COMPUTER AUGMENTED TELECOMMUNICATIONS PERFORMANCE ANALYSIS

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Summary The increased range, greater accuracy, and complex trajectory of modern ICBM's create a telemetry data acquisition problem which cannot be adequately analyzed by classical manual techniques. To ensure that flight test data requirements are satisfied, systems personnel must order and quantify (model) the elements of a very complex system, i.e., communications system, acquisition stations, flight trajectory, data processor, etc. To satisfy this need, MINUTEMAN Instrumentation Systems personnel developed ISMAP (Instrumentation System Margin Analysis Program); a computer augmented technique for accurately evaluating the performance of ICBM data acquisition systems.

Introduction The direction during the mid '60's, to move telemetry to higher frequencies (L&S Bands) coupled with concurrent development of ICBM's capable of highly complex missions, created a seemingly insurmountable problem for the Instrumentation System engineer. The highly complex trajectory required that the receiving sites receive adequate signal marginwith aspect (look) angles over the entire radiating sphere, thus effectively degrading the nominal RF link performance. The normal solution, increased output power, was precluded by practical limitations imposed by the requirement to operate in L or S Band. The luxury of grossly calculating the RF link budget and adding a 10-20 db RF power pad, was no longer an available option.

In order to make sensible system trades in developing MINUTEMAN III telemetry and associated ground support, the responsible personnel embarked upon an ambitious activity to totally model the airborne and ground system including flight dynamics and geodetics. The objective was to develop a technique which would provide a comprehensive prediction of system performance for some set of assumed parameters or conditions with a minimum uncertainty.

This activity resulted in the development of a computerized model which accepts the communications system parameters, the antenna pattern data, receiving station performance parameters, flight trajectory and geodetic data and computes the expected performance of a communications system for some given set of parameters, support geometry, and flight trajectory. While this computerized model proved invaluable during development of MINUTEMAN III instrumentation systems, its subsequent value as a tool for performing routine analyses of the developed systems has exceeded all expectations.

In a telecommunications link, S/N ratio is the determining success criteria. Until the integration of the computer into the process, the problem depicted in Figure 1 was answered very crudely with manual computations. The number of time points where S/N ratio had to be computed along the trajectory for an adequate analysis made manual computations prohibitive. The parameter groups shown in the chart are integrated together with the range link equation. The computer evaluates the range link equation for each discrete trajectory point and prints out the value. If the margin equals a positive number, then the signal available is greater than the signal requirement and we can predict that acquisition of signal, during actual flight, will be attained. However, if the margin is below zero, we will predict the possibility of loss of data with the desired accuracy.

G_A, the missileborne antenna gain is the most difficult parameter to model. Antenn gain patterns are taken as a function of aspect angles θ and $\emptyset$ relative to an isotropic radiator. The radiated gain varies with relative attitude (look angle) of the missile with respect to the ground antenna. Measureme-ts are made every two degrees and result in a 91 x 180 antenna pattern matrix. The program predicts margin at discrete time points during the trajectory (approximately every two seconds to every 30 seconds) and computes margin for each station that is required to be tracking at that time. When the vehicle is maneuvering, the program must scan an area of the pattern that corresponds to the limits of the maneuver (i.e., a 10 x 180 matrix is typical). For one time point the link equation may be computed as many as 8,000 times to cover the maneuvering of a vehicle.

The predicted gain for each station at each time is then determined and recorded, along with aspect angles, slant ranges, minimum possible gain, maximum possible gain, etc. In this form the data can be easily worked with, graphed, (Figures 3, 4 and 5) and used for performance analysis.

Link Equation The type of RF system being considered dictates the final form of the link equation, i.e., telemetry, pulsed radar beacons, c.w. transponders, communications, or command control/destruct. The range balance equation forms may be found in most electrical engineering handbooks. The form considered by this paper is that of an S-band PCM telemetry system.

