-B squitter	Az-Alt verify	2.2
3	ADS-B squitter	Range-az-alt verify	3.5
4	ADS-B squitter	Range-az-alt surveil	3.5
5	ADS-B squitter	TCAS range-az-alt	4.8
6	ADS-B squitter	Passive ML	8.5
7	ADS-B squitter	Active ML	8.5
8	ADS-B squitter	ATCBI GIC-B / MSSR	12.6
9	ATCBI GIC-B	ATCBI MSSR	10.4
10	ATCBI MSSR	(none)	10.4

COST CALC	ALT 1-2	ALT 3-4	ALT 5	ALT 6-7	ALT 9-10
Power used, kw	1.71	2.71	3.71	2.17	8
Hours/year	8766	8766	8766	8766	8766
$/kw-hr	0.064	0.064	0.064	0.064	0.064
# Sites	116	116	116	348	116
# Years	20	20	20	20	20
COST ($M)	2.2	3.5	4.8	8.5	10.4

POWER CALC (watts)				
Computer	400	400	400	800
Monitor	300	300	300	300
1090 Rx	1000	1000	2000	1000
1030 Tx		1000	1000	
Modem	10	10	10	70
SUM	1710	2710	3710	2170

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Operational Personnel**

DESCRIPTION
Salary and benefits for operations staff.

METHODOLOGY
Used ATCBI-6 cost for MSSR with SI and GIC-B as baseline. Estimated other alternatives based engineering judgment of relative effort.

COSTS ($M)

ALT. NO.	PRINCIPAL	COMPLEMENTARY	Relative Effort per Site	Annual Cost per Site ($K)	Number Sites	Number Years	TOTAL COST ($M)
1	ADS-B squitter	(none)	50%	2.4	116	20	5.5
2	ADS-B squitter	Az-Alt verify	50%	2.4	116	20	5.5
3	ADS-B squitter	Range-az-alt verify	75%	3.5	116	20	8.2
4	ADS-B squitter	Range-az-alt surveil	75%	3.5	116	20	8.2
5	ADS-B squitter	TCAS range-az-alt	100%	4.7	116	20	11.0
6	ADS-B squitter	Passive ML	67%	3.1	348	20	21.9
7	ADS-B squitter	Active ML	67%	3.1	348	20	21.9
8	ADS-B squitter	ATCBI GIC-B / MSSR	167%	7.9	116	20	18.3
9	ATCBI GIC-B	ATCBI MSSR	100%	4.7	116	20	11.0
10	ATCBI MSSR	(none)	90%	4.2	116	20	9.9

ATCBI-6 annual cost per site ($K) 4.7

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Operations Personnel Travel**

DESCRIPTION
Travel costs (non-labor)

METHODOLGY
Used ATCBI-6 cost per site, for every site regardless of alternative.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	Annual Cost/Site	Number Sites	Number Years	TOTAL COST ($M)
1	ADS-B squitter	(none)	107	116	20	0.2
2	ADS-B squitter	Az-Alt verify	107	116	20	0.2
3	ADS-B squitter	Range-az-alt verify	107	116	20	0.2
4	ADS-B squitter	Range-az-alt surveil	107	116	20	0.2
5	ADS-B squitter	TCAS range-az-alt	107	116	20	0.2
6	ADS-B squitter	Passive ML	107	348	20	0.7
7	ADS-B squitter	Active ML	107	348	20	0.7
8	ADS-B squitter	ATCBI GIC-B / MSSR	107	116	20	0.2
9	ATCBI GIC-B	ATCBI MSSR	107	116	20	0.2
10	ATCBI MSSR	(none)	107	116	20	0.2

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Recurring Operational Training**

DESCRIPTION

Costs of refresher training, training on new system elements, and training for new staff.

METHODOLOGY

ATCBI-6 cost study used for MSSR with SI and GIC-B. Other alternatives estimated based on engineering judgment of "relative effort".

COSTS

ALT. NO.	PRINCIPAL	COMPLEMENTARY	Relative Effort	Number Sites	Number Years	COST ($M)
1	ADS-B squitter	(none)	50%	116	20	0.7
2	ADS-B squitter	Az-Alt verify	50%	116	20	0.7
3	ADS-B squitter	Range-az-alt verify	75%	116	20	1.0
4	ADS-B squitter	Range-az-alt surveil	75%	116	20	1.0
5	ADS-B squitter	TCAS range-az-alt	133%	116	20	1.8
6	ADS-B squitter	Passive ML	67%	348	20	2.7
7	ADS-B squitter	Active ML	67%	348	20	2.7
8	ADS-B squitter	ATCBI GIC-B / MSSR	150%	116	20	2.1
9	ATCBI GIC-B	ATCBI MSSR	100%	116	20	1.4
10	ATCBI MSSR	(none)	90%	116	20	1.2

ATCBI-6 annual cost per site ($) 591.3

MAJOR CATEGORY	**Operations and Maintenance (O&M)**
SUBCATEGORY	**Telecommunications**

DESCRIPTION

Costs of autonomous sites (Alts 1-5 and 8-10) estimated based on line charges for connection to ARTCC or Surveillance Server. Networked multilateration alternatives (6-7) costs estimated based on line chages for interfacility communications and connections to ARTCC/Server.

