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FINAL APPROACH SPACING TOOL (FAST) VELOCITY ACCURACY PERFORMANCE ANALYSIS

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Abstract

The NASA passive Final Approach Spacing Tool (FAST) provides advisory information to the terminal air traffic controller for sequencing and merging of landing aircraft. It consists of the Trajectory Synthesizer (TS) and the Scheduling Logic (SL). FAST has undergone extensive field testing and performance evaluations of the FAST TS algorithms have been conducted. However, no analytical performance evaluations of the FAST SL logic have been performed to date.

This paper evaluates the sensitivity of the FAST SL algorithms to velocity errors which are introduced by the radar tracking software. A linear error covariance analysis was performed of the terminal area radar and its alpha-beta tracking filter software. For comparison, an alternate Kalman tracking filter was also evaluated. Using these radar tracking velocity estimation error histories for a typical aircraft flight profile, the FAST TS estimated time of arrival (ETA) statistics history was obtained. To determine the impact of the velocity and ETA errors on FAST SL, figures of merit were defined which predict the probability that FAST SL will reach an incorrect aircraft sequencing decision. These figures of merit were then evaluated, based on the velocity and ETA statistics histories.

Introduction

Passive FAST is a decision aid to the air traffic controller which consists of two key modules.[1-10] The first is the Trajectory Synthesizer (TS) which is used to predict the aircraft trajectory history to the runway threshold based on the current time, position, and speed.[9,10] The second module is the Scheduling Logic (SL) which determines the air traffic controller preferred sequencing of aircraft within a flight segment or merging of aircraft onto a common flight segment.[7,8] This is accomplished by examining the trajectory variables from two aircraft at a time, for all aircraft in the Terminal Radar Approach Control (TRACON) and by evaluating a set of fuzzy logic propositions to determine the preferred choice.

Figure 1 illustrates the data flow surrounding and through FAST. The aircraft horizontal position and velocity estimates are obtained from the ARTS radar and its tracking software. This data is combined by the FAST TS with altitude information, provided by the aircraft barometric altimeter, to obtain predicted aircraft flight path histories. FAST uses these predicted trajectories to determine the preferred sequencing or merging of aircraft in the TRACON.

The logic flow of the error analysis is illustrated in Figure 2. The analysis approach consists of deriving the velocity estimation error model, based on an estimation error analysis of the ARTS radar and its tracking software.

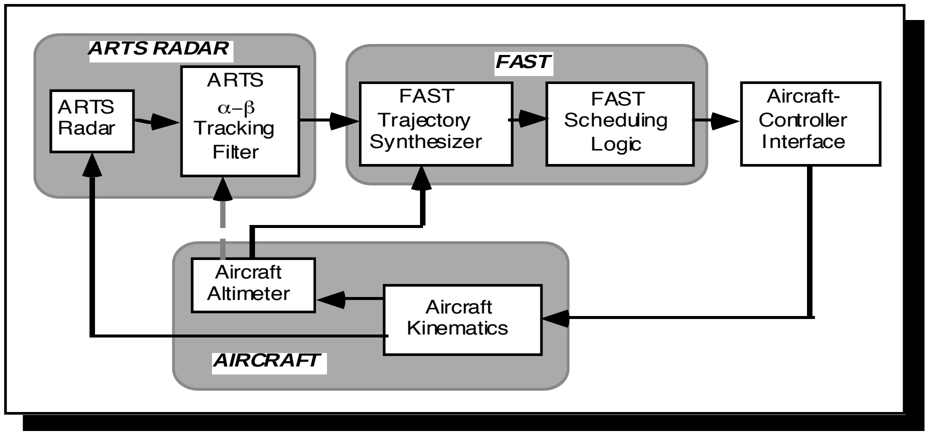

Figure 1. FAST Data Flow

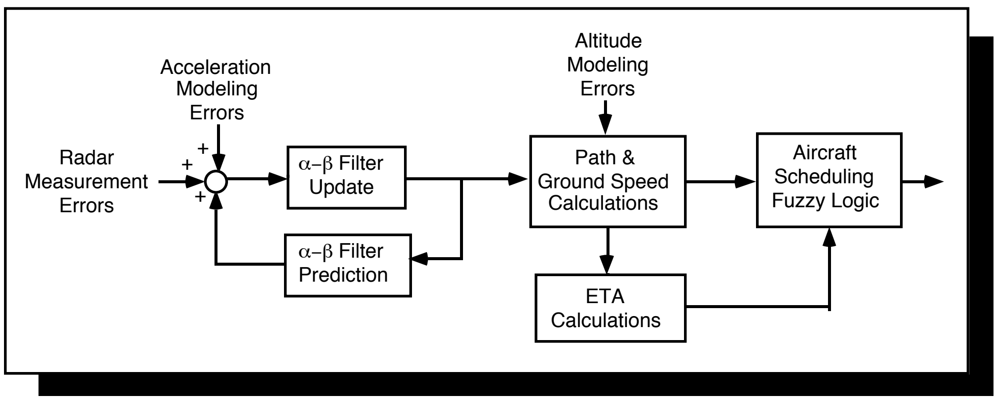

Figure 2. FAST Velocity Error Analysis Flow Diagram

The velocity estimation error history then is obtained by propagating the error models over a typical TRACON aircraft flight profile using the FAST TS simulation.

