DESIGN CONSIDERATIONS IN ACHIEVING MLS CATEGORY III CONTINUITY OF SERVICE REQUIREMENTS

By

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ABSTRACT

This paper addresses system design aspects that should be considered in designing Microwave Landing Systems (MLS) to meet Category III Continuity of Service Requirements. Experience with Instrument Landing Systems (ILS) has shown that the continuity of service achieved in the field is at least two times worse than performance predictions based on equipment reliability. This is primarily due to outages caused by environmental factors. In the development of MLS it has been assumed that it would be more immune to environmental outages than ILS. This paper addresses these and other factors that should be considered in designing MLS to achieve Category III continuity of service requirements.

INTRODUCTION

A number of state aviation authorities have development activities underway in designing MLS ground equipment to meet the requirements for Category III precision landing operations. Minimum performance standards for Cat III have been adopted by the International Civil Aviation Organization (ICAO) [1]. Various authorities have further developed these standards in the form of equipment specifications [2,3]. For the most part these standards are identical to those required of Instrument Landing Systems (ILS) [4]. The two key performance aspects needed to meet Cat III requirements are Integrity and Continuity of Service. Integrity is the probability of not radiating false guidance signals. Continuity of Service (COS) is the probability of no interruption in the transmission of the radiated guidance signals. This paper will deal only with the Continuity of Service aspects of MLS design. In addition, this paper will only be discussing the angle (Azimuth and Elevation) and Data functions of MLS and not DME/P, although many of the principles are common to both.

ILS has had many years of field experience with a large number of systems which demonstrate their ability to meet Cat III requirements. On the other hand, MLS does have some 10 years of operational field experience, but with a very limited number of systems. These systems have been designed to provide only Category I service. As of this writing no MLS ground equipment has been certified for Category II or III operations. It is the purpose of this paper to discuss some important aspects of system design in meeting Cat III Continuity of Service requirements.

CONTINUITY OF SERVICE REQUIREMENTS

We first must define what the Continuity of Service requirements are. These are given by ICAO as listed in Table 1.

Table 1. Category III Continuity of Service Requirements [1]

Equipment	Continuity of Service	Equivalent Mean Time Between Outages (MTBO)	Critical Time Interval (sec.)
Azimuth	$1-(2.0\times10^{-6})$	4000	30.0
Elevation	$1-(2.0\times10^{-6})$	2000	15.0

The U.S. Federal Aviation Administration (FAA) has chosen to use a critical time interval of 60 seconds for Azimuth, therefore the corresponding MTBO would be a minimum of 8000 hours rather than 4000. The reason for the longer time interval was to allow for future Cat III operations that include guidance during runway rollout. The 30-sec. time interval does not take this operation into account. Compliance with the requirements in Table 1 must be demonstrated in field operations.

ILS PERFORMANCE

ILS achieved performance (MTBO) is typically two or more times worse than predictions based on equipment reliability. This results from external factors causing outages that are not due to random failures of the equipment. For this reason, ICAO recommends that the system be designed with a reliability much higher

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than the MTBOs specified in Table 1 [1]. Data collected on ILS equipments operating in the U.S. for the past five years (1987-91) is summarized in Table 2.

Table 2. ILS Reliability in U.S. [5]

	Equipment OPMH	**External OPMH**	**Total MTBO (hrs.)**
Localizers	111.4	81.5	5183
Glide Slopes	74.9	64.5	7172

Note: 1. OPMH = Outages Per Million Hours
2. Data are averages based on 911 localizers and 810 Glide Slopes
(Category I, II and III combined)

As can be seen, the number of outages caused by external factors is only slightly less than those due to random equipment failures. In recent years the reliability of ILS has improved significantly. For example, the average MTBO of Localizers has gone from 4300 hrs. to 6300 hrs. over the 5-year period. Similarly, for Glide Slopes the average MTBO has gone from 5000 hrs. to 8300 hrs. This is largely due to the elimination of older type equipments. But it may also be partially due to the elimination of the field monitors. FAA policy currently is that only integral monitors are used, with no field monitors [6]. This was done to eliminate problems caused by the use of near-field monitors, such as ground plane effects. The only exceptions are the use of a far field monitor with Cat II and III localizers and a near field monitor with End-Fire Glide Slopes.

