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**Development of FMS  
Approach Procedure  
Screening Model**

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12. Abstract FAA Order 8260.40A generated a requirement for an FMS Approach Procedure Screening Model. This would allow procedure designers to verify that an aircraft equipped with an FMS "slant-E" and some "slant-F" category navigation system could be expected to meet the 0.3 NM navigation system performance required by the order. The model takes the proposed approach flight track and the navaid environment (DME facilities in view) and uses a Kalman filter to optimally estimate the aircraft position and probable navigation system performance based on the DME signals and an onboard Inertial Reference System. The model will also identify critical facilities. It passes the performance data and the critical facilities list to an IAPA based production version or a PC based engineering version of the program.		
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## Table of Contents

	Page
Executive Summary	iii
1.0 Introduction	1
2.0 Discussion	
3.0 Methods	2
4.0 Results	4
5.0 Summary	4
Appendices	
Appendix I	1
Appendix II	7

## EXECUTIVE SUMMARY

This report documents the development of a Flight Management System (FMS) Approach Procedure Screening Model. The model is a computer program which will be used by procedure designers to determine if sufficient DME facilities with the necessary geometry exist to support an FMS approach procedure using the criteria in FAA Order 8260.40A, Flight Management System (FMS) Instrument Procedures Development. The model may also be used for determining the acceptability of other types of FMS procedures.

## BACKGROUND

The FAA has developed instrument procedure criteria for FMS equipped aircraft with a multi-sensor navigation capability. The target audience for this criteria is the large proportion of FMS aircraft using Inertial Reference Units (IRU) updated by information from multiple Distance Measuring Equipment (DME) stations. The criteria covers FMS departure, approach, missed approach and transition to precision final approach and is published as 8260.40A, Flight Management System (FMS) Instrument Procedures Development. In order to apply 8260.40A criteria, the procedure designer must be able to determine if sufficient DME facilities with the necessary geometry exist to support a proposed procedure. To assist the procedure designer in making this determination, an FMS Approach Procedure Screening Model has been developed.

The model is a software program designed to run on a desktop PC or workstation. The navigation solution is modeled as the output of a Kalman filter which combines distance information from multiple DME stations and position estimates from an IRU. The Kalman filter provides an optimal estimate of position by applying knowledge of the uncertainties associated with the individual inputs, in this case, the IRU drift rate and DME signal noise characteristics. Given the proposed route of flight, the model will predict the ability of the FMS navigation system to maintain a 95% Navigation System Error (NSE) of 0.3 NM or less. In addition to the predicted NSE, the model will also determine which, if any, of the DME facilities are "critical". A critical facility is one whose outage would prevent achieving the required NSE during the procedure.

## RESULTS

The core routines and the Kalman filter algorithm for the FMS Approach Procedure Screening Model have been completed. The programs and details of I/O requirements have been passed to the Instrument Approach Procedures Automation (IAPA) Program Manager for development of the IAPA interface. The engineering version has been completed and is in use in Flight Standards.

It should be emphasized that this model will only provide an expected level of performance given that a particular set of NAVAID's is available, not an absolute answer to the question of whether an approach is flyable or not. It is only intended to eliminate extreme cases and indicate areas of particular concern for flight inspection which will be the only way to really verify the fly-ability of a particular approach.

# DEVELOPMENT OF FMS APPROACH PROCEDURE SCREENING MODEL

## 1.0 INTRODUCTION

The FAA has developed instrument procedure criteria for Flight Management System (FMS) equipped aircraft with a multi-sensor navigation capability. The target audience for this criteria is the large proportion of FMS aircraft using Inertial Reference Units (IRU) updated by information from multiple Distance Measuring Equipment (DME) stations. The criteria covers FMS departure, approach, missed approach and transition to precision final approach and is published as FAA Order 8260.40A, Flight Management System (FMS) Instrument Procedures Development. In order to apply 8260.40A criteria, the procedure designer must be able to determine if sufficient DME facilities with the necessary geometry exist to support a proposed procedure. To assist the procedure designer in making this determination, an FMS Approach Procedure Screening Model has been developed.

The model is a software program designed to run on a desktop PC or workstation. The navigation solution is modeled as the output of a Kalman filter which combines distance information from multiple DME stations and position estimates from an IRU. The Kalman filter provides an optimal estimate of position by applying knowledge of the uncertainties associated with the individual inputs, in this case the IRU drift rate and DME signal noise characteristics. Given the proposed route of flight, the model will predict the ability of the FMS navigation system to maintain a 95% Navigation System Error (NSE) of 0.3 NM or less. In addition to the predicted NSE, the model will also determine which, if any, of the DME facilities are "critical". A critical facility is one whose outage would prevent achieving the required NSE during the procedure.

While optimized for approach applications, the model is equally applicable for other FMS procedures which require a certain navigational performance level. The default pass-fail criteria is 0.3 NM but can be changed via user input.

## 2.0 DISCUSSION

Initial discussions were held with FMS manufacturers Honeywell, Smiths Industries, and Universal. The capabilities of the systems produced by these three companies were surveyed to establish a minimum set of requirements which all systems could be expected to meet.

Aircraft performing the FMS operations developed under order 8260.40A require an advanced onboard navigation system, redundant IRU's, and multi-channel DME receivers. The screening model applies only DME based inputs to update the IRU position. This model does not consider updates from satellite systems.

There are two versions of the screening model software, one intended for production work on the Instrument Approach Procedures Automation (IAPA) workstations used by the FAA for procedure design, and one intended as an engineering tool for analysis of any problem sites designed to run primarily on PC's. Both versions have the same Kalman filter, noise, and track calculation routines. The IAPA version is meant solely for developing 8260.40A type approach procedures. The IAPA System Manager has begun development of the necessary IAPA user interface routines for the master program and input and output data requirements. When it becomes available, the user's manual and instructions for the IAPA version will be attached to this document as appendix III. The engineering version has more options in terms of setting initial values and limits and provides a much more detailed set of output information. All non-IAPA versions of the program will have to include appropriate DME facility databases. A user's manual for the current PC version is attached as appendix II.

### 3.0 METHODS

The FMS Approach Procedure Screening Model accepts as inputs: (1) a file containing the list of waypoints and altitudes defining the navigation track; (2) a file listing the available DME NAVAID's that are within range of any point on the navigation track; and (3) the airport elevation. The airport elevation is required by the model to correctly calculate the radio horizon which determines DME stations in view. Optional user inputs include: directing the program to include ILS/DME's; directing the program to calculate altitudes based on a smooth VNAV descent profile; resetting the navigation performance limit; resetting the initial offset (navigation error); and specifying a reference facility whose reception is required for the procedure. The reference facility must be one of the DME's used for navigation on the intermediate and final segments. (Note that the reference facility in this context is one of the components of a rho-rho solution and not the single component of a rho-theta solution.)

The initial aircraft position is offset from the first waypoint to model pre-existing navigation errors. This default offset value is set to 0.3 NM based on the assumption that the aircraft was previously navigating under FMS/DME guidance. The offset can be adjusted to larger values if the navigation track is being entered from an oceanic route or other situations where the initial navigation solution might not reasonably be expected to be within the 0.3 NM limit. A list of suggested values is shown in table 1. The table is based on number of hours since the last DME-DME update could have occurred. The procedure designer will have to determine a reasonable value for this number.

**TABLE 1. INITIAL OFFSET VALUES**

Hours Since Last Update	Initial Offset Value (NM)
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18

The initial aircraft altitude is set to the lowest value permitted for the segment to minimize the number of facilities visible (the worst case). The speed is set to the highest value permitted for that altitude and segment type as shown in table 2.

**TABLE 2. SPEED SELECTION CRITERIA**

Altitude or Segment Restriction	Speed (No wind)(knots)
Final or Intermediate Segment	175
Initial Segment	220
Altitude <18,000 ft.	250
Altitude >18,000 ft.	310

The program takes the aircraft position and scans through the list of NAVAID's to identify appropriate DME's, taking into account the DME power levels, the aircraft-NAVAID altitude difference, and earth curvature to determine the signal coverage. If a reference facility has been specified and the aircraft is on the intermediate or final segment of an approach, the program verifies that the reference DME is in range and in view. If not, it exits with an appropriate message. Up to ten of the closest DME's are then paired in all possible combinations and a weight assigned to each pairing. The weight is zero if the pairing is unacceptable or positive if it is acceptable. If a reference facility has been specified and the aircraft is on the intermediate or final segments, the "weights" of all pairings not including the reference DME are set to zero. If there are insufficient NAVAID's available (i.e., less than two DME's or no acceptable pairings), the program informs the user that there are not enough NAVAID's available at the current range from the next waypoint of the approach route and coasts using the IRU's until another acceptable pairing can be acquired. Otherwise, the Kalman filter algorithm is called.

The Kalman filter algorithm computes the new aircraft position by combining the slant ranges measured from the optimal DME pair with the position estimate of the Inertial Reference Unit on board the aircraft. The optimal DME pair is determined by comparing the NSE's generated by all non-zero weighted pairs and selecting the lowest. By appropriate weighting based on the relevant noise models and using recursive methods to eliminate most of the noise components, an optimal estimate of the position of the aircraft is obtained along with an estimate of the probable error limits on the position solution. The value of the error limit is the critical output as it estimates the potential NSE. Noise models for the filter inputs were kept very simple. The IRU drift was modeled as a linear function of time (up to 2 NM/hr). The DME signal noise was treated as a normal distribution with a standard deviation of .05 NM plus .005 times the slant range. A detailed discussion of the Kalman filter algorithm employed in the model is attached as appendix I.

One of the outputs of the Kalman filter is the velocity of the aircraft. The heading is determined by examining the last few position estimates. The filter then calculates the next position of the aircraft (after a 1 second time step) along with the appropriate error and noise matrices and returns to the main program. The filter function returns the estimated NSE.

The main program continues to call the filter routine until the aircraft has completed the specified navigation track. The current NSE, the maximum NSE for the segment, the radio horizon, the DME pair used and the range, bearing, and altitude difference to each NAVAID are all stored in a user specified output file. For the intermediate and final segments of an approach, statistics are accumulated to determine if the approach can meet the NSE requirements, and a list of all facilities used on those segments is generated. A special file to generate flight inspection requirements is saved that contains a list of all facilities in range and in view at the final approach fix.

The main routine also provides guidance around turns, which are all flown as fly-bys, since abrupt changes in bearing may cause the Kalman filter to report excessively high errors. The program also provides vertical guidance by changing the aircraft altitude at a predefined descent rate (300 ft/NM) or climb rate (200 ft/NM) or, if the VNAV option is selected, by calculating a smooth descent rate between waypoint altitudes.

Once the navigation track has been completed, the program evaluates the NSE statistics for the segments labeled "intermediate" or "final" and issues a pass/fail message. If the approach passes with all navigation facilities available, the process is repeated with each of the DME's used on the intermediate and final segments removed in turn. If the approach fails with one of these DME's removed, that DME is added to the critical facilities and flight inspection lists.

While the IAPA routine is not completed yet, the intent is for it to provide the user with a pass/fail indication for the approach. It will generate lists of critical facilities and facilities to be flight inspected and allow the user to edit the facility list input to the routine (if one DME cannot be received along the approach due to terrain, for instance.)