The performance of FAST is then evaluated in the presence of input velocity errors from the ARTS tracking software, as propagated through the FAST TS. The FAST SL performance is based on several figures-of-merit, which are derived and evaluated. Since most of the FAST SL decision logic involves the ground speed, rather than the total velocity vector, this paper will primarily focus on the ground speed errors. Overall, this study consists of a bottom-up nominal and statistical performance analysis, rather than a top-down Monte Carlo analysis of the FAST software. The simulations which are used in this paper were developed by the authors.[7-10,15] The NASA FAST software, which forms part of the Center-TRACON Automation System (CTAS) software suite, was not used.

ARTS Radar Performance

The radar which is used in the TRACON is the ARTS III radar. This radar tracks multiple aircraft in range and azimuth, but not elevation, using a horizontal sweep which takes 4.6 seconds to complete. Using these range and azimuth measurements, the radar tracking software then computes the current range, range rate, azimuth, and azimuth rate estimates for each aircraft using a variable gain four state $\alpha-\beta$ filter.[12-14]

Aircraft Nominal Flight Path Histories

To determine the radar performance using the radar error models, a nominal aircraft flight path history is required. Typical TRACON flight paths for landing aircraft are illustrated in Figure 3. This figure shows the two approaches from the Acton metering fix to Runway 18R at Dallas-Ft. Worth Airport. Also shown in Figure 3 is a flight path extension which is used in the FAST TS to delay aircraft to allow the FAST SL to separate or merge aircraft. For reference, the sequence of maneuvers are summarized in Table 1 for a jet aircraft. Note that the altitude and heading maneuvers may overlap as the aircraft approaches the outer marker.

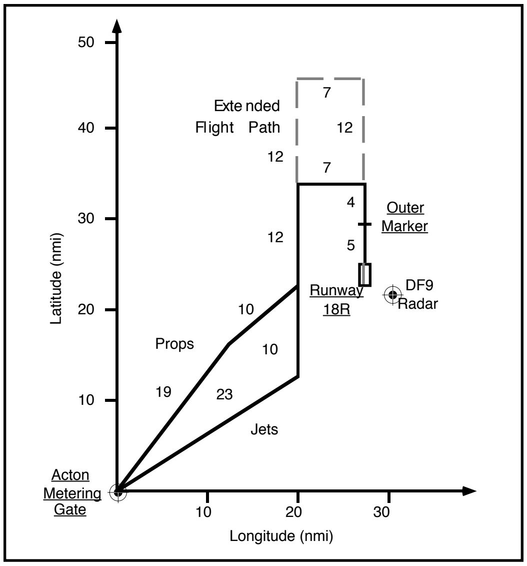

Figure 3. Dallas- Ft. Worth Approach to Runway 18R

Table 1. Jet Aircraft Sequence of Maneuvers

Start (min)	Stop (min)	Maneuver
0	1.16	13.0 kft to 11.0 kft Altitude
1.16	1.62	280 kts to 250 kts Ground Speed
2.78	3.42	250 kts to 210 kts Ground Speed
3.78	8.33	11.0 kft to 5.0 kft Altitude
5.68	6.30	57.9^0 to 0^0 Heading
11.50	12.28	5.0 kft to 4.0 kft Altitude
11.54	12.49	0^0 to 90^0 Heading
13.50	14.66	4.0 kft to 2.5 kft Altitude
13.58	14.52	90^0 to 180^0 Heading
14.65	15.13	210 kts to 180 kts Ground Speed
15.28		Outer Marker

The flight path history for a simulated jet aircraft is plotted in Figures 4 and 5.

ARTS Tracking Software Performance Analysis

Based on the radar measurement errors and the modeling error histories shown in Figure 6, the $\alpha-\beta$ tracking filter ground speed estimation error history of Figure 7 was obtained. In Figure 7, the ground speed mean estimation error appears to vary between -25 and 20 knots during and following speed and heading maneuvers. The standard deviation of the ground speed estimation error varies between 0.5 and 7 knots. The root-mean-square (rms) errors peak up to 25 knots.

The excursions of Figure 7 appear to correlate well with aircraft speed changes at 1.5, 2.5, and 15 minutes as well as with the heading changes at 6, 12, and 14 minutes. To understand the reason for these significant excursions, it is worthwhile to examine the acceleration modeling errors in Figure 6. While the first two speed reductions only involve a deceleration of 1.8 ft/sec^2, the length of time that these maneuvers are active leads to 30 and 40 knot range rate modeling errors, respectively. While these large errors are partially minimized by the $\alpha-\beta$ filter, they do lead to the ground speed mean velocity spikes in Figure 7.