PROJECTED MLS PERFORMANCE

What differences (if any) can we expect in the achieved COS of MLS compared to ILS? The basic equipment reliability should be about the same. Both use primarily solid state electronic components (older generation ILS equipments used analog devices). They will be installed in identical environments so there won't be any difference in the conditions to which the equipment is subjected. The question is, are there any fundamental differences in the two systems that would result in a difference in achieved Continuity of Service? Before we can make any predictions, we should examine what a typical Cat III design will look like.

BASIC CAT III DESIGN

Figure 1 is a basic diagram of a Cat III MLS design. Most of the electronics will be redundant. These would include the transmitter components, timing and control, power supplies, uninterruptible power supply (battery back-up), antenna beam steering, and executive monitor. The elements that may not be redundant are indicated with shading. In normal operation, upon a detected failure in transmitter A, switchover to B is effected by the control and transfer unit.

At least two executive monitors will be required, although several different configurations are possible.

- (1/1) - Each monitor is associated with one transmitter. Only one monitors the radiated signal. Switchover occurs upon failure of either the transmitter or monitor
- (2/2) - Both monitors actively monitor the radiated signal. Both must agree that an out of tolerance condition exists to declare alarm and effect switchover
- (1/2) - Both monitors actively monitor the radiated signal. Only one has to indicate an out of tolerance condition to declare alarm
- (2/3) - All three monitors actively monitor the radiated signal. Two out of three must agree that an out of tolerance condition exists to declare alarm and effect switchover.

All four configurations should be satisfactory from a COS point of view, with the possible exception of the (1/2). The reason for that is that certain failure modes in one monitor that result in an alarm will be indicated on both transmitters, the second after switchover, resulting in total shutdown. Whether this is acceptable or not depends upon the failure rate for these type of failure modes. It should be noted that both the 2/2 and 2/3 require a voting logic circuit, which is not needed for the 1/1 and 1/2.