## **4.0 RESULTS**

The model has been used for evaluating approaches to Washington National, Boston-Logan International, Metropolitan Oakland International, Houston George Bush Intercontinental, and Charlotte Douglas International, with generally satisfactory results.

As an example, the initial analysis of Houston showed ample DME coverage and very low NSE values throughout the approach. However, flight inspection reported that several of the DME's used in the initial analysis were not useable on the approach path even though they were nominally in view. A second analysis with those facilities removed from consideration showed the approach was still acceptable but identified an on-airport DME facility as critical.

## **5.0 SUMMARY**

The core routines and the Kalman filter algorithm for the FMS Approach Procedure Screening Model have been completed and passed preliminary testing. The programs and details of i/o requirements have been passed to the IAPA Program Manager for development of the IAPA interface. The engineering version has been completed and is in use in Flight Standards.

It should be emphasized that this model will only provide an expected level of performance given that a particular set of NAVAID's is available, not an absolute answer to the question of whether an approach is flyable or not. It is only intended to eliminate extreme cases and indicate areas of particular concern for flight inspection which will be the only way to really verify the flyability of a particular approach. Because of the statistical nature of much of the data generation within the Kalman filter, consecutive runs on the same input data will not produce identical outputs. However, the results should be quite similar.

## **Appendix I**

# Recursive Maximum Likelihood Estimation of Aircraft Position using Multiple Range and Bearing Measurements

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*Abstract* - In this paper an algorithm is presented that recursively computes the maximum likelihood (ML) estimates of an aircraft's position in space. By combining an a priori ML estimate of the aircraft's state vector and its error covariance matrix with multiple range and bearing measurements, updated estimates are obtained. This technique is particularly useful in situations where distance measuring equipment (DME) coverage or geometry is poor and VHF OMNI range (VOR) signals are available.

## INTRODUCTION

Increasingly crowded airways have produced a greater need for more accurate estimates of an aircraft's position. This is especially true if an aircraft is flying in the close proximity of an airport. An aircraft's inertial navigational system's (INS) position estimate can drift with a drift rate that can exceed one nautical mile per hour. Therefore, it is important that the aircraft's flight management system (FMS) use other navigational aids such as DME and VOR signals to improve the position estimates.

In this exposition, we study a technique that could be used by the FMS to recursively compute the ML estimates of an aircraft's position using multiple DME range measurements and VOR bearing measurements. Since this algorithm has the ability to handle both DME and VOR measurements, it could be used in situations where DME coverage and/or geometry is poor and VOR signals are available. Since each range and bearing measurement used reduces the variance of the position estimate, this method could also be used when the navigational system error (NSE) is expected to be below a certain threshold. In the derivation of this method, we assume that the DME and VOR measurements are independent, unbiased and that each can be modeled using a Gaussian distribution.

Once the aircraft receives the DME and VOR signals, the algorithm integrates the range and bearing measurements

with a priori ML estimates of the aircraft's position and velocity. It then produces updated estimates of the aircraft's position and velocity. In the derivation of the formulas that produce the estimates, it is assumed that the aircraft's forward speed, heading and pitch can be modeled as independent Markov processes. Finally, we show that the estimates obtained using this algorithm coincide with those obtained using the extended Kalman filter.

## PROBLEM STATEMENT

Suppose that  $N$  noisy range measurements  $\rho_{\#}, i = 1, 2, \dots, N$ , and  $M$  noisy bearing measurements  $\theta_{\#}, i = 1, 2, \dots, M$ , are made at time  $k$  of an aircraft's position from DME stations located at  $(p_i, q_i, r_i), i = 1, 2, \dots, N$ , and VOR stations located at  $(u_i, v_i, w_i), i = 1, 2, \dots, M$ , respectively. If the aircraft's position at time  $k$  is  $(x_k, y_k, z_k)$ , then  $\rho_{\#}$  and  $\theta_{\#}$  can be computed from the following equations

$$\rho_{\#} = \rho_{\#}^* + n_{\#} \quad (1)$$

$$\theta_{\#} = \theta_{\#}^* + e_{\#}, \quad (2)$$

where  $\rho_{\#}^*$  and  $\theta_{\#}^*$  are defined as

$$\rho_{\#}^* = \sqrt{(p_i - x_k)^2 + (q_i - y_k)^2 + (r_i - z_k)^2}$$

$$\theta_{\#}^* = \arctan\left(\frac{v_i - y_k}{u_i - x_k}\right).$$

The term  $\rho_{\#}^*$  represents the true range from the  $i$ th DME station to the aircraft and the term  $\theta_{\#}^*$  represents the true

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bearing—that the aircraft makes with the  $i$ th VOR station. The variables  $n_{ik}$  and  $e_{ik}$  are used to represent noises that are contained in the measurements  $\rho_{ik}$  and  $\theta_{ik}$ . We will assume that  $n_{ik}$  and  $e_{ik}$  are terms from independent, Gaussian sequences that have zero means and variances given by

$$E\{n_{ik}n_{jk}\} = \delta_{ij}\delta_{kl}\sigma_{\rho,k}^2$$

$$E\{e_{ik}e_{jk}\} = \delta_{ij}\delta_{kl}\sigma_{\theta,k}^2$$

and

$$E\{n_{ik}e_{jk}\} = 0 \quad \forall i, j, k, l$$

The symbol  $\delta_{ij}$  denotes the Kronecker delta and the symbol  $E$  is used to denote the operation of expectation. Since the quality of the range measurements  $\rho_{ik}$  depend on the distance that the aircraft is from the DME facility, the variance  $\sigma_{\rho,k}^2$  of  $n_{ik}$  is a function of time  $k$ . This accounts for the use of the subscript  $k$  in the expression  $\sigma_{\rho,k}^2$ .

A measurement vector  $z_k$  at time  $k$  can be constructed as follows

$$z_k = [\rho_{1k}, \rho_{2k}, \dots, \rho_{Mk}, \theta_{1k}, \theta_{2k}, \dots, \theta_{Mk}]^T.$$

This vector represents a noisy version of the vector  $z_k^*$ , where  $z_k^*$  defined as

$$z_k^* = [\rho_{1k}^*, \rho_{2k}^*, \dots, \rho_{Mk}^*, \theta_{1k}^*, \theta_{2k}^*, \dots, \theta_{Mk}^*]^T.$$

Thus, we can write

$$z_k = z_k^* + e_k \quad (3)$$

where

$$e_k = [n_{1k}, n_{2k}, \dots, n_{Mk}, e_{1k}, e_{2k}, \dots, e_{Mk}]^T.$$

Since the noise terms  $n_{ik}$  and  $e_{ik}$  are independent, zero mean, Gaussian random variables with variances given by  $\sigma_{\rho,k}^2$  and  $\sigma_{\theta,k}^2$ , the vector  $e_k$  in (3) is a  $N+M$  dimensional, Gaussian random vector with zero mean and a covariance matrix given by

$$E\{e_k e_k^T\} = \delta_{kl} R_k,$$

where

To estimate the position  $(x_k, y_k, z_k)$  of the aircraft at time  $k$  using the noisy vector  $z_k$ , we will define our state vector  $s_k$  to be

$$s_k = [x_k, \dot{x}_k, y_k, \dot{y}_k, z_k, \dot{z}_k]^T.$$

The components  $x_k$ ,  $y_k$  and  $z_k$  of  $s_k$  give the aircraft's position at time  $k$  and the components  $\dot{x}_k$ ,  $\dot{y}_k$  and  $\dot{z}_k$  give the aircraft's velocity in the  $x$ ,  $y$  and  $z$  directions.

We will assume that the ML estimate  $\hat{s}_{k/k-1}$ , where

$$\hat{s}_{k/k-1} = [\hat{x}_{k/k-1}, \hat{\dot{x}}_{k/k-1}, \hat{y}_{k/k-1}, \hat{\dot{y}}_{k/k-1}, \hat{z}_{k/k-1}, \hat{\dot{z}}_{k/k-1}]^T,$$

of  $s_k$  and its error covariance matrix  $P_{k/k-1}$  have been computed prior to receiving  $z_k$ . The notation  $\hat{s}_{k/k-1}$  is used to denote the ML estimate of  $s_k$  given all measurements up to and including  $z_{k-1}$ . The error covariance matrix  $P_{k/k-1}$  of  $\hat{s}_{k/k-1}$  is defined as

$$P_{k/k-1} = E\{(\hat{s}_{k/k-1} - s_k)(\hat{s}_{k/k-1} - s_k)^T\}.$$

Our problem is to update the ML estimate  $\hat{s}_{k/k-1}$  of  $s_k$  and its error covariance matrix  $P_{k/k-1}$  using the new measurement vector  $z_k$ . The updated estimate of  $s_k$  denoted  $\hat{s}_{k/k}$  and its error covariance matrix will be denoted by  $P_{k/k}$ .

## THE LOG-LIKELIHOOD FUNCTION

Since ML estimates are consistent and asymptotically Gaussian, we will assume that the probability density function of the a priori estimate  $\hat{s}_{k/k-1}$  can be approximated by a Gaussian density with mean  $s_k$  and covariance matrix  $P_{k/k-1}$ . Specifically, we will assume that the probability density function  $f(\hat{s}_{k/k-1})$  of  $\hat{s}_{k/k-1}$  is given by

$$f(\hat{s}_{k/k-1}) = \beta_1 \exp\left\{-\frac{1}{2}(\hat{s}_{k/k-1} - s_k)^T P_{k/k-1}^{-1}(\hat{s}_{k/k-1} - s_k)\right\}$$

where  $\beta_1$  is defined as

$$\beta_1 = \frac{1}{(2\pi)^3 |P_{k/k-1}|^{3/2}}$$

Since  $e_k$  in (3) is a zero mean, Gaussian random vector with covariance  $R_k$ , the vector  $z_k$  is a Gaussian random vector with mean  $z_k^*$  and covariance  $R_k$ . Therefore, the probability density function  $g(z_k)$  of  $z_k$  is given by

$$g(z_k) = \beta_2 \exp\left\{-\frac{1}{2}(z_k - z_k^*)^T R_k^{-1}(z_k - z_k^*)\right\}$$

where  $\beta_2$  is defined as

$$\beta_2 = \frac{1}{(2\pi)^{(N+K)/2} |R_k|^{1/2}}$$

The likelihood function  $l(s_k)$  of  $s_k$  given  $\hat{s}_{k/k-1}$  and  $z_k$  is given by

$$l(s_k) = f(\hat{s}_{k/k-1})g(z_k).$$

The negative of the log-likelihood function  $L(s_k)$  can now be computed and it is equal to

$$-L(s_k) = (\hat{s}_{k/k-1} - s_k)^T P_{k/k-1}^{-1} (\hat{s}_{k/k-1} - s_k) + (z_k - z_k^*)^T R_k^{-1} (z_k - z_k^*), \quad (4)$$

where the constant terms have been deleted. To obtain the ML estimate of  $s_k$  given  $\hat{s}_{k/k-1}$  and  $z_k$ , we must minimize  $-L(s_k)$  with respect to  $s_k$ . This can be denoted as follows

$$\hat{s}_{k/k} = \arg \min_{s_k} \{-L(s_k)\}.$$

#### APPROXIMATING THE LOG-LIKELIHOOD FUNCTION

By examining equations (1) and (2) we can see that the state variables  $x_k$ ,  $y_k$  and  $z_k$  enter the measurements  $\rho_k$  and  $\theta_k$  in a nonlinear fashion. In order to obtain a linear relationship between the state variables and the measurements, we will linearize both equations around the ML estimate  $\hat{s}_{k/k-1}$ . The linearization of the range measurements can also be found in [2] and [3].