The range balance equation RF link parameters are organized according to a power budget. An abbreviated form for the range balance equation may be given as

$$M = \Sigma_k + G_m - R_n$$

where M is the RF instrumentation system margin in db, or the signal strength at the receiving antenna in db, depending upon the program option selected; Σ_k is the summation of all normalized constants from the general range balance equation in db; G_m is the instrumentation system missileborne antenna gain, relative to an isotropic radiator, as a function of aspect angles ϕ and θ given in db, and R_n is the normalized slant range from ground station to missile given in db. The unknown (M) is a function of a constant (Σ_k) and two variables (G_m and R_n). Two major subroutines are used to compute the variables. The constant term represents the algebraic sum of the remaining parameters found in the range balance equation

$$\Sigma_k = P + G - 2F \quad L - C - K - T_s - BW - S_t$$

where

P = transmitter output power (dbw or dbm)

G ground station antenna gain (db)

F = normalized transmitted frequency (db)

L = airborne system losses (db)

C = path loss factor (db)

K = Boltzmann's constant (db)

Ts = system noise temperature (db)

BW = noise bandwidth (db)

S_t = signal threshold required (db) to meet data quality criterion

Slant Range Subroutine The position of the missile along its trajectory as a function of flight time, is given in an X, Y, Z launch-centered, earth-fixed (LCEF) coordinate system as shown in Figure 2. The launch site is the origin of this coordinate system. In order to compute the slant range from any ground station to the missile, at any point in time, it is necessary to locate the ground station in this coordinate system. This computation can be accomplished by the following equation. No geodetic-astronomic deflection of vertical correction is made.

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix}_o = AB \left[C \begin{bmatrix} R_i{*} \cos \lambda_i \\ 0 \\ R_i{*} \sin \lambda_i \end{bmatrix} - \begin{bmatrix} R_o{*} \cos \lambda_o \\ 0 \\ R_o{*} \sin \lambda_o \end{bmatrix} \right]$$

where

$$A = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 1 & 0 \\ -\sin \lambda_o^* & 0 & \cos \lambda_o^* \\ \cos \lambda_o^* & 0 & \sin \lambda_o{*} \end{bmatrix}$$

$$C = \begin{bmatrix} \cos \Delta_i & -\sin \Delta_i & 0 \\ \sin \Delta_i & \cos \Delta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Subscript i referes to the i[th] ground station; subscript o refers to the origin or launch site.

α = trajectory azimuth angle measured from East (degrees)

$\lambda*$ = geodetic latitude (degrees)

$\theta*$ = geodetic longitude (degrees)

λ = $\tan^{-1} [1 - \epsilon)^2 \tan \lambda*$ = geocentric latitude (degrees)

ϵ = ellipticity of reference ellipsoid

Δ = $\theta_i* - \theta_o*$(degrees)

$R*$ = $r+H+N$ radius from center of the reference ellipsoid to the point of concern (feet)

$$r = \left[\frac{a^2 (1 - \epsilon)^2}{1 + (1 - \epsilon)^2 - 1 \cos^2} \right]^{\frac{1}{2}}$$ = radius of reference ellipsoid

a = semi-major axis of the reference ellipsoid (feet)

H = height above mean sea level (feet)

N = geoidal separation (feet)

The slant range distance (R) from a ground station to the missile is computed by the equation.

$$R_i = \left[(x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2\right]^{1/2}$$

where x, y, and z are the cartesian coordinates o the ground station location (subscript i) and of the missile location (subscript m), respectively, in the LCEF coordinate system. R is initially computed in feet but may be converted to any desired units of distance by a conversion factor (c) before it is normalized to units of db for use in the range balance equation by the following formula:

$$R_{n_i} = 20 \log \frac{R_i}{c}$$

It should be noted that the units of R may be any unit of distance provided they are consistent with the units used for the velocity of light in the path loss factor (C) of the Σ_k equation.

Missileborne Antenna Gain Subroutine The missileborne antenna patterns must be provided in accordance with Reference 1 for all missiles flight tested on any of the national ranges. The antenna pattern requirement is basically that the RF wave's intensity and its polarization characteristics relative to a receiving antenna system be given for each missileborne antenna in a prescribed format. The RF wave's directional characteristics vary with change in relative attitude of the missile with respect to a ground antenna; radiation characteristics must be known over the entire spherical surface surrounding missile. The antenna relative gains are measured and recorded as a function of the aspect angles and which also serve as the two ordinates of the antenna's spherical coordinate system. The resulting relative gain pattern may be though of as a large matrix, the size of which depends upon the measurement grid size. Measurements made every two degrees result in a 91 x 180 element matrix. All elements of the matrix are biased by a constant value called the reference level in order to make the sign of all gains the same. The bias is removed before the gain is used in the range balance equation.

