

**Project Report  
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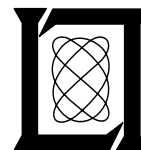
# **GPS-Squitter Capacity Analysis**

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**20 May 1994**

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16. Abstract  GPS-Squitter is a system concept that merges the capabilities of Automatic Dependent Surveillance (ADS) and the Mode S beacon radar. The result is an integrated concept for seamless surveillance and data link that permits equipped aircraft to participate in ADS and/or beacon ground environments. This concept offers many possibilities for transition from a beacon to an ADS-based environment. This report provides the details of the techniques used to estimate GPS-Squitter surveillance and data link capacity. Surveillance capacity of airborne aircraft is calculated for the omni and six-sector ground stations. Next, the capacity of GPS-Squitter for surface traffic is estimated. The interaction between airborne and surface operations is addressed to show the independence of these systems. Air ground data link capacity for GPS-Squitter is estimated, together with an estimate of the use of the Mode S link to support other ground surveillance and data link activities as well as TCAS operation. The analysis indicates the low transponder occupancy resulting from the total effect of these activities. Low occupancy is a key requirement in avoiding interference with the operation of the current ATCRBS and future Mode S interrogators.			
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## 1.0 INTRODUCTION

The International Civil Aviation Organization (ICAO) has defined a concept for communications, navigation, and surveillance for the next century known as the Future Air Navigation System (FANS). A cornerstone of the FANS is the increasing reliance on the use of satellite-based navigation systems such as the Global Positioning System (GPS). A second thrust of the FANS is surveillance based on the downlinking of aircraft-derived satellite position information. This technique is known as Automatic Dependent Surveillance (ADS).

The general application of ADS under the FANS concept will require that all aircraft in a region of airspace be equipped with satellite navigation and some form of data link. Since such general equipment will take many years, early implementation is expected to take place in regions where other surveillance techniques are not practical, e.g., over ocean and in remote areas. Planning is currently underway for ADS to support Air Traffic Control (ATC) management of oceanic routes. Significant economic benefits are anticipated due to the reduction in separation (and the resultant capacity increase) made possible by ADS. This form of ADS connects an aircraft via a point-to-point link with the controlling oceanic ATC facility.

The application of ADS in terminal and overland areas requires a more general form of ADS in which the aircraft broadcasts its position in an omni-directional fashion. This makes it possible for one ADS transmission to simultaneously serve the surveillance needs of multiple ground ATC and airborne collision avoidance activities.

GPS-Squitter [1] is a system concept that merges the capabilities of Automatic Dependent Surveillance and the Mode S beacon radar [2] via the randomly timed transmission of a Mode S 112-bit reply known as a squitter. The result is an integrated concept for seamless surveillance that permits equipped aircraft to participate in ADS or beacon ground environments. GPS-Squitter is a natural way to transition National Airspace System (NAS) surveillance from a ground-based beacon radar system to a GPS-ADS based environment. It also offers several other possibilities for significant benefits to the NAS.

### 1.1 SURVEILLANCE APPLICATIONS

The GPS-Squitter transmission can be received by omni-directional or sector-beam ground units in order to support air traffic control activities of airborne aircraft. Surveillance of aircraft on the airport surface can also be provided based on the same squitter transmission. Special surveillance applications such as the monitoring of closely-spaced parallel runways can also be supported.

A 56-bit squitter containing just the aircraft Mode S address is currently the basis for TCAS acquisition of Mode S-equipped aircraft. The address is then used to discretely interrogate the Mode S aircraft for TCAS surveillance purposes. If TCAS aircraft are equipped for GPS-Squitter (i.e., there is an onboard GPS unit), a modification to the TCAS equipment to receive the long squitter containing the ADS data will permit TCAS to perform most of its surveillance by passively listening to squitters. The information available from GPS can also serve as the basis for a form of TCAS that generates horizontal maneuvers as resolution advisories, in contrast to the current vertical-only maneuvers.

The squitter can also serve as the basis for Cockpit Display of Traffic Information (CDTI). In this role, the squitters would be received by nearby aircraft, as would be done for TCAS. For CDTI, the receiving aircraft has the ability to display nearby aircraft to the pilot, but no resolution advisories are

generated. This mode of operation is similar to the traffic advisory portion of TCAS as provided in TCAS 1. The squitter will make it possible to provide this service to general aviation at low cost.

## **1.2 DATA LINK CAPABILITY**

Since GPS-Squitter is based on the use of a Mode S transponder, the capability exists to provide two-way data link to equipped aircraft. The ground component of this data link can be provided by the 143 Mode S narrow-beam interrogators now being fielded, or it can be provided by omni-directional or sector-beam ground stations, including those used for surface surveillance.

## **1.3 REPORT OVERVIEW**

This report provides the details of the techniques used to estimate GPS-Squitter surveillance and data link capacity.

Surveillance capacity of airborne aircraft is calculated for the omni and 6-sector ground stations. Next, the capacity of GPS-Squitter for surface traffic is estimated. Finally, the interaction between airborne and surface operations is addressed to show the independence of these systems.

Air ground data link capacity for GPS-Squitter is estimated, together with an estimate of the use of the Mode S link to support other ground surveillance and data link activities as well as TCAS operation. The analysis indicates the low transponder occupancy resulting from the total effect of these activities. Low occupancy is a key requirement in avoiding interference with the operation of the current ATCRBS and future Mode S interrogators.

## 2.0 AIRBORNE SURVEILLANCE CAPACITY

### 2.1 ANALYSIS MODEL

The technique used to estimate GPS-Squitter surveillance performance is based upon the Poisson probability model for the reception of transponder transmissions. This is the standard technique for estimating the probability of the arrival of randomly generated events in a listening time window.

### 2.2 INTERFERENCE MECHANISM

Mode S transponders transmit squitters on 1090 MHz. This frequency is reserved principally for beacon radar use so it is shared with ATCRBS activities. The interference events of interest then are ATCRBS replies, and short (56-bit) and long (112-bit) Mode S replies. The length for each of the reply types is as follows:

ATCRBS	20 $\mu$ sec
56-bit Mode S	64 $\mu$ sec
112-bit Mode S	120 $\mu$ sec.

The interference effect of an individual reply is a function of its length. Thus, the analysis must treat the effect of each reply separately.

### 2.3 ANALYSIS TECHNIQUE

The Poisson model is applied separately to each reply type to calculate the probability of an interfering reply in the 120  $\mu$ sec listening window needed to receive a squitter.

For the 112-bit Mode S reply, the probability of receiving zero replies in a 240  $\mu$ sec window is calculated. The window of 240  $\mu$ sec is used, since a squitter may not be correctly received if any part of the squitter is overlapped with a Mode S fruit reply.

The calculation for the 56-bit case is similar, except the a window of 184  $\mu$ sec is used to account for the short Mode S reply.

The ATCRBS interference effect is estimated by calculating the probability of zero or one ATCRBS in a 140  $\mu$ sec window. One reply is permitted in the listening window since Mode S has an error correction function that can correct for the effect of a single ATCRBS.

The individual probabilities are than multiplied to obtain the probability of successful squitter reception with the assumed fruit rate for each of the reply types.

### 2.4 PROBABILITY OF FIVE-SECOND UPDATE

The above analysis yields the probability of a successful reception of a squitter for each reception opportunity. GPS-Squitter transponders will generate squitters randomly over a period of 0.4 to 0.6 seconds. With high probability, this will lead to a total of at least 9 reply opportunities within the 5-second update interval.

The probability of an update each 5 seconds is calculated as one minus the probability of zero successful receptions out of 9 reply opportunities.

## **2.5 DETAILED ANALYSIS**

The details of the technique used for the estimation of airborne capacity is presented in Table 2-1.

## **2.6 AIRBORNE FRUIT MODEL**

The reply rates assumed for each aircraft in the traffic model are presented in Table 2-2. A breakdown of the assumed origin of the replies for Case 1 is presented in Table 2-3. Note that Case 1 is an extreme worst case. It assumes the highest ground ATCRBS interrogation rate that had been measured in high-density locations during the development of Mode S and TCAS. Measured rates of this type always occurred in "hot spots" of tens of miles. Case 1 assumes that the 100 ATCRBS replies per second is the average value seen by all aircraft within signal range of the ground receiver. The Mode S reply rates for all three cases also represent an extreme worst case, yielding 40 short and 30 long Mode S replies over a 5-second scan period.

## **2.7 GROUND STATION TYPES**

GPS-Squitter ground stations will be of two types. The terminal configuration will use an omnidirectional antenna with a single receiver and will be able to provide surveillance to 50 nmi. The en route configuration will use a 6-sector antenna with six receivers to provide a range of 100 nmi.

In addition to providing more antenna gain for longer range, the 6-sector antenna has the effect of reducing the reply rate seen by each receiver since each antenna receives replies from only a portion of the total aircraft population. The increase in operating density provided by the 6-sector antenna may be utilized in the terminal case as required.

As indicated in Table 2-1, the effect of the 6-sector antenna is to reduce the reply rate to each receiver by a factor of 2.5 relative to the total reply rate. Details of the analysis leading to this conclusion are presented in Appendix A. Note that this technique is extendible in that antennas with a greater number of sectors can be deployed if higher capacity is required.

## **2.8 AIRBORNE OPERATING DENSITY**

The omni detection probability for each half second is presented in Figure 2-1 for each of the cases analyzed. Figure 2-2 shows the effect of multiple squitter opportunities on the probability of receiving at least one successful reply. This multiple squitter effect is combined with the half second performance of Figure 2-1 to produce the 5-second detection probability in Figure 2-3. Similar results for the 6-sector case are presented in Figures 2-4 and 2-5.

The point where each curve of Figures 2-3 and 2-5 cross the 0.995 value is selected to define the maximum GPS-Squitter operating density for that case. The results of this analysis for the omni and 6-sector cases is presented in Table 2-4.

## **2.9 INTERPRETATION OF DENSITY RESULTS**

The performance summarized in Table 2-4 is conservative in that worst case values are used for the ATCRBS interrogation rate for Case 1, and worst case Mode S reply rates were used for all of the cases. The results are conservative in another way in that no credit was taken for the fact that Mode S

reply reception is tolerant to interfering replies that are of lower signal strength than the desired squitter. This is due to the use of dynamic thresholding and pulse-position modulation.

Dynamic thresholding derived from the squitter preamble is used to limit the effect of lower strength fruit replies. Pulse position modulation is a coding technique in which the bit value is determined from the position of a half- $\mu$  second pulse in the leading or trailing half of a one microsecond window. Bit value declaration is made by sampling the amplitude of the leading and trailing pulse positions and assigning the bit values based on the sample with the higher amplitude.

The analysis assumes that any reply within line of sight of the receiver, out to maximum listening range (150 nmi for the omni and 250 nmi for the 6-sector antenna) can interfere with a squitter reception. Thus, the reply probability over 5 seconds applies to an aircraft at maximum operational range (50 nmi for the omni and 100 nmi for the 6-sector antenna). The reply probability will increase as the range to the ground receiver decreases. This will result in the reception of replies at a higher update rate than the five seconds used in the analysis.

## **2.10 OPERATION IN HIGHER DENSITY ENVIRONMIENTS**

The above analysis indicates that the GPS-Squitter concept has more than adequate capacity to operate in moderate to low density traffic environments, the intended operational environment for its potential initial implementation. If required in the future, operation in higher density environments is possible through the use of antennas with an increased number of sectors. For example, Table 2-5 indicates the capacity increase obtainable with antennas of 9 and 12 sectors.

**Table 2-1.**

**GPS-Squitter Airborne Capacity Analysis Model**

- Poisson model used to calculate probability of successful reply

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

- Success is defined for ATCRBS interference as the probability of zero or one reply overlaying the desired squitter (error correction can handle one ATCRBS fruit reply).

$$n = 0 \text{ or } 1$$

$\lambda$  = total number of ATCRBS fruit replies per second

$$t = (20 + 120) * 10^{-6}$$

- Success for Mode S interference is defined as probability of zero replies overlaying the desired squitter.

$$n = 0$$

$\lambda$  = total number of short Mode S fruit replies per second

$$t = (64 + 120) * 10^{-6}$$

$$n = 0$$

$\lambda$  = total number of long Mode S fruit replies per second

$$t = (120 + 120) * 10^{-6}$$

- For the omni-directional case,  $\lambda$  for each reply type is the product of the assumed reply rate per aircraft times the number of aircraft.
- The effect of the 6-sector antenna is to lower the value of  $\lambda$  by a factor of 2.5.
- Probabilities are calculated separately for ATCRBS, Mode S short and Mode S long fruit replies.
- Overall reply probability ( $p$ ) is the product of the individual probabilities.
- For the 2 squitter per second case, the probability of at least one reply in 5 seconds is

$$1 - (1 - p)^9.$$

- 9th (rather than 10th) power is used to account for the fact that the maximum time between squitters is 0.6 seconds.