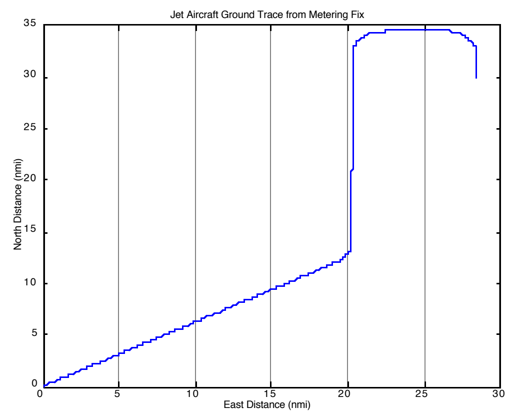

Figure 4. Jet Aircraft Ground Trace from Metering Fix

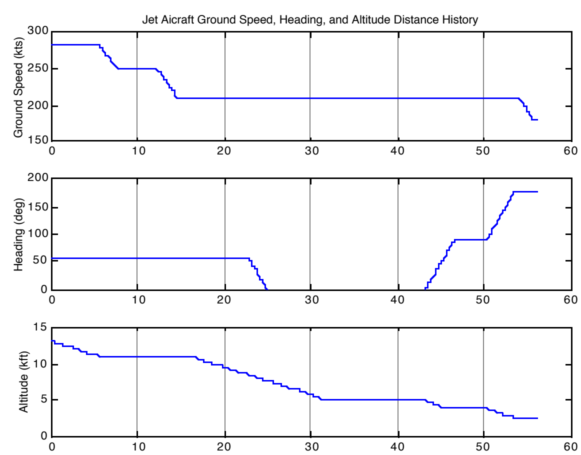

Figure 5. Ground Speed, Heading, and Altitude Time History

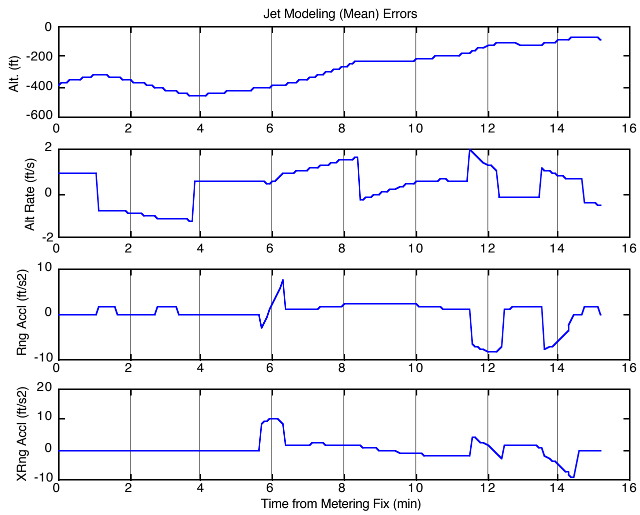

Figure 6. ARTS α–β Tracking Filter Modeling (Mean) Errors

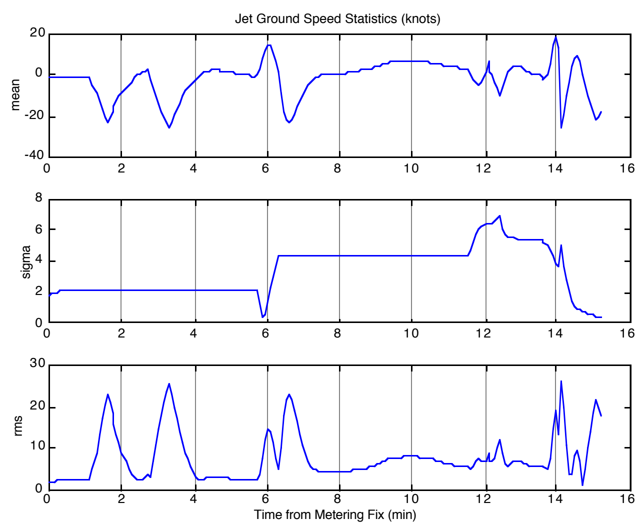

Figure 7. ARTS α–β Filter Ground Speed Estimation Error

An alternate ARTS radar tracking filter, based on a position and velocity Kalman filter developed for the FAA, was also evaluated.[11] This Kalman filter formulation was enhanced by the authors, by modeling the horizontal velocity errors as first-order Gauss Markov errors.[15] This formulation provides a more robust formulation in the presence of unexpected aircraft speed and heading maneuvers, as shown in Figure 8.

The enhanced Kalman filter is able to keep the ground speed rms estimation errors below 5 knots. Hence, this enhanced Kalman filter considerably outperforms the current ARTS tracking software with its α–β filter.

