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Use of Linear Aircraft Intent Response for Tactical Trajectory Based Operations

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Abstract — **A method is proposed for exchanging information that allows a ground system to estimate the aircraft intent response to a ground instruction. This method approximates the intent response as a linear function of ground instruction parameters. The approach is described and applied to the case of an aircraft in climb subject to a controlled time-of-arrival. When subject to either lateral maneuvers or altitude constraints, the provision of the aircraft intent response allows for significant improvements in prediction accuracy. Over a 150 nautical mile look-ahead horizon, accuracy is improved between 34% to 81% in the lateral maneuver case and 71% to 93% in the altitude maneuver case. Improved knowledge of the expected intent response allows ground systems to develop more accurate trajectories for application to tactical functions such as separation and trajectory management in higher density environments.**

Keywords-aircraft intent,trajectory, trajectory-based operations, accuracy.

I. INTRODUCTION

One of the major transformations in the Next Generation Air Transportation System (NextGen) is “the use of trajectory-based operations (TBO) as the main mechanism for managing traffic in high-density or high-complexity airspace” [1]. This transformation is predicated on the ability to create, exchange and execute four-dimensional trajectories (4DTs). We first discuss some issues related to these important capabilities.

With regards to the ability to create a 4DT, two important considerations are relevant to the work presented here: the desired level of fidelity, and the information available to the entity responsible for creating the 4DT. When one refers to the ability to create a 4DT, implicit in this statement is the requirement that the trajectory that is executed by the flight is within some required tolerance of the created 4DT. The ability of an entity to accomplish this is dependent on the quality of information that is available to it when creating the 4DT. For ground systems, this information includes the reaction of the flight to modifications or constraints.

On the issue of exchange of a 4DT, the required form of the exchanged information is strongly dependent on the intended application. If the recipient is a ground system seeking to conduct conflict detection, a 4DT specifying the future flight path is desirable. If the recipient is a ground-based decision support system providing a decision that will alter the trajectory, just having the unaltered 4DT will not suffice. Finally, with an aircraft as a recipient, information must be provided that allows the aircraft to execute the desired 4DT.

The execution of a 4DT by the aircraft requires first that the trajectory be feasible. For climbing and descending flight, information used to generate the trajectory must be accurate. Even if a 4DT is feasible, the information provided to the aircraft to execute that trajectory will not likely be the flight path unless there is a significant departure from current aircraft guidance and control methods.

The NextGen Concept indicates that the 4DT is expected to be used to perform certain processes such as Separation Management (SM) and Trajectory Management (TM). Both of these will alter the 4DT to achieve their objectives.

The Trajectory Management process manages trajectories to ensure efficient trajectories within a flow. Objectives include: management of flow complexity, assignment of limited resources, and management of trajectories transitioning to/from different operational realms (e.g., flow corridors, self-separation operations).

Under TBO, Separation Management relies on automation to ensure separation from other aircraft, designated airspace and other hazards (e.g., weather, terrain or other obstructions). Automation is used to identify conflicts and solutions. Solutions provided by automation will have to consider and apply downstream trajectory constraints imposed by TM. These can include time, speed or altitude constraints.

In this effort, we focus on a specific circumstance: the creation and exchange of 4DT by tactical ground-based decision support systems. These systems would typically support the TM and SM functions described above.

The focus on tactical systems is a result of the time available to create a feasible solution. In a strategic environment, significant cooperation can occur, allowing iteration with a 4DT generated by the aircraft operator.

This effort was produced while employed at CSSI Inc. under contract for the Federal Aviation Administration.

For the case of a tactical, ground-based decision support system (DSS), the ground system must be able to:

- Obtain and use a 4DT to determine if a problem exists requiring a trajectory modification.
- Create a new, feasible and accurate 4DT that solves the predicted problem.
- Provide information to the aircraft resulting in an executed 4DT within tolerances of the created 4DT.

One of the difficulties of the above task is that the direct manipulation of the trajectory by a ground system will not easily lead to a feasible and accurate 4DT. Typically, input variables to a trajectory generation process must be varied. In order for the third bullet to be realized, both the air and ground information and trajectory generation processes must be well synchronized to ensure that the resulting executed 4DT will resemble the 4DT generated by the ground system. This issue is described in more detail below.