By taking a Taylor's series expansion of  $\rho_k$  in (1) around  $\hat{s}_{k/k-1}$  and then dropping the second and higher order terms, we will obtain

$$\rho_k = \hat{\rho}_k + \cos \hat{\alpha}_k \cos \hat{\phi}_k (x_k - \hat{x}_{k/k-1}) + \sin \hat{\alpha}_k \cos \hat{\phi}_k (y_k - \hat{y}_{k/k-1}) + \sin \hat{\phi}_k (z_k - \hat{z}_{k/k-1}) + n_k, \quad (5)$$

where the following definitions were used

$$\hat{\rho}_k = \sqrt{(p_l - \hat{x}_{k/k-1})^2 + (q_l - \hat{y}_{k/k-1})^2 + (r_l - \hat{z}_{k/k-1})^2}$$

$$\hat{\alpha}_k = \arctan\left(\frac{q_l - \hat{y}_{k/k-1}}{p_l - \hat{x}_{k/k-1}}\right)$$

$$\hat{\phi}_k = \arcsin\left(\frac{r_l - \hat{z}_{k/k-1}}{\hat{\rho}_k}\right).$$

The terms  $\hat{\rho}_k$ ,  $\hat{\alpha}_k$  and  $\hat{\phi}_k$  represent the estimated range, azimuth angle and elevation angle from the  $k$ th DME station to the estimated location of the aircraft at time  $k$ . The  $k$ th

DME station is located at  $(p_l, q_l, r_l)$  and the aircraft's estimated position is  $(\hat{x}_{k/k-1}, \hat{y}_{k/k-1}, \hat{z}_{k/k-1})$ .

By rearranging the terms in (5), we can obtain the following relationship

$$\bar{\rho}_k = x_k \cos \hat{\alpha}_k \cos \hat{\phi}_k + y_k \sin \hat{\alpha}_k \cos \hat{\phi}_k + z_k \sin \hat{\phi}_k + n_k$$

where

$$\bar{\rho}_k = \rho_k - \hat{\rho}_k + \hat{x}_{k/k-1} \cos \hat{\alpha}_k \cos \hat{\phi}_k + \hat{y}_{k/k-1} \sin \hat{\alpha}_k \cos \hat{\phi}_k + \hat{z}_{k/k-1} \sin \hat{\phi}_k$$

The term  $\bar{\rho}_k$ , which is calculated using the raw measurement  $\rho_k$  and the a priori estimates  $\hat{x}_{k/k-1}$ ,  $\hat{y}_{k/k-1}$  and  $\hat{z}_{k/k-1}$ , is referred to as a pseudo-range measurement [3].

By taking a Taylor's series expansion of  $\theta_k$  in (2) around  $\hat{s}_{k/k-1}$  and then dropping the second and higher order terms, we will obtain

$$\theta_{\#} = \hat{\theta}_{\#} + \frac{\sin \hat{\theta}_{\#}}{\hat{d}_{\#}} (x_k - \hat{x}_{k/k-1}) - \frac{\cos \hat{\theta}_{\#}}{\hat{d}_{\#}} (y_k - \hat{y}_{k/k-1}) + e_{\#}, \quad (6)$$

where

$$\hat{\theta}_{\#} = \arctan\left(\frac{v_l - \hat{y}_{k/k-1}}{u_l - \hat{x}_{k/k-1}}\right)$$

$$\hat{d}_{\#} = \sqrt{(u_l - \hat{x}_{k/k-1})^2 + (v_l - \hat{y}_{k/k-1})^2}.$$

The terms  $\hat{\theta}_{\#}$  and  $\hat{d}_{\#}$  represent the estimated bearing and horizontal range from the  $\#$ th VOR station, which is located at  $(u_l, v_l, w_l)$ , to the estimated location of the aircraft at time  $k$ .

From (6) we can obtain

$$\tilde{\theta}_{\#} = \frac{\sin \hat{\theta}_{\#}}{\hat{d}_{\#}} x_k - \frac{\cos \hat{\theta}_{\#}}{\hat{d}_{\#}} y_k + e_{\#},$$

where

The term  $\tilde{\theta}_{\#}$ , which is calculated using the raw measurement  $\theta_{\#}$  and the a priori estimates  $\hat{x}_{k/k-1}$  and  $\hat{y}_{k/k-1}$ , is referred to as a pseudo-bearing measurement.

By repeating the linearization procedure described above on each range measurement  $\rho_{\#}$  and each bearing measurement  $\theta_{\#}$ , we will obtain the following pseudo-measurement vector

The vector  $\tilde{z}_k$  can also be obtained via the matrix equation

(7)

where

(8)

$$H_k = \begin{bmatrix} \cos \hat{\alpha}_{1k} \cos \hat{\phi}_{1k} & 0 & \sin \hat{\alpha}_{1k} \cos \hat{\phi}_{1k} & 0 & \sin \hat{\phi}_{1k} & 0 \\ \cos \hat{\alpha}_{2k} \cos \hat{\phi}_{2k} & 0 & \sin \hat{\alpha}_{2k} \cos \hat{\phi}_{2k} & 0 & \sin \hat{\phi}_{2k} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cos \hat{\alpha}_{\#k} \cos \hat{\phi}_{\#k} & 0 & \sin \hat{\alpha}_{\#k} \cos \hat{\phi}_{\#k} & 0 & \sin \hat{\phi}_{\#k} & 0 \\ \frac{\sin \hat{\theta}_{1k}}{\hat{d}_{1k}} & 0 & -\frac{\cos \hat{\theta}_{1k}}{\hat{d}_{1k}} & 0 & 0 & 0 \\ \frac{\sin \hat{\theta}_{2k}}{\hat{d}_{2k}} & 0 & -\frac{\cos \hat{\theta}_{2k}}{\hat{d}_{2k}} & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\sin \hat{\theta}_{\#k}}{\hat{d}_{\#k}} & 0 & -\frac{\cos \hat{\theta}_{\#k}}{\hat{d}_{\#k}} & 0 & 0 & 0 \end{bmatrix}$$

By using the linear approximation of (3) given in (7), we will obtain the following first order approximation of  $-L(s_k)$ .

$$-L(s_k) = (\hat{s}_{k/k-1} - s_k)^T P_{k/k-1}^{-1} (\hat{s}_{k/k-1} - s_k) + (\tilde{z}_k - H_k s_k)^T R_k^{-1} (\tilde{z}_k - H_k s_k). \quad (9)$$

Thus, in order to obtain the ML estimate of the state vector  $s_k$  at time  $k$ , we must minimize  $-L(s_k)$  with respect to  $s_k$ .

#### OPTIMIZING THE LOG-LIKELIHOOD FUNCTION

In this section, we will describe how to minimize  $-L(s_k)$  with respect to  $s_k$ . This can be accomplished by setting  $\nabla L(s_k) = 0$  and then showing that the Hessian  $-\nabla^2 L(s_k)$  of  $-L(s_k)$  is positive definite. By setting  $\nabla L(s_k) = 0$  and then using (8), yields

(10)

where the matrix  $G_k$  is defined as

$$G_k = (P_{k/k-1}^{-1} + H_k^T R_k^{-1} H_k)^{-1} H_k^T R_k^{-1}.$$

The matrix  $G_k$  is called the "gain" matrix and it can be shown to be equivalent to

The Hessian  $-\nabla^2 L(s_k)$  of  $-L(s_k)$  is given by

$$-\nabla^2 L(s_k) = 2(P_{k/k-1}^{-1} + H_k^T R_k^{-1} H_k),$$

and is positive definite. Therefore,  $\hat{s}_{k/k}$  is the unique global minimizer of  $-L(s_k)$ . The error covariance matrix of  $\hat{s}_{k/k}$  is given by

$$\begin{aligned} P_{k/k} &= E[(\hat{s}_{k/k} - s_k)(\hat{s}_{k/k} - s_k)^T] \\ &= (P_{k/k-1}^{-1} + H_k^T R_k^{-1} H_k)^{-1} \\ &= (I - G_k H_k) P_{k/k-1} \end{aligned}$$

Therefore, the procedure for computing  $\hat{s}_{k/k}$  given  $\hat{s}_{k/k-1}$ ,  $P_{k/k-1}$  and  $z_k$  can be summarized as follows

1. Compute  $G_k = P_{k/k-1} H_k^T (H_k P_{k/k-1} H_k^T + R_k)^{-1}$
2. Compute  $\hat{s}_{k/k} = \hat{s}_{k/k-1} + G_k (z_k - \hat{z}_k)$
3. Compute  $P_{k/k} = (I - G_k H_k) P_{k/k-1}$

It should be noted that these equations are the same as the measurement-update equations used in the extended Kalman filter [1].

#### COMPUTING $\hat{s}_{k+1/k}$ AND $P_{k+1/k}$ GIVEN $\hat{s}_{k/k}$ AND $P_{k/k}$

When we computed  $\hat{s}_{k/k}$  and  $P_{k/k}$  in the previous section, we assumed that the ML estimate  $\hat{s}_{k/k-1}$  and its error covariance matrix  $P_{k/k-1}$  were given. Thus, when we want to compute  $\hat{s}_{k+1/k}$  at time  $k+1$ , it will be necessary for us to have the ML estimate  $\hat{s}_{k+1/k}$  and its error covariance matrix  $P_{k+1/k}$ . In this section, we will describe how to obtain  $\hat{s}_{k+1/k}$  and  $P_{k+1/k}$  using  $\hat{s}_{k/k}$  and  $P_{k/k}$ . We will conduct our analysis like the one given in [1]. However, unlike the presentation given in [1], we will be working in three dimensions rather than in two.

The state of the aircraft will change from one time instant to the next according to the following equation

$$s_{k+1} = F s_k + w_k$$

where

$$F = \begin{bmatrix} 1 & \Delta T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & \Delta T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \Delta T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The entries  $\Delta T$  in  $F$  are used to represent the time period between the samples. The vector  $w_k$ , which is given by

$$w_k = [w_{1k}, w_{2k}, w_{3k}, w_{4k}, w_{5k}, w_{6k}]^T,$$

represents noise and it is used to describe the somewhat random path that an aircraft makes as it travels through space. We will assume that  $w_k$  has a Gaussian distribution.