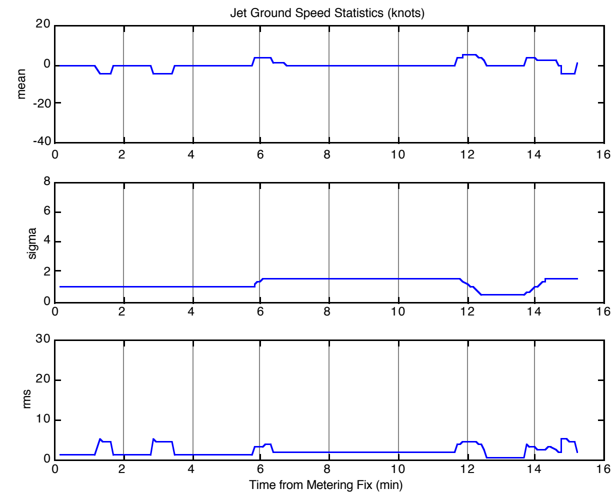

Figure 8. Enhanced Kalman Filter Ground Speed Estimation Error

FAST TS ETA Error Analysis

The principal role of the FAST TS is to predict the time required by an aircraft to reach the runway threshold, from its current position. This is the estimated time of arrival (ETA). This ETA is obtained by propagating the aircraft over the nominal flight path segments, altitude profiles, heading changes, and speed changes to the runway with a point-mass four degree-of-freedom trajectory simulation.

Figure 9 presents the estimation error mean and sigma of the ETA for the jet aircraft based on the ARTS radar α–β tracking software estimation errors. The scenario is the same one used in the previous section. The mean error of Figure 9 is seen to be generally small except for several spikes of between -0.5 and 1.5 minutes. The spikes which start at 1.5 and 2.5 minutes are connected with the aircraft deceleration which last for 0.5 and 0.6 minutes, respectively. However it takes the α–β filter nearly another minute to damp out these transients. The next three spikes in the mean ETA are connected with the three heading changes while the last spike is connected with the last deceleration.

With the enhanced Kalman filter, the ETA statistics of Figure 10 are obtained. With this tracking filter, the mean ETA estimation errors are bounded by -/+0.53 minutes. Clearly, the ETA errors are considerably smaller, particularly during the heading and speed maneuvers.

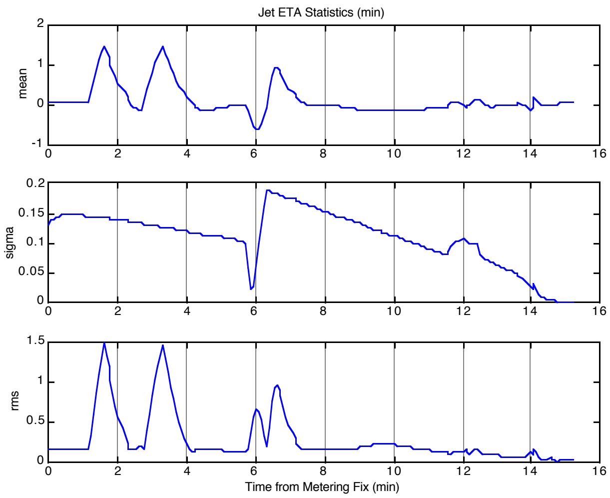

Figure 9. ETA Estimation Error Statistics ($\alpha-\beta$ Tracking Filter)

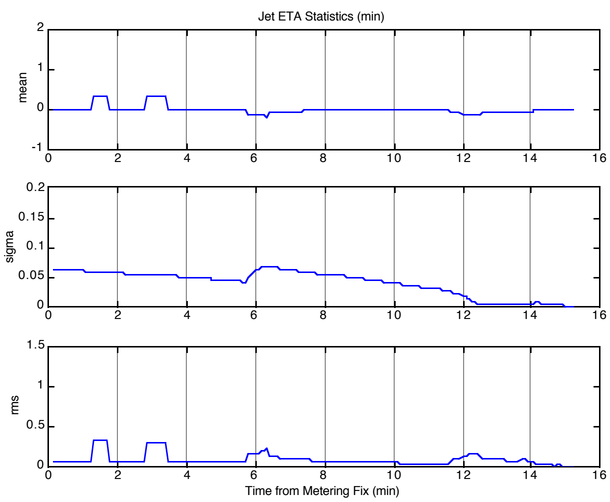

Figure 10. ETA Estimation Error Statistics (Kalman Tracking Filter)

FAST SL Performance Analysis

SL Fuzzy Logic

The FAST SL incorporates a fuzzy decision logic methodology to determine the preferred sequence of aircraft landing on the same runway. This sequence assures that minimum separation constraints are met, unwanted overtakes are avoided, and delays in reaching the runway are minimized. The design of this logic has evolved over several years incorporating inputs from air traffic controllers, who also tested the logic. As a result, this decision methodology closely mimics the decision process that air traffic controllers use in scheduling aircraft.

FAST uses four primary sets of scheduling decisions:

- Ordering Procedure of a GENERAL-type Spatial Constraint
- Merging Procedure of a GENERAL-type Spatial Constraint
- Ordering Procedure for a FINAL-type Spatial Constraint
- Merging Procedure for a FINAL-type Spatial Constraint

A Spatial Constraint is any group of aircraft whose trajectories currently, or in the future, will pass through the same section of airspace in the TRACON. A GENERAL-type Spatial Constraint is a set of aircraft on a particular trajectory segment, other than the Final segment.