This paper describes an approach for improving the feasibility and accuracy of the ground-generated 4DT. The approach assumes the communication from air to ground of the Aircraft Intent Response (AIR) to a candidate set of controller actions.

II. USE OF 4DT

A. Obtaining the 4DT

Trajectory based operations are based upon knowledge, by automation, of a 4DT to a level of precision required. We consider the trajectory as the future time evolution of the aircraft state vector. The precision of such a trajectory will depend on many factors ([2]-[11]). One of these factors is the accuracy and extent of input information including the aircraft intent ([12]-[14]).

To understand aircraft intent, instructions and constraints are often specified to the aircraft in a manner that allows flexibility and ambiguity on the trajectory. As examples: point constraints (e.g., altitude or time) can be reached through a multitude of flight paths; flights have significant latitude on meeting specified speeds; and there are several modes available for climbing and descending. Aircraft intent represents unambiguously how the aircraft will fly after decisions have been made by the operator, flight crew and aircraft systems (e.g. Flight Management Computer (FMC)). Given this information, the aircraft trajectory is entirely dictated by the physics of the situation. Figure 1 illustrates the process.

It is assumed that a 4DT can be obtained from an entity with access to the aircraft intent information and a good model of the physics. This may be the aircraft itself, a ground system with detailed knowledge of how to determine aircraft intent, or a ground system provided with the aircraft intent.

With the aircraft intent, the aircraft can execute the intent with a resulting trajectory matching the predicted 4DT within the accuracy limits of the physical models.

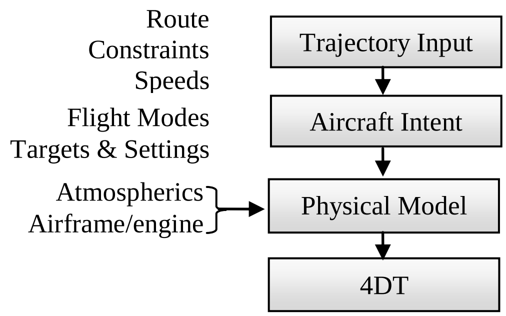

Figure 1. Obtaining the 4-D Trajectory

A ground system executing TM or SM functions would use the 4DT to diagnose whether a trajectory adjustment is required.

B. Altering the Trajectory

Once a trajectory adjustment is required, ground-based systems operate on the trajectory input so as to provide the aircraft with the degrees-of-freedom necessary to meet specified constraints. Furthermore, a direct manipulation of the aircraft intent is not always possible. With this approach come ambiguities on the resulting aircraft intent and 4DT.

As an illustration of ambiguities, consider a flight on descent subject to a predicted conflict using the nominal 4DT. A DSS responsible for separation management will test cases by altering the route or imposing constraints. In order to determine if these lead to conflict-free trajectories, the DSS must determine the 4DT after the proposed changes. For example, an altitude constraint may force an early descent. If this was imposed, the aircraft may have to alter its speed profile to meet a desired time of arrival. Since there are many possible solutions to the speed profile, it is a challenge for the DSS to predict the resulting aircraft intent response.

One could attempt to tightly control the resulting trajectory by imposing speeds; however since operator preferences are not known, the resulting profile may not be desirable. As an alternative, this work proposes communication of a linear aircraft intent response. This provides the change in aircraft intent variables as a linear function of a parameter known to the ground. The parameter depends on the nature of the instruction (e.g., path-stretch, time/altitude constraint) as described below.

III. AIRCRAFT INTENT RESPONSE

The concept of aircraft intent has been discussed in the literature and at symposia ([15]- [19]) as a means of providing an unambiguous description of the intent. This can be described at various levels, but the description is fundamentally tied to aircraft dynamics.

Aircraft dynamics and control is a mature field with classic references available (e.g., see [20], [21]). For coordinated flight of conventional fixed-wing aircraft, three degrees-of-freedom can be independently controlled at once. The result is that the aircraft intent can be expressed as targets on three control variables with switching conditions specified when the mode or target changes.

As an example, during a climb, the aircraft intent can specify a constant heading, a target calibrated airspeed and a specified power setting. A switch to a target Mach number can also be specified. When a cruise altitude is reached, the power is switched to target an altitude (See Figure 2).

