SERVICE AVAILABILITY FOR AIR TRAFFIC CONTROL AIR/GROUND VOICE COMMUNICATIONS IN THE GULF OF MEXICO

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ABSTRACT

This paper discusses the service availability criteria that representatives of the Federal Aviation Administration (FAA) Air Traffic Organization (ATO) have defined for air traffic control (ATC) air/ground (A/G) voice communications in the Gulf of Mexico. In order to evaluate these criteria, models that relate airspace coverage with the availability of ground-based communications systems had to be developed. This paper discusses the development of the models and their application to four en route sectors in the Gulf of Mexico.

Keywords: Air/Ground Communications, Air Traffic Control, Availability, Gulf of Mexico, Reliability

1.0 INTRODUCTION

This paper describes the work performed by the MITRE Corporation's Center for Advanced Aviation System Development (CAASD) in support of the Federal Aviation Administration (FAA) Safe Flight 21 En Route/Oceanic program. This work involved evaluating service availability criteria that representatives of the FAA Air Traffic Organization (ATO) have defined for air/ground (A/G) voice communications service provided to air traffic in the Gulf of Mexico (GOMEX).

The FAA partitions its en route airspace into sectors, which are three-dimensional volumes of airspace, generally of polygonal shape. The lowest portion of the sector is referred to as the *floor* and the highest portion, the *ceiling*. A sector is controlled by a single controller team where communications between the controller team and pilot is provided by means of connectivity to one or more radio sites located at varying distances from the control facility. Some radio sites could be over 100 nautical miles (nmi) from the control facility, while others are much closer. In the case of the Gulf of Mexico, Houston Air Route Traffic Control Center (ARTCC) is the control facility, and is referred to as ZHU. There are four sectors covering the Gulf of Mexico: ZHU24, ZHU28, ZHU72 and ZHU79. ZHU24 and ZHU28 are low en route sectors with floors of 1,500 ft. and ceilings of 7,000 ft.; and ZHU72 and ZHU79 are high en route sectors with floors of 28,000 ft. and ceilings of 45,000 ft. These sectors serve two distinct user groups: 1) low-altitude helicopter and fixed-wing aircraft supporting the offshore oil/gas and fishing industries, and 2) high-altitude en route commercial and business aircraft. The low en route sectors serve a great deal of helicopter traffic to and from oil/gas company platforms. ZHU28 extends rather far southward. Due to the limited range of VHF radios, and the availability of platforms, the application of the A/G service availability requirements for ZHU28 is restricted to the 95% helo region, which is that portion of ZHU28 that contains 95% of the helicopter traffic. These GOMEX sectors are large and require several radio sites for complete coverage. The number of radio sites required for coverage of a sector is a function of the locations of the radio sites and the extent of coverage of the radio site. To obtain the maximum possible coverage the FAA has decided to use 150 ft. antennas and 50 watts of power for the radios supporting GOMEX sectors. "Limits of Coverage" curves in Figure 18 of Appendix 2 in FAA Order 6050.32A [1] for 50 watts power and 150 ft. antennas are used to determine coverage for the low en route sectors, but the range values are decreased by a couple of nautical miles to be conservative. Thus, for 50 watts, 60 nmi is used for the low en route sectors. For the high en route sectors 218 nmi is used, which is a couple of nautical miles less than line of sight. In order to extend coverage to the line-of-sight, linear power amplifiers (LPAs) must be used with the radio transmitters.

Most of the remote radio sites for GOMEX sectors must be placed on platforms, usually owned by oil companies that are located in the Gulf of Mexico. Communications connectivity from land to the platforms is leased by the FAA from satellite or microwave system service providers. The FAA uses telecommunications circuits ordered from its leased telecommunications contract to provide terrestrial connectivity from ZHU to the locations of the GOMEX communications service providers who provide communications over the Gulf of Mexico. The FAA currently has a leased telecommunications contract with the Harris Corporation called FAA Telecommunications Infrastructure (FTI) that began in 2002. The FAA is transitioning to FTI from its former Leased Interfacility National Airspace System (NAS) Communications System (LINCS) contract with MCI that began in 1992. Circuits that have not yet been cut over to FTI are being provided under a LINCS bridge contract, an extension of the LINCS contract that began in March 2002.