By skillful programming a 91 x 180 antenna pattern matrix may be put directly into computer core storage in a 32K memory computer of the IBM 7094 class along with the remainder of the computer program. In smaller computers a disc file may be used for storage at the expense of access time.

The computation of the aspect angles Θ and ϕ is accomplished by the following equations with sign conventions shown in Figure 2:

$$\Theta_i = \cos^{-1}(\cos \alpha_{i\xi}), \quad 0 \leq \Theta_i \leq 180^\circ$$

$$\phi_i = \tan^{-1}\left(\frac{\cos \alpha_{i\zeta}}{\cos \alpha_i}\right), \quad 0 \leq \phi_i \leq 360^\circ$$

$\cos \alpha_{i\xi}$, $\cos \alpha_{i\eta}$, and $\cos \alpha_{i\zeta}$ are the direction cosines of the angles formed by the slant range vector, R_i, measured relative to the missile body axis ξ, η, ζ and .

$$\begin{bmatrix} \cos \alpha_{i\xi} \\ \cos \alpha_{i\eta} \\ \cos \alpha_{i\zeta} \end{bmatrix} = D\phi_g \, D\psi_g \, D\Theta_g \begin{bmatrix} -\cos \beta_{i_x} \\ -\cos \beta_{i_y} \\ -\cos \beta_{i_z} \end{bmatrix}$$

where

$$D\phi_g = \begin{bmatrix} 0 & 0 & 1 \\ -\cos\phi_g & \sin\phi_g & 0 \\ -\sin\phi_g & -\cos\phi_g & 0 \end{bmatrix}$$

$$D\psi_g = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_g & \sin\psi_g \\ 0 & -\sin\psi_g & \cos\psi_g \end{bmatrix}$$

$$D\Theta_g = \begin{bmatrix} \cos\Theta_g & 0 & -\sin\Theta_g \\ 0 & 1 & 0 \\ \sin\Theta_g & 0 & \cos\Theta_g \end{bmatrix}$$

and $\cos\beta_{ix}$, $\cos\beta_{iy}$, and $\cos\beta_{iz}$ are the direction cosines of the slant range vector, R_i, measured relative to the ground station-centered, earth-fixed coordinate axes U_i, V_i, and W_i. θ_g, ψ_g, and ϕ_g are the missile pitch, yaw, and roll attitude angles, respectively.

$$\begin{bmatrix} \cos\beta_{ix} \\ \cos\beta_{iy} \\ \cos\beta_{iz} \end{bmatrix} = \frac{1}{R_i} \begin{bmatrix} x_m - x_i \\ y_m - y_i \\ z_m - z_i \end{bmatrix}$$

The airborne antenna gain as used in the system margin equation is

$$G_{m_i} = \left[L_r - G_{r_i}(\Theta, \phi) \right]$$

where L_r is the airborne antenna pattern re erence level and G_r is the airborne antenna relative gain as a function of Θ and ϕ.

Flight Test Planning Tool The basic computer program described in this paper was developed for use as a planning tool to help support missile flight test program. The flight test program had a basic requirement to provide continuous telemetry data coverage, for the duration of powered flight, from a flight test vehicle that would be experiencing radical maneuvers along its trajectory. The computer program accurately modeled an S-band PCM telemetry link such that a detailed analysis of data coverage capability could be made. Special laboratory experiments were conducted to obtain the most efficient modulation technique which established the system bandwidths and the signal to noise ratio required at the bit synchronizer necessary to provide the desired bit error rate. With this information known, the Range provided ground station parameters such as ground antenna gains, system noise temperatures and signal to noise ratios required,at the preamp input.