We will assume that the aircraft's speed  $s_{k+1}$ , heading angle  $\gamma_{k+1}$  and pitch angle  $\psi_{k+1}$  at time  $k+1$  can be modeled as independent Markov processes. Thus we may write

$$s_{k+1} = s^* + c_s (s_k - s^*) + \tau_k$$

$$\gamma_{k+1} = \gamma^* + c_\gamma (\gamma_k - \gamma^*) + \xi_k$$

$$\psi_{k+1} = \psi^* + c_\psi (\psi_k - \psi^*) + \zeta_k$$

The terms  $s^*$ ,  $\gamma^*$  and  $\psi^*$  are constants that represent the aircraft's mean speed, heading and pitch, respectively. The terms  $c_\psi$ ,  $c_s$ , and  $c_\gamma$  are constants that are used to keep the variances of  $s_k$ ,  $\gamma_k$  and  $\psi_k$  bounded. Their values can be determined according to the performance of the aircraft and are equal to numbers that are greater than zero and less than one. The variables  $\tau_k$ ,  $\xi_k$  and  $\zeta_k$  represent noise at time  $k$  and are assumed to be terms from independent, white Gaussian sequences that have zeros means and variances  $\sigma_\tau^2$ ,  $\sigma_\xi^2$  and  $\sigma_\zeta^2$ , respectively. Under these assumptions, we can show that the following formulas hold for all  $k$ .

$$E[s_k] = s^*, \quad \sigma_s^2 = E[(s_k - s^*)^2] = \frac{\sigma_\tau^2}{1 - c_s^2}$$

$$E[\gamma_k] = \gamma^*, \quad \sigma_\gamma^2 = E[(\gamma_k - \gamma^*)^2] = \frac{\sigma_\xi^2}{1 - c_\gamma^2}$$

$$E[\psi_k] = \psi', \quad \sigma_\psi^2 = E[(\psi_k - \psi')^2] = \frac{\sigma_\zeta^2}{1 - c_\psi^2}$$

Assuming that  $\sigma_s^2$  and  $\sigma_\zeta^2$  are small,  $\sigma_\psi^2$  is much smaller than  $s_k^2$ ,  $c_\psi \approx 1$ ,  $c_\gamma \approx 1$  and  $c_\gamma \approx 1$ , we can then show that

$$\dot{x}_{k+1} \approx E[\dot{x}_{k+1}] = s_k \cos \gamma_k \cos \psi_k$$

$$\dot{y}_{k+1} \approx E[\dot{y}_{k+1}] = s_k \sin \gamma_k \cos \psi_k$$

$$\dot{z}_{k+1} \approx E[\dot{z}_{k+1}] = s_k \sin \psi_k$$

$$\begin{aligned} \sigma_{x_{k+1}}^2 \approx E[(\dot{x}_{k+1} - \dot{x}_{k+1}^*)^2] &= s_k^2 (\sigma_\psi^2 \cos^2 \gamma_k \sin^2 \psi_k \\ &+ \sigma_\gamma^2 \sin^2 \gamma_k \cos^2 \psi_k + \sigma_\gamma^2 \sigma_\psi^2 \sin^2 \gamma_k \sin^2 \psi_k) \\ &+ \sigma_s^2 \cos^2 \gamma_k \cos^2 \psi_k \end{aligned}$$

$$\begin{aligned} \sigma_{y_{k+1}}^2 \approx E[(\dot{y}_{k+1} - \dot{y}_{k+1}^*)^2] &= s_k^2 (\sigma_\psi^2 \sin^2 \gamma_k \sin^2 \psi_k \\ &+ \sigma_\gamma^2 \cos^2 \gamma_k \cos^2 \psi_k + \sigma_\gamma^2 \sigma_\psi^2 \cos^2 \gamma_k \sin^2 \psi_k) \\ &+ \sigma_s^2 \sin^2 \gamma_k \cos^2 \psi_k \end{aligned}$$

$$\sigma_{z_{k+1}}^2 \approx E[(\dot{z}_{k+1} - \dot{z}_{k+1}^*)^2] = s_k^2 \sigma_\psi^2 \cos^2 \psi_k + \sigma_s^2 \sin^2 \psi_k$$

$$\begin{aligned} \sigma_{x_{k+1}, y_{k+1}} \approx E[(\dot{x}_{k+1} - \dot{x}_{k+1}^*)(\dot{y}_{k+1} - \dot{y}_{k+1}^*)] &= (s_k^2 \sigma_\psi^2 \sin^2 \psi_k \\ &- s_k^2 \sigma_\gamma^2 \cos^2 \psi_k + \sigma_s^2 \cos^2 \psi_k) \cos \gamma_k \sin \gamma_k \end{aligned}$$

$$\begin{aligned} \sigma_{x_{k+1}, z_{k+1}} \approx E[(\dot{x}_{k+1} - \dot{x}_{k+1}^*)(\dot{z}_{k+1} - \dot{z}_{k+1}^*)] \\ = (\sigma_s^2 - s_k^2 \sigma_\psi^2) \cos \gamma_k \cos \psi_k \sin \psi_k \end{aligned}$$

$$\begin{aligned} \sigma_{y_{k+1}, z_{k+1}} \approx E[(\dot{y}_{k+1} - \dot{y}_{k+1}^*)(\dot{z}_{k+1} - \dot{z}_{k+1}^*)] \\ = (\sigma_s^2 - s_k^2 \sigma_\psi^2) \sin \gamma_k \cos \psi_k \sin \psi_k, \end{aligned}$$

where estimates of  $s_k$ ,  $\gamma_k$  and  $\psi_k$  are obtained using the sequence  $\{\hat{s}_{k/k}\}$ . These results imply that

$$E[w_{2k}] = 0, \quad E[w_{4k}] = 0, \quad E[w_{6k}] = 0,$$

$$\sigma_{w_{2k}}^2 \approx E[w_{2k}^2] = \sigma_{x_{k+1}}^2, \quad \sigma_{w_{4k}}^2 \approx E[w_{4k}^2] = \sigma_{x_{k+1}, y_{k+1}}^2$$

$$\sigma_{w_{6k}}^2 \approx E[w_{6k}^2] = \sigma_{y_{k+1}}^2, \quad \sigma_{w_{8k}}^2 \approx E[w_{8k}^2] = \sigma_{x_{k+1}, y_{k+1}}^2$$

$$\sigma_{w_{10k}}^2 \approx E[w_{10k}^2] = \sigma_{y_{k+1}}^2, \quad \sigma_{w_{12k}}^2 \approx E[w_{12k}^2] = \sigma_{y_{k+1}, z_{k+1}}^2$$

In addition, the remaining terms  $w_{1k}$ ,  $w_{3k}$  and  $w_{5k}$  of  $w_k$  should be chosen so that  $w_{1k} = 0.5\Delta T w_{2k}$ ,  $w_{3k} = 0.5\Delta T w_{4k}$  and  $w_{5k} = 0.5\Delta T w_{6k}$ . (See [1].) As a result the vector  $w_k$  has zero mean and a covariance matrix  $Q_k$  at time  $k$  given by

$$E[w_k w_k^T] = \delta_k Q_k,$$

where the entries of  $Q_k$  can be computed using  $\sigma_{x_{k+1}}^2$ ,  $\sigma_{y_{k+1}}^2$ ,  $\sigma_{x_{k+1}, y_{k+1}}^2$ ,  $\sigma_{x_{k+1}, z_{k+1}}^2$ ,  $\sigma_{y_{k+1}, z_{k+1}}^2$  and  $\sigma_{z_{k+1}}^2$ .

The ML estimate of  $s_{k+1}$  given the ML estimate  $\hat{s}_{k/k}$  and  $P_{k/k}$  is given by

$$\hat{s}_{k+1/k} = F \hat{s}_{k/k}. \quad (11)$$

and its error covariance matrix is given by

$$\begin{aligned} P_{k+1/k} &= E[(\hat{s}_{k+1/k} - s_{k+1})(\hat{s}_{k+1/k} - s_{k+1})^T] \\ &= F_k P_{k/k} F_k^T + Q_k \end{aligned} \quad (12)$$

It should be noted that equations (11) and (12) are the same as the time-update equations used in the extended Kalman filter.

## REFERENCES

- [1] B. D. O. Anderson and J. B. Moore, *Optimal Filtering*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1979.
- [2] R. G. Brown and P. Y. C. Hwang, *Introduction to Random Signals and Applied Kalman Filtering*. New York: John Wiley & Sons, Inc., 1992.
- [3] R. J. Milliken and C. J. Zoller, "Principle of Operation of NAVSTAR and System Characteristics," *Global Positioning System*, Vol. I, Washington, D.C.: Institute of Navigation, 1980.
- [4] W. W. S. Wei, *Time Series Analysis - Univariate and Multivariate Methods*, Reading, Massachusetts: Addison-Wesley Publishing Company, Inc., 1993.

## Appendix II

## Appendix II - User's Manual for PC version of FMS Screening Model

DME\_SCRN is the PC/DOS version of the FMS Screening Model. When called with a '?' (or an invalid parameter) it will display the following usage message.

### FIGURE 1. USAGE MESSAGE FROM DME\_SCRN

```
Usage: DME_SCRN
/E:elev[/A:name] [/C:name] [/F:name] [/I] [/N:limit] [/O:value] [/R:fac] [/V] [/W:name]
/E:airport elevation in feet (default: 0.0) ** Required
/A:to-be-flight-inspected-list filename (default: FLT_INSP.DAT)
/C:critical facility filename (default: CRITICAL.DAT)
/D:filter output filename (default: NSE_OUT.DAT)
/F:facilities list filename (default: FACILITY.DAT)
/I:flag to use ILS/DME's (default: FALSE)
/N:navigation performance limit in NM (default: 0.3) ** Not available in IAPA version.
/O:initial offset value in NM (default: 0.3) ** Not available in IAPA version
/R:reference facility (default: none)
/V:flag to smooth descents (default: FALSE)
/W:route filename (default: ROUTE.DAT)
/? prints this message
Note: order of parameters is not significant.
```

Each of these parameters will be dealt with in detail in the following sections as well as the required input and generated output files.

Before DME\_SCRN can be run, the user must prepare two input files, ROUTE.DAT, which contains the path definition for the aircraft track, and FACILITY.DAT, a database of DME stations from which DME\_SCRN will select. Typical examples of these files are shown and explained below in figures 2 and 3.

### FIGURE 2. TYPICAL ROUTE.DAT FILE

295933.08	0954338.41	3900	initial
295934.37	0953750.15	2900	intermediate
295935.74	0952820.38	1900	final
295936.31	0952117.86	500	missed
295936.49	0951556.57	2200	holding
301738.84	0951017.51	2200	xxx

ROUTE.DAT is simply a listing of waypoints composing a route. The four columns are latitude, longitude, and altitude of each waypoint plus a string identifying the segment following that waypoint. The identifier is mandatory, even for the last waypoint (note the "xxx" in the figure). Multiple segments may have the same identifier. If the screening model is being used on an approach, there must be at least one segment identified as "intermediate" and one as "final". Note that the lat/long data is entered in "ddmmss.ss" format with the western and northern hemisphere positive. Eastern hemisphere longitudes and southern hemisphere latitudes will be negative values. The units for altitude are feet-MSL. If the /W parameter is used, ROUTE.DAT can have any valid DOS filename, i.e., DME\_SCRN /W:KOKC\_35L.RTE would cause the screening model to load its route information from a file named "KOKC\_35L.RTE".