For communications over the Gulf of Mexico, two service providers are assumed for each sector. For this paper, they are denoted as service providers P and S. Typical service providers have a single land location through which all communications to platforms in the Gulf of Mexico is provided. A catastrophic event, such as an earthquake or a flood, could cause severe damage to one of these locations disrupting communications service to all platforms it serves. To minimize the impact of such a catastrophic event to ATC A/G communications provided to a GOMEX sector, the sector's radio sites should be apportioned in some optimal way to the two service providers such that as large a percentage as possible of the sector remains covered after the loss of any one of the service providers.

The A/G communications service provided by the FAA from an ARTCC is called en route communications service, or ECOM service. ECOM service is considered a critical service. Critical services must achieve a steady-state availability of 0.99999 [2, 3]. The ECOM service availability is computed [4] based on the availabilities of the ground components of the end-to-end strings comprising the service that include the voice switch at the ARTCC (i.e., the Voice Switching and Control System [VSCS]), radio control equipment (RCE), radio transmitters and receivers, electric power, antennas, terrestrial telecommunications circuits and GOMEX communications circuits. Figure 1 shows the end-to-end connectivity. Figure 2 shows the components of a remote radio site.

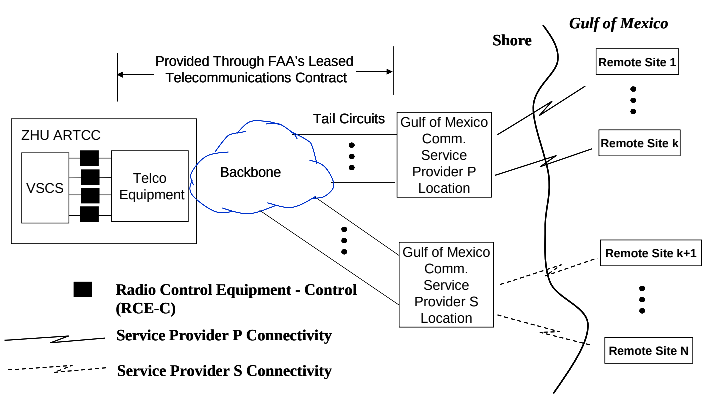
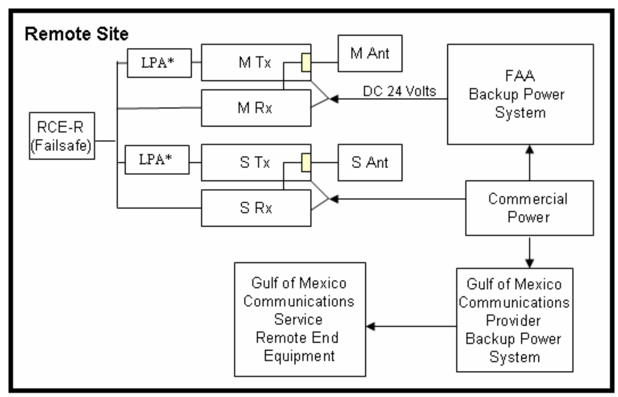


Figure 1. End-to-End Connectivity

There is redundancy built into the equipment at a remote radio site as Figure 2 shows. In case of a main transmitter or receiver failure, the controller can access the standby units. Standby units can be used in conjunction with main units. Both the FAA and the GOMEX communications service provider have their own backup power systems in case of failure of the commercial power supplied to the platform. Linear power amplifiers are required if the FAA wishes to extend the range of the radio site coverage. The RCE equipment (RCE-C in Figure 1 and RCE-R in Figure 2) appear to be common points of failure; however, this equipment is failsafe in that any of its failures does not affect ongoing communications. An RCE failure would reduce or eliminate some of the functionality of the RCE such as the ability to switch to a standby unit in the event of a failure of a main unit.

For a sector covered by multiple radio sites, many different failure events can occur that would cause an inability of the controller team to talk to aircraft in one or more portions of a sector. These are failure events that prevent transmission over or reception from the radios at the radio sites covering those portions. These could be failures in: components of the radio site; the telecommunications infrastructure connecting the GOMEX communications service provider to the VSCS; the communications connecting the radio site to the GOMEX communications service provider; the VSCS; or ECOM-related communications equipment.



LPA = Linear Power Amplifier
M Ant = Main Antenna
M Rx = Main Receiver
M Tx = Main Transmitter
RCE-R = Radio Control Equipment – Remote Site
S Ant = Standby Antenna
S Rx = Standby Receiver
S Tx = Standby Transmitter

*** Included only when extended range is required**

Figure 2. Remote Radio Site Components

When it is said that there is a failure of a radio site to provide coverage, or that a radio site is in a failed state, it is meant that there is a failure in the controller team's ability to use that radio site to access aircraft in the portion of the sector for which the radio site is known to provide coverage based on power, antenna height, and other considerations. This inability to use the radio site would be due to one or more of the above failure events.

