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Structuring Criteria for Automated Separation Assurance

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Abstract

A careful look at separation criteria defined in today's ATM systems reveals a need to create a more rational structure for future automated Separation Assurance Systems (SAS). The new structure turns out to be more complex than one might think since there are two major methods of accomplishing SAS. First, there are strategic methods which can be called CONFLICT MANAGEMENT (using another ATC function eligible for automation called CONFORMANCE MANAGEMENT). Second, there are tactical methods which will be called ENCOUNTER MANAGEMENT here.

In describing the operational possibilities for ENCOUNTER MANAGEMENT, there appear to be four separation criteria which are needed for the operation of SAS - all of which are strongly dependent on the accuracy of predictions of the future paths of aircraft. These four criteria are described in this paper.

Generic ATC Functionality

The context for this paper is a generic description for the functionality and information flows for generation of ATC Clearances in a sector taken from Reference 1. It is postulated that there are five major functions in ATC:

1) Conformance Management
2) Separation Assurance
3) Congestion Flow Management
4) Flight Plan Generation
5) Flight Plan Data Management

These functions are highly inter-dependent, and the flow of information between them as they work together to convert Flight Plan Requests into ATC Clearances is shown in Figure 1. Also shown are the necessary input information such as aircraft performance, wind/weather, ATC criteria and procedures, ATC capacities, Flight Plans from other ATC sectors and facilities, surveillance data, etc. As can be seen, there are four feedback control loops in the information flows;

1) Conformance Control Loop,
2) Congestion Management Loop,
3) Conflict Management Loop,
4) Encounter Control Loop.

These last two loops are used to perform Separation Assurance.

Separation Assurance

Separation Assurance can be divided into two different functions:

1) **Conflict Management,** which is a strategic planning function dealing with conflicting flight plans and clearances; and

2) **Encounter Management**, which is a tactical real-time operating function which can be further divided into two types:

2a) **Hazard Management** which deals with potential short term violations of separation criteria (say less than 1 minute); and

2b) **Intrusion Management** which makes longer term projections of aircraft trajectories to identify potentially hazardous encounters which are 1 to 20 minutes away.

Both types of Encounter Management have Monitoring and Resolution Processes, but Intrusion Resolution (unlike the shorter term Hazard Resolution which must intervene quickly to resolve the Hazard event) has three distinct resolution options (as described later):

1) **Defer**;
2) **Advise**; and
3) **Intervene**.

It is the Intrusion Resolution Process and its Options which lead to the four new Separation Assurance criteria described in this paper. The basic problem is how to deal with the uncertainty of the predictions for the future paths of aircraft; over a longer Time-to-Go; and consequently, the larger, time-varying uncertainty of the predicted separation at passage.

Uncertainty in Predicting Future Tracks of Aircraft

It is useful to introduce a number of new terms and three sets of variables to describe the geometry of path prediction. First, there are the **P-variables** which cover the present position and the <u>actual past path</u>, and which are used to estimate some of the current state variables of the aircraft. Next, there are the **F-variables** which describe the <u>intended future path</u>, as defined, perhaps partially, by the current flight plan, or ATC clearance. Finally, there are the **T-variables** which are used to make a best estimate of the <u>most probable future path</u> for an aircraft which will be called its **Trajectory**

Figure 2 shows the differences between the actual past path, the intended path, and the most probable future path (ie., Trajectory). There is always a deviation of the actual path from the intended path due to errors in guidance, variations in the wind direction and speed along the path, errors in navigation signals, errors in surveillance, etc. The aircraft's Flight Guidance System (or the pilot manually) is usually correcting the path to return it in some manner to the intended path. Today, the controller does not know when or how the aircraft will return to its intended path, and tolerates moderate path deviations.

There are two types of processes for estimating the future path which can be defined: first, there is a **Path Projection** process, **PP**, which makes a straight line, unaccelerated projection from the current position using best estimates of the current speed, track, and vertical rate; ie., it only uses P information. Secondly, there is a **Trajectory Process**, **TP**, which uses P information, but which also uses additional F information about future changes in aircraft rates, (such as turns, changes in vertical rate or airspeed, next waypoints, mode of the Flight Guidance system, etc).