FACILITY.DAT is a list of potential DME facilities that might be useable along the route defined in ROUTE.DAT. Since this list is searched and tested for every point along the route, it should be kept small but should also be certain to include any DME that might be used by the system. The technique used so far is to take in all facilities within 2 degrees of latitude from any point on the route and 2 - 4 degrees of longitude, depending on the latitude (whatever translates to about 120 NM.) This list may be further reduced by removing ILS/DME's, if they will not be used by the user's FMS's.

The file includes facility type, facility identification, latitude, longitude, altitude, and a power level flag that is used to determine if the user aircraft is within the coverage area of the facility. Again, lat/long data is in "dddmmss.ss" format and altitude is in feet MSL. The default filename for this data is "FACILITY.DAT" but by using the /F flag, it can be named any legal DOS name, i.e., DME\_SCRN /F:OKC\_GOU.FAC would cause the screening model to load its facility information from a file named "OKC\_GOU.FAC".

**FIGURE 3. TYPICAL FACILITY.DAT FILE**

ILS/D	JNX	353307.83	782307.01	155.0	I
VTAC/T	CRE	334848.50	784330.30	20.0	L
ILS/D	GKK	355347.53	784627.58	412.0	I
VTAC/T	RDU	355221.14	784700.02	430.0	H
ILS/D	DMP	355220.68	784815.21	374.0	I
VDME/D	FAY	345907.99	785230.19	180.0	L
ILS/D	TDF	361725.80	785835.25	581.0	I
VTAC/T	SBV	364030.10	790052.25	530.0	L
VTAC/T	LYH	371516.70	791411.30	880.0	L
VTAC/T	SDZ	351255.70	793516.60	590.0	L
VTAC/T	LIB	354841.84	793645.35	830.0	L
VTAC/T	FLO	341358.56	793925.61	110.0	H
VTAC/T	GSO	360244.49	795834.94	880.0	H
ILS/D	SZK	371919.63	795841.56	1166.0	I
ILS/D	UVM	363802.67	800137.08	939.0	I
VTAC/T	ROA	372036.38	800413.65	3060.0	L
VDME/D	CTF	343901.66	801629.74	610.0	L
ILS/D	BCB	371217.60	802359.30	2135.0	I
VTAC/T	VAN	332829.39	802655.11	135.0	L
VDME/D	RUQ	353837.30	803120.92	770.0	T
ILS/D	JQF	352234.77	804245.60	615.0	I
VTAC/T	PSK	370515.74	804246.44	2120.0	H
VTAC/T	MMT	335526.82	804808.56	249.0	T
VDME/D	EDS	332720.56	805130.33	201.0	T
ILS/D	BQC	351333.75	805613.66	745.0	I
VDME/D	CLT	351125.70	805707.20	758.0	L
VTAC/T	FML	345920.73	805717.27	650.0	L
ILS/D	CUB	335832.79	810009.62	190.6	I
VTAC/T	CAE	335126.05	810313.84	410.0	H
ILS/D	UKF	361402.89	810558.90	1307.0	I
ILS/D	IPJ	352835.53	811008.16	867.9	I
VTAC/T	BLF	371823.22	811139.34	2899.7	L
VDME/D	BZM	355207.87	811425.90	1880.0	L
ILS/D	JUH	362554.34	812539.01	3198.0	I
VTAC/T	SPA	350201.14	815537.38	910.0	H
ILS/D	FQD	352608.20	815607.26	1065.0	I
ILS/D	VJI	364058.28	820222.65	2056.7	I
VDME/D	GZG	364930.39	820444.37	4200.0	L
VTAC/T	HMV	362613.40	820746.56	4321.0	L
VTAC/T	GRD	341505.64	820914.94	630.0	L
VTAC/T	IRQ	334226.47	820943.43	420.0	H
VTAC/T	SUG	352423.42	821607.01	3970.0	L
ILS/D	OWN	365858.84	823218.20	2670.1	I
VTAC/T	ELW	342509.08	824704.89	740.0	L

After the two input files are created and saved as DOS text files, the user must determine the settings for several flags. The only required input is the airport elevation flag "E". For example, Charlotte/Douglas International Airport has a field elevation of 749'. This would be entered as DME\_SCRN /E:749.

If it is known that all aircraft using the approach will be capable of using ILS/DME's, then /I may be added to the command line to include the extra DME's. The most current data we have indicates that most Boeing aircraft can receive the ILS/DME's but most McDonnell-Douglas, Airbus and lowend systems cannot.

The /V flag will cause the program to drive the model into smooth descents between two waypoints. In the default case, the aircraft descends at 300 ft/NM until it reaches the next waypoints altitude. If the VNAV flag is set, the program calculates a smooth rate of descent between the two altitudes and applies that. The setting does not affect climbs which are all done at 200 ft/NM.

The default value for the navigation performance limit is 0.3 NM. This is used to calculate the pass/fail value for the approach. If the navigation system error (NSE) is greater than 0.3 NM more than 2% of the time spent on the intermediate and final segments, the approach is considered a failure. The /N parameter allows the user to modify the limit value. /N:0.25 would set the navigation performance limit to a quarter mile.

The aircraft is initially positioned 0.3 NM off course to simulate existing navigation error. In cases where the aircraft may have been without DME updates for some time, such as oceanic travel, a larger value may be appropriate. Table 1 suggests some values corresponding to various periods without update.

**TABLE 1. INITIAL OFFSET VALUES**

Hours Since Last Update	Initial Offset Value (NM)
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18

In some circumstances, it may be desirable to specify a reference facility whose reception is required to successfully complete an approach with acceptable NSE. The facility would be coded in the FMS database for the approach so that the FMS would know to use it on the intermediate and final segments of the approach. The /R parameter allows the user to input a reference facility. The program will verify that it is in the master facility list and that it should be useable for the entire intermediate and final segments.

In addition to its graphical results (discussed later), the program produces three output files. CRITICAL.DAT contains a list of those facilities determined by the model to be critical to the approach, i.e., if that facility is unavailable, the approach cannot be successfully accomplished. If a reference facility is specified, it is automatically added to the critical list. Critical facilities are identified in the model by re-running a successful approach with each facility used on the intermediate and final segments removed from the master facility list, in turn. If the approach fails with that facility eliminated, it is considered critical. Critical facilities are not relevant on approaches that fail with all facilities considered or on non-approach applications. The critical facility list also does not consider multiple "failures", where more than one facility is unavailable. CRITICAL.DAT can be renamed to any valid DOS filename with the /C parameter, i.e., DME\_SCRN /C:NEWARK.CRI will cause the critical facilities to be written to a file called NEWARK.CRI.

FLT\_INSP.DAT contains a list of all facilities that the program considers useable at the final approach fix (FAF), i.e., in view and in coverage. Facilities that are in view but more than 40 NM away are included with an asterisk and a comment that an Extended Service Volume study will be necessary for their use. Critical facilities will also be added to the list, although they will generally be duplicated in the main list. A sample file is included as figure 4. Facilities in FLT\_INSP.DAT are identified so that they may be flight inspected. The screening model assumes that all facilities in the master list that are closer than the radio horizon and the facility coverage limits will be useable. If flight inspection reveals this is not the case, the model will need to be run again with those facilities

removed from the master facility list. This will be discussed again in the example below. FLT\_INSP.DAT can be renamed to any valid DOS filename with the /F parameter, i.e., DME\_SCRN /F:NEWARK.FI will cause the flight inspection list to be written to a file called NEWARK.FI.

#### FIGURE 4. TYPICAL FLT\_INSP.DAT FILE

\*VUH viewable at FAF, type L, ESV required.  
MHF viewable at FAF, type L.  
EFD viewable at FAF, type L.  
HUB viewable at FAF, type H.  
IAH viewable at FAF, type H.  
DAS viewable at FAF, type H.  
\*TNV viewable at FAF, type H, ESV required.  
IAH identified as critical

NSE\_OUT.DAT contains the output from the Kalman filter and all the data it used to arrive at the result. Figure 5 contains excerpts from several sections of a sample NSE\_OUT.DAT file. Each section is prefaced by a header that identifies the facilities being considered. The first section is always "ALL FACILITIES". The number of additional sections will depend on the number of facilities used on the intermediate and final segments. Each additional section will be labeled "XXX EXCLUDED" where XXX is the facility that has been removed from the master list for that run. A long approach in a dense DME environment can produce a very large NSE\_OUT.DAT file.

There are 15 columns in the NSE\_OUT.DAT file. The fields are as follows:

- 1.) Number of time steps (normally seconds) from beginning of run
- 2.) Navigation system error from Kalman filter for that step
- 3.) Maximum navigation system error for current segment
- 4.) Radio horizon for current altitude and airport elevation (in feet)
- 5.) DME #1 identifier
- 6.) DME #1 range (in NM)
- 7.) DME #1 bearing (in degrees)
- 8.) DME #1 elevation difference from aircraft (in feet)
- 9.) DME #2 identifier
- 10.) DME #2 range
- 11.) DME #2 bearing
- 12.) DME #2 elevation difference
- 13.) Segment number
- 14.) Segment identifier
- 15.) Range to next waypoint (in ft.)

In figure 5, the first several lines are from the start of the file. Note the initially high NSE value until the filter cycles a few times. The second group illustrates a segment change from feeder to initial. The third group illustrates the model flying into an area where there are no useable pairs of DME's. In this case, EFD and IAH are both in range but are less than 30° apart in angular separation, rendering them unacceptable, and no other DME's are either visible or in an acceptable geometry. The XXX and YYY in the DME id fields are indicators that the model is in coast mode. The last group shows the start of another section with MHF excluded from the master facility list. Compare this section with the first section, where MHF was one of the two DME's initially selected.



As an example, we will construct a hypothetical FMS overlay to the ILS approach to runway 36R at Charlotte/Douglas International Airport (CLT). The FACILITY.DAT file is the same as the example shown in figure 3. The ROUTE.DAT file is shown in figure 6 below. For tracking purposes, we will name the facility file CHARLOTT.FAC and the route file KCLT\_36R.RTE.