In a failure state there can be some operational (or surviving) radio sites and some failed radio sites. Some failure states are "acceptable" and provide reduced service, while others provide unacceptable service. An acceptable state or "success" state is one whose probability of occurrence would contribute to the overall probability of success. The probability of being in at least one success state is called the GOMEX ECOM service availability and is required to be at least 0.99999. A failure state that provides reduced service is considered a success state. ATO representatives have defined a success state for a GOMEX sector to mean the following. A state is a success state if the surviving radio sites cover 65% or more of each of the areas of the sector floor that was previously covered by each of the failed radio sites. Thus, while sector floor coverage of 70%, for example, would provide reduced service, it is still considered a success state under the agreed upon definition.

This 65% criterion is one of two criteria. The second criterion is that, in the state where all radio sites supporting the sector are operational, the coverage at the sector floor must be 100%. It is important to note that the first criterion can be met even though the second criterion is not met.

Mathematically, the first criterion can be expressed as:

$$\begin{aligned}&\Pr[\text{surviving radio site(s) cover 65\% or more of}\\&\quad\text{the coverage that was provided by each failed}\\&\quad\text{radio site at the sector floor}] \geq 0.99999\end{aligned}$$

This first criterion can also be translated as follows: the percentage of the sector floor covered by each radio should not fall below 65% for more than 5.26 minutes per year (i.e., 8760 hours in a year $\times$ [1-0.99999]) due to failures in the ground elements supporting A/G communications.

2.0 APPROACH

The following five-step model development approach was used to determine GOMEX ECOM service availability.

1. Develop a *remote site availability model* as shown in Figure 2, taking into account all of the redundancies of the radio units and electric power, and the failsafe nature of the RCE.
2. Enhance an existing MITRE/CAASD *sector coverage model* called the Radio Coverage Mapping System (RACOMS) so that it can: (i) identify a set of radio sites, which when all are operational, can provide as near as possible to 100% coverage of the floor of a given sector, in order to meet the second criterion; and (ii) identify the quasi-optimal apportionment of the radio sites identified in (i) to GOMEX communications service providers P and S.
3. Further enhance RACOMS to enable it to determine if the failure state of *n* surviving and *m* failed radio sites satisfies the first criterion (i.e., the 65% criterion). The $n + m$ radio sites are those that were selected in step 2 as being able to provide as near as possible to 100% coverage of the sector floor.
4. Develop a *ground infrastructure and sector coverage availability model* that can be applied to any failure state of the radio sites that incorporates the ground infrastructure, including the remote site availability model of step 1. Although applicable to any state, this model would be applied only to the state where all radios are operational and to failure states providing reduced service according to the first criterion. Thus, the state where all radios are operational and those states identified in step 3 as providing reduced service are used as input into this ground infrastructure availability model.
5. Develop a logical procedure to generate the necessary states in order to compute GOMEX ECOM service availability. If the procedure does not generate them as mutually exclusive states, some method must be developed to generate mutually exclusive states from them in order to facilitate the computation of GOMEX ECOM service availability.

Details of steps 1 through 3 are not presented in this paper. The concentration of this paper is on the development of the ground infrastructure and sector coverage availability model, the integration of the outputs from steps 1 through 3 with it, and the generation of the necessary states in order to compute GOMEX ECOM service availability. As alluded to in Step 5, further processing of the states may be required in order to derive mutually exclusive states from them, if they have not been generated as such. This extra processing is discussed later for a particular manner of generating necessary states.

3.0 END-TO-END CONNECTIVITIES

Failures of the RCE-C at the ARTCC, represented by black squares in Figure 1, affect A/G communications only at the remote sites with which they are associated. The RCE-C availability is incorporated into the availability of its associated remote radio site. It will be assumed that the availabilities of all remote sites are equal to the same value that is denoted by A_R . Also, it is assumed that the service providers' links fail independently and these failures affect only the remote sites they serve. Each service provider's link from a radio site is assumed to be in series with the corresponding tail circuit from the FAA backbone to the GOMEX service provider's location. The availability of this series combination of links from the FAA backbone through a service provider's location to a remote radio site is denoted as A_P or A_S, respectively. Let $A_{\text{rem P}} = A_R A_P$ and $A_{\text{rem S}} = A_R A_S$.