The fuzzy logic propositions and consequents for the Ordering or Merging Procedure of a GENERAL-type Spatial Constraint are summarized in Table 2. In this table, ‘A’ is one aircraft and ‘B’ is another aircraft, for aircraft taken two at a time. The propositions in Table 2 are also examined with the order of aircraft A and B reversed and the sign of the output values reversed. Hence, if these reverse order propositions are formally added to this table, the actual number of propositions is doubled.

The input variables are the normalized separation distance (NSD), relative ground speed (ΔV_G), relative separation (Δd), and relative altitude (Δh). NSD is either referenced to track (TRK) or to the first common time point (FCTS). The FCTS is the earliest time both aircraft are predicted to reach the same flight path segment; or equivalently, the first time they both belong to the same spatial constraint. Since aircraft may merge from separate segments onto a common segment at different times, the FCTS is a convenient reference point.

Table 2 Ordering and Merging Procedure of a GENERAL-Type Spatial Constraint

Number	Proposition	Input Variable	Consequent	Output Value
1	A is significantly ahead of B at FCTS	NSD_{FCTS}	A is significantly favored	45
2	A is ahead of B at FCTS	NSD_{FCTS}	A is favored	30
3	A is slightly ahead of B at FCTS	NSD_{FCTS}	A is slightly favored	15
4	A is ahead of B at current position	NSD_{TRK}	A is slightly favored	15
5	A is faster than B at FCTS	ΔV_G	A is marginally favored	7.5
6	A is lower than B at current position	Δh	A is marginally favored	7.5
7	(A is close to B) AND (A is faster than B at FCTS)	Δd & ΔV_G	A is slightly favored	15

Each proposition in Table 2 produces either a positive or negative consequent function output value, depending on which proposition is correct. These output values also are assigned a variable weight (0 to 5) which depends on the degree to which the proposition is satisfied (degree of membership) for the two aircraft.

The decision on whether to maintain the current order or reverse the order of these two aircraft is determined by the weighted sum of the output values from all proposition-consequent function pairs of this GENERAL-Type Spatial Constraint. Hence, if the weighted sum is negative, the current order of the two aircraft is reversed.

From Table 2, the membership function: "A is faster than B at FCTS", and its associated consequent function: "A is marginally favored, " is illustrated in Figure 11.

In this example, aircraft A is 75 knots faster than aircraft B. This leads to a membership and consequent value of 0.67. The output value for this membership-consequent function pair is then +7.5. The weight associated with this output is the shaded area which equals 4.4 out of a maximum weight of 5.

In addition to the membership functions of Table 2, the FINAL-Type Spatial Constraint involves several additional input variables which include the relative ETA. Of the ten input functions, used by the GENERAL-type and FINAL-type spatial constraints, six depend on ground speed.

Relative Ground Speed Figure of Merit

The relative ground speed membership and consequent function pair is illustrated in Figure 12. The left-hand membership function ('B is faster than A') is used with the left-hand consequent function ('B is marginally favored over A'). While the right-hand membership function ('A is faster than B') is used with the right-hand consequent function ('A is marginally favored over B').

For the negative relative ground speeds less than -25 knots, the output value is -7.5. For the positive relative ground speeds greater than 25 knots, the output value is: 7.5. Otherwise, the output value is zero.