**FIGURE 6. ROUTE FILE: KCLT\_36R.RTE**

345844.03	0805454.57	3600	initial
350327.63	0805518.77	3600	intermediate
350713.60	0805537.99	2400	final
351203.46	0805602.84	1100	missed
352522.45	0805523.10	3600	holding

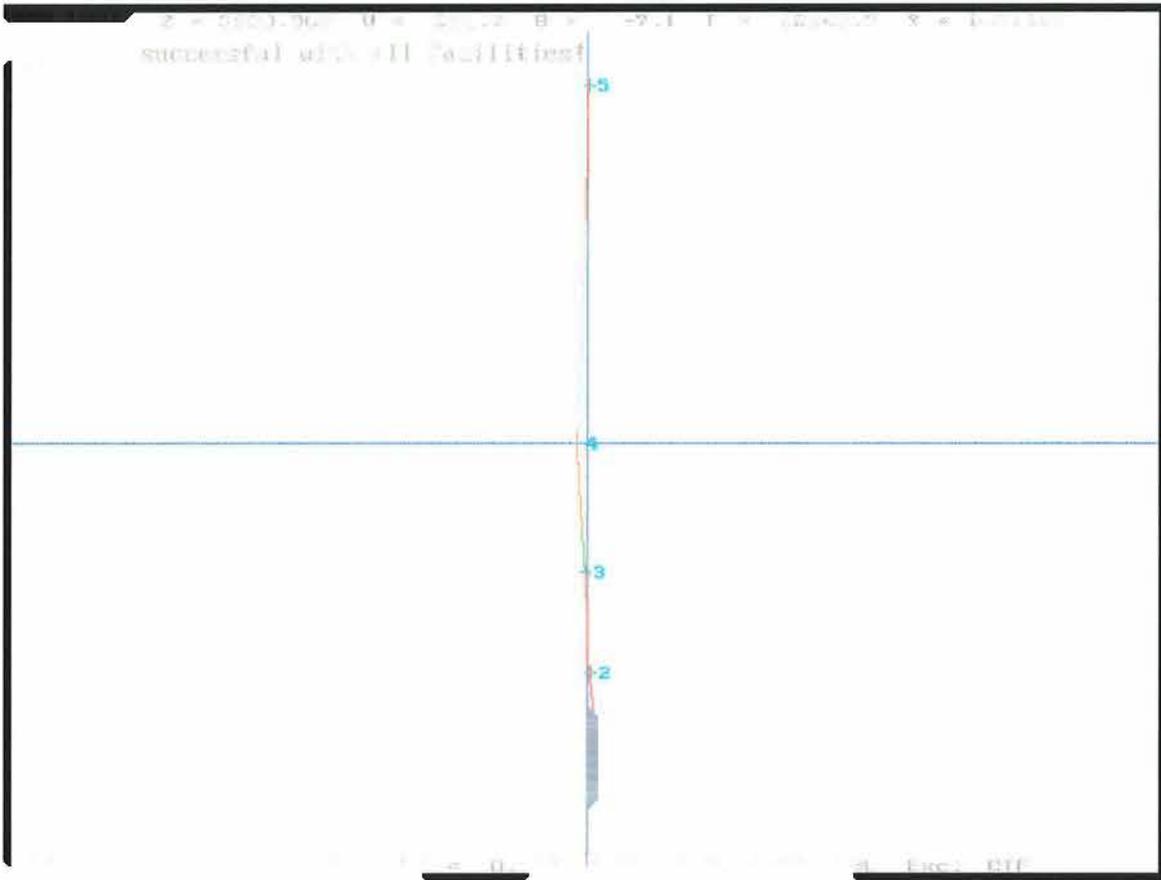
Execute the screening model with the following command:

```
DME_SCRN /E:749 /W:KCLT_36R.RTE /F:CHARLOTT.FAC /V
```

The user has a mixed fleet, including McDonnell-Douglas aircraft, so we cannot assume ILS/DME's will be useable. The user does intend to use VNAV, so the /V flag is included. There is no reason to consider a reference facility or to make any changes to the navigation performance limit or initial offset value.

When the model is running, the screen will show the waypoints defining the track (numbered 1 through whatever), and a variety of information, much of which will probably be changing too fast to clearly see. The track will be shown in red when the model is in DME-DME mode and green when it is coasting. The information on the top line is the time into the current run, the aircraft altitude, the aircraft speed, the aircraft heading, the distance to go on the current segment (in feet), and the segment type. The bottom line shows the instantaneous NSE, the maximum NSE for the current segment, the two DME's being used, and the excluded DME. The excluded DME will say NONE on the first run. If the first run passes, the message "Approach successful with all facilities!" will be displayed in the upper left corner of the screen. Figure 7 shows a screen shot of the model shortly after starting the second run of the Charlotte case. The colors have been adjusted to make the figure more readable.

**FIGURE 7. DME\_SCRN TRACK DISPLAY**



The approach passes the initial run easily. No critical facilities are identified. However, the flight inspection list, Figure 8, shows that 3 of the 5 stations received at the FAF are outside their nominal service volume.

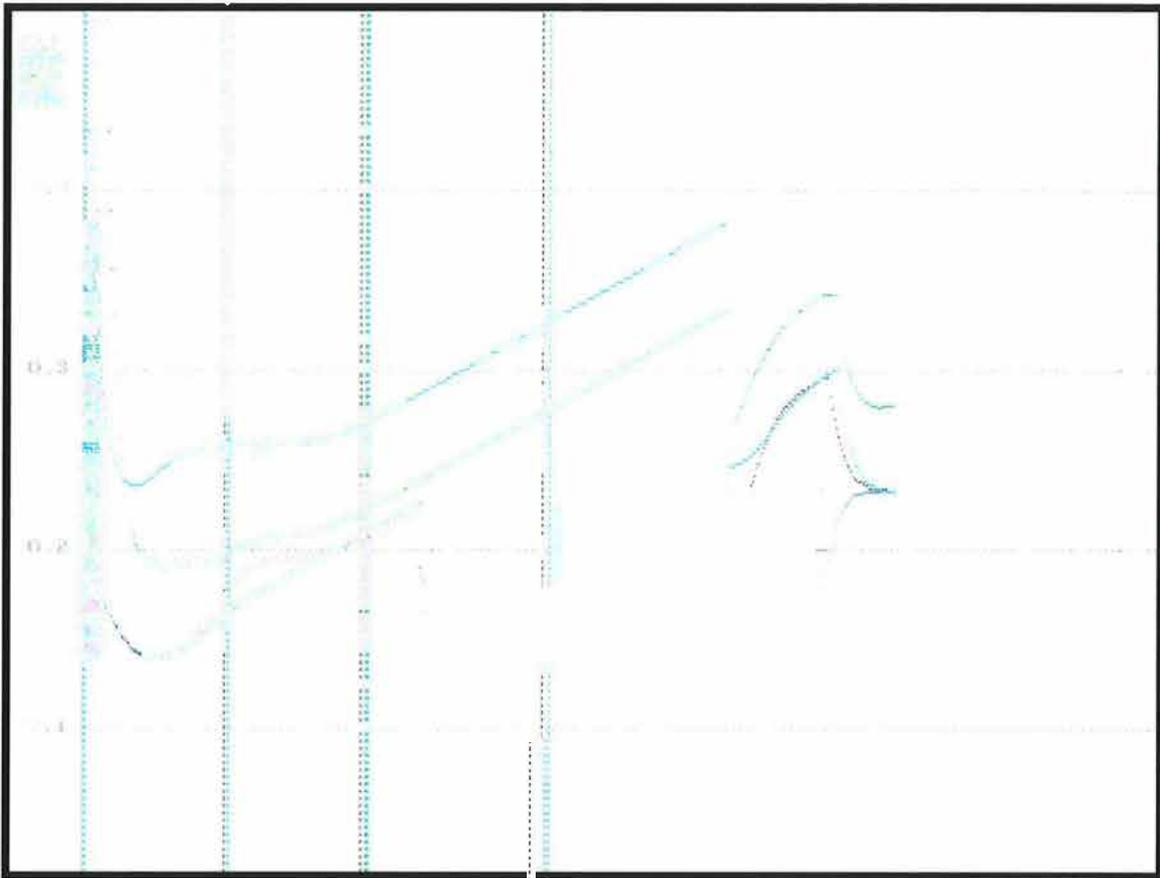
**FIGURE 8. FLIGHT INSPECTION FILE: FLT\_INSP.DAT**

- \*CTF viewable at FAF, type L, ESV required.
- CLT viewable at FAF, type L.
- FML viewable at FAF, type L.
- \*BZM viewable at FAF, type L, ESV required.
- \*SPA viewable at FAF, type H, ESV required.

A subsequent flight check shows that neither SPA nor BZM can be received at the FAF. This necessitates re-running the model with a new facility list, CHARLOT2.FAC, with the two facilities deleted. The approach still passes, but FML is now a critical facility. Dispatch will be responsible for monitoring the availability of the facility and declaring the approach out of service when it is not useable.

Figure 9 shows the NSE output plot from the program. The vertical axis is NSE and the horizontal is time with the right hand edge of the plot representing 600 seconds (which is longer than the flight track, in this case.) The list of facilities in the upper left hand corner is color coded to match the plotted lines. It is apparent that the model is running in coast mode for extensive parts of the tracks, where the track is smoothly increasing. These periods are primarily due to geometry (when two facilities are less than 30 degrees apart or between 150 and 180 degrees apart) and when the track comes out of one of these zones of bad geometry, the facilities are near enough to provide a good fix.

**FIGURE 9. NSE OUTPUT PLOT - NSE vs. TIME (FULL SCALE IS 600 SEC.)**



The vertical lines represent where each track starts a new segment. The variation in the vertical lines is due to variations in speed and track distance for each run. The segments are initial, intermediate, final and missed approach. Note that the CYAN (highest) line passes the 0.3 NM level roughly half way through the final segment. This indicates that FML will be a critical facility.

\*\*\*\*\*

**Please note: This attachment contains information on operating the latest version of the FMS approach screening model. It supersedes the appendix in the formal report. These changes reflect substantial improvements in the user interface but do not affect the filter or navigation routines discussed in the report.**

\*\*\*\*\*

## User's Manual for PC version of FMS Screening Model

The PC/DOS version of the FMS Screening Model is started by typing GO at the appropriate DOS prompt or running GO.BAT from a Windows Run screen. The first screen that comes up is the disclaimer shown in Figure 1:

```
***** DISCLAIMER *****
The FMS/DME Screening Model is a computer program that estimates the
navigation performance possible with a given set of DMEs updating an IRU
system. This estimate may then be compared with the required navigation
performance values for the maneuver and the acceptability determined.

There are significant differences in the position evaluation capabilities
of FMS's across aircraft types, manufacturers, and even software versions.
Each unique configuration that may use the routes examined by this model
should be thoroughly tested in VFR conditions prior to any IFC flights.
The Model also assumes the availability of all DME's in line of sight.
This availability must be verified by flight inspection.

Neither the FAA nor any parties involved in the creation or distribution
of this program take any responsibility for the correctness of the data
entered into this model or for the applicability of this model to any
specific case. It is the responsibility of the user to verify all data
used and generated by this model for the specific maneuver.
***** DISCLAIMER *****
..... HIT ANY KEY TO START SCREENING MODEL .....
```

Figure 1. Disclaimer

Hitting a key will bring up the Main Menu for the FMS Screening Model which has the following options:

1. Load Existing Route File
2. Create New Route File
3. Edit Current Route File
4. Save Current Route File
5. Generate Initial Facilities
6. Execute FMS Screening Program
7. Show ENP Plots
8. Remove DMEs From List
9. Exit Program

Option 1 allows the user to load an existing route file. Route files define the maneuver (generally an approach) being modeled and include the approach name, airport elevation, several flags and limiting values, and a list of the waypoints defining the maneuver. A typical route file will look like Figure 2:

```

* KIAH_08      97 N N N None      0.30 0.25
N 29 59 33.08 W 95 43 38.41 3900 initial
N 29 59 34.37 W 95 37 50.15 2900 intermediate
N 29 59 35.74 W 95 28 20.38 1900 final
N 29 59 36.31 W 95 21 17.86 500 missed
N 29 59 36.49 W 95 15 56.57 2200 holding
N 30 17 38.84 W 95 10 17.51 2200 xxx

```

Figure 2. Route file example

The asterisk on the first line tells the programs that it is not a waypoint but an information line containing the approach or maneuver name, the airport elevation (in feet MSL), flags indicating whether ILS/DME's should be considered, whether baro-VNAV will be used to smooth the vertical profile, and whether a reference facility has been selected. The next field is the name of the reference facility or "None" if no facility is used (note that this field cannot be left blank). The last two entries on the line are the navigation performance limit for the maneuver and the initial offset from desired course.