With both processes, there will be considerable uncertainty in estimating the future path of aircraft which will limit the quality of performance of the separation assurance function - and indeed, may determine its feasibility as an acceptable automated process for ATC operators. The degree of uncertainty in future paths will vary from encounter to encounter since it depends on six "encounter factors":

1) **Wind Variability** - both in strength and direction which varies over time and space. The nature and size of the variability of the wind can be quite different from one day to the next, or from one hour to the next, or from one minute to the next. On certain days with strong and

variable winds, an aircraft which holds heading, direction, and airspeed exactly constant will not fly a straight line track over the ground due to wind currents in the atmosphere similar to currents in the sea.

2) **Flight Guidance Mode** - if the aircraft is "tracking" (ie., attempting to fly a fixed track/altitude), it will be correcting its deviations from with small changes of heading, vertical rate, airspeed with varying frequency or response times; and with various guidance laws for anticipating turns, level offs, etc.;

3) **Path Complexity** - the number of changes in the direction, or airspeed, or vertical rate along the intended path;

4) **Navigation Performance** - completeness of the definition of intended path, and the accuracy of navigation sensors;

5) **Surveillance** - completeness and quality of information about the current position, speed, and direction of aircraft available on the ground;

6) **Time-to-Go** - or distance/time ahead of the aircraft. As Time-to-Go increases, the uncertainty may increase or decrease, depending on the above factors; and the probability that the intended track includes a turnpoint, or a change of vertical or horizontal rate increases.

We know very little today about the impacts of these factors, (especially about the short term variability of winds under differing atmospheric conditions) and consequently, the degree of uncertainty in future paths using any particular path or trajectory prediction process,. However, it is possible to postulate that there are patterns of uncertainty which are a function of the above six factors. Figure 3 shows such patterns for Path Projection as a function of the mode of the Flight Guidance System of the aircraft. Note that the size of the uncertainty can increase, or decrease, or be constant along the future path.

Figure 4 shows patterns of uncertainty for a Trajectory where the intended path has a simple turn comparing a case where the next leg is defined by only a new heading versus the case where another waypoint on the next leg is known.

In estimating the separation-at-passage, it is necessary to know where the passage will occur along the predicted future paths of both aircraft in order to estimate the compounded uncertainty of the predicted separation at passage. Any automated process will be providing only a best estimate of the separation at passage with considerable stochastic variation present as the time-to-passage increases. It will be difficult to place much confidence in this best estimate of the predicted separation-at-passage, particularly at longer times-to-passage.

Types of Encounter Events

With this distinction made in the process which makes an estimate of the future path of an aircraft, it is now sensible to define two types of events which can occur in Separation Assurance, namely, a Hazard Event, and an Intrusion Event; and then define two corresponding types of Encounter Management, namely Hazard Management and Intrusion Management.

A **Hazard Event** is a separation assurance event where there is a short term, current estimate for violation of separation criteria using Projected Paths to estimate the separation-at-passage for two aircraft. "Short term" is defined by a critical response time T_{cr} required to execute the intervention which resolves the encounter. T_{cr} depends on:

1) communication speeds and reliability,
2) lags in human response after alerting,
3) aircraft maneuverability.

To define a Hazard Event in today's ATC environment, the Probe Time can be arbitrarily chosen as 1 minute or less, which means that T_{cr} and the time-to-passage must be less than 1 minute. Due to this short time, the SAS function called **Hazard Management** has no alternative to intervening quickly to change one or both aircraft paths in resolving the Hazard Event.

An **Intrusion Event** is a separation assurance event where there is a longer term, current estimate for a probable violation of Encounter criteria when Trajectories are used to estimate the separation-at-passage. Longer term becomes greater than 1 minute, and perhaps up to 10 minutes or more, with feasible operation depending on the size of uncertainties in trajectory estimation processes. Intrusions will be handled by a SAS function called **Intrusion Management.**

Intrusion Management

Since it has a longer time-to-passage, Intrusion Management does not need to act immediately; consequentlly, it has three options which it can exercise:

1) **Defer**

This option continues to monitor the encounter, initiating another ATC function called **Close Conformance Monitoring**, and continuously estimating the time remaining before the critical resolution time T_{cr}. This requires knowledge about the resolution maneuver(s) which would be used. It can defer executing any intervention since it can safely wait to see if the encounter resolves itself, or if later estimates of separation-at-passage continue to indicate the necessity to intervene. This option is commonly practiced by today's ATC radar controllers.