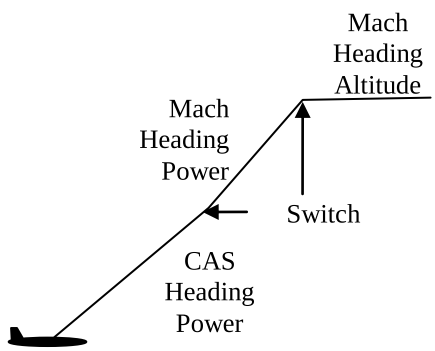

Figure 2. Aircraft Intent in a climb

For the purpose of tactical separation or trajectory management, a ground-based system would typically impose only a limited set of modifications to the flight. These would be: altering the lateral path or imposing altitude, time or speed constraint(s). When a DSS evaluates which modification to impose in a trajectory-based environment, it will do so by first determining the impact of the modification on the trajectory, then determining whether the trajectory achieves the objective.

One may consider a purely constraint-based approach, in which the constraint itself resolves the detected problem. However, in such an environment, the DSS must still ensure that: the constraint is feasible, downstream constraints can still be met, and all possible trajectories meeting the constraint are protected from conflicts. In a very low density environment (e.g., only one crossing flight to be avoided), one constraint per flight is sufficient. However, having a range of possible trajectories requires increased airspace to be protected. This is not desirable in high-density environments.

Generating a constraint that just resolves the initial problem still requires the evaluation of a resulting trajectory. For tactical applications, it is not practical to query the aircraft for a trajectory; in particular it is not clear how the ground system should modify the constraints should the trajectory not solve the problem.

One approach to the above is for the ground system to obtain information that allows it to decrease the range of possible trajectories when the ground imposes a constraint or modifies the route. This information should capture the aircraft intent response to the trajectory modification.

With control actions limited to lateral path changes and constraints on time, altitude and speed, this is a small set of actions for which intent responses may be parameterized. To understand how this can be achieved, we provide some examples.

A. *Response to Lateral Maneuver*

If we consider the climb example provided in Figure 2, a lateral maneuver will result in a change in time of arrival. If the aircraft is subject to a controlled time of arrival (CTA), the speeds must be adjusted to accommodate the change. Even without a CTA, the flight itself may prefer to adjust the speeds slightly to meet its schedule, or to not adjust the speeds at all.

Since multiple speeds can be selected, the solution is not unique. To circumvent this non-uniqueness, the aircraft intent response is communicated. The AIR expresses the linear change in the intent as a result of the lateral maneuver. In this case, the change in the climb CAS is expressed as a linear function of the resulting path-stretch (time or distance). If a time constraint exists, the Mach number would now be unique. Without a time constraint, the target Mach number in the intent description would also be expressed as a linear function of the path-stretch.

In practice the above could be encoded as a specific aircraft intent response template with only one or two additional information items: the slope of the change in CAS and Mach number (if applicable).

B. *Response to Time Constraints*

The imposition of a time constraint at a location is similar to the preceding example. Since the response of the flight will be to alter the speeds in order to meet the times, these can be expressed as a linear function of the change in time required. In this case, pre-determined points would have to be specified, with appropriate interpolation for the imposition of a CTA at a different location.

C. *Response to Altitude Constraints*

An altitude constraint is parameterized with both the duration and the altitude at which the constraint is imposed. However, there are several potential speed responses to this constraint, depending on how the speed is treated during the level-off. Returning to the example in Figure 2, the aircraft may continue at the local target speed during the level segment. Alternatively, the aircraft could accelerate while level to a separate target speed and resume the climb at the new target. Depending on the response, there can be two or three speeds to be selected.

In order to express the AIR, the template of the intent response must be expressed. Two example cases are described below:

- Constant CAS, Mach Climb at climb power. If the level-off occurs below transition: power set to maintain altitude at target CAS. Otherwise, power set to maintain altitude at target Mach. Resume climb at target speeds when level-off end point has been reached.
- Constant CAS, Mach at climb power. If the level-off occurs below the transition: accelerate at specified power to maintain altitude and reach a new target CAS. If the level-off occurs above the transition: accelerate at specified power to maintain altitude and reach a new target

Mach. Resume climb at the new target speeds when level-off end point has been reached.

In the above cases, the new target speeds can be expressed as a linear function of target altitude and initial level-off distance.

D. Using the Aircraft Intent Response

When a ground-based DSS seeks a tactical solution, it can consider the aircraft intent response to an instruction in order to estimate what the aircraft intent will be after the instruction is provided. This work shows that the provision and use of such information improves the accuracy of the resulting trajectory.