**Table 2-2.**

**Interference Cases (1090 MHz)**

<b>CASE</b>	<b>REPLIES PER SECOND PER AIRCRAFT</b>		
	<b>ATCRBS</b>	<b>MODE S SHORT</b>	<b>MODE S LONG</b>
1	120	8	6
2	60	8	6
3	0	8	6

**Table 2-3.**

**Details of Case 1 (1090 MHz)**

	<b>MODE S</b>		
	<b>ATCRBS</b>	<b>SHORT</b>	<b>LONG</b>
GROUND	100	2	4
SQUITTER		1	2
TCAS	20	5	
<b>TOTAL</b>	<b>120</b>	<b>8</b>	<b>6</b>

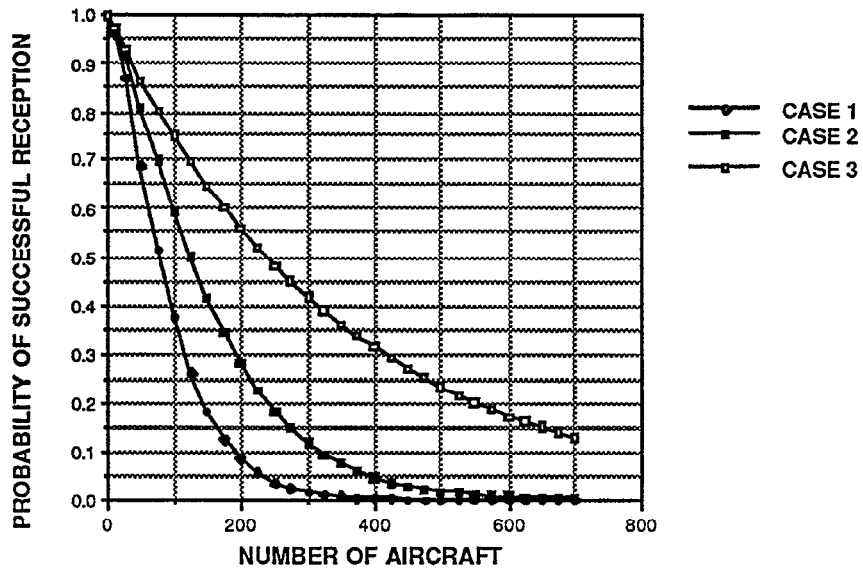


Figure 2-1. Omni detection probability each half second.

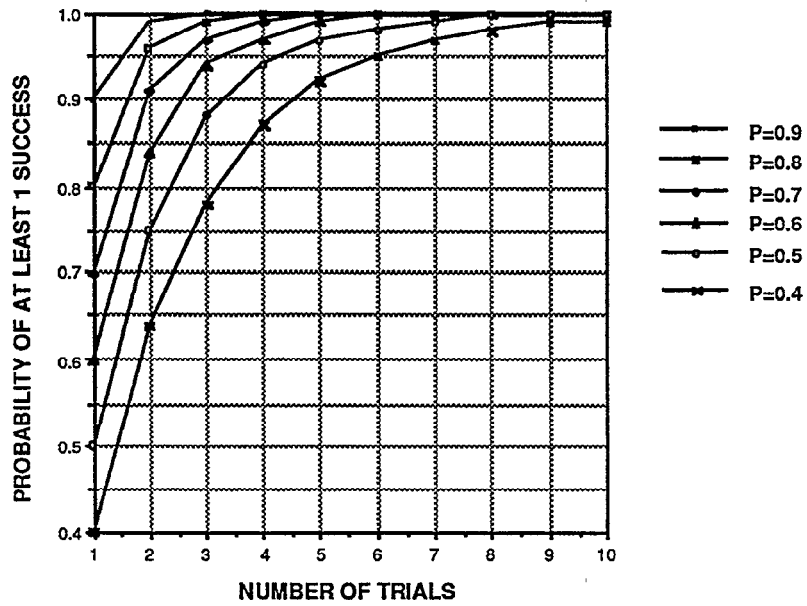


Figure 2-2. Effect of multiple squitters.



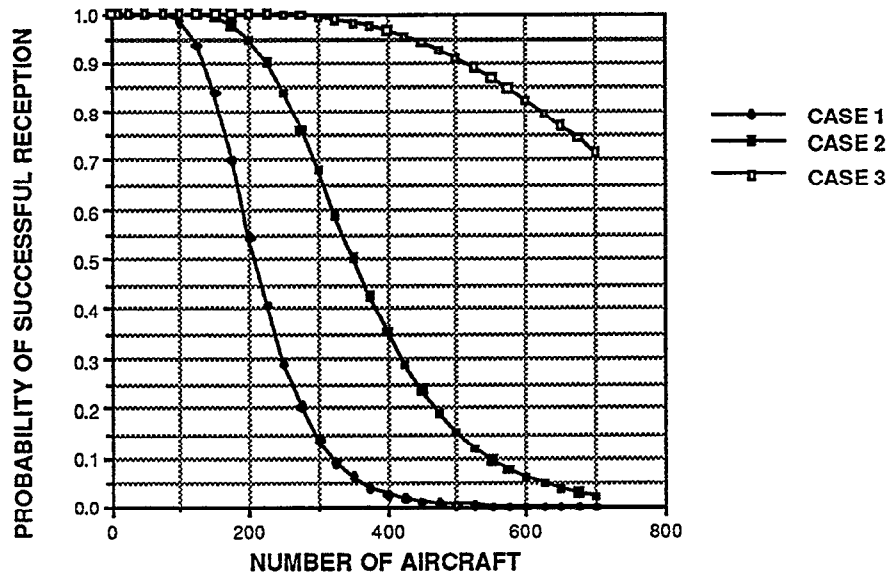


Figure 2-3. Omni detection probability over 5 seconds.

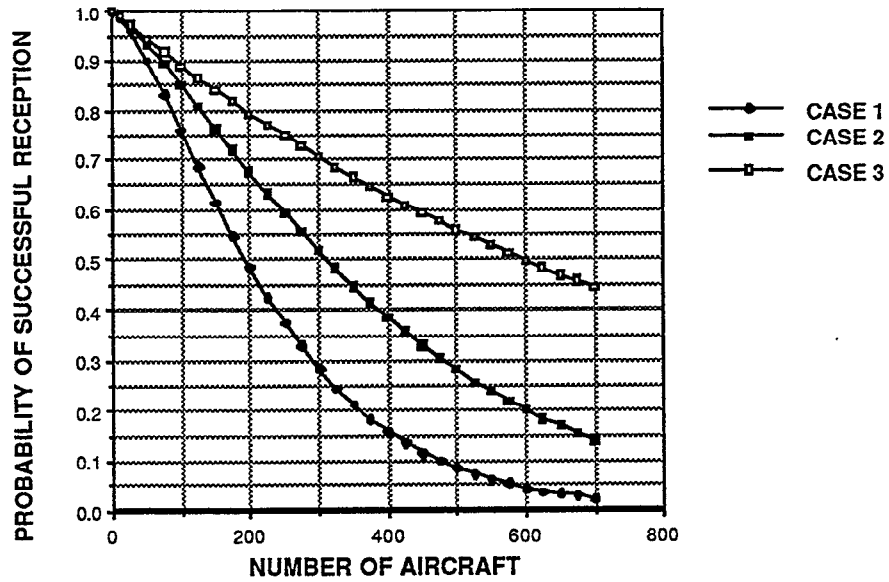


Figure 2-4. 6-sector detection probability each half second.

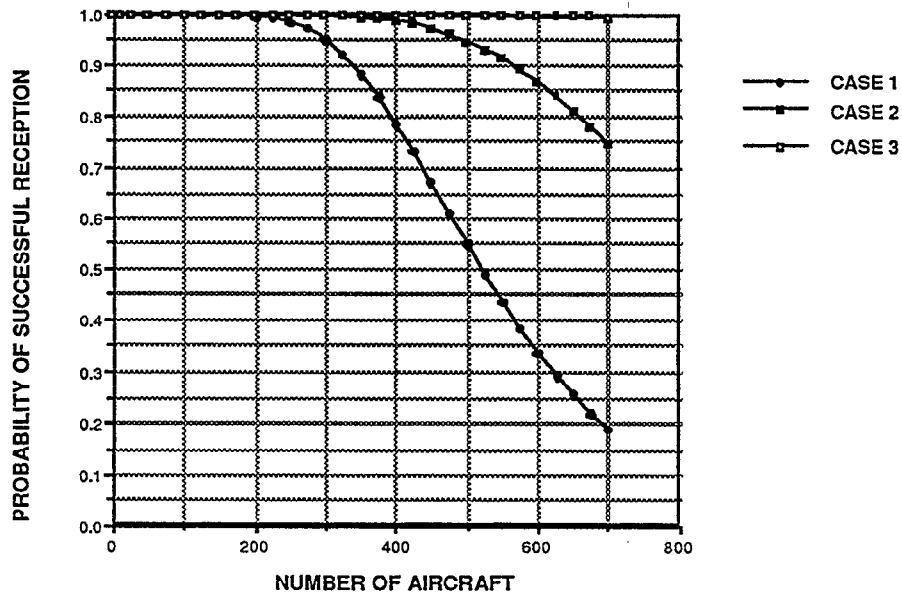


Figure 2-5. 6-sector detection probability over 5 seconds.

Table 2-4.

**GPS-Squitter Air Surveillance Operating Density  
5-Second Update, Probability  $\geq$  99.5 %**

CASE	REPLIES/AIRCRAFT/S		MAXIMUM AIRCRAFT IN RADIUS R	
	ATCRBS	MODE S	OMNI R=150 nmi	6-SECTOR R=250 nmi
1	120	14	85	215
2	60	14	140	350
3	0	14	280	700

**Table 2-5.**

**Air Surveillance Operating Density vs. Number of Antenna Sectors  
5-Second Update, Probability  $\geq 99.5\%$**

CASE	REPLIES/AIRCRAFT/SEC		MAXIMUM AIRCRAFT			
	ATCRBS	MODE S	OMNI	6-SECTOR	9-SECTOR	12-SECTOR
1	120	14	85	215	325	425
2	60	14	140	350	525	700
3	0	14	280	700	1050	1400

**2.11 CAPABILITY OF PSEUDO-RANDOM SQUITTER**

The above analysis provides an interesting perspective on the ability of the pseudo-random approach used for the GPS-Squitter concept to satisfy aviation surveillance requirements. The TCAS surveillance requirement is for a 1.0-second update rate out to 14 nmi. A 5-second update is required for terminal ATC operation for aircraft out to 60 nmi. En route sensors currently provide a 12-second update rate to a range of 200 nmi.

A TCAS GPS-Squitter receiver would operate at a sensitivity level adequate for 14 miles. This means that the TCAS squitter receiver would process squitters from a small fraction of the aircraft visible to a terminal or en route squitter receiver. This permits the TCAS to operate at a squitter probability level suitable for a 1.0-second update. The en route and terminal receivers operate with a much higher signal traffic density due to their greater operating range. While this leads to a lower probability of reception of a single squitter, the multiple squitter opportunities produce a high probability of an update during the 5-second or 12-second update period. Both requirements are handled simultaneously by the same pseudo-random squitter.



## **3.0 SURFACE SURVEILLANCE CAPACITY**

### **3.1 INTRODUCTION**

The same model and interference mechanism used for airborne surveillance capacity is used for the surface case.

### **3.2 ANALYSIS TECHNIQUE**

For the surface case, the principal interference is the long squitters generated by other surface aircraft.