2) **Advise**

This option has two types of Advisories which are issued by controllers today to the pilots involved in the encounter: the common **Traffic Advisory**, and a rare **"Prevent" Advisory**.

There are two reasons for a Traffic Advisory:

a) to prevent a surprise (in the event the pilots would be able to see each other near passage);

b) to enlist the pilots' cooperation in conforming closely to current intended tracks and altitudes, especially if there is an imminent intended path change which should acheive the desired separations without intervention.

Whenever pilots have been allowed some freedom to maneuver away from their flight plan (yes, this has been possible under current IFR in the USA for many years, eg., a Cruise Clearance - which opens up more than one altitude for the pilot to fly; or a "Direct" Clearance - which does not imply that the aircraft should go directly to some further waypoint along it's flight plan but rather releases it to maneuver around cumulus buildups), it is possible that an encounter might require the issuance of a **Prevent Advisory** which then retracts some or all of the maneuver freedom until the time of passage. It does not intervene to change the current path of an aircraft, and it is not a Traffic Advisory. It is a restriction on maneuvering under the current clearance.

3) **Intervene**

This option can also be divided into two types:

1) **Resolution Intervention** - This is the usual action which changes one or both planned paths of the encounter aircraft to meet separation criteria; and

2) **Precautionary Intervention** - This is an intervention which is probably not necessary, but which ensures that a possible encounter will not occur. It is a common practice of controllers today to ensure safety in high workload conditions, or when it is difficult to predict the separation at passage with sufficient accuracy. It may be issued instead of the Traffic Advisory rather than count on the pilots to execute good conformance, especially if there would not be time to intervene if they failed to execute an

intended change in the path near the point-of-passage.

For example, for an encounter situation 10 minutes away between two climbing/descending aircraft at an airway intersection, a controller may make a Precautionary Intervention by issuing a Climb/Descent Restriction to both aircraft. This releases the controller from closely monitoring the encounter over the next ten minutes, and ensures that even if the controller becomes busy with other aircraft at the time these aircraft arrive at the intersection, they will pass with, at least, the required vertical separation. Usually, the controller will be able to find time to remove the restrictions as the aircraft near passage and it turns out that they will not actually violate separation criteria.

Encounter Criteria

Given this description for the operation of future automated Separation Assurance, the issues become "How should Encounter Criteria be defined? Is there a common set of simple criteria for Hazard and Intrusion Management? If separation criteria for automated SAS are to be incrementally reduced from current levels, how can each reduction be monitored in the field to demonstrate its safety to controllers and pilots?

The first problem is to give a rational structure for ATC Encounter Criteria. ATC separation criteria is usually an area of confused and non-rigorous analysis today. The new structure needs to be able to handle the uncertainties in predicting future paths of aircraft, even in cases where we don't have a high degree of confidence in the predictions, and must be understandable to the current operators (pilots and controllers) and their managers.

The following structure is proposed to stimulate further discussion and refinement. In the interests of simplicity for the operators, it would use only lateral and vertical distance criteria and would keep them directionally uniform in order to relate them directly to today's lateral radar and vertical altimetry criteria.

It is proposed that there would be four geometric volumes surrounding the "target" aircraft which the "intruder" aircraft's path might be predicted to penetrate, and which would determine the actions of automated SAS:

1) **Collision Criterion C** - a sphere of radius **C** around the target aircraft which should "never" be violated during an <u>actual</u> passage since that would be considered a collision.

Example values are:

C = 500 feet which would correspond to the definition of a Near Miss by the FAA today.

2) **Protection Criteria P** - a disc of radius $\mathbf{R_p}$ and height $\mathbf{2S_p}$ centered on the sphere. It is a lower limit on the simultaneous values of all components of the <u>expected</u> or <u>average</u> separation at passage between two aircraft which will encounter each other at some future time. Any <u>predicted</u> violation will cause an "Encounter Alert" to be issued which would change the operational mode of SAS monitoring. But the major difference from today's separation criteria is that <u>small</u> violations of the Protection Criteria at <u>actual</u> passage would be tolerated. The objective of SAS is to avoid actual violation of the Collision Criteria **C**, not to avoid the violation of the Protection Criteria, **P**.