The final targeting and trajectory generation for flight test missiles is often completed only a few dqys prior to their actual launching. Therefore, a flight planning (nominal) trajectory was used as a reference for making the RF link analysis study prior to the beginning of the flight test program. At each point along the planning trajectory the missile was exercised in simulation through all possible combinations of attitudes bounded only the design limits of the missile’s guidance system. The computer program was designed to compute the available signal margin at each missile attitude, for up to five ground stations at a time, using the appropriate parameters for each RF link. In this manner the worst case RF link conditions that a flight test would be likely to experience were determined. The RF link analysis showed that data could be lost, during certain periods of flight, from most of the planned flight test missiles. Subsequently, higher gain ground station antennas were procured for two ground stations at the Eastern Test Range and one other ground station at the We,;tern Test Range in order to satisfy the flight test program requirements.

Postflight System Performance Analysis The computer program has been used in postflight analysis to provide a standard for comparison with the actual received signal levels. In this application, the actual flight trajectory data was used to drive the computer program. This data was derived from the on-board guidance system computer. Figure 3 illustrates the close agreement between predicted signal margin and actual recorded signal margin for a recent flight test at AFETR.

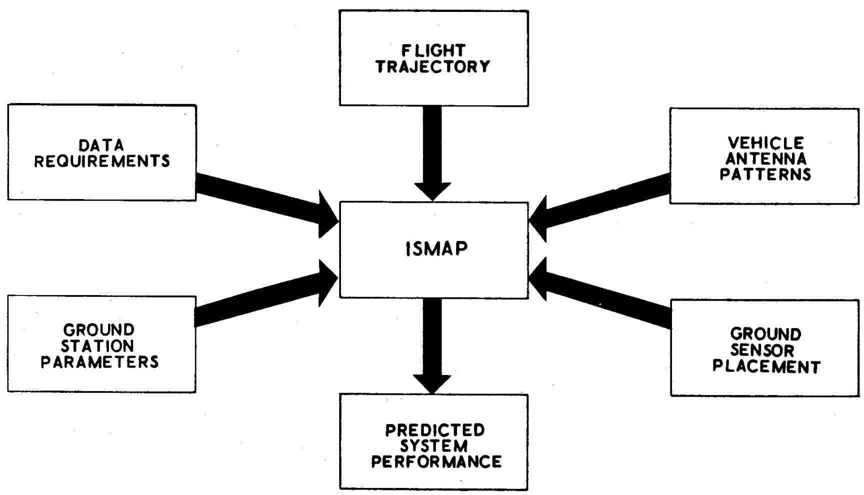
Figure 4 illustrates a discrepancy between the predicted and actual signal margins. A closer investigation of this particular station revealed an antenna tracking problem. This problem is pointed out clearly by Figure 5.

Conclusion With the ISMAP model, efficient development and performance analysis of the communications system can be made. System performance can now be evaluated under a varying number of different conditions for both preflight performance prediction and postflight evaluation. Parameter values are constantlyunder scrutiny to assess and insure accuracy of the model. By comparing the antenna gain possible at each point along the trajectory and assessing the number of them that will complete the link equation satisfactorily, a risk factor (probability of completing the link with specified equipment performance) can be assessed. Thus for any given flight, under any given conditions, a systematic, repeatable and quantitative analysis of the ground station support configuration can be generated. Uncertainties can be quantitatively defined, and risk versus margin, cost, and alternate solutions can be very definitely studied. Management decisions can be made with confidence. Proposed station support can be evaluated for adequacy and many critical errors prevented. In addition, postflight analysis is done with actual flight trajectory data and enables several functions to be performed. The detection and isolation of anomalies during flight test is the most important of these. By comparing the post and preflight ISMAP, unexpected events can be flagged out that may have previously been undetected or misunderstood. Additional (Figure 4) benefits are that the modeling prediction accuracy may be evaluated against the actual results with feedback providing increased accuracy in future preflight analyses and increased confidence in management’s ability to define and evaluate the problem presented.

ISMAP has proven invaluable in helping MINUTEMAN management define an instrumentation and range configuration appropriate to the system needs that otherwise would have meant inability to meet program requirements. For the future, ISMAP is being developed to define system parameter requirements (i. e., antenna pattern required to meet a specific flight test program criteria), as well as a constantly refining and increasing role in the management's decision-making process.