If it is known that all aircraft using the approach will be capable of using ILS/DMEs, then the ILS flag should be set to 'Y' to include the extra DMEs. The most current data we have indicates that most Boeing aircraft can receive the ILS/DMEs but most McDonald-Douglas, Airbus and lowend systems cannot.

The baro-VNAV flag, if set to 'Y', will cause the program to drive the model into smooth descents between two waypoints. In the default case, the aircraft descends at 300 ft/nm until it reaches the next waypoints altitude. If the VNAV flag is set, the program calculates a smooth rate of descent between the two altitudes and applies that. The setting does not affect climbs which are all done at 200 ft/nm.

In some circumstances, it may be desirable to specify a reference facility whose reception is required to successfully complete an approach with acceptable NSE. The facility would be coded in the FMS database for the approach so that the FMS would know to use it on the intermediate and final segments of the approach. Setting the reference facility flag to 'Y' allows the user to input a reference facility. The program will verify that it is in the master facility list and that it should be useable for the entire intermediate and final segments.

The default value for the navigation performance limit is 0.3 nm. This is used to calculate the pass/fail value for the approach. If the navigation system error (NSE) is greater than 0.3 nm more than 2% of the time spent on the intermediate and final segments, the approach is considered a failure.

To model errors in navigation prior to the maneuver under study, a nav offset error is applied to the initial position of the aircraft. By default this is 0.25 NM but for maneuvers beginning after a long period without updates, such as trans-oceanic flight, larger values may be appropriate.

All subsequent lines in the route file specify waypoints defining segments. Each line has the latitude, longitude, altitude (in feet MSL) and the name of the segment starting at that waypoint. Each waypoint must have a segment name, even the last one. Segments named "final", "intermediate", and "initial" convey special meaning to the program and should only be used where appropriate. Latitudes and longitudes are expressed as H DDD MM SS.ss where H is either N, S, E, or W depending on the hemisphere, DDD is degrees, MM is minutes, and SS.ss is seconds.

**\*\*\*Note: When an existing route file is loaded, it is necessary to save it before running the remaining options to ensure that all data files are properly updated.**

Option 2 allows the user to create a new route file. It prompts the user for the number of segments and then presents the input screen in Figure 3.

```

-----Route Data Entry Form-----
Approach: _____ Airport Elevation: 0 _____
Use ILS/DMEs (Y/N): N      Use VNAV (Y/N): N
Define Reference Facility (Y/N): N      Facility: None__
Nav Error Limit (NM): _0.30      Initial Nav Error (NM): _0.25

Latitude      Longitude      Altitude      Segment Name
N 00°00'00.00" W 000°00'00.00" _____ 0 _____

```

Figure 3. Route Data Entry Form

The user may cursor between entry fields. There is a minimal level of error checking on the input data. Help messages are currently not available but may be added in a later version of the software (or may be added by the user.) When the last segment name is entered, the user will be prompted to accept the screen or continue editing.

Option 3 calls up the same edit window with the current route file information already loaded. Use the cursors or enter key to move to whatever field requires modification. There is currently no way to add or delete waypoints.

Option 4 saves the current route file after prompting the user for a name.

Option 5 calls the scandmes program. Scandmes is currently configured to access the text file "USA\_DMES.LST" which contains a list of all the DME facilities in the US National Airspace System. An excerpt from the file is shown in Figure 4. Note that North and West hemispheres are positive. Latitudes and longitudes are in the DDDMMSS.ss format. The last character in each line indicates the power level of the

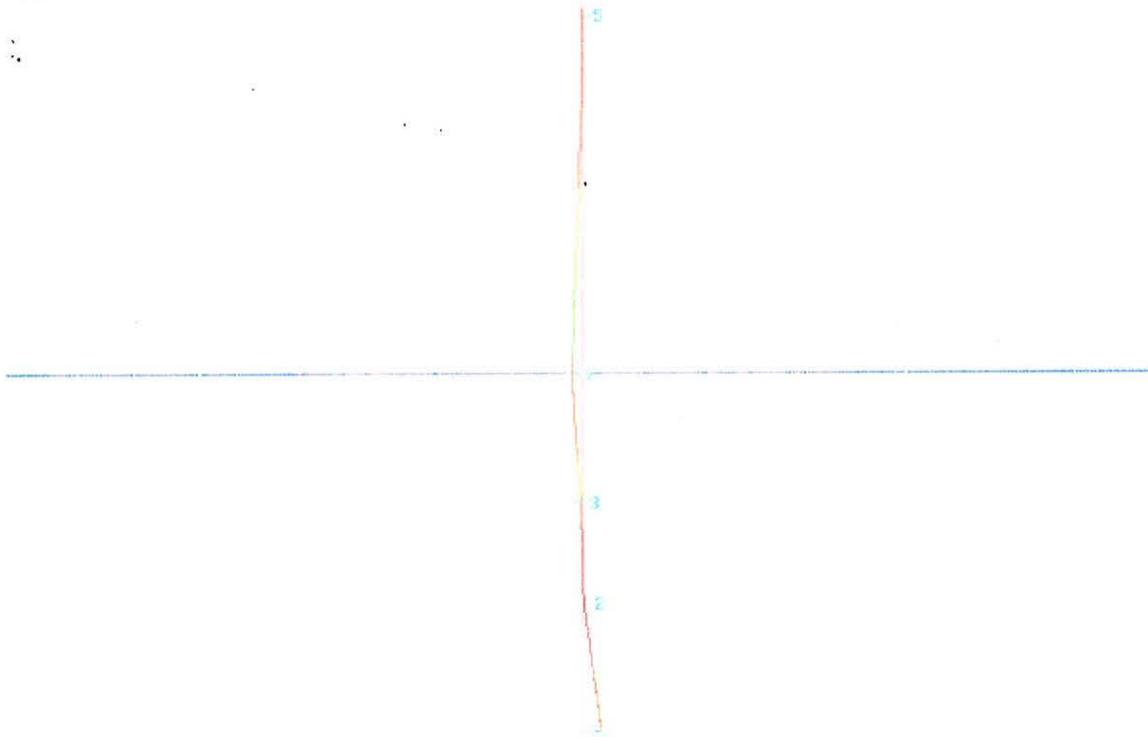
facility. 'I' denotes an ILS/DME, 'T' represents a terminal facility, 'L', 'X', and 'H' indicate low, medium and high power stations, respectively. (The source code for scandmes.c is included on the disk to allow whatever user modifications are required.) Scandmes generates a list of all DME facilities within approximately 120 miles of any point on the route in a file called "FACILITY.DAT".

VDME/D	KIN	175825.71	765338.26	38.0	L
VDME/D	PSE	175932.80	663109.10	20.0	L
VDME/D	PJM	180214.44	630707.89	9.1	X
VDME/D	AYR	181329.12	773030.12	3263.0	L
VDME/D	BHO	181516.02	710748.10	27.6	T
VDME/D	MAZ	181523.20	670903.70	20.0	L
ILS/D	TMN	182018.75	645739.47	23.0	I
VDME/D	STT	182120.80	650128.30	700.0	L
VDME/D	CDO	182558.50	694002.70	38.0	H
VDME/D	OBN	182614.00	721629.00	53.7	X
ILS/D	CDO	182627.63	694021.49	40.0	I
VTAC/T	SJU	182646.60	655922.20	7.0	H
VDME/D	MBJ	182911.29	775542.63	11.4	H

Figure 4. Excerpt from USA\_DMES.LST

Option 6 executes the FMS screening model. (This is actually a separate program "DME\_SCRN.EXE".) When the model is running, the screen will show the waypoints defining the track (numbered 1 through whatever), and a variety of information, much of which will probably be changing too fast to clearly see. The track will be shown in red when the model is in DME-DME mode and green when it is coasting. The information on the top line is the time into the current run, the aircraft altitude, the aircraft speed, the aircraft heading, the distance to go on the current segment (in feet), and the segment type. The bottom line shows the instantaneous NSE, the maximum NSE for the current segment, the two DMEs being used, and the excluded DME. The excluded DME will say NONE on the first run. If the first run passes, the message "Approach successful with all facilities!" will be displayed in the upper left corner of the screen. Figure 5 shows a screen shot of the model shortly after starting the second run. If the approach is successful, additional runs will be made with each facility used on the final or intermediate excluded in turn to identify critical facilities.

Y = 30 Z = 3600.000 U = 214.9 B = -7.1 D = 18145.7 S = initial  
Approach successful with all facilities!



NSE = 0.144 Segment Max NSE = 0.345 DME1: GLT DME2: FML Exc: CTF

Figure 5. DME\_SCRN Output screen

When the screen stops changing the user should hit any key and the estimated navigation performance values will be plotted as shown in Figure 6.