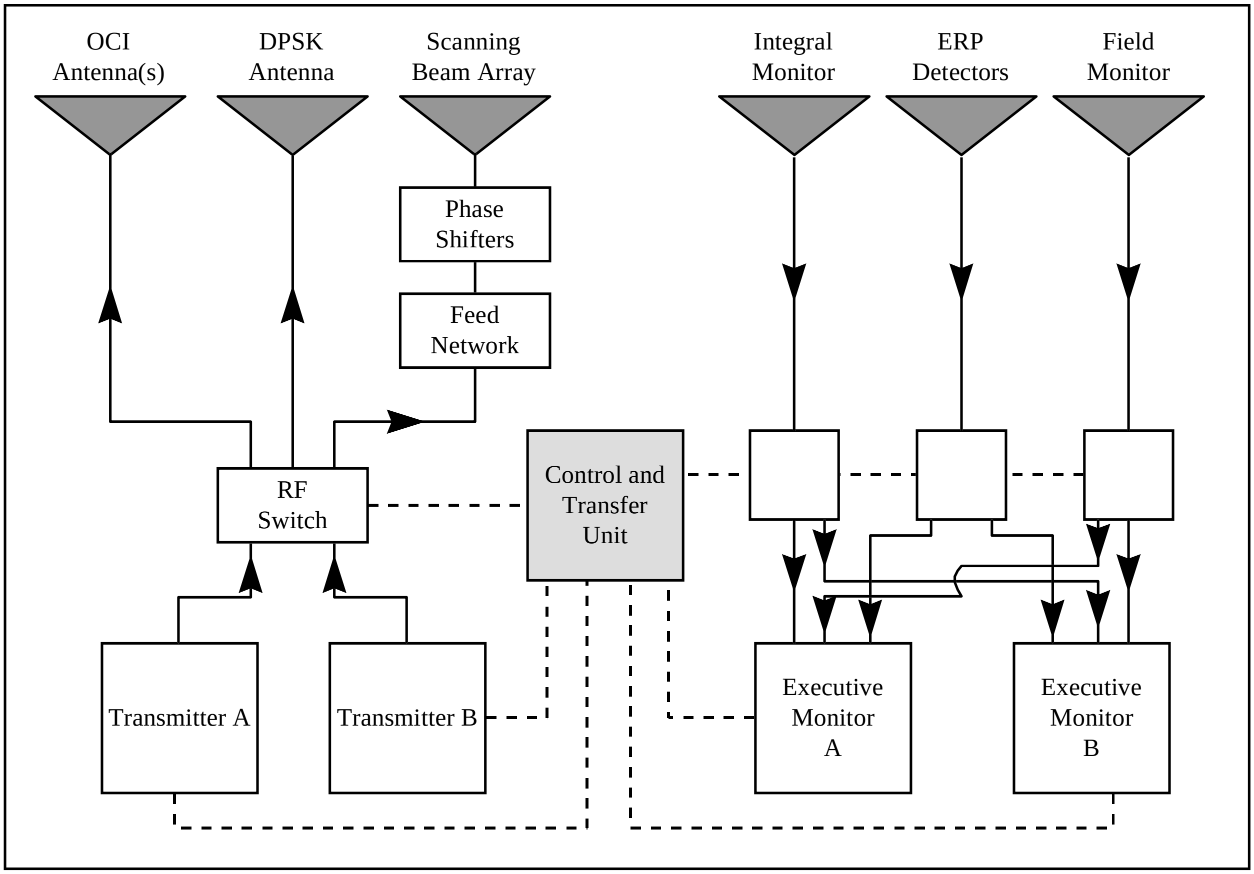

Figure 1. CAT III MLS Architecture

CONTINUITY OF SERVICE CALCULATIONS

The probability of experiencing no failures over a given time period is:

$$P = e^{-\lambda t} \quad (1)$$

λ = failure rate of the component (per hour)
t = time interval (hours)

The computation of COS is different for parallel and series equipments. Since a Cat III MLS is a combination of parallel and series elements, the overall value is a product of the two.

$$P_c = P_p P_s \quad (2)$$

P_c = COS of the combination of parallel and series components
P_p = COS of the parallel components
P_s = COS of the series components

Calculation of the COS of the parallel components is given by:

$$P_p = P_1 + P_2 - P_1 P_2 \quad (3)$$

P_1 = Path #1 (primary equipment)
P_2 = Path #2 (secondary equipment)

The parallel elements are not a factor in the overall COS because it requires a failure of both of the redundant elements to cause an outage. For example, with parallel equipments each having an MTBO of only 1000 hrs., the resulting COS is 5×10^{-10} (using a 30-sec. critical time period). It is the series elements that end up being the determining factor for achieving COS.

As indicated in Figure 1 the series elements are primarily antenna components such as power dividers, cabling, and antenna elements (DPSK and OCI). These are all passive devices with very low failure rates and will have minimal impact on overall MTBO. The scanning beam antennas have built in redundancy.

This results from the fact that some failures can occur (phase shifters and elements) with little impact on performance, given proper design. The integral and field monitors probably don't need to have redundancy, again because they are passive devices with low failure rates. Any active components associated with these monitors, such as RF detectors, might need redundancy.

The conclusion is that it should not be difficult to achieve the required MTBO in terms of the equipment reliability. The experience with ILS bears this out. As shown in Table 2, even Category I ILS equipments achieve MTBOs for equipment failures of approximately 10,000 Hrs.

It should be a design goal for Cat III MLS equipment to make the achieved COS a function of low failure rates in the non-redundant parts of the system and to minimize outages due to external effects.

INTEGRITY PARAMETERS

Let's take a look at those parameters that can cause the system to alarm and cause a shutdown. ICAO Annex 10 parameters that are required to cause cessation of radiation upon an out of tolerance condition are:

- ground equipment mean error contribution to PFE (Path Following Error) such that total system PFE is out of tolerance
- ERP (Effective Radiated Power)
- DPSK Data transmissions
- TDM (Time Division Multiplex) synchronization [7]

In addition to these the FAA has specified additional parameters [2]. These are: peak dynamic sidelobes, erroneous signals between functions, automatic integrity check status, end-to-end integrity check status, and phase shifters status.

Several of these parameters are monitored at more than one location:

- PFE is measured by both integral and field monitors
- ERP is monitored on the scanning beam, OCI, and the preamble DPSK, which also functions as the monitor for the basic and auxiliary data ERP since the same antenna is used for all three
- DPSK data is monitored for the function preambles, basic data, and auxiliary data

Most of these parameters should not be a source of difficulty in achieving the required COS. These are discussed first.