Define the following parameters:

N_x^U = Number of remote sites using x for which there is success to access

N_x^D = Number of remote sites using x for which there is failure to access

x = P or S

Set $N_x^U = N_x^D = 0$ if remote sites using x ($x = P$ or $x = S$) are not part of the state description

The possible states that can arise fall into the following generic types:

1. Of the remote radio sites that P and S each serve, they each have at least one remote site for which communications is successful. For this type of state:

$$N_P^U > 0, N_S^U > 0, N_P^D \geq 0, N_S^D \geq 0$$

2. Either successful communications cannot occur for any remote site connected to P (i.e., a P remote site) or no P remote sites appear in the state, and there is at least one remote site connected to S for which communications is successful. For this type of state:

$$N_P^U = 0, N_P^D \geq 0, N_S^U > 0, N_S^D \geq 0$$

3. Either successful communications cannot occur for any remote site connected to S (i.e., an S remote site) or no S remote sites appear in the state, and there is at least one remote site connected to P for which communications is successful. For this type of state:

$$N_S^U = 0, N_S^D \geq 0, N_P^U > 0, N_P^D \geq 0$$

For states of type 1, the backbone (BB) must be available to sites connected to both P and S. This leads to BB state 1 whose availability is denoted by $A^{P\&S}$.

For states of type 2, two states of the BB must be considered, depending on the states of the remote sites and off-backbone access: (1) the BB is available for remote sites connected to both P and S, and (2) the BB is available for remote sites connected to S, but is not available for remote sites connected to P. This latter BB state is referred to as BB state 2 and is denoted by $A^{\overline{P}\&S}$.

For state type 2 whether the condition is that there is no successful communications to any of the P remote sites, or that there is no P remote site appearing in the state, the BB can be in a failed or operative state regarding P remote sites. First consider the case where there is no successful communications to any P remote site. If the BB is in an operative state regarding P remote sites, then in order that there be no successful P remote site communications, there must be some off-BB P remote site access failures (i.e., some P remote site access failures not on the BB), and/or some failures in the P remote sites themselves, that when these two types of failures occur together must cause failure to communicate over all P remote sites. On the other hand, if the BB is in a failure state regarding P remote sites, then the off-BB P remote site access and the P remote sites can be either failed or operative, as the failed BB will prevent successful communications over all P remote sites.

Next consider the case where no P remote site appears in the state. All possible combinations of failed and successful communications over those P remote sites must be considered. Since all possible combinations for P remote sites are considered, their probabilities sum to 1, thus effectively removing any consideration of P remote sites from the probability expression for the state and leaving a probability expression involving only S remote sites. This will be seen explicitly in equation form later.

States of type 3 are similar to those of type 2, except that the roles of P and S are exchanged. This leads to an analogous BB state 3 denoted as $A^{P\&\overline{S}}$.

As examples of the generic types of states, consider the case where there are 5 radio sites covering a sector. Assume that radio sites 1, 2, and 3 are assigned to P; and radio sites 4 and 5 are assigned to S.

An example of a generic state type 1 is:

P: radio site 1 operational, radio sites 2 and 3 failed
S: radio site 4 failed and radio site 5 operational

An example of generic state type 2 is:

P: radio sites 1, 2, and 3 failed
S: radio site 4 operational, radio site 5 failed

Another example of generic state type 2 state is:

S: radio site 4 operational

In this latter example, radio sites 1, 2, 3, and 5 do not appear in the state. Thus all possible states with radio site 4 operational must be considered.

The availability expressions for the three types of end-to-end states are:

For an end-to-end state of type 1

$$A_{type1} = A_{VSCS} A_{\text{rem P}}^{N_P^U} A_{\text{rem S}}^{N_S^U} (1 - A_{\text{rem P}})^{N_P^D} (1 - A_{\text{rem S}})^{N_S^D} A_{BB}^{P\&S}$$

$$N_P^U > 0, N_S^U > 0, N_P^D \geq 0, N_S^D \geq 0$$

For an end-to-end state of type 2

$$A_{type2} = A_{VSCS} A_{\text{rem S}}^{N_S^U} (1 - A_{\text{rem S}})^{N_S^D} \left[A_{BB}^{\bar{P}\&S} + (1 - A_{\text{rem P}})^{N_P^D} A_{BB}^{P\&S} \right]$$

$$N_P^U = 0, N_P^D \geq 0, N_S^U > 0, N_S^D \geq 0$$

When no P remote sites appear in the state then:

$$N_P^U = 0, N_P^D = 0, N_S^U > 0, N_S^D \geq 0$$

which results in

$$A_{type2} = A_{VSCS} A_{\text{rem S}}^{N_S^U} (1 - A_{\text{rem S}})^{N_S^D} A_{BB}^S, A_{BB}^S = A_{BB}^{\bar{P}\&S} + A_{BB}^{P\&S}$$