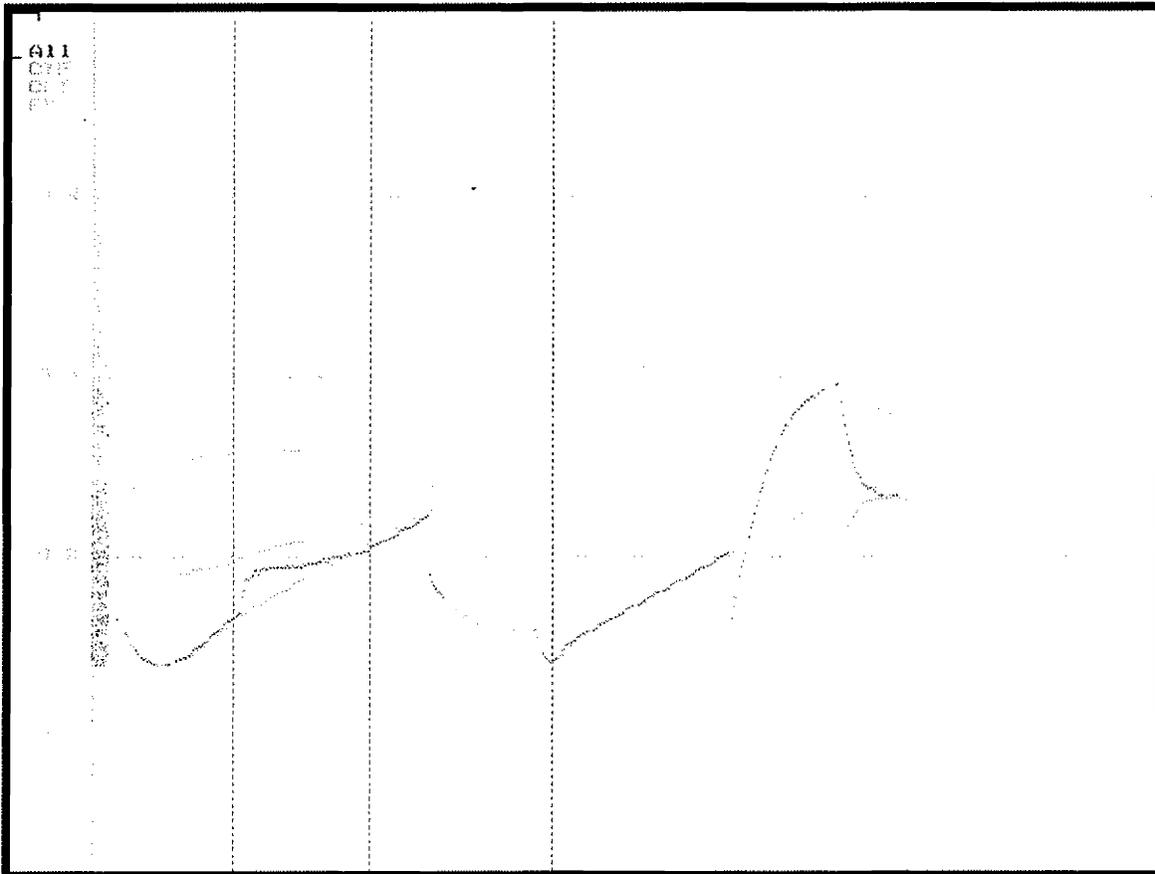


Figure 6. Plot of Estimated Navigation Errors

In addition to its graphical results, the program produces three output files. CRITICAL.DAT contains a list of those facilities determined by the model to be critical to the approach, i.e. if that facility is unavailable, the approach cannot be successfully accomplished. If a reference facility is specified, it is automatically added to the critical list. Critical facilities are identified in the model by re-running a successful approach with each facility used on the intermediate and final segments removed from the master facility list, in turn. If the approach fails with that facility eliminated, it is considered critical. Critical facilities are not relevant on approaches that fail with all facilities considered or on non-approach applications. The critical facility list also does not consider multiple “failures”, where more than one facility is unavailable.

FLT\_INSP.DAT contains a list of all facilities that the program considers useable at the final approach fix (FAF), i.e. in view and in coverage. Facilities that are in view but more than 40 nm away are included with an asterisk and a comment that an Extended Service Volume study will be necessary for their use. Critical facilities will also be added to the list, although they will generally be duplicated in the main list. An sample file is shown in Figure 7. Facilities in FLT\_INSP.DAT are identified so that they may be flight inspected. The screening model assumes that all facilities in the master list that are closer than the radio horizon and the facility coverage limits will be useable. If flight inspection

reveals this is not the case, the model will need to be run again with those facilities removed from the master facility list. This will be discussed again in the example below.

After a key is hit on the Estimated Navigation Errors plot screen shown in Figure 6, CRITICAL.DAT and FLT\_INSP.DAT are displayed. Once the user hits another key to proceed, he will be back to the main menu. At this juncture, he must reselect option 1 and re-enter the approach name to get the program back to the right files.

```
*VUH viewable at FAF, type L, ESV required.  
MHF viewable at FAF, type L.  
EFD viewable at FAF, type L.  
HUB viewable at FAF, type H.  
IAH viewable at FAF, type H.  
DAS viewable at FAF, type H.  
*TNV viewable at FAF, type H, ESV required.  
IAH identified as critical
```

Figure 7. Typical FLT\_INSP.DAT file

The third file generated by the model, NSE\_OUT.DAT, contains the output from the Kalman filter and all the data it used to arrive at the result. Figure 8 contains excerpts from several sections of a sample NSE\_OUT.DAT file. Each section is prefaced by a header that identifies the facilities being considered. The first section is always "ALL FACILITIES". The number of additional sections will depend on the number of facilities used on the intermediate and final segments. Each additional section will be labelled "XXX EXCLUDED" where XXX is the facility that has been removed from the master list for that run. A long approach in a dense DME environment can produce a very large NSE OUT.DAT file.

There are 15 columns in the NSE OUT.DAT file. The fields are as follows:

- 1.) Number of time steps (normally seconds) from beginning of run
- 2.) Navigation system error from Kalman filter for that step
- 3.) Maximum navigation system error for current segment
- 4.) Radio horizon for current altitude and airport elevation (in feet)
- 5.) DME #1 identifier
- 6.) DME #1 range (in nm)
- 7.) DME #1 bearing (in degrees)
- 8.) DME #1 elevation difference from aircraft (in feet)
- 9.) DME #2 identifier
- 10.) DME #2 range
- 11.) DME #2 bearing
- 12.) DME #2 elevation difference
- 13.) Segment number
- 14.) Segment identifier
- 15.) Range to next waypoint (in ft.)

In figure 8, the first several lines are from the start of the file. Note the initially high NSE

All Facilities															
1	0.602	0.602	66.12	MHF	35.15	171.5	2862	DAS	11.14	70.3	2826	1	feeder	61019.2	
2	0.430	0.602	66.12	MHF	35.10	171.4	2862	DAS	11.20	70.1	2826	1	feeder	60587.7	
3	0.350	0.602	66.12	MHF	35.04	171.4	2862	SBI	49.73	121.6	2890	1	feeder	60156.9	
4	0.306	0.602	66.12	MHF	34.99	171.3	2862	DAS	11.32	69.7	2826	1	feeder	59724.3	
5	0.281	0.602	66.12	MHF	34.94	171.2	2862	DAS	11.38	69.5	2826	1	feeder	59296.1	
6	0.268	0.602	66.12	MHF	34.89	171.1	2862	SBI	49.75	121.4	2890	1	feeder	58864.5	
.															
139	0.260	0.602	66.12	MHF	29.37	157.4	2862	IAH	20.09	-97.2	2810	1	feeder	2253.8	
140	0.259	0.602	66.12	MHF	29.35	157.2	2862	IAH	20.03	-97.1	2810	1	feeder	2103.8	
141	0.258	0.602	66.12	MHF	29.35	157.1	2862	IAH	19.96	-97.0	2810	1	feeder	2049.9	
142	0.257	0.602	66.12	MHF	29.34	157.0	2862	IAH	19.89	-96.9	2810	1	feeder	2097.1	
143	0.257	0.257	66.12	MHF	29.33	156.8	2862	IAH	19.83	-96.9	2810	2	initial	29397.1	
144	0.256	0.257	66.12	MHF	29.36	156.7	2862	IAH	19.76	-96.9	2810	2	initial	28967.7	
.															
467	0.334	0.334	33.46	EFD	25.03	158.2	720	IAH	2.29	-169.4	660	6	missed	47664.2	
468	0.348	0.348	33.77	EFD	25.05	158.1	734	IAH	2.28	-171.1	674	6	missed	47242.9	
469	0.349	0.349	34.08	XXX	0.00	0.0	0	YYY	0.00	0.0	0	6	missed	46819.9	
470	0.349	0.349	34.39	XXX	0.00	0.0	0	YYY	0.00	0.0	0	6	missed	46400.4	
471	0.350	0.350	34.69	XXX	0.00	0.0	0	YYY	0.00	0.0	0	6	missed	45982.9	
.															
.															
MHF Excluded															
1	0.788	0.788	66.12	VUH	51.35	-178.8	2890	DAS	11.14	70.3	2826	1	feeder	61019.2	
2	0.527	0.788	66.12	VUH	51.30	-178.8	2890	SBI	49.73	121.7	2890	1	feeder	60590.3	
3	0.436	0.788	66.12	EFD	35.07	-152.3	2870	SBI	49.74	121.6	2890	1	feeder	60157.0	
4	0.379	0.788	66.12	VUH	51.19	-178.9	2890	DAS	11.32	69.7	2826	1	feeder	59727.5	
.															
.															
.															

Figure 8. Sample NSE\_OUT.DAT excerpts

value until the filter cycles a few times. The second group illustrates a segment change from feeder to initial. The third group illustrates the model flying into an area where there are no useable pairs of DMEs. In this case, EFD and IAH are both in range but are less than 30( apart in angular seperation, rendering them unacceptable, and no other DMEs are either visible or in an acceptable geometry. The XXX and YYY in the DME id fields are indicators that the model is in coast mode. The last group shows the start of another section with MHF excluded from the master facility list. Compare this section with the first section, where MHF was one of the two DMEs initially selected.

Option 7 on the Main Menu will redraw the estimated navigation performance plots generated by the model. Since it plots whatever is in the NSE\_OUT.DAT file, care should be taken to ensure the correct data file is available.

Option 8 allows the user to delete DME's from the FACILITY.DAT file used by the filter. If flight inspection reveals that one or more stations cannot be received, they should be deleted and the model re-run. The user prompts include the facility type as well as the name to insure deletion of the correct facility.

Option 9 exits the program gracefully. It will notify the user if the current route file has not been saved.

As an example, we will construct an FMS overlay to the ILS approach to runway 36R at Charlotte/Douglas International Airport (KCLT). The ROUTE.DAT file is shown in Figure 9 below.

```
* KCLT__36R      749 N Y N None      0.30 0.25
N 34 58 44.03   W 080 54 54.57      3600  initial
N 35 03 27.63   W 080 55 18.77      3600  intermediate
N 35 07 13.60   W 080 55 37.99      2400   final
N 35 12 03.46   W 080 56 02.84      1100  missed
N 35 25 22.45   W 080 55 23.10      3600  holding
```

Figure 9. Route file: KCLT\_\_36R.RTE

The facility file is generated by the scandmes.exe program.

The user has a mixed fleet, including McDonald-Douglas aircraft, so we cannot assume ILS/DMEs will be useable. The user does intend to use VNAV, so that flag is set to 'Y'. There is no reason to consider a reference facility or to make any changes to the navigation performance limit.

When the model is running, the screen will look very much like Figure 5 and the ENP plots will look similar to Figure 6. The approach passes the initial run easily. No critical facilities are identified. However, the flight inspection list, Figure 10, shows that 3 of the 5 stations received at the FAF are outside their nominal service volume.

\*CTF viewable at FAF, type L, ESV required.  
CLT viewable at FAF, type L.  
FML viewable at FAF, type L.  
\*BZM viewable at FAF, type L, ESV required.  
\*SPA viewable at FAF, type H, ESV required.

Figure 10. Flight Inspection file: FLT\_INSP.DAT

A subsequent flight check shows that neither SPA nor BZM can be received at the FAF. This necessitates re-running the model after deleting the two facilities. The approach still passes, but FML is now a critical facility. Dispatch will be responsible for monitoring the availability of the facility and declaring the approach out of service when it is not useable.

Figure 6 shows the NSE output plot from the re-running of the program. The list of facilities in the upper left hand corner is color coded to match the plotted lines. It is apparent that the model is running in coast mode for extensive parts of the tracks. These periods are primarily due to geometry (when two facilities are less than 30 degrees apart or between 150 and 180 degrees apart) and when the track comes out of one of these zones of bad geometry, the facilities are near enough to provide a good fix.