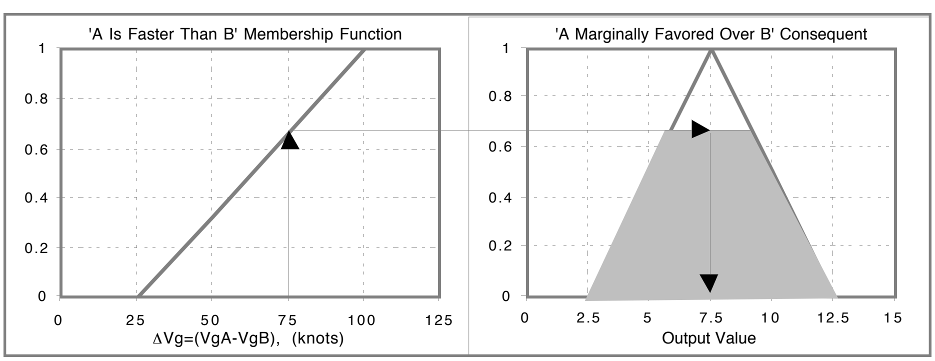

Figure 11. Obtaining an Output Value for a Specific Input Value

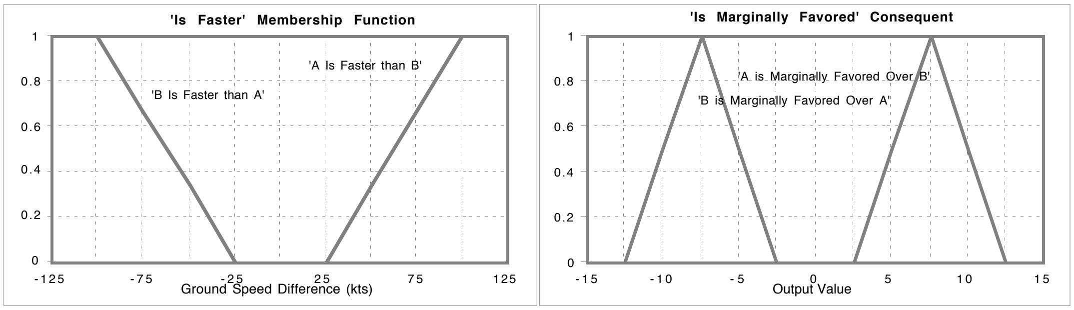

Figure 12. Relative Ground Speed Membership and Consequent Functions

For the relative ground speed membership-consequent function pair, the decision error cases shown in Table 3 may occur. The figures of merit are then defined as the probability that each of these error cases will occur. For Case 1, the error cases are illustrated in Figures 13. A secondary consequence of the uncertainties in the relative ground speed estimates is that it introduces an uncertainty in the output weighting function.

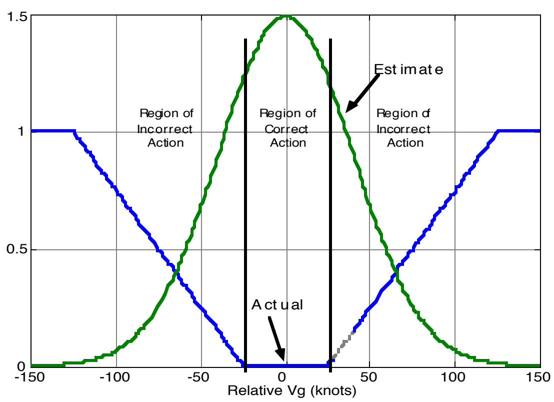

Figure 13. Figure of Merit for Relative Ground Speed in Deadband (Case 1)

In Figure 13, it is assumed that the estimated relative ground speed has a Gaussian probability density function (pdf). Furthermore, it is assumed that this pdf has a mean value which equals the actual relative ground speed. This pdf has been arbitrarily scaled up for clarity in this figure.

In Table 3, the distinction is made between: a) keeping the same order (output is 7.5), b) reversing the order (output is -7.5), or c) taking no action (output is zero). This distinction becomes important when the individual weighted output values are summed to obtain a decision for an Ordering or Merging Procedure for these two aircraft.

To evaluate these figures of merit, consider two aircraft which are nominally spaced one minute apart with zero actual relative velocities. This case corresponds to a normal situation requiring no traffic controller action.

When the $\alpha-\beta$ tracking filter errors are introduced, the relative velocity error statistics histories of Figure 14 are obtained. This figure shows that the relative velocity mean error can vary between –/+30 knots while the standard deviation reaches a maximum of 9 knots.

Since under normal conditions, the relative velocity between two neighboring aircraft is zero, the Case 1 figure of merit is more likely to occur. Hence, using the relative velocity statistics of Figure 14 to evaluate the Case 1 figures of merit, the probability histories of Figure 15 are obtained.

Table 3 Relative Ground Speed Decision Error Cases

Case	Actual ΔV_G	Estimated ΔV_G	Action Taken	Action Required
1 a 1 b	–25 kts < $\Delta V_{G,A}$ < 25 kts	ΔV_G < –25 kts ΔV_G > 25 kts	Reverse order Keep order	None
2 a 2 b	$\Delta V_{G,A}$ < –25 kts	–25 kts < ΔV_G < 25 kts ΔV_G > 25 kts	None Keep order	Reverse order
3 a 3 b	$\Delta V_{G,A}$ > 25 kts	–25 kts < ΔV_G < 25 kts ΔV_G > –25 kts	None Reverse order	Keep order