(i.e., an expression involving only S remote sites)

For an end-to-end state of type 3

$$A_{type3} = A_{VSCS} A_{\text{rem P}}^{N_P^U} (1 - A_{\text{rem P}})^{N_P^D} \left[A_{BB}^{P\&\bar{S}} + (1 - A_{\text{rem S}})^{N_S^D} A_{BB}^{P\&S} \right]$$

$$N_S^U = 0, N_S^D \geq 0, N_P^U > 0, N_P^D \geq 0$$

When no S remote sites appear in the state then:

$$N_S^U = 0, N_S^D = 0, N_P^U > 0, N_P^D \geq 0$$

which results in

$$A_{type3} = A_{VSCS} A_{\text{rem P}}^{N_P^U} (1 - A_{\text{rem P}})^{N_P^D} A_{BB}^P, A_{BB}^P = A_{BB}^{P\&\bar{S}} + A_{BB}^{P\&S}$$

(i.e., an expression involving only P remote sites)

4.0 ASSIGNING REMOTE SITES TO SERVICE PROVIDERS

Given a set of remote radio sites that together cover as much of the floor of the sector as possible (the goal according to criterion 2 is 100% coverage), the remote sites must be assigned in some quasi-optimal manner to service providers P and S. As described in Section 2.0, Step 2 of the approach, RACOMS is used to select the radio sites to attempt to meet criterion 2, and also to generate various options for splitting these radio sites into two groups for assignment to P and S, respectively. The user then reviews the options and selects one that will result in the highest possible percentage of coverage of the sector when either P or S suffers a catastrophic failure. The best option is not only one where each group provides as high a percentage of coverage of the sector floor as possible, but also one where the coverage is as equally distributed between the two groups as possible.

Figure 3 shows sector ZHU72 and the selection of remote radio sites from all available remote radio sites for the highest percentage of coverage of ZHU72. The 100% coverage goal could not be achieved; however, coverage of 99.85% was achieved. The small uncovered area is pointed out in the figure. Table 1 shows the optimal assignment of radio sites to P and S. In this case, the coverage provided by each group is very nearly equal with 92.60% for P and 92.68% for S. Thus when either GOMEX service provider (P or S) fails in such a way as to cause all radio sites it serves to lose communications, the other carrier can still cover at least 92% of the sector floor.

Figures 4, 5, and 6, and Tables 2 through 4 show the results for criterion 2 and the optimal assignment of radio sites to P and S for the other three sectors.

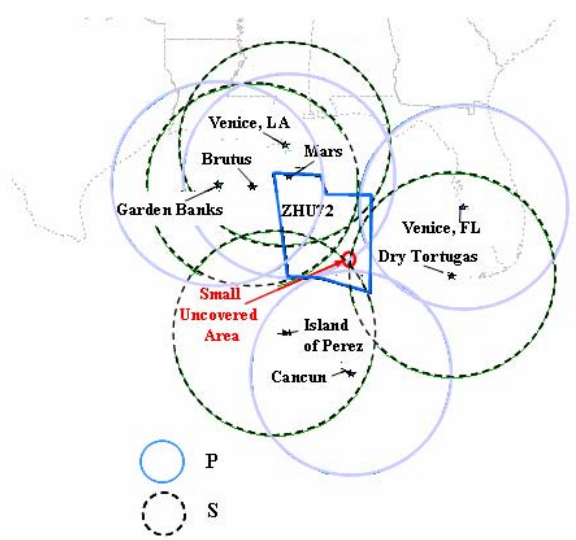


Figure 3. Remote Site Coverage of Sector ZHU72

Table 1. Assignment of Remote Sites to P and S for ZHU72

GOMEX Service Provider	Site Name	Percent Coverage of Sector Floor 50W, 150 ft. Antenna (218 nmi SV Radius)
P	Cancun, MX	Coverage Provided by P Sites 92.60%
P	Mars, LA	
P	Venice, FL	
P	Garden Banks, LA	
S	Brutus, LA	Coverage Provided by S Sites 92.68%
S	Venice, LA	
S	Island of Perez, MX	
S	Dry Tortugas, FL	
Coverage provided at Sector Floor by all 8 sites		99.85%