### **3.3 PROBABILITY OF A ONE-SECOND UPDATE**

On average, there are two squitter reception opportunities in each 1-second interval. The probability of an update each 1 second is calculated as one minus the probability of zero successful receptions out of two reply opportunities.

### **3.4 DETAILED ANALYSIS**

The details of the technique used for the estimation of surface capacity is presented in Table 3-1.

### **3.5 SURFACE FRUIT MODEL**

Each aircraft on the surface is assumed to generate an average of 2.2 long squitters per second. This includes two ADS position squitters per second, plus the effect of one identity squitter every 5 seconds. No other replies can be elicited from the surface aircraft since GPS-Squitter transponders do not respond to ATRBS or Mode S All-Call interrogations while on the surface. Additionally, the short squitter (retained for compatibility with current TCAS equipment) will not be generated by GPS-Squitter transponders while on the surface.

Fruit replies from airborne aircraft are a minor factor in calculating surface capacity. The Mode S 1090 MHz wave form uses pulse position modulation that is tolerant to lower level interference. Replies can normally be successfully decoded if the interfering reply is at least 3 dB below the desired signal. The operating range on the surface is very short, nominally less than 2 nmi. This means that replies from aircraft beyond about 6 nmi will not effect surface performance. In addition, the antennas used for reception of surface squitters will have vertical aperture in order to discriminate against replies from close range, high elevation airborne aircraft. The combination of the tolerance of the Mode S squitter to lower level interference and the vertical antenna pattern minimizes the effects of transmissions from airborne aircraft on the performance of surface operation. A detailed analysis of this effect is presented in Appendix B.

### **3.6 SURFACE GROUND STATION TYPES**

In general, surface ground stations will have antennas that provide full coverage of the airport surface. The beamwidth of these full coverage antennas will depend on their location on the surface. A centrally sited station will use an omni-directional antenna. One at the periphery of the airport will use an antenna beam just wide enough to cover the entire maneuvering area of the airport.

As for the airborne case, an antenna with reduced horizontal coverage can be used to provide additional surface capacity beyond that provided by full coverage antennas. The use of a sector-beam permits the surface traffic to be broken into subsets to reduce the fruit rate at the antenna. The use of sector beam antennas will increase the required number of listening stations beyond the omni case since multiple coverage of all runways and taxiways is generally required for reliable reception on the surface. A typical configuration of four listening stations for the omni case would translate to about six stations for the sector-antenna case.

The use of sector-beam antennas can achieve a reduction factor of two in the total received reply rate. This is less than the factor of 2.5 used for the airborne case and reflects the greater sensitivity of antenna sidelobes to replies from nearby aircraft. Details of the analysis of this effect are presented in Appendix C.

### **3.7 SURFACE OPERATING DENSITY**

In addition to reply loss due to collisions with fruit replies, reception on the airport surface involves some loss of replies due to multipath. Surface measurements made at Logan Airport indicate that with four omni ground stations, a probability of reception of greater than 96 percent is achieved when there is no interfering fruit reply in the listening window. This means that the half second reply probabilities calculated using the equations of Table 3-1 must include a factor of 0.95 to yield the effective reception probability including the multipath effect. An additional effect that must be included is the reply loss due to the assumed 20 Case 2 airborne aircraft that are within range of the surface ground stations.

The results of performing this calculation are presented in Figure 3-1 for reception probability each half second. Performance over 1 second for these data is presented in Figure 3-2. A summary of surface operating performance is given in Table 3-2.

### **3.8 VARIABLE SQUITTER RATE ALTERNATIVE**

The capacity analysis presented above assumes that all aircraft generate surveillance squitters at a constant rate of two per second while the aircraft are on the airport surface. This approach has been shown to meet the required capacity using reduced coverage antennas at the highest density terminals. An alternative squitter strategy is under study that reduces the average squitter rate and meets the highest density capacity requirements with full coverage antennas.

The approach is to use two squitter rates depending upon aircraft motion. If the aircraft is moving, it transmits surveillance squitters at the 2 per second rate. If it is stationary, the squitter rate drops to 1 squitter every 5 seconds. The rate returns to the higher rate immediately when the aircraft begins to move. Provision is also be made for the ground system to command an aircraft to remain at the higher rate, independent of aircraft motion, for cases where continued high rate monitoring of a stationary aircraft is required, e.g., when an aircraft is stopped on a taxiway at an intersection with an active runway.

Table 3-1.

GPS-Squitter Surface Capacity Analysis

- Poisson model is used to calculate probability of successful reply
$$p[n] = (e^{-\lambda t}) * ((\lambda t)^n) / n!$$
$$n = \text{number of overlapping replies that can be tolerated}$$
- Success for Mode S interference is defined as probability of zero replies overlaying the desired squitter
$$n = 0$$
$$\lambda = \text{total number of long Mode S replies per second}$$
$$t = (120+120) * 10^{-6}$$
- For the omni-directional case,  $\lambda$  for each reply type is the product of the assumed reply rate per aircraft times the number of aircraft.
- The effect of the sector antennas is to lower the value of  $\lambda$  by a factor of 2.  
The probability of a reply per 0.5 second is
$$p_{0.5} = p * 0.95 * p_a$$
, where 0.95 accounts for replies lost due to multipath and  $p_a$  equals the probability of a successful squitter reception in an environment with 20 Case 2 airborne aircraft
- The probability of at least one reply in 1 second is
$$1 - (1 - p_{0.5})^2$$

**Table 3-2.**

**GPS-Squitter Surface Operating Density**

- 1-second update rate
- Multipath factor of 95%
- 20 airborne aircraft per receiver (Case 2)

<b>ANTENNA TYPE</b>	<b>CAPACITY</b>	<b>RELIABILITY</b>
FULL COVERAGE	250	95%
	500	90%
REDUCED COVERAGE	500	95%
	700	93%



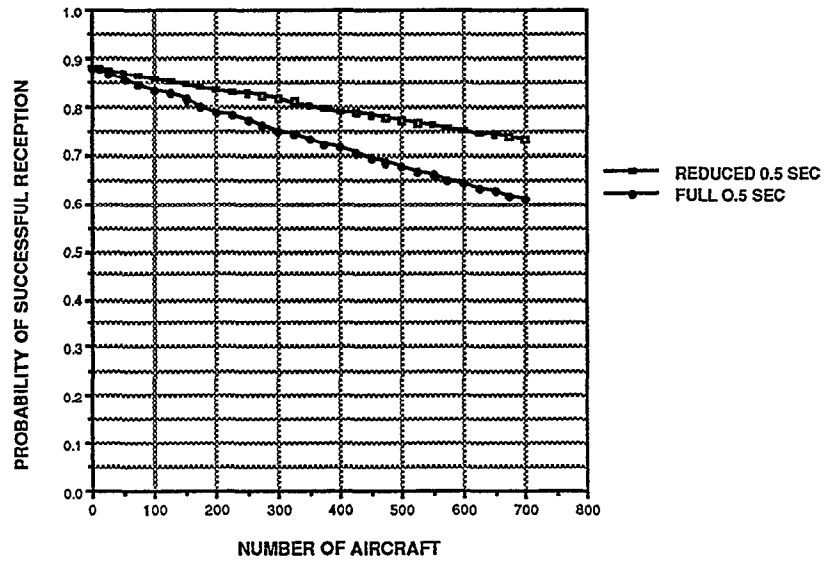


Figure 3-1. Surface squitter reception probability each half second.

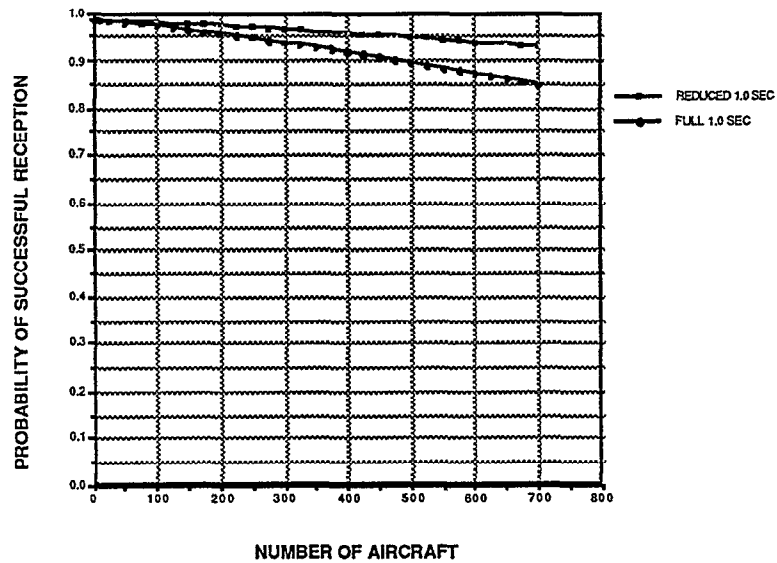


Figure 3-2. Surface squitter reception probability over 1 second.



## **4.0 DATA LINK CAPACITY**

### **4.1 DATA LINK OVERVIEW**

The principal use of GPS-Squitter for air surveillance is as a replacement for a conventional Mode S sensor in moderate to low density airspace, i.e., areas not covered by the Mode S sensors currently being implemented. In order to provide the same service as the Mode S sensor, the GPS-Squitter station must also provide a two-way data link. This can be readily accomplished since the surveillance function of these stations requires the ability to transmit on 1030 MHz (for DGPS broadcast) and receive on 1090 MHz (for squitter reception). Thus, the provision of a two-way data link only requires the addition of a modest data link interface and protocol control function in the GPS-Squitter ground station.

### **4.2 CAPACITY CONSIDERATIONS**

The capacity of the two-way data link capability is defined by the following considerations.

#### **4.2.1 Self Interference Limit**

The station will not be able to receive squitters while it is transmitting on 1030 MHz or during the reception of elicited replies on 1090 MHz, therefore the interrogation rate must be kept low.

#### **4.2.2 Transponder Occupancy Limit**

Each Mode S interrogation has the effect of occupying ATCRBS transponders for 35  $\mu$ sec or Mode S transponders (other than the addressed transponder) for 45  $\mu$ sec. The GPS-Squitter stations use omni or sector-beam antennas to transmit Mode S interrogations, as opposed to the narrow-beam (2.4 degree) antennas used by Mode S sensors. Thus, each Mode S interrogation from a GPS-Squitter station will affect aircraft over a larger region than the same interrogation transmitted using a Mode S sensor. This leads to the conclusions that (1) the GPS-Squitter interrogation rate must be kept low and (2) GPS-Squitter data link activity must be avoided in high-density environments where transponder occupancy is a concern. This latter condition is easily met since Mode S sensors are already being provided for data link use in high-density environments.

Selective use of omni or sector-beam transmissions to airborne aircraft in high-density environments may be needed for applications that require access times shorter than available from the rotating beam sensor. This is possible provided these interrogations are kept to a low rate.

#### **4.2.3 Maximum Link Utilization**

The approach used for this analysis is to assume that (like TCAS) GPS-Squitter two-way data link activity is allowed a 1-percent occupancy of Mode S and ATCRBS transponders. Note that (like TCAS) this one percent is a maximum that can be generated by all of the GPS-Squitter data link activity in a region of airspace. In areas where GPS-Squitter stations have overlapping coverage, the joint transponder occupancy caused by all stations must be kept to no more than 1 percent.

As GPS-Squitter is implemented, the active interrogation rate of TCAS will be reduced since it will be able to provide surveillance of nearby aircraft by passively listening to the ADS squitters. In the

limit, TCAS will become almost completely passive. At this point, GPS-Squitter stations may be allowed to increase their activity to 2 percent, to take advantage of the decreased TCAS link activity.

## 4.3 INTERROGATION RATE LIMIT

### 4.3.1 Omni Antenna Station

A Mode S interrogation occupies a Mode S transponder for 45  $\mu$ sec and an ATCRBS transponder for 35  $\mu$ sec. The longer occupancy time of the Mode S transponder is used to define the allowable interrogation rate. One percent utilization of a Mode S transponder is equal to 10 ms. Thus, the maximum interrogation rate is equal to 10 ms/sec divided by 45  $\mu$ sec or 220 interrogations per second. A 2 percent limit would yield a maximum interrogation rate of 440 per second.