In addition to using the aircraft intent response, it is assumed that the ground system will possess a proper model of the limits of intent variables. These include the maximum/minimum allowable speeds and power levels. These may also vary as a function of operational conditions, such as speed due to turbulence penetration. By using these limits, the feasibility of solutions can be evaluated.

Figure 3 illustrates a process for separation management using the aircraft intent, 4DT and AIR. A precise trajectory is used for initial detection. If action is required, SM would consider the application of constraints to resolve the conflict and not create others. The response of the aircraft is estimated using the aircraft intent response. This must consider limits on intent variables, known to the DSS. The trajectory is obtained using an accurate model and the resulting trajectory is evaluated to determine if it meets constraints and is conflict-free within the time window of the SM function. If not, the constraints are altered and the process repeats until a solution is found.

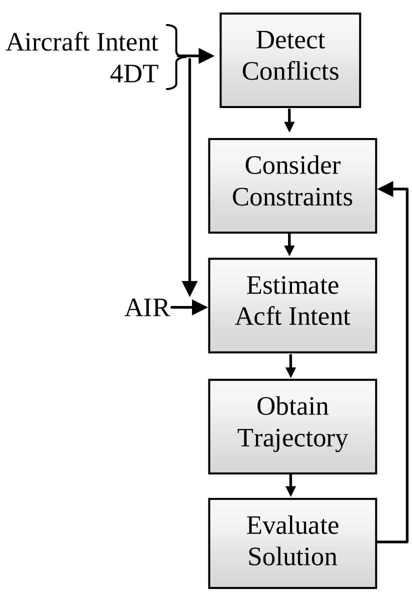

Figure 3. Example use of AIR for Resolution

The above approach is generic and allows for different algorithms to be implemented at each step of the process.

IV. EVALUATION OF APPROACH

The proposed approach of using the aircraft intent response to improve the prediction of a post-instruction trajectory was evaluated in simulation. Two cases were investigated: a path-stretch and an altitude hold in climb. For each case, scenarios were constructed with a minimum cost objective on the aircraft side. The linear aircraft intent response was developed and trajectory obtained. This was compared to the trajectory using the optimized aircraft intent response. The comparison applied specific accuracy metrics. The accuracy was then compared to range of feasible solutions when the intent response is unknown.

A. Path Stretch Response

This scenario investigated the behavior of an aircraft in climb subject to a controlled time of arrival at a fixed location. The flight is operating at 10,000 feet and 250 knots and will climb to a specified cruise altitude at climb power. The flight will accelerate to a specified CAS while climbing by using a specified energy share factor (ESF). The flight will climb at a target CAS. Upon reaching a target Mach number, the flight will continue climbing at that target Mach and level off at the cruise altitude.

When the flight is provided a path-stretch, the need to meet a controlled time of arrival requires an increase in the target climb speeds during climb. However, as multiple solutions are possible, the linear aircraft intent response to the estimated delay at the CTA point is used to estimate these target speeds.

In this scenario, the aircraft uses a cost index (CI) to determine the climb speed schedule. The CI is adjusted to meet the CTA, and the target CAS/Mach values are specified in the intent. The CI expresses the ratio of the time to the fuel cost and is used to determine the total cost as follows:

$$Cost = Fuel + 100 \cdot CI \cdot Time \qquad (1)$$

The aircraft intent response to a path-stretch is computed by determining the sensitivity of the speeds (CAS/Mach) to the estimated arrival time at the CTA point, as the CI is increased.

Nine cases were investigated involving an aircraft operating at three different weights operating to three different cruise altitudes. Figure 4 illustrates the climb CAS versus the estimated arrival time at the CTA point as the CI is varied. Various weights are shown at a cruise altitude of 29000 feet. The nominal case had an arrival time of 1300 seconds. The linear AIR for the climb CAS would be the slope at 1300 seconds. This indicates the speed change required to still meet the CTA as a linear function of the delay due to the path-stretch.

The figure shows that the CAS is limited to 340 knots and has a slight nonlinearity. Other cruise altitudes exhibited similar behavior.

The Mach number behavior is shown in Figure 5. Two approaches were investigated, one in which the climb Mach intent is obtained from the linear response. However, in this case the CTA is not met due to nonlinearities. The second approach computes the required Mach number to reach the CTA assuming the linear response climb CAS.