Example values are:

$\mathbf{R_p}$ = 18000 feet = 3nm laterally, and $\mathbf{S_p}$ = 1000 feet vertically.

The example value of lateral separation is deliberately chosen to equal today's radar separation criteria in the terminal area, but it is expected that after operational experience, it could be reduced. These might be initial values for an automated SAS. Note that today small violations of the vertical separation criterion at passage are tolerated.

3) **Resolution Criteria R** - a disc whose values exceed the **P** criteria by some margin so that any intervention to resolve the encounter will result in new paths which have a high probability of continuing to satisfy **P** over the time remaining until passage. This would ensure that the Encounter Alert generally remains off during the remainder of an encounter, and that there is only one intervention per encounter.

Example values (given **P** as above) are;

$\mathbf{R_r}$ = 24000 feet = 4 nm laterally, and

$\mathbf{S_r}$ = 1500 feet vertically

Here, the margin above **P** has been chosen as 1 nm laterally, and 500 feet vertically. This is a function of the uncertainty in estimating separation-at-passage which might allow different margins under different encounter factors and encounter situations. It need not be simple for an automated system.

4) **Monitoring Criteria M** - a disc whose values are less than the **P** criteria by some margin such that any <u>actual</u> violation of this criteria at passage is defined as an unacceptable operation of the automated SAS. It would result in an **Operational Error Alert** and an automatic recording of the pertinent operational circumstances of the encounter and any SAS actions. This creates extended operational software requirements for the automated SAS, and implies that there would be a continuous management review of its operations. The margin is chosen to keep **OE** rate small - but not zero so that a continuing statistical record of actual field performance can be made.

Note that a violation of **M** is not an "unsafe" event since a collision has not occurred. Instead, it is an "unacceptable" event since a "large" violation of **P** has occurred. **M** is a measure of "unacceptable" performance of any SAS.

Example values are:

$\mathbf{R_m}$ = 12000 feet = 2 nm laterally, and

$\mathbf{S_m}$ = 500 feet vertically

Here the margin below **P** has also been chosen as 1 nm laterally, and 500 feet vertically. The margins need not be identical to the **R** margins, nor simple across all encounter factors and situations.

The typical operation of an automated SAS system using these Encounter criteria is illustrated in Figure 5. When it is estimated that the expected separation at passage is less than the Protection criterion about 10 minutes ahead of passage, the monitoring becomes more frequent and more rigorous in its predictive activities. It can defer any action, or can issue an advisory, or might introduce a precautionary intervention. But it is not until the predictions indicate, at about 4 minutes ahead of passage, that the Monitoring criteria will likely be violated that the SAS issues an intervention which quickly increases the expected separation at passage to the Resolution criteria. Actual passage seems to have achieved a value equal to the Resolution criterion, **R**, although there are errors in this estimate so the probability that this is true is of the order of 50%. There is a higher probability that the actual separation-at-passage was greater than the Protection criterion, **P**, and a very high probability that it exceeded the Monitroing criteria, **M**. In other cases, the estimate for separation-at-passage might stay around the **P** value so that intervention would be avoided, and then the actual separation at passage would be **P** or greater (with a probability of 50%), or would be **M** or greater with a much higher probability. The objective in all cases is that probability that the separation-at-passage does not exceed **C** is extremely small (eg., one in ten million).

Conclusion

This structuring of Encounter Criteria is important to establish before the introduction of automated SAS functions, both on the ground and in the cockpit; and it is essential for trading off their safety and efficiency. The proposed structure is really only an explicit formalization of values which are being used implicitly today by every controller.

As we attempt to achieve lower values of separation in future ATM systems with improved guidance/navigation, datalink communications, and more precise and extended forms of surveillance which give aircraft current states and future intentions, the problem of designing a safe automated decision support system becomes more complex. A consistent structure will be needed to aid in gaining acceptance by certification and operational personnel in the aviation community around the world.