Integral Monitor PFE. This should not be a problem because current antenna technology allows the design of antennas that are very stable electrically. For 1^o beamwidth antennas, the FAA spec. requires that the Azimuth mean error on boresight remain within $\pm 0.02^o$ over temperature (-50^o to $+50^oC$). The spec for Elevation is $\pm 0.03^o$. Data collected during factory testing of the Hazeltine 2600 MLS was within these tolerances [8]. In the phased array antennas used for MLS, the largest contributor to beam pointing errors are phase changes in the feed network. The stability specified by the FAA can be achieved with the use of antenna materials that are phase stable over temperature and/or with the use of on-line calibration techniques, as used by Hazeltine.

ERP. The primary cause for ERP being out of tolerance will be a failure of the exciter or RF power amplifier in the traditional system design. These types of failures present no problem for COS since these elements will be redundant. Recently a different type of phased array antenna has emerged called a distributed array. In this design there is a small transmitter module associated with each antenna element, rather than a single power amplifier. This may have some benefit for the COS of a single thread Category I or II design since it reduces the probability of outages due to power amplifier failures. In this design a number of modules can be allowed to fail and still meet the minimum ERP.

DPSK Data. This should not be a problem for COS because normally either a software or firmware failure has to occur to cause bad data to be radiated. These elements are redundant so failures will not cause an outage. As indicated previously the radiating antennas, although single thread, are passive devices with low failure rates.

TDM Sync. This parameter monitors the TDM synchronization of the functions. This could potentially be a problem for Elevation. The normal situation is that if sync. is bad, Elevation is shut down, but Azimuth can keep transmitting. The FAA has theoretically eliminated this as a problem by designing in a two-minute coast mode. The concept here is that the clocks used for timing in the equipment are designed to be stable enough such that over a 2 minute period they will not drift more than ± 100 microseconds. This will prevent function overlap since a 200-microsecond guard band exists at the end of each function. These two minutes are enough time to allow an aircraft, if it is in the critical phase of the approach, to complete the final approach following the failure. When sync is lost a warning is given to Air Traffic personnel, indicating that Cat III service will be lost in two minutes. At that point no additional aircraft will be allowed to execute approaches. The whole purpose of this is to eliminate outages in Cat III operating conditions due to loss of communications between equipments. If this is not done then a failure in the communications network would have to be considered in the COS calculations. Redundancy of some sort might even have to be provided if this coast mode is not implemented. With the FAA design all that is required is for the communications design to minimize false shutdowns. For example, a typical system command would be to shutdown Elevation after Azimuth has declared an alarm. The communications system must have enough integrity to minimize the likelihood of this command being sent accidentally, or another command being misinterpreted as a shutdown command.

<u>Peak Dynamic Sidelobes.</u> This parameter should not cause outages since the alarm threshold is set to -12 dB relative to the peak. The design sidelobes will be on the order of -25 dB or lower, so significant degradation would have to occur causing them to rise to this level. Normally other parts of the monitoring would have detected problems with the antenna well before this level of degradation of performance has occurred.

<u>Erroneous Signals Between Functions.</u> The purpose of this parameter is to detect the presence of functions being transmitted at erroneous times, which could cause function overlap. This might be due to an RF switch failure resulting in loss of isolation. This type of failure should occur with a low enough probability that it is not an issue for COS.

<u>Failure of Auto Integrity Check.</u> This must be an integrity parameter since a failure of this check will jeopardize integrity. An alarm on this parameter is normally due to a failure in the monitoring components, and since they're redundant, this won't affect COS. There are failures, however, in the auto integrity check circuit itself that could affect COS.

<u>Failure of End-to-End Integrity Check.</u> This will not normally have any effect on COS when in Cat III operations. That is because the End-to-End Integrity Check will not be run when conducting Cat III operations, since as part of the check the system is shutdown. It will be run at other times when availability of the equipment is not critical. Therefore by definition it could not cause an alarm in Cat III operations.