### 4.3.2 Six-Sector Antenna Station

If a 6-sector antenna is used, a higher data rate can be supported since each interrogation only occupies the aircraft covered by the beam that was used for the interrogation. The surveillance benefit of a 6-sector antenna compared to an omni antenna has been estimated to be equivalent to a traffic reduction of 2.5. As shown in Appendix A, this is due to the division of the traffic population among the 6 beams, taking into account traffic bunching and antenna sidelobe effects. These are the same considerations that would be used to determine the effective occupancy of Mode S transponders in the coverage area of a GPS-Squitter station transmitting over a 6-sector antenna. Therefore, the maximum rates calculated for the omni antenna case can be increased by a factor of 2.5 for the 6-sector antenna case. This yields an interrogation rate of 550 and 1100 interrogations per second for the one and two percent limits, respectively.

## 4.4 DATA LINK CAPACITY ESTIMATE

The data link capacity corresponding to the interrogation rates limits determined above are estimated as follows:

1. Estimate the average reply probability .

The average reply probability to an interrogation must be estimated in order to determine the number of interrogations that must be transmitted for a successful delivery of downlink data. This probability also applies to uplink addressed data transfer since the Mode S link protocol requires that a successful reply be received as a technical acknowledgment of the uplink transfer. Failure to receive a reply will result in a repeat of that interrogation.

The maximum surveillance capacity for each of the interference cases analyzed is presented in Table 2-4. Applying the capacity for each case to the curves of Figure 2-1 (for the omni case) and Figure 2-4 (for the 6-sector case) it can be seen that the single reply reception probability is around 0.45. This probability applies to an aircraft in a fade at maximum range. Aircraft not in a fade and at closer range will have higher reply probabilities, approaching 1.0 for an aircraft at minimum range.

Traffic measurements indicate that terminal traffic count is linear in range, i.e., more dense near the terminal. Use of this traffic model indicates an average reply probability of about 0.7. For the en route case, it is expected the GPS-Squitter station will have overlapping

coverage. While surveillance would be provided to maximum range, data link service would be provided to a shorter range by the station nearest the aircraft.

These two considerations lead to an estimated average reply probability of 0.7 for the capacity analysis.

2. Estimate the percentage of uplink vs. downlink traffic.

For the Mode S standard length message (SLM), each interrogation can deliver a 56-bit uplink message and extract a 56-bit downlink message. The extended length message (ELM) protocol allows multiple 80-bit segment transfers to be controlled by a single command. For an uplink ELM, up to 16, 80-bit segments (each delivered in a Comm-C interrogation) can be acknowledged by a single Comm-D reply. For a downlink ELM, a single Comm-C interrogation can elicit up to 16, 80-bit message segments (each delivered in a Comm-D reply). Thus, the downlink ELM is more efficient from an interrogation limit standpoint.

The aeronautical data link applications currently in development (such as the delivery of traffic alerts or graphical weather products to the cockpit) indicate that the majority of the data transfer will be on the uplink. For this reason, it has been assumed that 80 percent of the interrogations are used for the transfer of uplink data, the remainder for downlink activity. This is a conservative estimate, since a higher capacity would have been achieved if more use of the downlink ELM had been assumed.

3. Calculate the data link capacity.

The data link capacity provided by a given interrogation rate limit can be calculated as follows:

$$\text{Uplink Capacity} = \text{IR} * \text{ARP} * \text{UL} * (\text{ELM} * 80 + (1 - \text{ELM}) * 56 * (1 + \text{TW}))$$

$$\text{Downlink Capacity} = \text{IR} * \text{ARP} * (1 - \text{UL}) * (\text{ELM} * 80 + (1 - \text{ELM}) * 56 * (1 + \text{TW}))$$

$$\text{Total Capacity} = \text{Uplink} + \text{Downlink Capacity}$$

Where:

IR = Interrogation rate

ARP = Average reply probability = 0.7

UL = Fraction of interrogations used for uplink transfer = 0.8

ELM = Fraction of uplink interrogations used for ELMs

TW = Fraction of two-way SLM transactions, i.e., Comm-A interrogations that elicit a Comm-B reply

The GPS-Squitter two-way data link capacity is presented in Tables 4-1 to 4-4 for TW in the range of zero to 100 percent for each of the following four cases:

1. Omni antenna, 220 interrogations per second (1% occupancy)
2. Omni antenna, 440 interrogations per second (2% occupancy)

3. 6-sector antennas, 550 interrogations per second (1% occupancy)
4. 6-sector antenna, 1100 interrogations per second (2% occupancy).

A comparison of the four cases for TW=0.4 is presented in Figure 4-1. A summary of the two-way data link capacity for GPS-Squitter stations is presented in Table 4-5.

**Table 4-1.**

**Omni Data Link Capacity (kps), Interrogation Rate = 220 per second.**

**UPLINK**

% COMM-B	% ELM				
	0%	20%	40%	60%	80%
0%	6.9	7.5	8.1	8.7	9.3
20%	8.3	8.6	8.9	9.2	9.5
40%	9.7	9.7	9.7	9.8	9.8
60%	11.0	10.8	10.6	10.3	10.1
80%	12.4	11.9	11.4	10.9	10.4
100%	13.8	13.0	12.2	11.4	10.6

**DOWNLINK**

% COMM-A	% ELM				
	0%	20%	40%	60%	80%
0%	1.7	5.3	8.9	12.5	16.1
20%	2.1	5.6	9.1	12.7	16.2
40%	2.4	5.9	9.3	12.8	16.3
60%	2.8	6.2	9.5	12.9	16.3
80%	3.1	6.4	9.7	13.1	16.4
100%	3.4	6.7	10.0	13.2	16.5

**TOTAL**

% TWO-WAY	% ELM				
	0%	20%	40%	60%	80%
0%	8.6	12.8	17.0	21.2	25.4
20%	10.3	14.2	18.0	21.9	25.7
40%	12.1	15.6	19.1	22.6	26.1
60%	13.8	17.0	20.1	23.3	26.4
80%	15.5	18.3	21.1	24.0	26.8
100%	17.2	19.7	22.2	24.6	27.1

**Table 4-2.**

**Omni Data Link Capacity (kps), Interrogation Rate = 440 per second.**

**UPLINK**

		% ELM				
% COMM-B		0%	20%	40%	60%	80%
0%		13.8	15.0	16.2	17.3	18.5
20%		16.6	17.2	17.8	18.5	19.1
40%		19.3	19.4	19.5	19.6	19.6
60%		22.1	21.6	21.1	20.7	20.2
80%		24.8	23.8	22.8	21.8	20.7
100%		27.6	26.0	24.4	22.9	21.3

**DOWNLINK**

		% ELM				
% COMM-A		0%	20%	40%	60%	80%
0%		3.4	10.6	17.8	25.0	32.2
20%		4.1	11.2	18.3	25.3	32.4
40%		4.8	11.7	18.7	25.6	32.5
60%		5.5	12.3	19.1	25.9	32.6
80%		6.2	12.9	19.5	26.1	32.8
100%		6.9	13.4	19.9	26.4	32.9

**TOTAL**

		% ELM				
% TWO-WAY		0%	20%	40%	60%	80%
0%		17.2	25.6	34.0	42.4	50.8
20%		20.7	28.4	36.1	43.8	51.4
40%		24.1	31.1	38.1	45.1	52.1
60%		27.6	33.9	40.2	46.5	52.8
80%		31.0	36.7	42.3	47.9	53.5
100%		34.5	39.4	44.4	49.3	54.2

**TABLE 4-3.**

**6-Sector Data Link Capacity (kps), Interrogation Rate = 550 per second.**

**UPLINK**

% COMM-B	% ELM				
	0%	20%	40%	60%	80%
0%	17.2	18.7	20.2	21.7	23.2
20%	20.7	21.5	22.3	23.1	23.9
40%	24.1	24.2	24.3	24.4	24.5
60%	27.6	27.0	26.4	25.8	25.2
80%	31.0	29.8	28.5	27.2	25.9
100%	34.5	32.5	30.6	28.6	26.6

**DOWNLINK**

% COMM-A	% ELM				
	0%	20%	40%	60%	80%
0%	4.3	13.3	22.3	31.3	40.3
20%	5.2	14.0	22.8	31.6	40.5
40%	6.0	14.7	23.3	32.0	40.6
60%	6.9	15.4	23.9	32.3	40.8
80%	7.8	16.1	24.4	32.7	41.0
100%	8.6	16.8	24.9	33.0	41.1

**TOTAL**

% TWO-WAY	% ELM				
	0%	20%	40%	60%	80%
0%	21.6	32.0	42.5	53.0	63.4
20%	25.9	35.5	45.1	54.7	64.3
40%	30.2	38.9	47.7	56.4	65.2
60%	34.5	42.4	50.3	58.2	66.0
80%	38.8	45.8	52.9	59.9	66.9
100%	43.1	49.3	55.4	61.6	67.8



**TABLE 4-4.**

**6-Sector Data Link Capacity (kps), Interrogation Rate = 1100 per second.**

**UPLINK**

		% ELM				
% COMM-B		0%	20%	40%	60%	80%
	0%	34.5	37.5	40.4	43.4	46.3
	20%	41.4	43.0	44.5	46.1	47.7
	40%	48.3	48.5	48.7	48.9	49.1
	60%	55.2	54.0	52.8	51.6	50.5
	80%	62.1	59.5	57.0	54.4	51.8
	100%	69.0	65.0	61.1	57.2	53.2

**DOWNLINK**

		% ELM				
% COMM-A		0%	20%	40%	60%	80%
	0%	8.6	26.6	44.6	62.6	80.6
	20%	10.3	28.0	45.6	63.3	80.9
	40%	12.1	29.4	46.7	64.0	81.3
	60%	13.8	30.8	47.7	64.7	81.6
	80%	15.5	32.1	48.7	65.3	82.0
	100%	17.2	33.5	49.8	66.0	82.3

**TOTAL**

		% ELM				
% TWO-WAY		0%	20%	40%	60%	80%
	0%	43.1	64.1	85.0	106.0	126.9
	20%	51.7	71.0	90.2	109.4	128.6
	40%	60.4	77.9	95.4	112.9	130.3
	60%	69.0	84.8	100.5	116.3	132.1
	80%	77.6	91.7	105.7	119.8	133.8
	100%	86.2	98.6	110.9	123.2	135.5

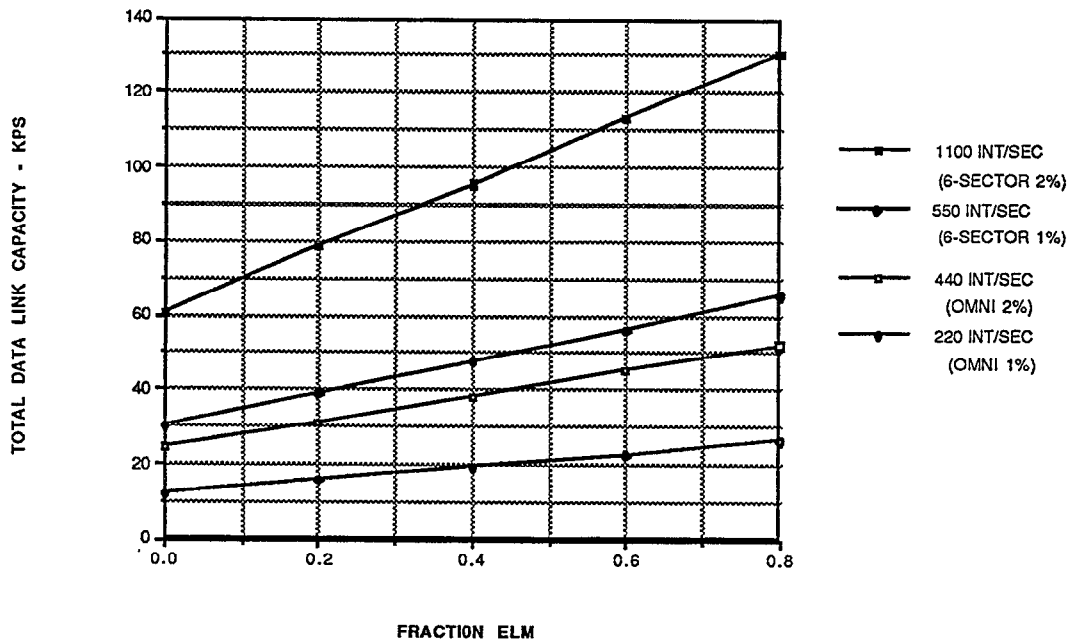


Figure 4-1. GPS-Squitter data link capacity vs. ELM use (kps).