Acknowledgement The authors are grateful to Major Steven Mastropaolo, MINUTEMAN Instrumentation Project Officer, for his technical contributions and support in the development and refinement of ISMAP.

Figure 1
ISMAP Flow Chart



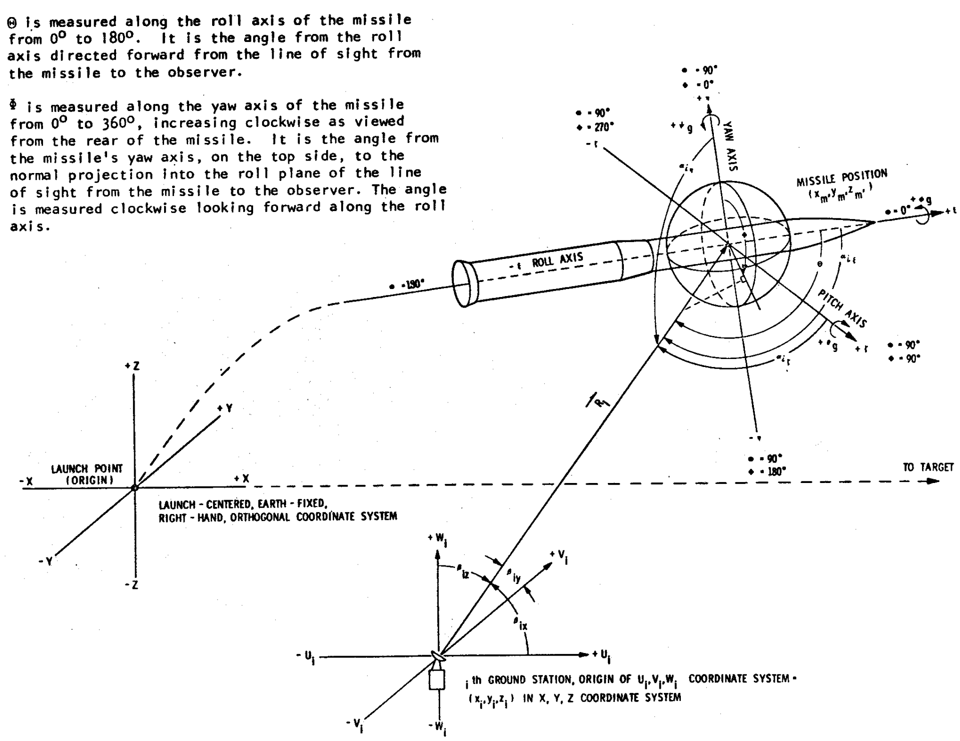


FIGURE 2. COORDINATE SYSTEMS AND ANGLE RELATIONSHIPS