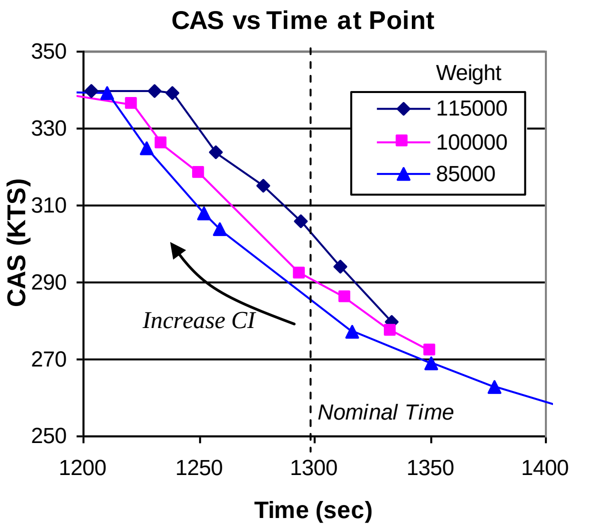

Figure 4. Climb CAS versus estimated arrival time at CTA point as vary Cost Index for various weights (in lbs.). Cruise altitude target of 29000 feet.

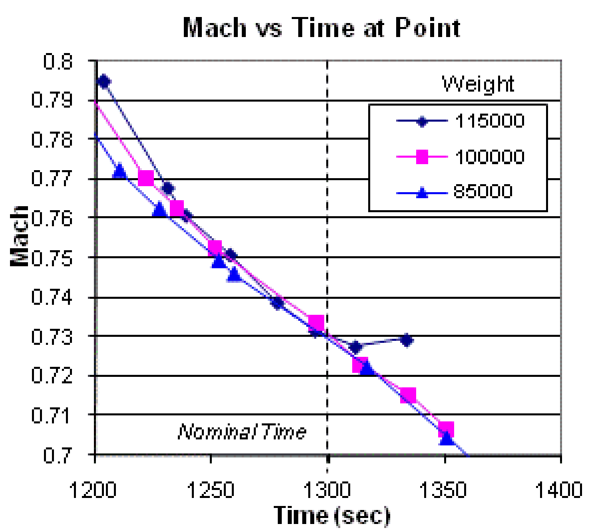

Figure 5. Climb Mach versus estimted arrival time at CTA point as vary CI for various weights (in lbs). Cruise altitude target of 29000 feet.

B. Path Stretch – Range of Solutions

Given the path stretch scenarios described previously, an exhaustive search was conducted on the combinations of CAS and Mach meeting the CTA. Each possible solution was compared to the modeled aircraft trajectory, accuracy metrics were obtained and statistics derived as described below.

C. Accuracy Measures Investigated

Many approaches for trajectory comparison metrics have been described in the literature ([22]-[24]). In this study, the following basic measures are applied:

- **Along-track position error** – The along-path distance error when reaching a specified event.
- **Time error** – The error in the time required to reach a specified event.
- **Altitude error** – The difference in altitude reached at a specified event.

The specified events being considered are: reaching a time, altitude or distance along-path. It is recognized that many of these measures are highly correlated ([25],[26]). The peak error in each is reported. As seen in Figure 6, the altitude error is shown as the difference in altitude between the aircraft trajectory and a predicted one at a specified time. The peak altitude error would be reported as the maximum value over the prediction horizon.

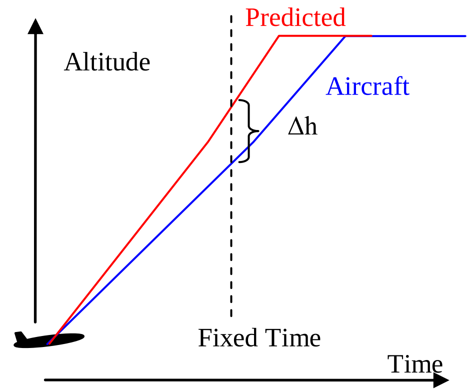

Figure 6. Altitude error at time

Comparison of each flight case provides a peak error metric. An RMS value is taken across all flight cases considered in a scenario. Thus, the peak refers to the peak error for an individual flight, but the RMS is over multiple flights comprising a scenario.

Cross-track error was not considered as errors in aircraft intent response are not expected to contribute to these (other than through coupling).