<u>Phase Shifter Failures.</u> It has been a fundamental design goal of MLS since its initial development to use antennas that have "fail soft" characteristics. This is achieved by having a large number of elements, such that the failure of a small percentage will not result in out of tolerance signals being radiated. This has been achieved for the most part in the systems designed to date. None however have been designed to meet Cat III COS requirements.

An integrity alarm for this parameter is declared when a number of failures occur which might result in an increase in sidelobe levels causing PFE or CMN (Control Motion Noise) to be out of tolerance. Examination of the effect of phase shifter failures reveals the following:

1) For Azimuth this alarm would be due to sidelobes causing CMN. But none of the standards require CMN to be an integrity parameter. This is because out of tolerance CMN does not cause a hazard to the aircraft. Thus, Azimuth does not have to be shutdown. Phase shifter failures can be treated as a maintenance warning, as is the CMN parameter itself.

2) For Elevation, phase shifter failures and the resulting increase in sidelobes primarily cause PFN (Path Following Noise). Therefore this should be an integrity parameter for Elevation. They could also cause CMN, depending upon siting and flight path geometry. The PFN tolerance is greater than the CMN (0.087^o vs. 0.067^o), thus the alarm limit for the number of phase shifter failures could be based on PFN rather than CMN, again since CMN does not cause a hazard.

An important aspect of this issue is that the system be designed to give maintenance warnings when failures have occurred. This allows the maintenance organization time to conduct preventive maintenance prior to initiation of Cat III operations and thereby reduce the likelihood of additional failures causing

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shutdown. Even for the Azimuth case, even though shutdown may not occur, it still is not desirable to allow excessive CMN. This is particularly true when conducting automatic landings, which will be the case for Cat III operations. The design goal should be that when conducting Cat III operations at least two phase shifter failures must occur prior to alarm. The reason for this is that the failure rates of phase shifters are on the order of 1 FPMH (Failure Per Million Hours). In a 120-element array the overall failure rate would be 120 FPMH. If a single failure results in alarm this would result in a COS of $1\text{-}10^{-6}$ (using a 30-sec. critical time interval), which exceeds the standards. Therefore allowance should be made for at least two failures.
Now we'll move on and examine the parameter that is a potential source of problems for COS.

Field Monitor PFE. It is asserted here that the only potential weak link in MLS achieving the required COS is outages occurring due to alarms declared by the field monitors. MLS will be susceptible to environmental factors associated with the field monitor. These include rain, wind, airport traffic movement and other multipath sources. But before we discuss these issues in detail we need to define the specific role of the field monitor. It is there primarily to detect physical movement of the antennas. The integral monitor will detect most bias (or mean course error) shifts due to electrical variations in the antenna. Only the field monitor will detect bias shifts due to such things as movement of the concrete mounting pads and tower rotation (when utilized). Tower rotation can be caused by wind and temperature effects.

One of the reasons MLS may be even more susceptible to external effects than ILS is because as already mentioned current FAA ILS policy is to minimize the use of near field monitors. The result of this is that few of the outages on ILS equipments in the U.S. are caused by alarms declared by the field monitor. Redundancy doesn't help the kind of outages caused by field monitors. So no matter how reliable the system electronics is, if outages due to these factors exceed the MTBO specified for Cat III, the required Continuity of Service will not be achieved. Before we discuss more of the details associated with the field monitors we need to define the overall error budget and its relationship to the field monitor.

PFE ERROR BUDGET

Table 3 presents PFE budgets for Azimuth and Elevation. The PFE is the value specified in the standards at the approach reference datum (runway threshold). The PFN given is a nominal value and not the maximum allowed. Flight test data collected to date on MLS facilities reveals that the PFN is consistently below 0.03°. It is only at stressful multipath sites that it will be larger than this. The purpose here is to use nominal values that can be utilized in developing budgets for the field monitors.