COST SUMMARY

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COSTS ($M)
1	ADS-B squitter	(none)	1.1
2	ADS-B squitter	Az-Alt verify	1.1
3	ADS-B squitter	Range-az-alt verify	1.1
4	ADS-B squitter	Range-az-alt surveil	1.1
5	ADS-B squitter	TCAS range-az-alt	1.1
6	ADS-B squitter	Passive ML	66.1
7	ADS-B squitter	Active ML	66.1
8	ADS-B squitter	ATCBI GIC-B / MSSR	1.1
9	ATCBI GIC-B	ATCBI MSSR	1.1
10	ATCBI MSSR	(none)	1.1

ADS-B

ARTCC Fusion Site, Receiving Target Messages from ADS-B/ML Sites

Bytes per Msg	Aircraft Surveilled	Messages per sec	Bits per sec per line
32	120	0.2	6,144

COST for leased line (250 mi, 9600 baud), $/month		325.0
COST for one ARTCC, per Year ($K)	8 inputs per ARTCC	2.6
ANNUAL COST for All ARTCCs ($M)	22 in number	0.1
TOTAL COST for All ARTCCs ($M)	20 years	1.1

Multilateration

ML Site, Receiving TOA Messages from Other Sites

Bits per TOA Msg	Aircraft Surveilled	Msgs. per A/C per sec	Bits per sec per line
52	100	1	5,200

COST for leased line (100 mi, 9600 baud), per month ($)		250.0
COST for One Site, per Year ($K)	6 bi-directional lines	9.0
ANNUAL COST for All Sites ($M)	348 in number	3.1
TOTAL COST for All Sites ($M)	20 years	62.6

NOTES
1. Assumes that 9600 baud line can be used bi-directionally simultaneously at that rate
2. TOA message content: Aircraft ID, 24 bits (Mode S or ATCRBS); TOA, 12 bits (in usec, modulo 4 sec; Header, 8 bits; Integrity check, 8 bits. Total 52 bits.
3. 100 aircraft with range of sensor site (e.g., 115 nm) includes all but the most dense airspace.

ARTCC Fusion Site, Receiving Target Messages from ADS-B/ML Sites

Bytes per Msg	Aircraft Surveilled	Messages per sec		Bits per sec per line
32	120	0.2		6,144

COST for leased line (250 mi, 9600 baud), per month		325.0
COST for one ARTCC, per Year ($K)	24 input lines	7.8
ANNUAL COST for All ARTCCs ($M)	22 in number	0.2
TOTAL COST for All ARTCCs ($M)	20 years	3.4

Radar

ARTCC Fusion Site, Receiving Target Messages from Radar Sites

Bytes per Msg	Aircraft Surveilled	Messages per sec		Bits per sec per line
32	120	0.2		#REF!

COST for leased line (250 mi, 9600 baud), $/month		325.0
COST for one ARTCC, per Year ($K)	8 inputs per ARTCC	2.6
ANNUAL COST for All ARTCCs ($M)	22 in number	0.1
TOTAL COST for All ARTCCs ($M)	20 years	1.1

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Hardware Maintenance Personnel**

DESCRIPTION
Labor cost of depot maintenance personnel.

METHODOLOGY
Cost for MSSR with SI and GIC-B taken from ATCBI-6 study. Costs for other alternatives estimated based on relative cost of Prime Mission Equipment and engineerng judgment of relative failure rate.