Table 4-5.

GPS-Squitter Data Link Capacity Summary, (kps)

INTERFERENCE BUDGET	OMNI					6-SECTOR				
	TOTAL	1	2	3	4	TOTAL	1	2	3	4
1 PERCENT	22.5	22.5	11.3	7.5	5.6	56	22.5	22.5	18.7	14
2 PERCENT	45	45	22.5	15	11.3	112	45	45	37.3	28

## 4.5 INTERROGATION LIMITS IN OVERLAPPING COVERAGE

As indicated earlier, the capacity values calculated in Section 4.4 apply to the total activity of all GPS-Squitter stations operating within signal range. An indication of the capacity for each station is given as a function of the number of interrogators in Table 4-5. Note that a single 6-sector antenna station cannot exceed the omni interrogation limit, even if it has no overlapping coverage with neighboring stations. This limit is imposed to ensure that a Mode S transponder close to the station is not occupied more than the occupancy limit due to reception of interrogations from the sidelobes of the sector antennas.

## 4.6 DATA LINK CAPACITY SUMMARY

The data link capacity limit for a GPS-Squitter is defined by the interference budget assigned to this activity. Capacity estimates have been calculated assuming one and two percent transponder occupancy. These estimates indicate that GPS-Squitter stations can provide a substantial data link capacity, sufficient for their intended use in low to medium density airspace.

The stationary omni and sector-beam antennas used for GPS-Squitter stations have the property of providing immediate aircraft data link access. In this respect, these antennas offer the same access time performance as an electronically scanned antenna. Some limited use of these stations might be desirable in high-density airspace in order to take advantage of this response time for applications that cannot be served by a scanning beam antenna.

If additional capacity is required beyond the capability of the omni and 6-sector beam antennas, it can be provided by antennas with a greater number of sectors or by an overlay of a data link-only electronically scanned antenna.



## **5.0 SUMMARY AND CONCLUSIONS**

### **5.1 CONCEPT**

GPS-Squitter is a concept that combines the capabilities of ADS and beacon radar. It takes advantage of the development and international standardization of the Mode S wave forms and protocols, as well as the substantial implementation of Mode S transponders in the air carrier fleet.

### **5.2 SURVEILLANCE CAPACITY**

GPS-Squitter ground stations provide substantial surveillance capacity using the omni and 6-sector beam antennas proposed for moderate to low-density terminal airspace. Higher capacity is achievable, if required, by using antennas with a greater number of sectors.

### **5.3 SURFACE CAPACITY**

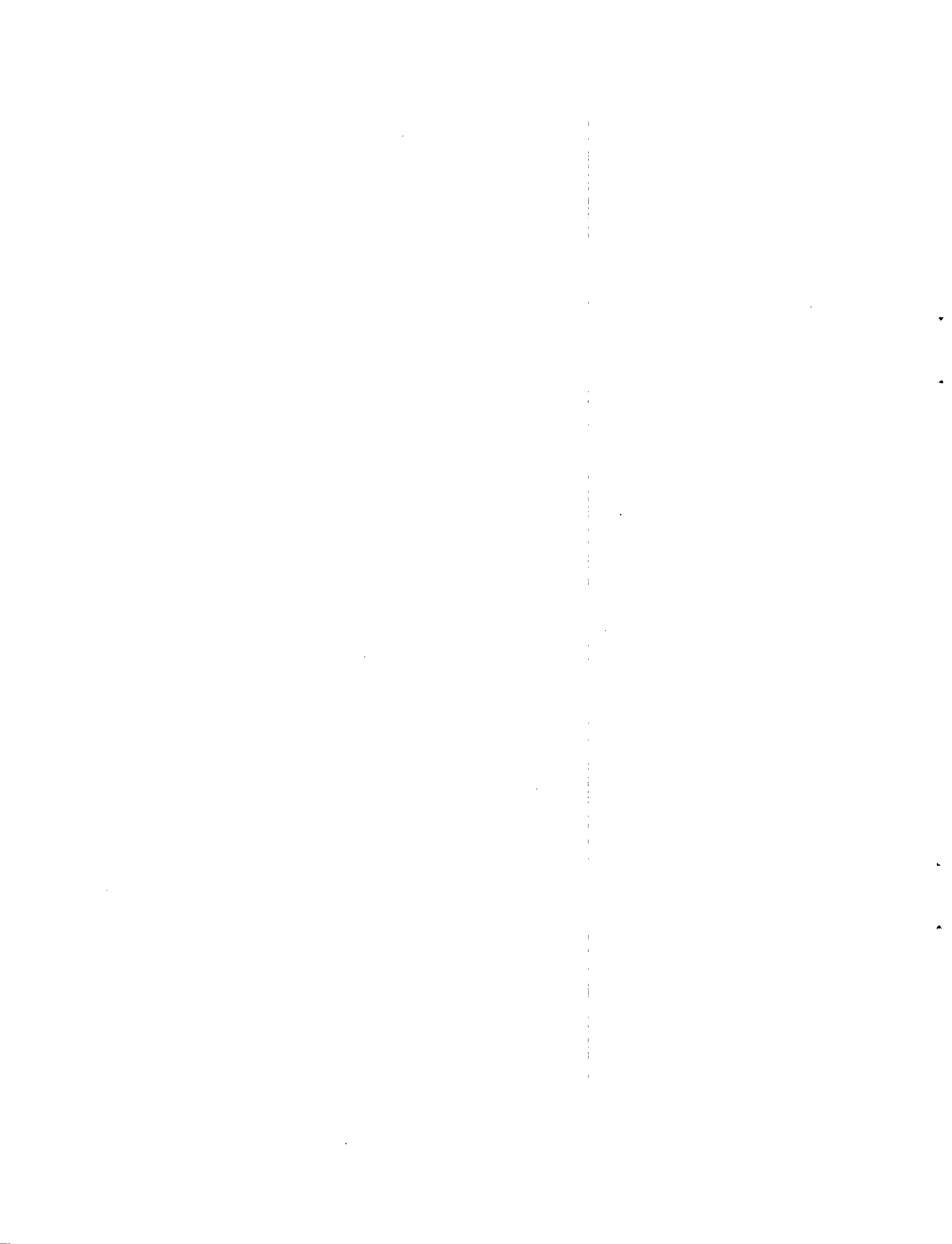
Surface surveillance is accomplished using a small number of ground stations at a terminal. The short operating range of the surface system and the use of antennas with vertical aperture limit the number of airborne aircraft that are visible to the surface system. The resulting capacity for surface surveillance is suitable for the largest terminals.

### **5.4 DATA LINK CAPACITY**

GPS-Squitter ground stations can provide useful data link capacity in regions not served by the high capacity Mode S narrow beam interrogators. The maximum data link capacity provided by the omni or 6-sector beam GPS-Squitter stations is determined by a 1-percent to 2-percent maximum transponder occupancy. This approach ensures that there will be no interference effects to the operation of ATCRBS or Mode S narrow beam interrogators or TCAS.

### **5.5 CONCLUSIONS**

The substantial surveillance and data link capacity provided by the GPS-Squitter concept makes it a natural augmentation to the current Mode S beacon radar in the transition to an ADS environment. The simple ground station equipment used for squitter reception and data link service offers the possibility of greatly reduced cost for ground surveillance and data link elements. The same low cost potential also exists for the application of squitter technology on the air-air link in support of collision avoidance and cockpit display of traffic information.



## APPENDIX A

### INCREASED AIRBORNE CAPACITY THROUGH THE USE OF A 6-SECTOR ANTENNA

#### A1.0 INTRODUCTION

In ADS Mode S, surveillance information is transmitted from an aircraft to a ground station in squitters. In order to receive these messages reliably over a range as great as 100 nmi, it will be necessary for the ground station to use a multiple-sector antenna to control the effects of fruit interference. Fruit consists of ATCRBS replies in Mode A, Mode C, and similar modes, which are replies to a number of ATCRBS interrogators. This appendix will calculate the degree of improvement that can be achieved through the use of a 6-sector antenna.

#### A2.0 CASE CONSIDERED

The analysis that follows applies to a long-range ADS station operating to 100 nmi. Error correction is used in reception. The ground antenna has 6 sectors, each having a 3 dB beam width of 60°.

#### A3.0 ANALYSIS

##### A3.1 Beam Center

Begin by considering an aircraft target located at the center of one of the beams. Assume a 10 dB power margin is required for link reliability. That is, assume that the signal received from the target aircraft is experiencing a fade of 10 dB whereas the interference receptions from other aircraft are not. Such a fade is a consequence of a number of factors: variations in aircraft antenna gain, vertical lobing at the ground antenna caused by reflection from the ground, deviation of the transmitter power relative to the nominal value, and possible excessive attenuation and mismatch losses between transponder and aircraft antenna.

Model the 6-sector antenna as having a quadratic beam shape and a sidelobe and backlobe level that is 25 dB below the peak.

$$\text{Antenna gain in dB} = \max[-3 (A/30^\circ)^2, -25]$$

where A = azimuth. Elevation angle is not included in the model. That is, the target aircraft and the fruit producing aircraft are considered to be at the same elevation angle.

Under these conditions, the region of fruit producing aircraft, for one of the 6 antenna beams, is as plotted in Figure A-1. The region extends 10 dB beyond the range of the target aircraft, to a range of 316 nmi.

Because of earth curvature, most of the aircraft in view are much closer than 316 nmi. To a first approximation, we might think of all of the aircraft being within 100 nmi. For a first-order model in which aircraft are uniformly distributed over a circle of radius 100 nmi, the improvement factor would be simply the fraction of this circle falling within the beam pattern shown in Figure 1. We see by inspection that the improvement factor is between 2 and 3 for this simple model.

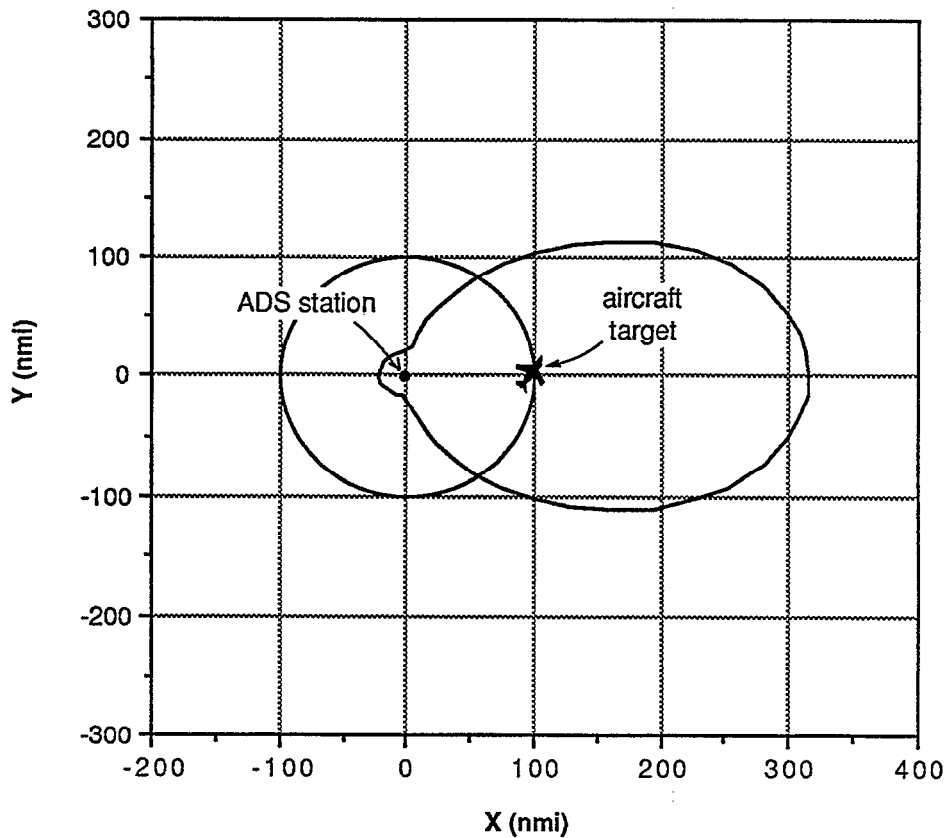


Figure A-1. Antenna pattern, limiting fruit receptions.