D. Altitude Hold response

This scenario investigated the behavior of the same nominal scenario described previously; however the flight is subject to an altitude constraint during the climb. The constraint is provided at a specific location.

When this flight is provided an altitude constraint, the aircraft intent response is assumed to follow the pattern illustrated in Figure 7. Upon reaching the constrained altitude, the flight maintains the altitude and accelerates to a new speed at a fixed power level. When the new speed is reached, the speed is held constant. Upon reaching the end of the constrained altitude, the climb resumes at the new speed and climb power, until a target Mach number is reached. Climb continues at this target until the flight is level at cruise. If the altitude is above the initial transition altitude, acceleration will occur to a new target Mach number.

For this scenario, the speed schedule for the aircraft is obtained by exhaustively searching speed combinations that lead to a minimum fuel solution. Speed combinations are not searched across the entire envelope, it is assumed that the level-off speed must be equal-to or greater than the preceding climb segment speed. The altitude of the level-off segment relative to the nominal CAS/Mach transition altitude, and relative to the Tropopause, will determine whether climb speeds will increase or decrease.

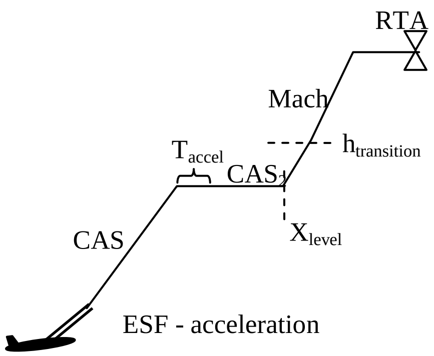

Figure 7. Aircraft intent response to altitude constraint

Each intent variable under consideration can be expressed in terms of a mathematical model expressing a relationship with the level-off altitude, extent of the level-off and bounds. For example, the CAS after the level-off can be expressed as the following bounded function:

$$V_C = \begin{bmatrix} 1 & \Delta x \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} 1 \\ h_{level} \end{bmatrix}$$
$$V_{CAS_2} = max\{V_{min}, min(V_{max}, V_C)\} \quad (2)$$

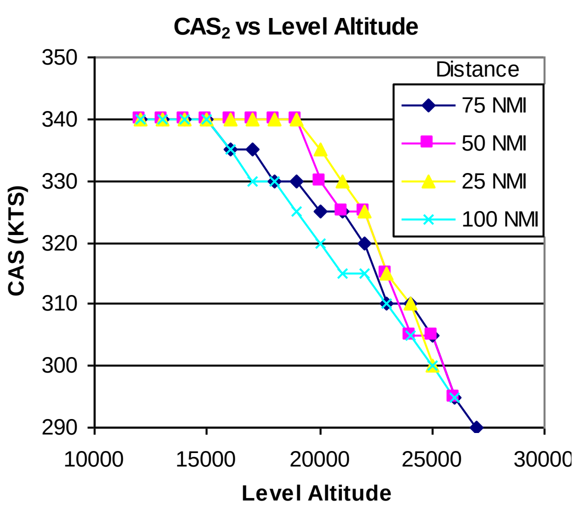

Figure 8. Response in level-off CAS vs altitude and distance of resumption of climb

For a specific case (e.g., specified aircraft model, fixed weight and cruise altitude), Figure 8 illustrates the variation of the CAS during the level-off segment. The figure shows the variation as a function of the altitude and distance at which the climb is resumed (X_{level} in Figure 7). Note that this speed only applies at level-off altitudes below the CAS/Mach transition. Figure 9 illustrates the quality of the above mathematical expression for various distances of level-offs.

In this example, the other intent variables: Mach number in climb and CAS prior to the hold can also be expressed in the above manner. Since a CTA is imposed, only one of the variables needs to be expressed as such, as the CTA provides a unique solution of the remaining intent variable. Figure 10 provides a description of the initial CAS variation. In this case, there is a small variation of the maximum limit with distance.