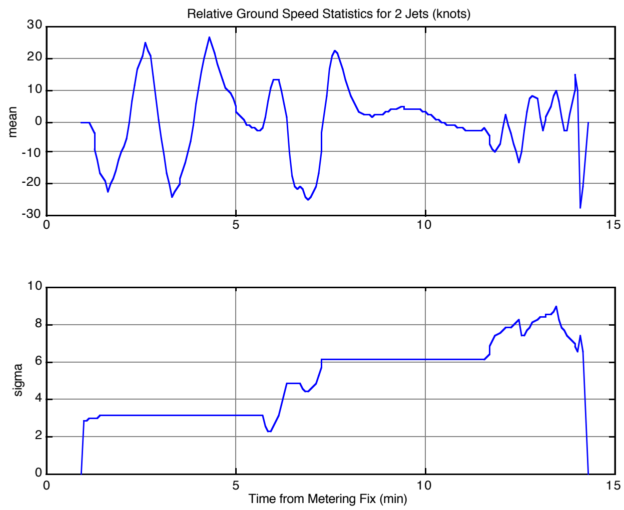

Figure 14. Relative Ground Speed Error Statistics Histories

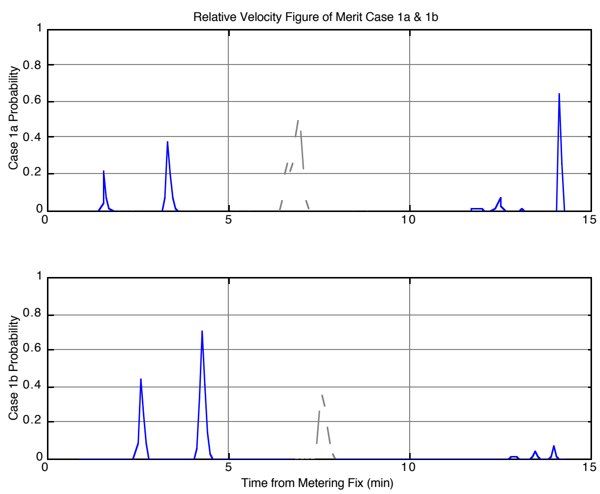

Figure 15. Relative Ground Speed Figure of Merit Histories (Case 1)

Figure 15 shows that the probability of a Case 1a event can peak as high as 65%, while for a Case 1b event it can peak as high as 70%. The significance of these spikes can only be determined by evaluating the remaining membership-consequent function pairs for that GENERAL-type spatial constraint and computing a weighted decision score.

Relative ETA Figures of Merit

The relative ETA's between two neighboring aircraft which are in-trail on the same flight path segment is described by the membership and consequent functions shown in Figure 16. This membership-consequent function pair is part of the Merging Procedure of a FINAL-Type Spatial Constraint.

For the relative ETA magnitude ($|\tau_{AB}|$) between 0 and 60 seconds, the output value is 7.5. Otherwise, the output value is zero and has zero weight. For this membership-consequent function pair, the error cases summarized in Table 4 may occur.

Case 1 corresponds to the situation where the actual relative ETA magnitude is close to zero, and hence the membership is 1 or a "yes". The estimated relative ETA magnitude, however, is large enough (close to 60 seconds or greater) to produce a membership of 0 or "no."

Case 2, is illustrated in Figure 17, corresponds to a more typical situation. In this case, the actual relative ETA magnitude is close to 60 seconds and hence the membership is 0 or "no." The estimated relative ETA magnitude, however, is close to 0 to produce a membership of 1 or "yes."

An alternate choice for these decision error cases might be based on selecting three regions corresponding to: 0 – 20 sec., 20 – 40 sec., and > 40 sec. Hence, the first region would correspond to a predominantly "yes" region. The last region would correspond to a predominantly "no" region. Finally, the middle region would correspond to an indeterminate or transition region. Clearly, these ETA decision error cases are less distinct than those for the relative ground speed.

To evaluate these figures of merit, consider the same two aircraft, from the last section, whose relative ETA is one minute. Their estimated relative ETA history is presented in Figure 18. This figure shows that the mean estimated relative ETA, which should be a constant one minute, can briefly vary between -0.5 and 2.5 minutes. The standard deviation of this estimate also reaches a maximum of 0.25 minutes.

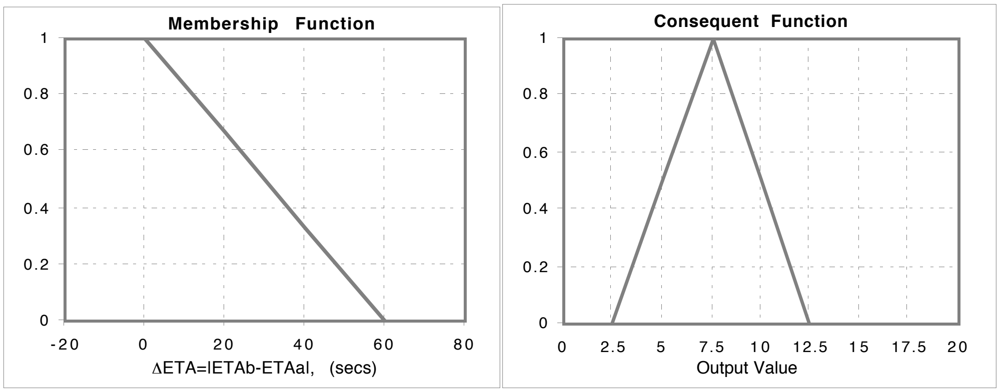

Figure 16 "Have In-Trail ETA's" Membership and Consequent Functions

Table 4 Relative ETA Magnitude Decision Error Cases

Case	**Actual Magnitude of τ_{AB}**	**Estimated Magnitude of τ_{AB}**	**Estimated Membership**	**Actual Membership**
1	$\lvert\tau_{AB,ACTUAL}\rvert < 30$ secs	$\lvert\tau_{AB}\rvert > 30$ secs	No	Yes
2	$\lvert\tau_{AB,ACTUAL}\rvert > 30$ secs	$\lvert\tau_{AB}\rvert < 30$ secs	Yes	No