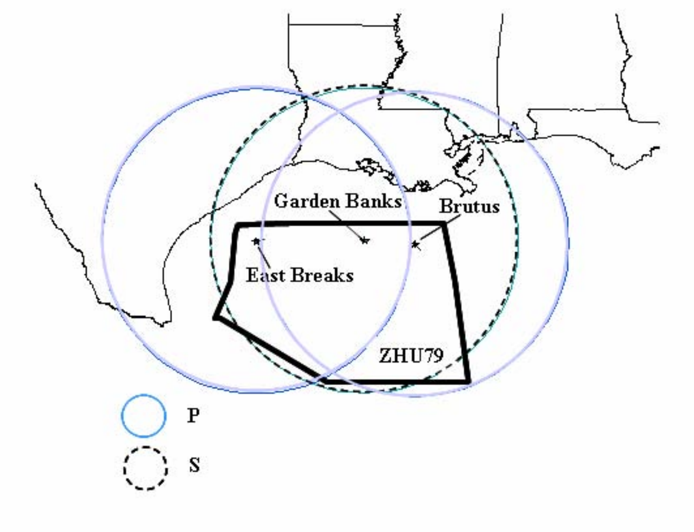


Figure 4. Remote Site Coverage of Sector ZHU79

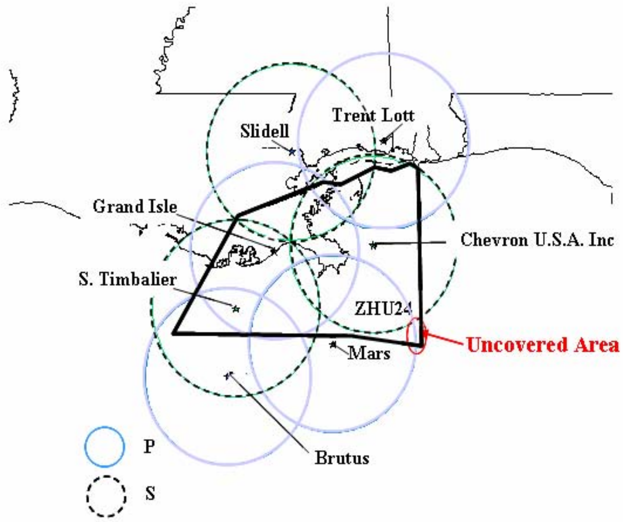


Figure 5. Remote Site Coverage of Sector ZHU24

Table 2. Assignment of Remote Sites to P and S for ZHU79

GOMEX Service Provider	Site Name	Percent Coverage of Sector Floor 50W, 150 ft. Antenna (218 nmi SV Radius)
P	Brutus, LA	Coverage Provided by P Sites 99.63%
P	East Breaks, TX	
S	Garden Banks, LA	Coverage Provided by S Site 97.49%
Coverage provided at Sector Floor by all 3 sites		100%

Table 3. Assignment of Remote Sites to P and S for ZHU24

GOMEX Service Provider	Site Name	Percent Coverage of Sector Floor 50W, 150 ft. Antenna (60 nmi SV Radius
P	Mars, LA	Coverage Provided by P Sites 87.88%
P	Grand Isle, LA	
P	Brutus, LA	
P	Trent Lott, MS	
S	Slidell, LA	Coverage Provided by S Sites 95.4%
S	Chevron USA Inc,. LA	
S	S. Timbalier, LA	
Coverage provided at Sector Floor by all 7 sites		99.53%