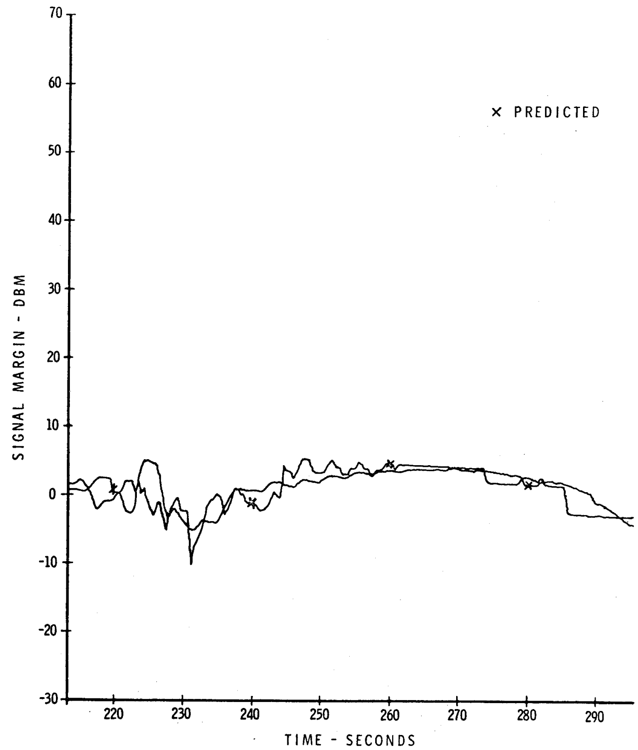


FIGURE 3 TYPICAL CLOSE AGREEMENT BETWEEN ACTUAL AND PREDICTED SIGNAL MARGINS

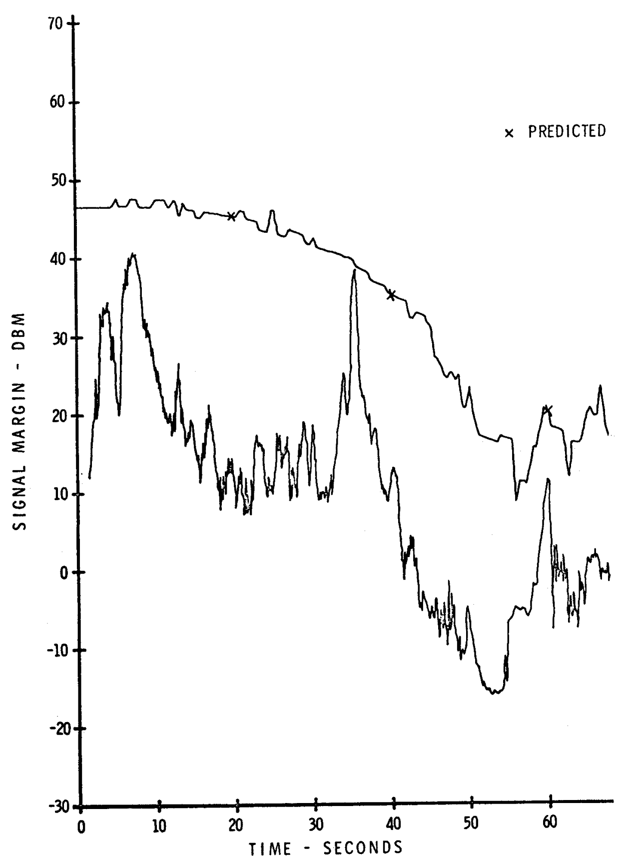


FIGURE 4 NONAGREEMENT FLAGS A PROBLEM

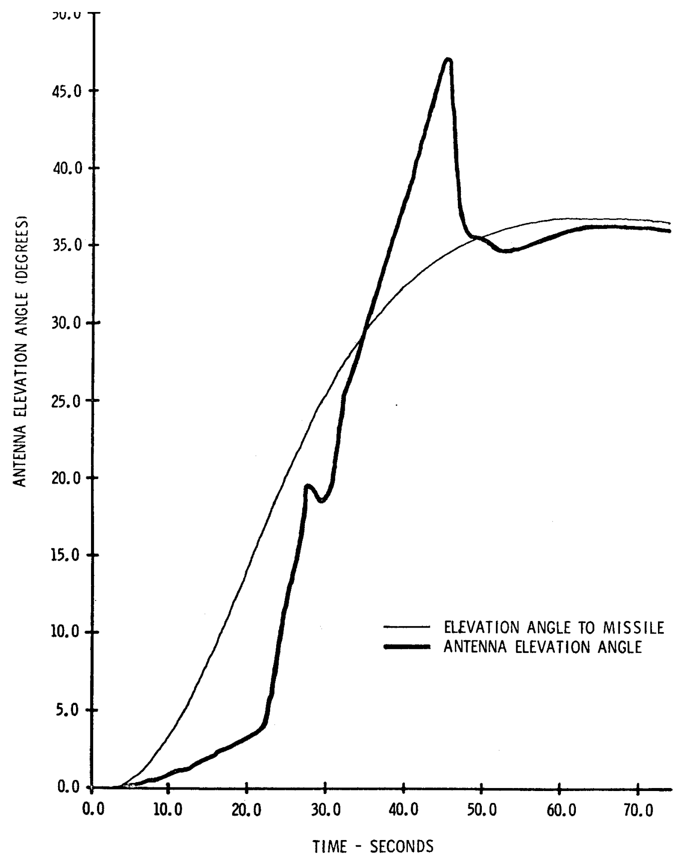


FIGURE 5 THE ANSWER TO THE PROBLEM