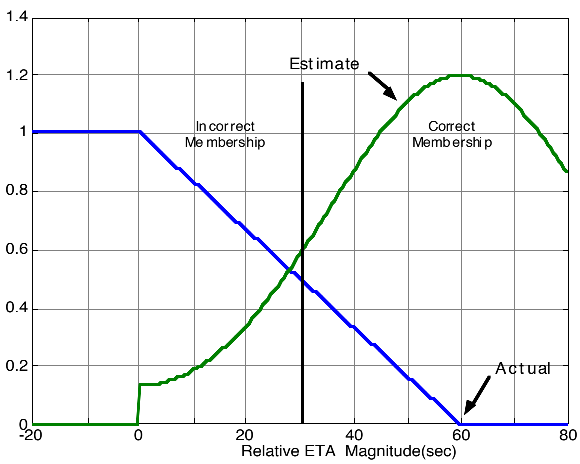

Figure 17. Figure of Merit for Relative ETA (Case 2)

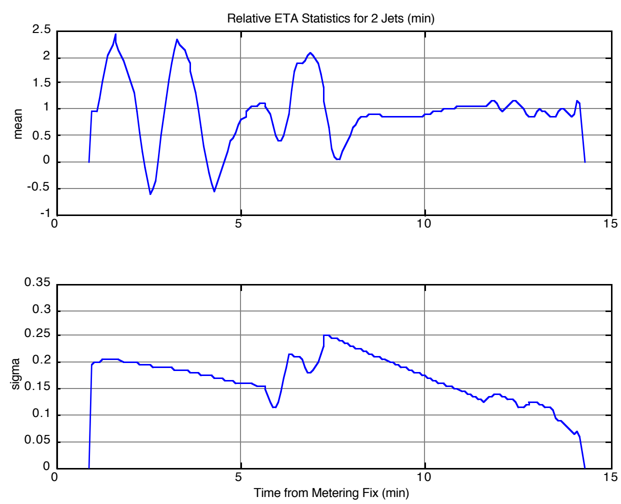

Figure 18. Estimated ETA Difference Statistics Histories (1 minute nominal spacing)

Using these statistics histories, the relative ETA curve of Figure 19 is obtained for the Case 2 figure of merit. This figure shows that the probability of a Case 2 decision error event can peak to greater than 90%. The significance of these results cannot be determined without evaluating the other membership-consequent function pairs for this FINAL-Type Spatial Constraint.

Summary and Conclusions

It was determined that significant velocity estimation error transients are introduced by the ARTS radar tracking software during aircraft speed and heading changes. These errors arise primarily due to the fact that the ARTS radar only measures the slant range and azimuth angle. Hence, the $\alpha-\beta$

tracking filter software uses sequential position measurements to estimate the aircraft ground speed. The radar tracking software also assumes that the aircraft velocity is constant during the 4.6 second radar sweep interval. These approximations introduce unmodeled radial and lateral acceleration errors which corrupt the aircraft ground speed estimates.

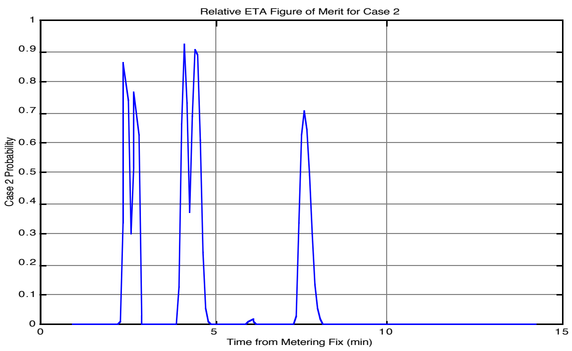

Figure 19. Relative ETA Figure of Merit Histories (Case 2)

As a result of these modeling errors, ground speed estimation rms errors were found to reach 25 knots during speed and heading maneuvers using the radar $\alpha-\beta$ tracking filter software. However, using a Kalman filter, in place of the $\alpha-\beta$ tracking filter, the ground speed estimation rms error can be maintained at 5 knots or less throughout the TRACON area.

In the analysis of the FAST software, it was determined that these ground speed errors corrupt six of the ten input variables used by the FAST SL logic. Hence, these ground speed errors may contribute to an incorrect decision result for a particular fuzzy logic membership-consequent function pair.

A simulation of the ETA estimation errors, which are a function of the ground speed errors, indicates that the mean ETA errors become significant during aircraft heading and speed changes. For example, a 1.5 minute ETA rms estimation error can occur during the first two speed maneuvers in the TRACON, with the current radar tracking software. If the Kalman filter tracking software is used, this ETA rms estimation error is reduced to less than 0.4 minutes.

For both the relative ground speed and the relative ETA FAST SL membership-consequent function pairs, figures of merit were defined. These were defined as the probability for the occurrence of a particular decision error. When the figures of merit for the relative ground speed and the relative ETA were evaluated, it was determined that the probability for the occurrence of some of the associated decision error cases can be significant during aircraft heading and speed maneuvers. The impact of these figure of merit probability transients could not be determined without further analysis of the remaining membership-consequent function pairs of the respective Spatial Constraint.

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