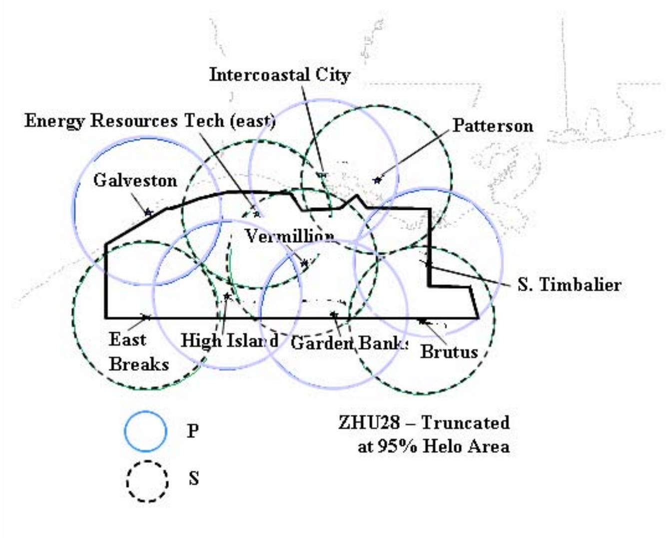


Figure 6. Remote Site Coverage of Sector ZHU28

Table 4. Assignment of Remote Sites to P and S for ZHU28

GOMEX Service Provider	Site Name	Percent Coverage of Sector Floor 50W, 150 ft. Antenna (60 nmi SV Radius)
P	Galveston, TX	Coverage Provided by P Sites 90.88%
P	Garden Banks, LA	
P	Intercoastal City, LA	
P	High Island, TX	
P	S. Timbalier, LA	
S	Vermillion, GL	Coverage Provided by S Sites 90.84%
S	East Breaks, GL	
S	Patterson, LA	
S	Energy Resources Tech E, TX	
S	Brutus, LA	
Coverage provided at Sector Floor by all 10 sites		100%

5.0 COMPUTING GOMEX ECOM SERVICE AVAILABILITY

In order to compute the GOMEX ECOM service availability, success states must be generated (see step 5 of the approach in Section 2.0). One method of computing success states is to generate all states, and then test each state to determine if the 65% criterion is met. If it is, then the probability of the state is computed as described above. The probabilities of all success states are then summed to obtain the GOMEX ECOM service availability. In this approach, every radio site covering the sector appears in each state and an indication is given regarding the success or failure of access of each radio site. This could lead to a large number of states. For example, for a sector covered by 12 sites, there are $2^{12} = 4{,}096$ states to examine.

The first step in minimizing the number of success states was to assign a random binary variable, R_n, to each remote radio site. RACOMS generated a list of every combination meeting the 65% coverage criteria. The combinations from RACOMS are not mutually exclusive events, as shown in the following three combinations:

$$R_1 R_4 R_5$$
$$R_2 R_4 R_6$$
$$R_1 R_2 R_4 R_5 R_6$$

The third combination is a subset of both the first and second combinations, thus they are not mutually exclusive. The probabilities of non-mutually exclusive events cannot be added to obtain the overall probability. By specifying the states in the following way, they are made to be mutually exclusive:

$$R_1 R_2' R_3' R_4 R_5 R_6'$$
$$R_1' R_2' R_3' R_4 R_5' R_6$$
$$R_1 R_2 R_3' R_4 R_5 R_6$$

Logical complements, denoted by primes, enable each state to be expressed as a mutually exclusive event. A logical complement signifies that a particular radio site is not operational. As shown, the third state combination is no longer a subset of either of the first two combinations. Every successful combination of operational radio sites is now only counted once in the RACOMS output. Because of the large number of combinations, another step was taken to reduce the number of probability computations needed to calculate the ECOM service availability for a sector.

A device that can be used for this state reduction is the Karnaugh map (K-map) [5]. For simplicity, Figure 7 shows a 4-by-4 K-map for a hypothetical sector containing four remote radio locations. The axes are labeled in Gray code binary, so that each row satisfies the adjacency condition [5]. Each cell of the leftmost column under $R_1 R_2$ contains two binary numbers – the left number associated with R_1 and the other with R_2. Similarly for the top row under $R_3 R_4$, the left binary number of each cell is associated with R_3 and the other with R_4. Each state corresponds to one entry cell of the K-map. For each state combination, a 1 was entered in the corresponding cell to denote successful sector coverage. For example, the first entry cell of the K-map would correspond to the state 0000, a state where all radio sites are failed. Thus a 1 is not entered in that cell. The K-map provides a way to minimize the logical expression that gives this outcome. Below the K-map is the corresponding logic expression.

	R_3R_4			
R_1R_2	00	01	11	10
00				
01			1	
11	1	1	1	1
10			1	1

$$R_1R_3 + R_1R_2R_3' + R_1'R_2R_3R_4$$

Figure 7. Karnaugh Map Example

As an example of how the logic expression was derived, consider the first term. This term is related to the encircled set of 4 cells in the lower right corner of the K-map. Whenever the condition (i.e., 1 – operational or 0 – failed) of a radio site changes from 0 to 1 or from 1 to 0, that radio site is not considered in the logic expression. When the condition of a radio does not change, it appears in the corresponding logic expression with that condition. Within the four encircled cells, it can be seen that in looking down either column, R_1R_2 changes from 11 to 10. The condition of R_1 is 1 in both states, but R_2 changes from 1 to 0. Thus, R_1 would appear in the logic expression, while R_2 would not. Going across either row within the encircled cells it can be seen that the condition of R_3 stays the same (i. e., operational), while that of R_4 changes. Thus, R_3 would appear in the logic expression, while R_4 would not. Thus the term R_1R_3 is obtained.