The range distribution of aircraft visible from an ADS ground station is limited at long ranges by the curvature of the earth, and is affected by the altitude distribution of aircraft. The following range distribution is based on the 4/3-earth line of sight model, a uniform-in area model for aircraft, and an altitude distribution obtained by measurements. The altitude distribution of aircraft was measured in the Boston area, over a range of 30 nmi.

Altitude (feet)	Cumulative Distribution (percent)
0	0
1000	7.3
2000	30.4
3000	51.8
6000	76.1
15000	93.9
50000	100

For a uniform-in-area model of aircraft having density  $D$  (aircraft/sq. nmi), the average number of aircraft within a small range ring from range  $R$  to  $R + dR$  is

$$dN = D 2 \pi R dR$$



At this range, the 4/3 earth horizon is

$$\text{altitude} = 0.662 R^2$$

for altitude in feet and range in nmi. Multiplying the number of aircraft dN by the percent in view gives the number in view, and these can be summed to yield the cumulative range distribution, which is plotted below.

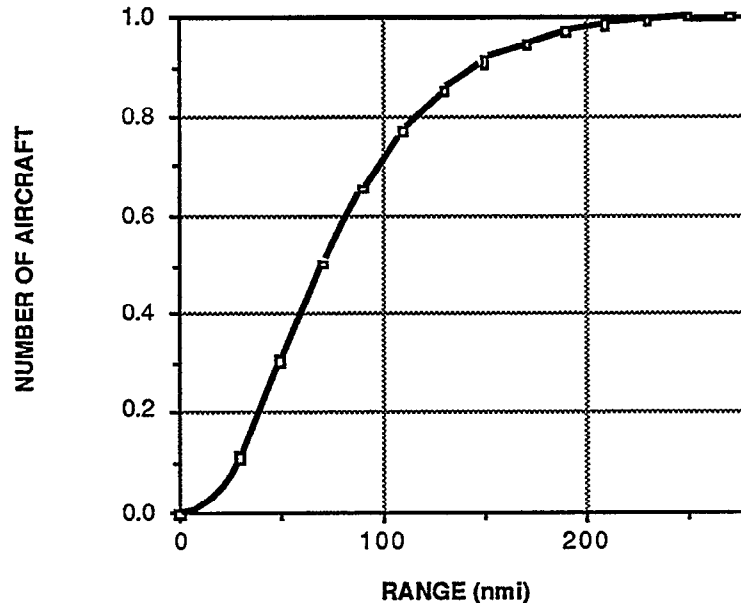


Figure A-2. Range distribution of aircraft.

For a more accurate calculation of the improvement factor, we use a range distribution function for aircraft appropriate for an en route ADS station. This distribution is given in Figure A-2, along with an explanation of its origin. Using this distribution the improvement factor is calculated as follows. The azimuth domain is divided into 10-degree wedges, in each of which the maximum range of interfering aircraft is calculated. Then for each such range, the fraction of all aircraft within that range is determined from Figure A-2. These fractions are summed over all azimuth wedges, and that result is compared with the result that would be obtained if all aircraft were counted. The ratio gives the improvement factor resulting from the directional ground antenna pattern. The resulting improvement factor is:

$$\text{Improvement factor} = 2.7 \text{ (target at beam center)}$$

### A3.2 Beam Edge

Next, consider an aircraft target at beam edge. Because the antenna gain is weaker by 3 dB in this direction, the region of fruit producing aircraft is larger. The calculation is carried out in the same manner as above, and result is

$$\text{Improvement factor} = 2.4 \text{ (target at beam edge, 1 receiver)}$$

Although this performance is somewhat less than in the first case, it is helpful that the signal is also received in a second receiver.

The second reception is beneficial because the two antenna beams are aimed in different directions, and the interference by fruit is therefore largely independent. To assess this effect quantitatively, we model them as independent. Then the probability of correct reception in at least one receiver is

$$P2 = 1 - (1 - P1^2)$$

where  $P1$  = probability of correct reception in one receiver. The system design for ADS Mode S uses 0.50 as a nominal value for the worst case operating point for squitter reception. Setting  $P2 = 0.50$ , it follows that the single-receiver performance can be as low as  $P1 = 0.29$ . Because error correction is used, the probability of correct reception in one receiver depends principally on fruit rate according to the formula:

$$P1 = \exp(-rt) + rt \cdot \exp(-rt)$$

where  $rt$  = the rate-time product. Comparing two values of  $P1$ ,

$$\text{If } P1 = 0.50, \quad \text{then } rt = 1.7$$

$$\text{If } P1 = 0.29, \quad \text{then } rt = 2.5$$

we see that this relaxation in the value of  $P1$  would permit the fruit rate to increase by a factor of  $2.5 / 1.7 = 1.5$ .

Putting the two effects together, for a target at beam edge,

Antenna directivity,      improvement factor = 2.4

Two receivers,              improvement factor = 1.5

Together,                      improvement factor = 3.6

Thus, the benefit of the second receiver more than compensates for the diminished performance resulting from the lower gain at beam edge.

### A3.3 Bunching

The above analysis has not included the effects of azimuth bunching of aircraft and fruit rate. Using 2.5 for the improvement factor, provides an allowance for some degree of bunching. Where more pronounced bunching may occur, the range of ADS surveillance may not extend to 100 nmi in that direction. If the bunching is caused by the existence of an area of high-density aircraft, then typically one or more surveillance ground stations will exist in that area, and therefore long range surveillance by the 6-sector antenna would not be needed in that direction.

## A4.0 SUMMARY OF RESULTS

In summary, the 6-sector antenna provides an improvement in aircraft capacity by a factor of 2.7 or better, not including azimuth bunching effects. To achieve this performance requires that each squitter is received by two receivers, the two nearest in azimuth to each aircraft.

## APPENDIX B

### THE EFFECT OF VERTICAL REFLECTIONS AND AIRBORNE-GENERATED FRUIT ON SURFACE RECEPTION

#### B1.0 INTRODUCTION

Consider a Mode S ground system for receiving squitters from aircraft on the surface. The following calculation is intended to estimate the number of airborne aircraft near enough to produce fruit interference.

#### B2.0 ASSUMED SURFACE SYSTEM CHARACTERISTICS

The following receiver characteristics are assumed for the analysis in this appendix:

1. The antenna is equivalent to the cellular-phone antenna AG-944W<sup>1</sup>
2. The azimuth beamwidth is adjusted to 140°
3. The horizontal tilt of the antenna is zero, such that the peak of beam is horizontal
4. The required surface surveillance range = 1 nmi or 2 nmi
5. The height of the surface antennas = 50 ft.
6. The power margin = 10 dB (that is, it is assumed that an aircraft under surveillance has a 10 dB fade, whereas the interfering aircraft do not).

#### B3.0 GROUND REFLECTION EFFECTS ON DESIRED SIGNALS.

The first step in the analysis is to determine the extent to which reflections via the ground affect signals from the aircraft on the surface. The reflection from the ground has a phase shift of 180° plus an additional amount due to the increased path length. For flat ground, the path difference is

$$\text{delta} = 2 H_1 H_2 / R$$

where:

H1 = height of aircraft antenna

H2 = height of ground antenna = 50 ft.

R = range

For a typical air carrier aircraft, the top antenna (H1) is about 17 ft. high. Thus for R = 2 nmi, it follows that delta = 0.14 ft. This is much less than a wavelength, which at 1090 MHz is  $\lambda = 0.902$  ft. Thus the phase difference of the ground reflection differs from 180° by  $0.14/\lambda = 0.16$  cycle = 56°. This is not small enough to constitute a deep fade.

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<sup>1</sup> Radiation Systems, antenna model AG-944, for cellular phone applications. Vertical aperture = 33 inches, vertical beamwidth = 24°. Variable wings used to adjust the horizontal beamwidth.

Thus, the 2-nmi range is not great enough to be in the 4th power region. The 4th power region is the set of conditions where the ground reflection cancels the direct signal causing a deep fade. Consider a fade to be "deep" when it exceeds 6 dB. This occurs when the phase difference is about 30° or less. This occurs when delta is  $\lambda/12$  or less.

$$\text{Deep fade: } 2 H_1 H_2 / R < \lambda / 12$$

The plot in Figure B-1 shows combinations of range and antenna height for which the ground reflection causes a deep fade. The conclusion is that this is not a significant effect over the range of interest (out to 2 nmi) and for most air carrier aircraft antennas, which are above 10 ft. high.

We might also consider higher-order vertical lobes, at shorter ranges. The next cancellation occurs when delta is nearly one wavelength. This occurs when

$$2 H_1 H_2 / R = (1 \pm 1/12) \lambda$$

Figure B-1 shows where this occurs for the first and second nulls above the horizontal. The fading is seen to be located in a series of narrow regions. They occur at shorter ranges, where the direct power is much stronger. Thus, they are relatively small and can be tolerated in the same manner as horizontal multipath, i.e., by diversity of ground antennas.

#### B4.0 THE EFFECT OF THE GROUND ANTENNA PATTERN

The vertical pattern of the ground antenna serves to limit the receptions from high elevation airborne aircraft to some extent. The vertical antenna pattern is plotted in Figure B-2.

For example, at 16-degree elevation angle, the antenna gain is 6 dB lower than the gain horizontally. This reduces the reception range by about 2:1. For an aircraft under surveillance on the airport surface at a range of 2 nmi, and assuming that this target is experiencing a 10 dB fade, interference can then be received from aircraft near the horizon within a range of

$$\text{Interference range} = 2 \text{ nmi} \times 10^{10 \text{ dB} / 20} = 6.3 \text{ nmi}$$

For aircraft flying at higher elevation angles the interference range is less because of the vertical antenna pattern. For example at 16°, the range is a factor of 2 smaller or 3.2 nmi. The following table gives other examples.

Elevation (dB)	Antenna Gain (nmi)	Range Angle
0°	0	6.3
5°	-0.4	6.0
10°	-2.1	4.9
15°	-5.0	3.4
20°	-9.0	2.1

These values are plotted in Figure B-3, showing the range-altitude region of airspace within which aircraft are near enough and low enough to cause interference. This region is seen to be quite small.

The number of airborne aircraft contributing interference is also limited by the horizontal pattern of the ground antenna. Since the azimuth beamwidth is  $140^\circ$ , the number of airborne aircraft covered is further limited by a factor of about  $140/360$ .

Putting these factors together leads to an estimate of the number of airborne aircraft contributing interference to the surface surveillance system. Consider a surveillance target aircraft at 2-nmi range, and experiencing a 10 dB fade. Then interfering aircraft can be as far away as 6.3 nmi, except as limited by antenna gain reductions in azimuth and elevation. To estimate the total number of aircraft within 6.3 nmi, we begin by considering Boston Logan Airport under current conditions and then generalize to other airports and future times. To determine the number of aircraft within 6.3 nmi, we use data from [3], which were obtained in 1976 together with more recent measurements in the airspace over Boston. These data indicate that a reasonable model is uniform in range with about 1 aircraft per nmi. Thus, within 6.3 nmi are about 6 airborne aircraft.

The azimuth beamwidth reduces this to  $(6 \text{ aircraft}) \times (140/360) = 2.5$ , and it is further reduced by the elevation pattern in Figure B-3. To get an approximate indication of the elevation effect, the aircraft distribution is modeled as being uniformly distributed in altitude up to 10,000 ft. With this model, the elevation reduction factor is simply the fraction of the area covered by the pattern plotted in Figure B-3, which is about 0.4. Altogether the average number of aircraft near enough to interfere is

$$6.3 \times (140/360) \times 0.4 = 1.0 \text{ aircraft} \quad \text{for a target at 2 nmi}$$

$$3.1 \times (140/360) \times 0.1 = 0.25 \text{ aircraft} \quad \text{for a target a 1 nmi.}$$

To allow for bunching of aircraft in azimuth, to tolerate growth of air traffic in the future and to apply to other airports, we conservatively apply a growth factor of 20:1 relative to the calculated averages. The result is

$$\begin{aligned} \text{Number of interfering aircraft} &= & 20 \text{ for a target at 2 nmi} \\ & & 5 \text{ for a target at 1 nmi} \end{aligned}$$

## B5.0 CONCLUSIONS

This analysis has considered the effect of ground reflections and airborne aircraft on the performance of a Mode S surface system. The effect of surface reflections is small and can be managed through the use of diversity antennas. This diversity is already an identified need to handle the effects of horizontal multipath.