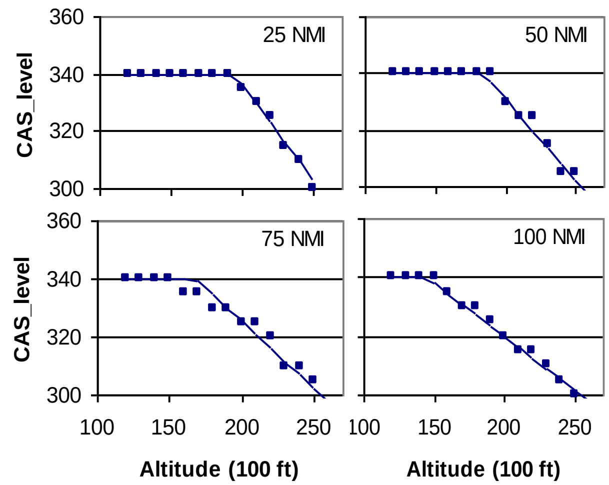

Figure 9. Approximation of level-off CAS versus altitude for various distances

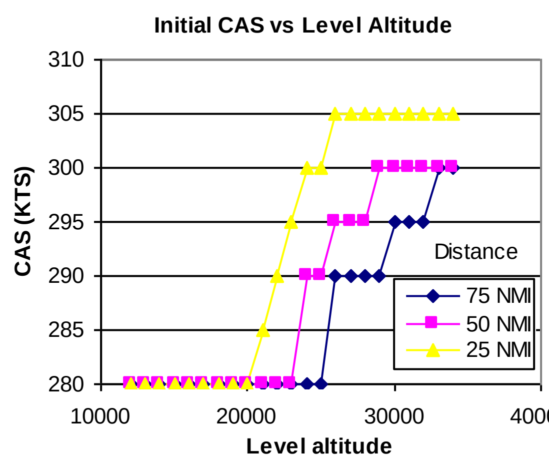

Figure 10. Response in initial CAS versus level-off altitude and distance of resumption of climb

E. Altitude Hold – Range of Solutions

As for the path-stretch scenario, an exhaustive search of the intent variables identified the possible solutions that would meet the CTA. However, assumptions on reasonable solutions were placed. This included limiting the speeds to monotonically increasing choices.

V. RESULTS

Results are presented and discussed for both the path-stretch scenario and the altitude hold scenario discussed previously.

A. Path Stretch - Results

The path stretch case was evaluated in the case of a path stretch leading to a 40-second and 80-second arrival delay at a CTA point established at 150 nautical miles from the start. We compare the RMS error across several metrics. The aircraft solution was compared to several solutions:

- The intent based upon the linear aircraft intent response in both the climb CAS and Mach (Linear CAS/Mach).
- The intent based upon the linear aircraft intent in just the CAS, with the Mach number computed based upon the required solution (Linear CAS only).
- All feasible climb CAS/Mach solutions that met the CTA (Range).

Table 1 provides a comparison of the results across various metrics for the 40 second and 80 second delay cases. The "X-sync" indicates that the metric compares trajectories at the same along-track points; "H-sync" is compared at the same altitude and "T-sync" at the same time.

Using the linear response in both the CAS and Mach yields solutions that do not meet the CTA constraint for the 80 second path-stretch case (within a 17.4 second RMS, versus < 5 seconds in other cases). Using a linear model to remove the ambiguity and solving for the second intent variable to meet the constraint allows the time constraint to better be met. This second approach provides peak error metrics that are reduced from 34% to 81% over the situation without knowledge of intent.

This result implies that a ground system using the linear Aircraft Intent Response would be able to apply the ground-generated solution using smaller buffers than without AIR. For tactical separation management functions, this leads to more efficient maneuvers and potentially higher capacity.

TABLE I. ERROR METRICS (RMS) FOR PATH-STRETCHING SCENARIOS COMPARING USE OF LINEAR AIRCRAFT INTENT RESPONSE TO SOLUTIONS WITHOUT KNOWLEDGE OF AIR

Case	**Delay (sec)**	**Peak Time (sec)**			**Peak Distance (NMI)**		**Peak Altitude (Feet)**	
		At CTA	***X-sync***	***H-sync***	***T-sync***	***H-sync***	***X-sync***	***T-sync***
Linear CAS, Mach	40	4.94	7.18	10.87	.904	1.36	366	308
Linear CAS only	40	0.31	5.94	9.55	.744	1.21	347	289
Range	40	3.58	14.64	49.7	1.83	5.71	882	810
Linear CAS, Mach	80	17.4	18.94	36.45	1.20	5.64	858	602
Linear CAS only	80	2.10	9.45	13.53	2.51	2.06	567	325
Range	80	3.79	12.73	43.03	1.64	4.98	931	777

B. Altitude Hold - Results

The altitude hold scenario described previously was evaluated for the test cases of an altitude hold lasting until the 50 and 75 nautical mile along-track point. As for the lateral path-stretch scenario, a controlled time of arrival at the 150 nautical mile point was imposed. The aircraft was assumed to respond to the altitude hold by seeking a minimum cost solution. The aircraft follows a procedure as illustrated in Figure 7 and optimizes for the parameters.