Using the K-map, the probabilities of only three instead of seven states (number of 1's in the K-map of Figure 7) need to be calculated. The same results could have been obtained by using algebraic manipulation of the original logic expression involving all success states. Logical identities can be used to obtain a minimal sum of products, thus minimizing the number of probability calculations needed to calculate the availability of the system.

6.0 SUMMARY OF RESULTS

The GOMEX ECOM service availability goal of 0.99999 could be met for sectors ZHU24 and ZHU79; however, it could not be met for ZHU28 and ZHU72, although it is approximately 0.99998 for both. The telecommunications tail circuits from the FAA's backbone to the GOMEX communications service providers' locations are the components of the end-to-end string with the lowest availability – 0.9991. A failure of one of these tail circuits causes a loss of ECOM service to the associated radio site. Increasing the availability of this connectivity is a step that the FAA can take to meet the ECOM service availability goal of 0.99999. Figure 8 shows one way of increasing the availability of the connectivity between the FAA's backbone and the GOMEX service providers' locations. This method involves multiplexing each set of multiple tail circuits onto a single higher capacity circuit for each GOMEX service provider and providing a diverse backup for the high capacity circuit. By doing this, the GOMEX ECOM service availability for ZHU28 and ZHU72 can be increased beyond 0.99999. Table 5 shows a summary of all the results for criterion 1 for all sectors with and without tail circuit diversity, and for criterion 2 for all four sectors.

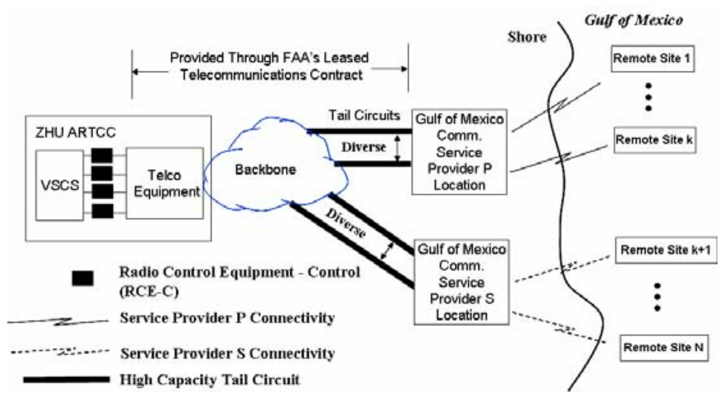


Figure 8. Increasing the Reliability of the FAA Backbone to GOMEX Service Provider

As Table 5 shows, the GOMEX ECOM service availability can be increased to a value exceeding 0.99999 for all GOMEX sectors if the connectivities between the FAA's backbone and the GOMEX communications service providers' locations is made more reliable and robust.

Table 5. Summary Criteria 1 and 2 Results

GOMEX Sector	Criterion 1 (Goal 0.99999)		Criterion 2 (Goal 100%)
	Service Availability	Service Availability With Diversity	Percent Coverage
ZHU24	0.9999916	0.9999966	99.53%
ZHU28	0.9999770	0.9999920	100.00%
ZHU72	0.9999842	0.9999943	99.85%
ZHU79	0.9999952	0.9999977	100.00%

REFERENCES

1. Department of Transportation, Federal Aviation Administration, *Spectrum Management Regulations and Procedures Manual*, Order 6050.32A, May 1998.
2. Department of Transportation, Federal Aviation Administration, *National Airspace System (NAS) System Requirements Specification*, NAS-SR-1000, March 1985.
3. Department of Transportation, Federal Aviation Administration, *National Airspace System (NAS) System Specification, Volume I, Functional and Performance Requirements for the National Airspace System, General*, NAS-SS-1000, April 1995.
4. Ebeling, Charles E., *An Introduction to Reliability and Maintainability Engineering*, McGraw-Hill, New York.
5. Ercegovac, Miloš D., Tomás Lang, Jaime H. Moreno, *Introduction to Digital Systems*, John Wiley & Sons, Inc., New York.