Airborne aircraft at a range and altitude identified as visible to the surface system will only be under surveillance by the local terminal radar and perhaps by TCAS. The total replies from these airborne aircraft is small compared to the replies being received from the surface aircraft in the worst case scenarios analyzed in Section 3 of the main body of the report. Therefore, replies from these aircraft will produce a negligible additional interference effect to the surface system.

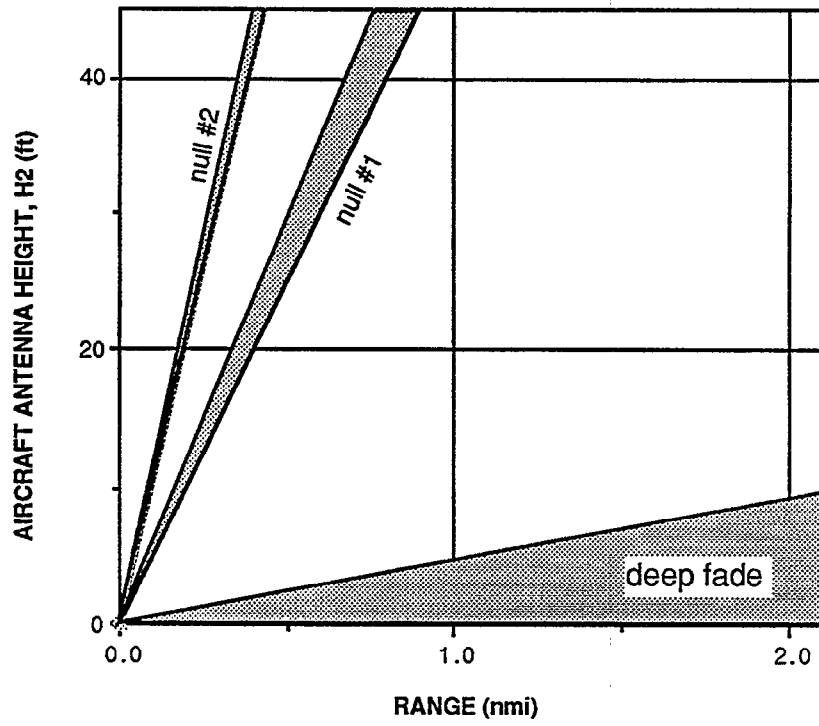


Figure B-1. Regions of fading.

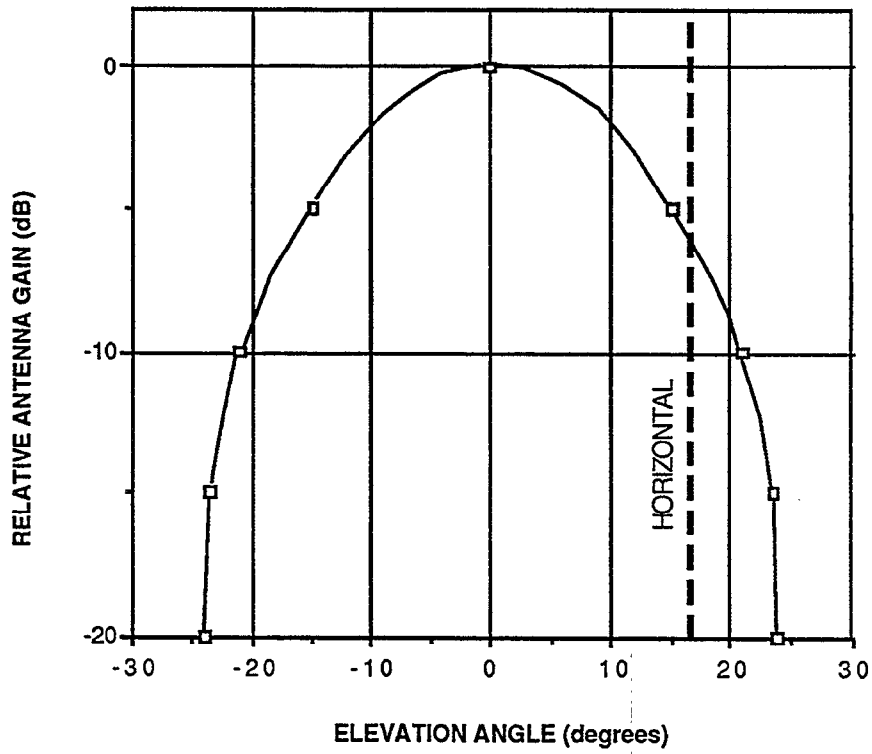


Figure B-2. Vertical antenna patterns.

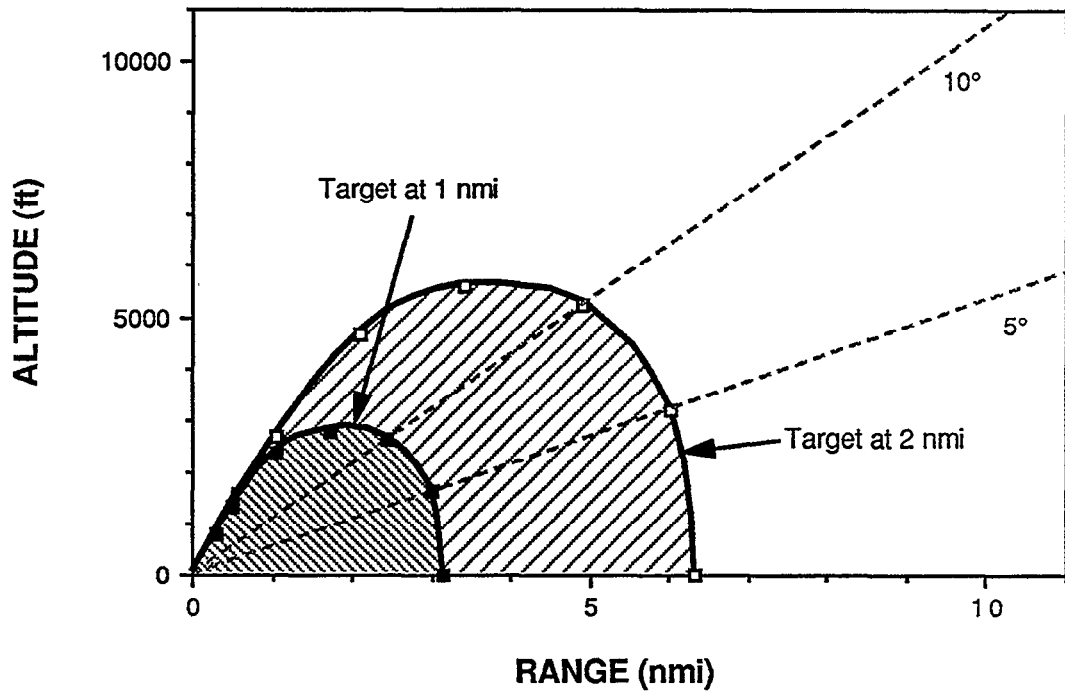
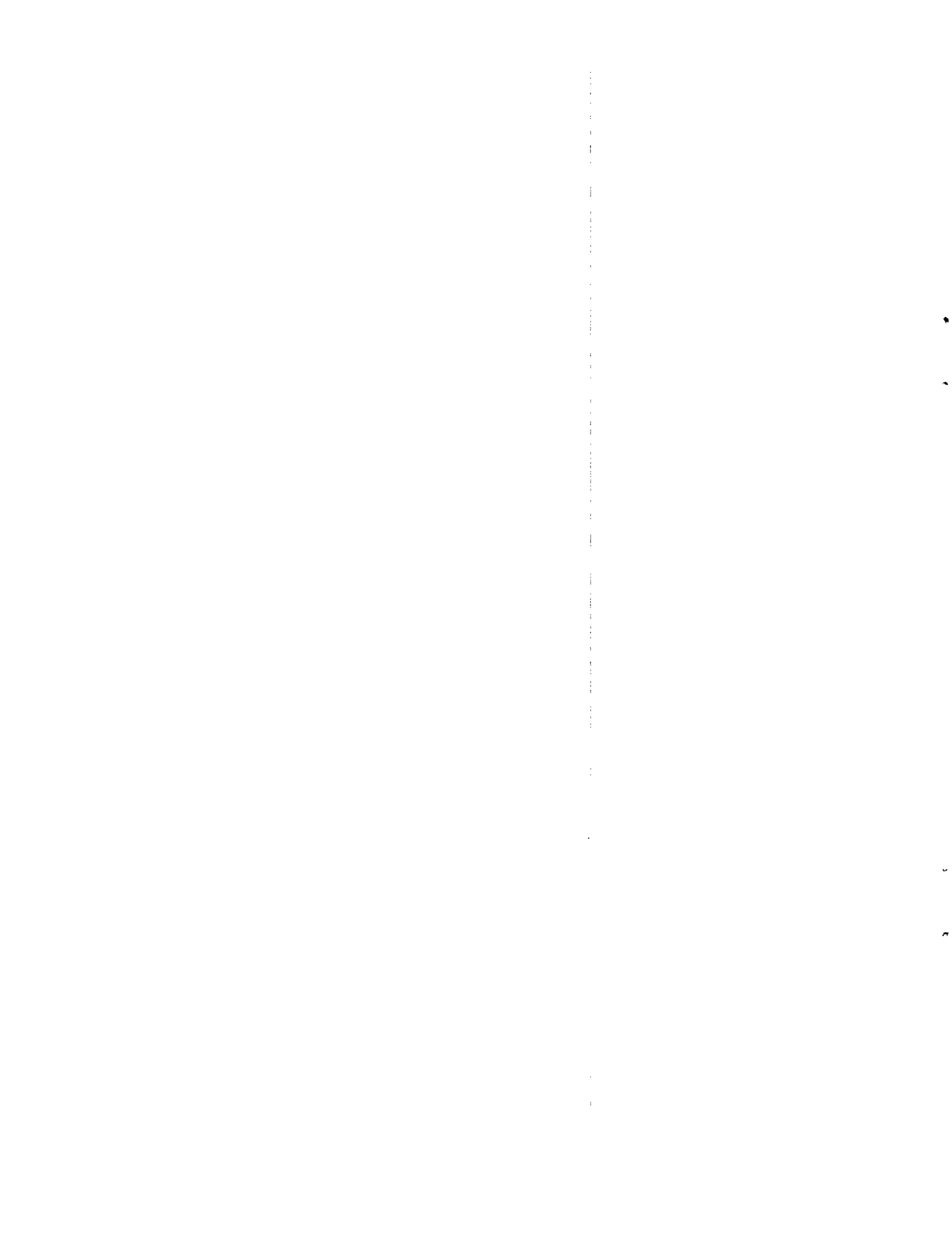


Figure B-3. Size of the interference region.





## APPENDIX C

### INCREASED SURFACE CAPACITY THROUGH THE USE OF SECTOR-BEAM ANTENNAS

#### C1.0 INTRODUCTION

To reduce the reception rate of interfering replies for surface surveillance, it is possible to use the multiple-sector technique discussed above for airborne surveillance. The basic principle is that each sector would cover a portion of the airport surface, and would therefore receive interference from a smaller number of aircraft. In determining the degree of improvement achievable, it is necessary to consider beam-edge effects as well as sidelobes and backlobes (in a manner similar to that in Appendix A).

#### C2.0 CASE CONSIDERED

Consider reception of Mode S 1090 MHz squitters from aircraft on the airport surface. Squitters constitute both the desired signals and the interference. Consider a total of 500 aircraft on the surface at one airport. Consider a 6-sector antenna, with all 6 beams having the same beamwidth.

#### C3.0 ANALYSIS

The shape of the airport and the location of the ground antenna affect the performance of a multiple sector antenna. Begin by considering an airport shape similar to that at Logan Airport, with a multiple sector antenna mounted centrally, on a terminal building or the control tower. The view of the airport surface from the antenna is primarily one-sided. Furthermore, for an antenna that is mounted on the surface of a building, which is an appropriate mounting location for minimizing multipath, the coverage area from this antenna excludes 180°.