COST

ALT.	PRINCIPAL	COMPLEMENTARY	PME Relative Cost	Est. Rel. Fail Rate	Annual Cost per Site ($K)	Number Sites	Number Years	Cost ($M)
1	ADS-B squitter	(none)	15%	2.0	2.3	116	20	5.4
2	ADS-B squitter	Az-Alt verify	15%	2.0	2.3	116	20	5.4
3	ADS-B squitter	Range-az-alt verify	17%	2.0	2.6	116	20	6.0
4	ADS-B squitter	Range-az-alt surveil	22%	2.0	3.3	116	20	7.5
5	ADS-B squitter	TCAS range-az-alt	19%	2.0	2.8	116	20	6.6
6	ADS-B squitter	Passive ML	11%	2.0	1.6	348	20	11.4
7	ADS-B squitter	Active ML	11%	2.0	1.6	348	20	11.5
8	ADS-B squitter	ATCBI GIC-B / MSSR	115%	1.5	13.0	116	20	30.1
9	ATCBI GIC-B	ATCBI MSSR	100%	1.0	7.5	116	20	17.4
10	ATCBI MSSR	(none)	92%	1.0	6.9	116	20	16.0

Annual Cost/Site for MSSR with SI, ($K) 7.5

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Recurring Maintenance Training**

DESCRIPTION
Cost of training maintenance personnel
Cost for MSSR with SI and GIC-B taken from ATCBI-6 study. Costs for other alternatives estimated based on engineering judgment of relative effort (time needed based on complexity of equipment).

ALT. NO.	PRINCIPAL	COMPLEMENTARY	Relative Effort	COST ($M)
1	ADS-B squitter	(none)	50%	0.165
2	ADS-B squitter	Az-Alt verify	50%	0.165
3	ADS-B squitter	Range-az-alt verify	75%	0.247
4	ADS-B squitter	Range-az-alt surveil	75%	0.247
5	ADS-B squitter	TCAS range-az-alt	133%	0.439
6	ADS-B squitter	Passive ML	67%	0.219
7	ADS-B squitter	Active ML	67%	0.219
8	ADS-B squitter	ATCBI GIC-B / MSSR	150%	0.494
9	ATCBI GIC-B	ATCBI MSSR	100%	0.329
10	ATCBI MSSR	(none)	90%	0.296

From ATCBI-6 study, recurring training total cost ($K) 329.2

MAJOR CATEGORY	**Operations and Maintenance (O&M)**
SUBCATEGORY	**Software Maintenance Personnel**

DESCRIPTION

Cost of personnel who maintain ground station code.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	COST ($M)	RATIONALE
1	ADS-B squitter	(none)	2.9	Two-thirds of MSSR w/o SI and GIC-B
2	ADS-B squitter	Az-Alt verify	2.9	Two-thirds of MSSR w/o SI and GIC-B
3	ADS-B squitter	Range-az-alt verify	6.7	Same as MSSR with SI and GIC-B
4	ADS-B squitter	Range-az-alt surveil	6.7	Same as MSSR with SI and GIC-B
5	ADS-B squitter	TCAS range-az-alt	9.6	ADS-B plus MSSR w/o SI and GIC-B
6	ADS-B squitter	Passive ML	4.4	1.5 times ADS-B
7	ADS-B squitter	Active ML	4.4	1.5 times ADS-B
8	ADS-B squitter	ATCBI GIC-B / MSSR	9.6	ADS-B plus MSSR with SI and GIC-B
9	ATCBI GIC-B	ATCBI MSSR	6.7	MSSR with SI and GIC-B
10	ATCBI MSSR	(none)	4.4	MSSR w/o SI and GIC-B

From ATCBI-6 study, in 1996 dollars, software maintenance estimates

MSSR	4.099
MSSR w/ SI	6.269

MAJOR CATEGORY **Operations and Maintenance (O&M)**
SUBCATEGORY **Replenishment Spares**

DESCRIPTION
Cost of spare parts for maintaining ground station equipment.

METHODOLOGY
Cost for MSSR with SI and GIC-B taken from ATCBI-6 study. Costs for other alternatives estimated based on relative cost of Prime Mission Equipment and engineerng judgment of relative failure rate.

ALT. NO.	PRINCIPAL	COMPLEMENTARY	PME Relative Cost	Est. Rel Fail Rate	Number Sites	Number Years	Cost ($M)
1	ADS-B squitter	(none)	15%	2	116	20	4.1
2	ADS-B squitter	Az-Alt verify	15%	2	116	20	4.1
3	ADS-B squitter	Range-az-alt verify	17%	2	116	20	4.6
4	ADS-B squitter	Range-az-alt surveil	22%	2	116	20	5.8
5	ADS-B squitter	TCAS range-az-alt	19%	1.5	116	20	3.8
6	ADS-B squitter	Passive ML	11%	2	348	20	8.8
7	ADS-B squitter	Active ML	11%	2	348	20	8.8
8	ADS-B squitter	ATCBI GIC-B / MSSR	115%	1.5	116	20	23.1
9	ATCBI GIC-B	ATCBI MSSR	100%	1	116	20	13.3
10	ATCBI MSSR	(none)	92%	1	116	20	12.2

Annual Spare Cost/Site for MSSR with SI ($K) 5.8

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