Table 3. PFE Error Budgets

Element	Azimuth	Elevation
PFE (Linear)	20 ft. (6 m)	2.0 ft. (0.6 m)
PFE (Angular)	0.115°	0.133°
PFN	0.030°	0.030°
Airborne	0.017°	0.017°
Monitor Limit (bias)	0.083°	0.102°

Note: 1. *Angular values based on antenna to threshold distances of 10,000 ft. for Azimuth and 861 ft. for Elevation.*
2. *All errors are values not to be exceeded on a 95% basis.*

The standards require that the alarm limit be set such that the total PFE not be exceeded on any commissioned approach. This means that if the PFN is low more allowance can be made for ground equipment bias. The methodology for determining the monitor alarm limit is as follows:

$$\text{PFE} = [(\text{Bias} + \text{PFN})^2 + (\text{Airborne})^2]^{1/2} \tag{4}$$

The bias and PFN are additive, while the airborne error is independent and therefore can be added on a Root-Sum-Square (RSS) basis. The alarm limit should be treated as approximately a 4σ value. The reason for this is that in order to meet the COS of $2.0\text{x}10^{-6}$ the probability of alarm must be lower than this value. It can't be treated as simply 2σ because this obviously will result in alarms occurring too frequently. Thus the alarm limit is related to the bias contribution to the PFE as follows:

$$\text{Monitor Limit} = 2 * (2\sigma\,\text{Bias}) \tag{5}$$

The relationship of the monitor alarm limit to the 2σ distribution is computed as follows. First it is assumed that the data has a normal distribution. The equation for computing the probability density function for a normal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-(x-\mu)^2/2\sigma^2} \qquad -\infty < x < \infty \tag{6}$$

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Assuming the mean (μ) equals zero and the variance (σ^2) is 1, the relationship between the standard deviation and probability is:

$$\text{f(x)} = \int_0^x \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx + 0.5 \qquad (7)$$

Equation 8 below is used to compute Outages Per Million Hours (OPMH) given the ratio between the monitor limit and 1? standard deviation (x).

$$\text{OPMH} = (10^6/t)\ [1 - \int_0^x \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx + 0.5] \qquad (8)$$

An important variable in the calculation is time (t). This is equal to the time over which the data are correlated. For this analysis a value of 24 Hrs was used. The study contained in reference [8] found that the field monitor data for the system analyzed had a basic periodicity of 24 hrs. This means that data samples separated by a time longer than this can be considered independent. Figure 2 shows the resulting OPMH as a function of the number of standard deviations ($N\sigma$) the monitor limit is set to.

The most stringent COS given in Table 1 is for Azimuth, requiring an OPMH of 250. From Figure 2 a monitor limit ratio of 3σ results in nearly 100 OPMH, which would use up too large a portion of the allowed outages. A ratio of 4σ would contribute only about 1 OPMH due to field monitor alarms. The conservative approach then would be to design the system such that the field monitor alarm limits are 4σ values.

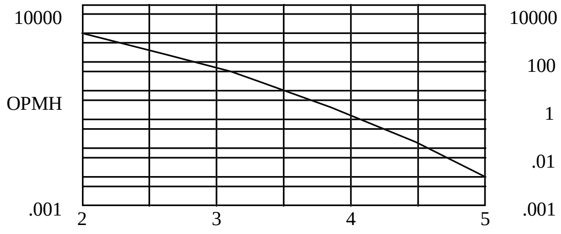

Figure 2. OPMH vs. Monitor Limit ($N\sigma$)

Conversion to 2σ values as indicated by equation (5) results in allocations of 0.042° for Azimuth and 0.051° for Elevation. We can now construct a budget for the ground equipment monitors based on these tolerances, as shown in Table 4.

Table 4. Field Monitor PFE Error Budgets

Element	Azimuth	Elevation
Monitor 2σ allocation	0.042°	0.051°
1. Antenna Drift	0.008°	0.012°
2. Antenna Noise	0.010°	0.010°
3. Wind	0.015°	0.015°
4. Monitor Noise	0.015°	0.015°
5. Multipath	0.010°	0.010°
Total (RSS 1-5)	0.027°	0.028°
Margin	0.032°	0.043°

Notes: 1. All values are RSSd since they are independent variables.
2. All values are 2σ.

The allocated values for antenna drift are based on the FAA spec which has not to be exceeded values (over the full range of environmental conditions) of 0.020° for Azimuth and 0.030° for Elevation. As indicated previously, factory data collected on the Hazeltine 2600 MLS indicated these are achievable values. Because these are not to exceed values, they can be considered at least 5σ, therefore these have been converted to 2σ in the table.

There are several other sources that contribute to bias errors, both in the far field and as measured by the field monitor. These are discussed below.