This procedure assumes an environment with data communication in which an altitude constraint at a fixed point would be provided for separation management. Two scenarios were compared to the aircraft response:

- The linear aircraft intent response was used to estimate the choice of intent parameters.
- All feasible solutions as described previously were considered.

The scenarios considered a flight with an altitude hold at any altitude from start to cruise in 1000-foot increments.

Table 2 shows the error metrics for the various cases considered. All scenarios met the CTA within 7 seconds. The provision of the linear AIR allows for a significant reduction of RMS peak errors in this set of scenarios. These peak errors are reduced by 71% to 93%.

A ground-based decision aid providing an altitude instruction (level until 50 NMI) would have a peak along-track error of 3.4 nautical miles. The peak altitude error would be 2315 feet. With the provision of the linear aircraft intent response, the peak along-track error can be reduced to 0.5 NMI, and the peak altitude to just 157 feet.

Note that the reported errors are those resulting explicitly from the lack of precise aircraft intent on the ground. There are other trajectory prediction errors that would occur in addition to the intent errors.

TABLE II. ERROR METRICS (RMS) FOR ALTITUDE HOLD SCENARIOS COMPARING USE OF LINEAR AIRCRAFT INTENT RESPONSE (AIR) TO SOLUTIONS WITHOUT KNOWLEDGE OF AIR

Case	**Level distance (NMI)**	**Peak Time (sec)**			**Peak Distance (NMI)**		**Peak Altitude (Feet)**	
		At CTA	***X-sync***	***H-sync***	***T-sync***	***H-sync***	***X-sync***	***T-sync***
Range	50	4.2	27.9	67.3	3.35	6.43	1476	2315
Linear Response	50	4.4	4.5	4.9	0.52	0.61	166	157
Range	75	4.7	24.0	75.2	2.91	8.14	1620	2259
Linear Response	75	6.8	7.0	8.32	0.82	1.04	364	266

VI. CONCLUSIONS

The use of trajectory-based operations can require that a ground system be capable of altering a 4D trajectory. However, direct variation of the trajectory itself is not possible as the trajectory is constrained by aircraft dynamics and performance limits. Furthermore, the ground system does not wish to over-constrain the flight, as the aircraft operator may have some flight objectives they seek to optimize.

Since direct variation of the trajectory itself is not feasible, a method is required that allows the ground system to unambiguously predict the impact of instructions on the trajectory. This method must also ensure that the proposed instructions are feasible. For tactical instructions, time is assumed to preclude negotiation. A method using the linear Aircraft Intent Response (AIR) to controller instructions has been proposed herein. Using the linear AIR, the ground system does not need to be aware of the optimization variables used by the flight deck

The linear AIR approach has been applied to an aircraft in climb subject to a controlled time-of-arrival at a downstream point. Both a path-stretch and an altitude hold maneuver were described. In both cases, a response on the part of the aircraft was assumed based upon the aircraft seeking an optimal solution. The aircraft intent response is expressed in terms of linear functions of the controller response variables.

For the path-stretch scenario, expressing the intent response to a sufficient level of detail to remove the intent response ambiguity yielded lower error over describing the linear response of all intent variables.

Results show that through use of the linear AIR, errors in the predicted trajectory due to unknown aircraft intent can be significantly reduced for both the path-stretch and the altitude hold scenarios. Metrics (RMS peak along-track, time and altitude errors) are reduced from 34% to 81% in the path-stretching case and 71% to 93% in the altitude hold case.

The lack of an accurate prediction of the resulting 4DT does not prevent the ground system from taking action. However, as the accuracy improves, fewer buffers are required to ensure separation. This allows the solutions to be developed and applied in a higher density environment.

This effort has demonstrated the application of the linear AIR approach for “what-if” trajectory analysis. However, additional effort is required for this concept to be applied further. The full range of aircraft intent conditions, and candidate aircraft intent responses to ground-issued instructions would need to be explored.

ACKNOWLEDGMENT

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