To be specific, begin by considering a rectangular airport shape, as illustrated in Figure C-1, with the antenna located at the center of one of the long sides. Because the desired coverage area extends 180° in azimuth, we make the sector beamwidth 30° for each of the 6 beams, and aim them uniformly over the coverage region. Thus, the beam centers are at 15°, 45°, 75°, 105°, 135°, and 165° (where zero azimuth is defined such that the coverage extends from 0 to 180°). Model the antenna pattern as having a quadratic beam shape and a sidelobe and backlobe level that is 25 dB below the peak.

$$\text{Antenna gain in dB} = \max[-3 ((A-A_0)/15^\circ)^2, -25]$$

where A = azimuth, A<sub>0</sub> = beam center.

Relative to the airborne surveillance discussed in Appendix A, for surface surveillance the multiple beam technique will be seen to be not as effective because of the shape of the coverage area. The worst case is the longest range target, which is located at the far corner, A = 45°. Assume a 10 dB power margin for link reliability, as in Appendix A. That is, assume that the signal received from the target aircraft is experiencing a fade of 10 dB whereas the interference receptions from other aircraft are not. Under these conditions, the region of fruit producing aircraft, for the beam pointing toward the maximum-range target, is as plotted in Figure C-2. By inspection one can see that the beam is substantially wider than its nominal 30° in the region where it intersects the airport surface. It is evident that the fraction of the airport surface within the beam is closer to 1/2 than to 1/6. Looking more closely at Figure C-2, one can

see that the improvement factor for this configuration is somewhat better than 2, assuming that the fruit producing aircraft are uniformly distributed over the rectangular airport. This improvement factor has been calculated more accurately by dividing azimuth into 2-degree sectors. The resulting value for the improvement factor is 2.3.

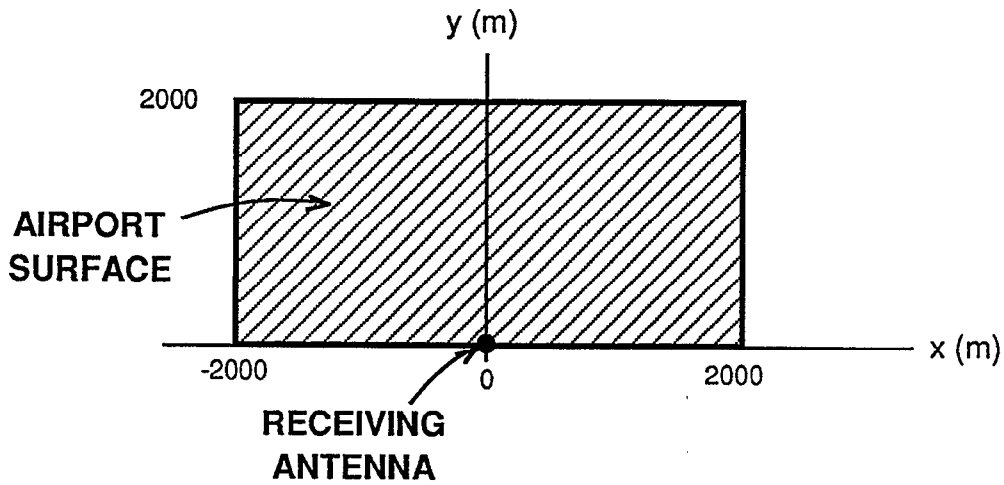


Figure C-1. Rectangular model for airport surface.

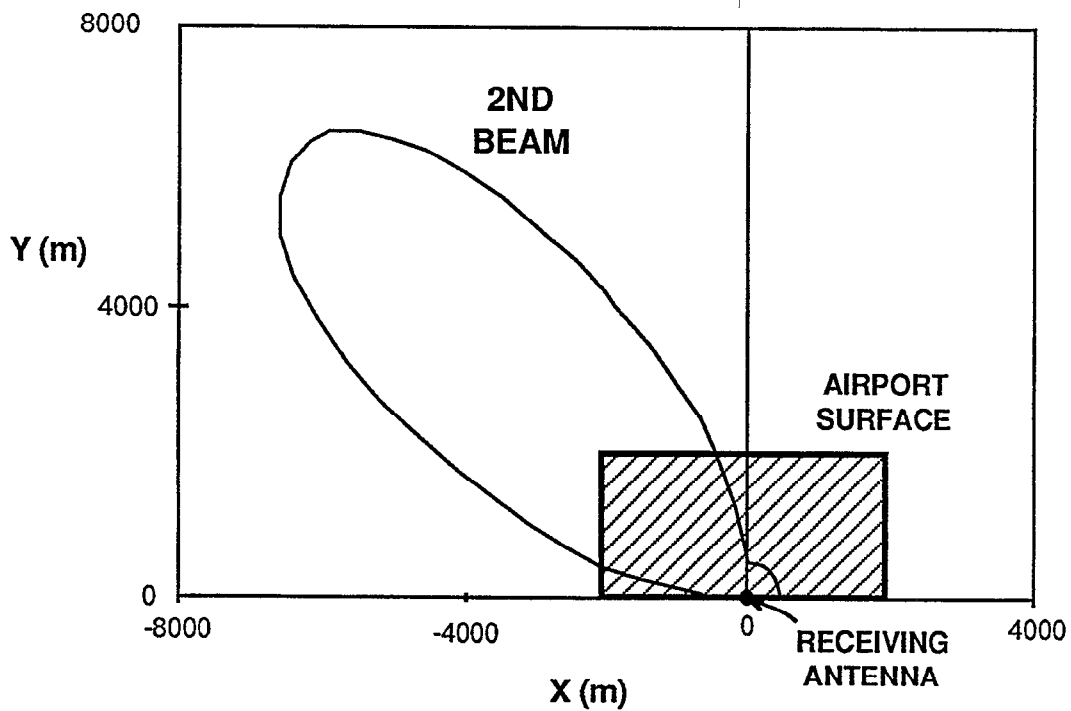


Figure C-2. Interference region within second beam.

This result describes the improvement in terms of the reduction in the airport surface area within which fruit receptions cause interference to the desired squitter reception. Assuming that the aircraft transmitting interference are uniformly distributed over the airport surface, the improvement factor in received fruit rate is the same factor. Because we are considering a very large number of interference generating aircraft on the airport, it seems reasonable to adopt this uniform model for the distribution of the aircraft.

This process has been carried out for targets in each of the 6 beams, producing the following results, for target at beam centers.

Improvement factor =	3.8	1st beam	A = 15°
	2.3	2nd beam	A = 45°
	3.0	3rd beam	A = 75°
	3.0	4th beam	A = 105°
	2.3	5th beam	A = 135°
	3.8	6th beam	A = 165°

### C3.1 Beam Edge

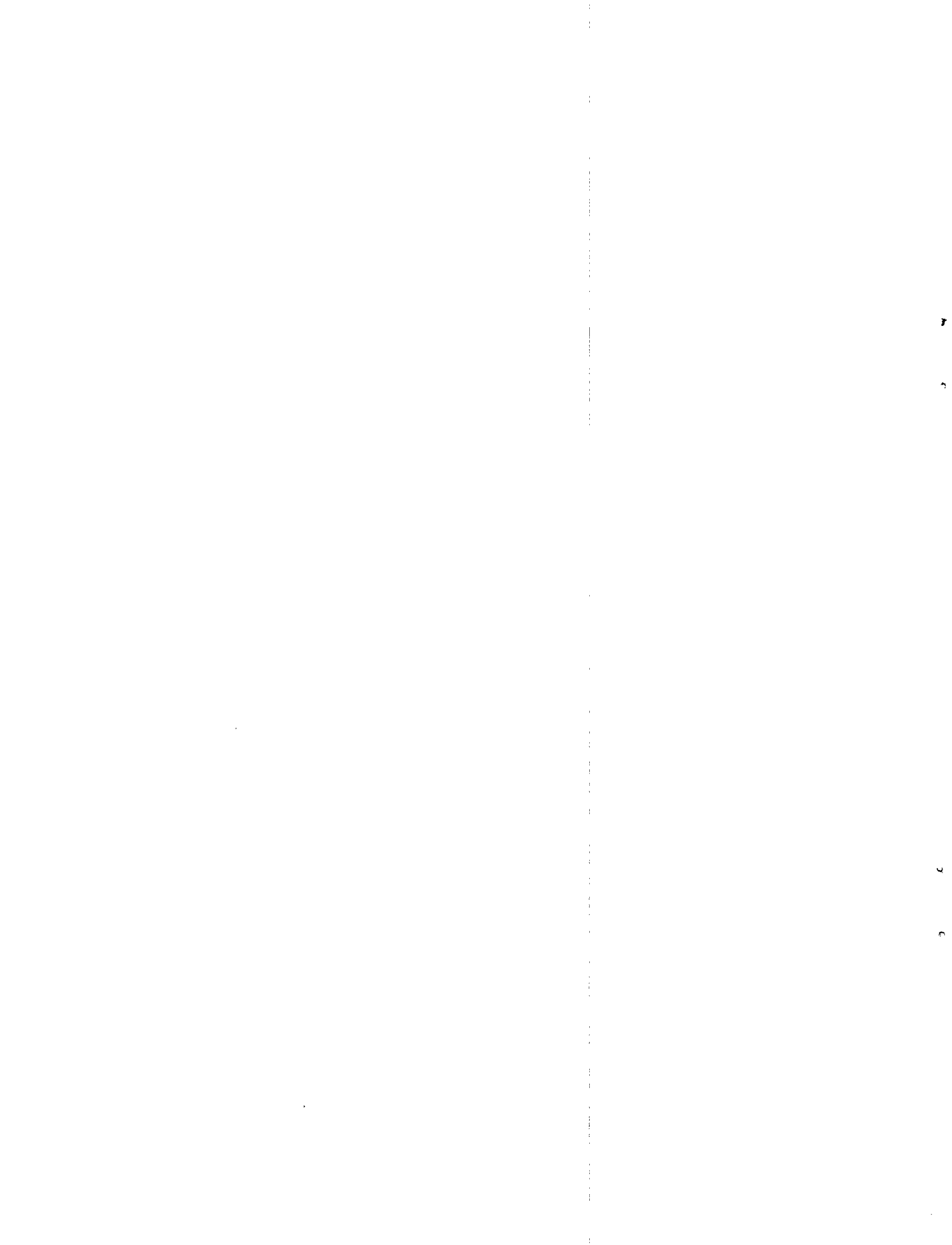
The above factors apply when the targets are located at the beam centers. Next consider an aircraft target at beam edge. Because the antenna gain is weaker by 3 dB in this direction, the region of fruit producing aircraft is larger. The calculation is carried out in the same manner, yielding values for the improvement factors for each case. Individually they are somewhat less, but the fact that each target is received in two beams offsets this degradation. The overall result of this analysis is that the improvement factor is greater than or equal to 2.2 in every direction.

To summarize the above results for a rectangular airport model, the 6-sector antenna improves performance by a factor of 2.2 or more in every direction, with the improvement being substantially more in most directions.

### C3.2 Airport Shape

Different airports have different shapes, and it is difficult to simply describe the many possibilities. The above results for the simple rectangular model serve to indicate certain general principles: (1) that the improvement factor is substantially less than the number of beams, (2) that the improvement factor is a function of direction, with the worst case being in the vicinity of maximum range, and (3) that the resulting improvement factor is consistently above 2:1, and substantially higher in most cases.

For purposes of assessing the capacity of GPS-Squitter, it is reasonable to characterize the beneficial effect of a 6-beam antenna on the airport surface conservatively by an improvement factor of 2.0. This describes the reduction in the rate of receiving interfering transmissions. This simple characterization is conservative in most cases. Allowing for the possibility of some cases in which the improvement is less than 2.0, and assuming that the density of aircraft is so high that interference reduction is necessary, then these situations can be considered to be candidates for an additional ground station, and thus the situation would be similar to multipath or obstructions by buildings.



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- [3] W. Harman, "Air Traffic Density and Distribution Measurements," Project Report ATC-80, MIT Lincoln Laboratory, May 1979.