Contributors to Field Monitor Errors

1. Near Field Effects. A previous study [7] showed greater variation in field monitor data than was measured in the far field. One of the reasons for this is the effects of operating in the near field of the antennas. The near field/far field boundary for 1° beamwidth antennas is 1440 ft. (using the $2D^2/\lambda$ rule). So a field monitor at a 200-300 ft distance is well in the near field, where the beam is not completely planar. One effect is that any phase errors in the antenna are magnified, causing an error as seen by the field monitor that does not exist in the far field. This problem could be alleviated with the use of signal processing techniques that replicate the far field signal.

2. Antenna mounting structure. The primary contributor to the far field bias is the antenna mounting structure. In the normal installation the antenna can be mounted directly to the concrete. In this case the most important design technique is to isolate the antenna from the shelter or enclosure, thus not allowing any physical movement of the

shelter to affect the antenna. A more challenging situation is one where the antenna has to be installed on a tower due to a fall-off in the local terrain. In this case the tower may be susceptible to temperature variations and wind causing pitch and yaw movements. These factors require the use of tower materials that have low temperature coefficients and good stiffness such as fiberglass and carbon composites. However another problem caused by the field monitors being so close is that small linear movements of either the field monitor or antenna (when tower mounted) are perceived as angular bias errors. For example, with a field monitor located at 200 ft, a 2 inch movement of either the transmitting antenna or field monitor results in a 0.048^o angular error. This also can occur with phase shifter failures. A phase shifter failure at one end of the array, resulting in loss of RF, causes the effective phase center to shift. Given an element spacing of 0.6λ, this would result in a phase center shift of 0.06 ft. Again, given a 200 ft monitor distance, this would cause a 0.017^o error, which is not insignificant. It should be noted of course that these small linear movements do not result in significant angular errors in the far field.

3. Rain/snow. It has been shown [9] that the presence of water on the antenna radome can cause signal errors. Hydrophobic antenna radomes are required to minimize this problem.

4. Multipath. The design should take into account potential multipath sources. Airport traffic (aircraft, maintenance vehicles) can be a source of multipath for signals arriving at the field monitor. Reflections off the ground can be a source of error for the elevation field monitor. For Azimuth there may be multipath sources such as approach lights below the line of sight between the transmitting and field monitor antennas. Studies have found approach lights to be a potential significant source of multipath [10]. The field monitor antenna should be designed with sufficient vertical aperture to reduce the amount of energy received from negative vertical angles and minimize these problems. Similarly lateral multipath can be received from aircraft and ground vehicles. Again, the field monitor antenna should have sufficient horizontal aperture to minimize this multipath source.

The Azimuth budget shown in the table is more difficult to achieve for antennas installed on long runways. With a 16,000 ft antenna to threshold distance the overall PFE limit is 0.072^o. This would result in a field monitor alarm limit of 0.040^o, again given a PFN of 0.030^o. The resulting 2σ value is 0.020^o, which is smaller than the 0.027^o calculated for all of the monitor error sources. Several of the error contributors would have to be minimized. One example would be to try to avoid using a tower for these installations when feasible, eliminating the wind component. Another would be placing the field monitor farther away, reducing near field effects.

Measurement Technique

Measurements made by the field monitors must be adequately averaged or filtered to eliminate transient effects. Typically 10 sec. averaging has been used. Application of the PFE filter also would remove outliers. The time constant on the Azimuth PFE filter is approximately 6 sec., while the Elevation is 2 sec. The optimum configuration might be the use of a combination of filtering and averaging. It should be kept in mind however that erroneous guidance radiation must be shut off within 1 sec. This can be achieved by adding a wide band monitor that will detect catastrophic type failures within the time required. In any event the design should take advantage of as much filtering and averaging of field monitor data as possible, without compromising integrity.

CONCLUSIONS

1. Category III MLS designs should maximize the amount of redundancy so that the single thread elements are only those that have very low failure rates, such that they have minimal impact on Continuity Of Service.

2. Ground equipment mean course error as measured by the field monitors is an area of system design that should be focused on in designing systems to meet Category III Continuity of Service requirements. Basic antenna stability should be such that the monitor alarm limit is the equivalent of at least a 4? value. This is needed in order to achieve a low probability of outages consistent with COS requirements.

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