References

1. Engineering of ATC Systems (unpublished manuscript for notes from MIT Course 16.78, Air Traffic Control, Robert W. Simpson,.

Figure 1- CLEARANCE GENERATION - INFORMATION FLOW IN A SECTOR

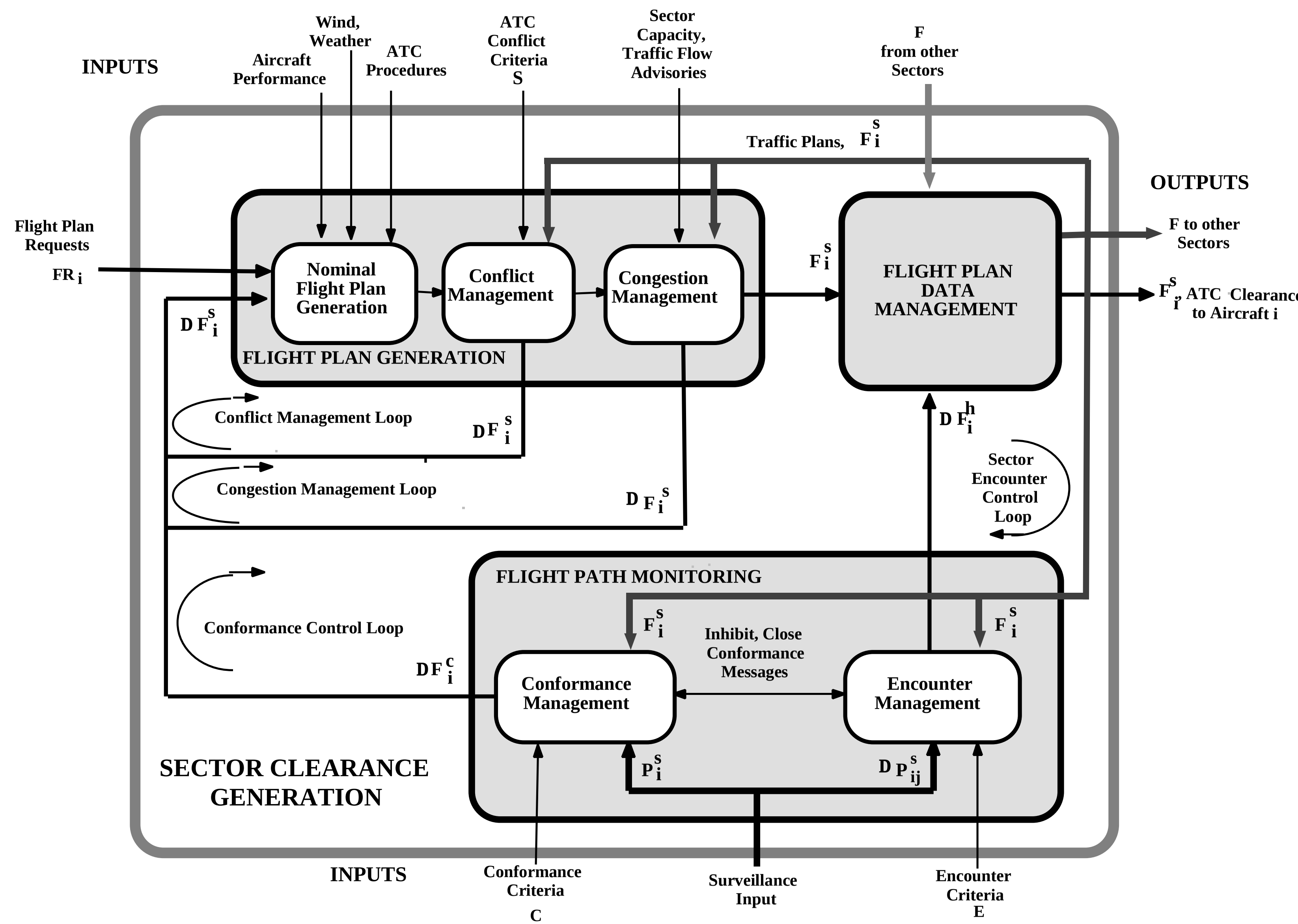


Figure 2 - DEFINITIONS FOR ATC PATH VARIABLES

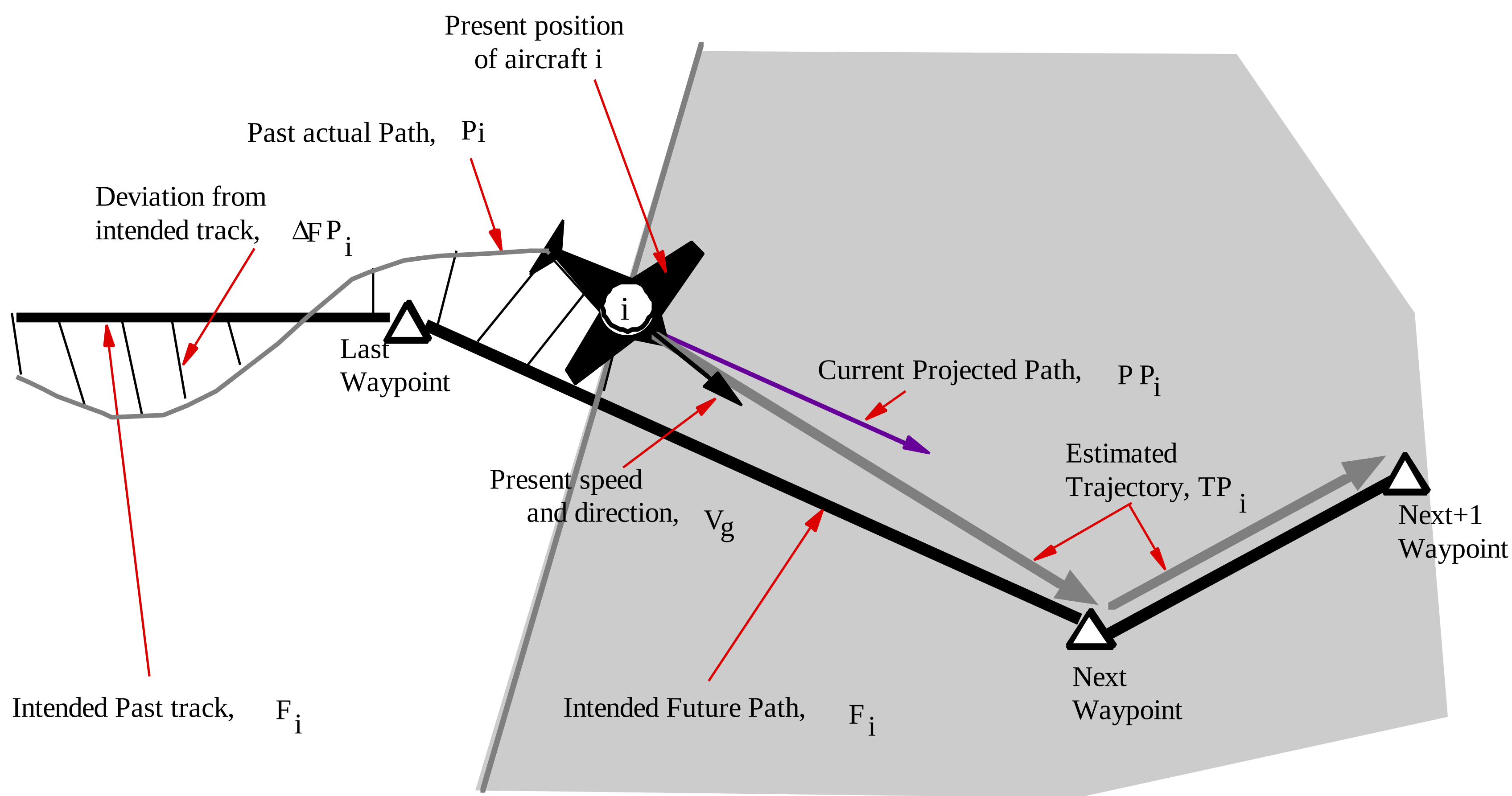


Figure 3 - Patterns of Projected Path Uncertainty - Different Guidance Modes

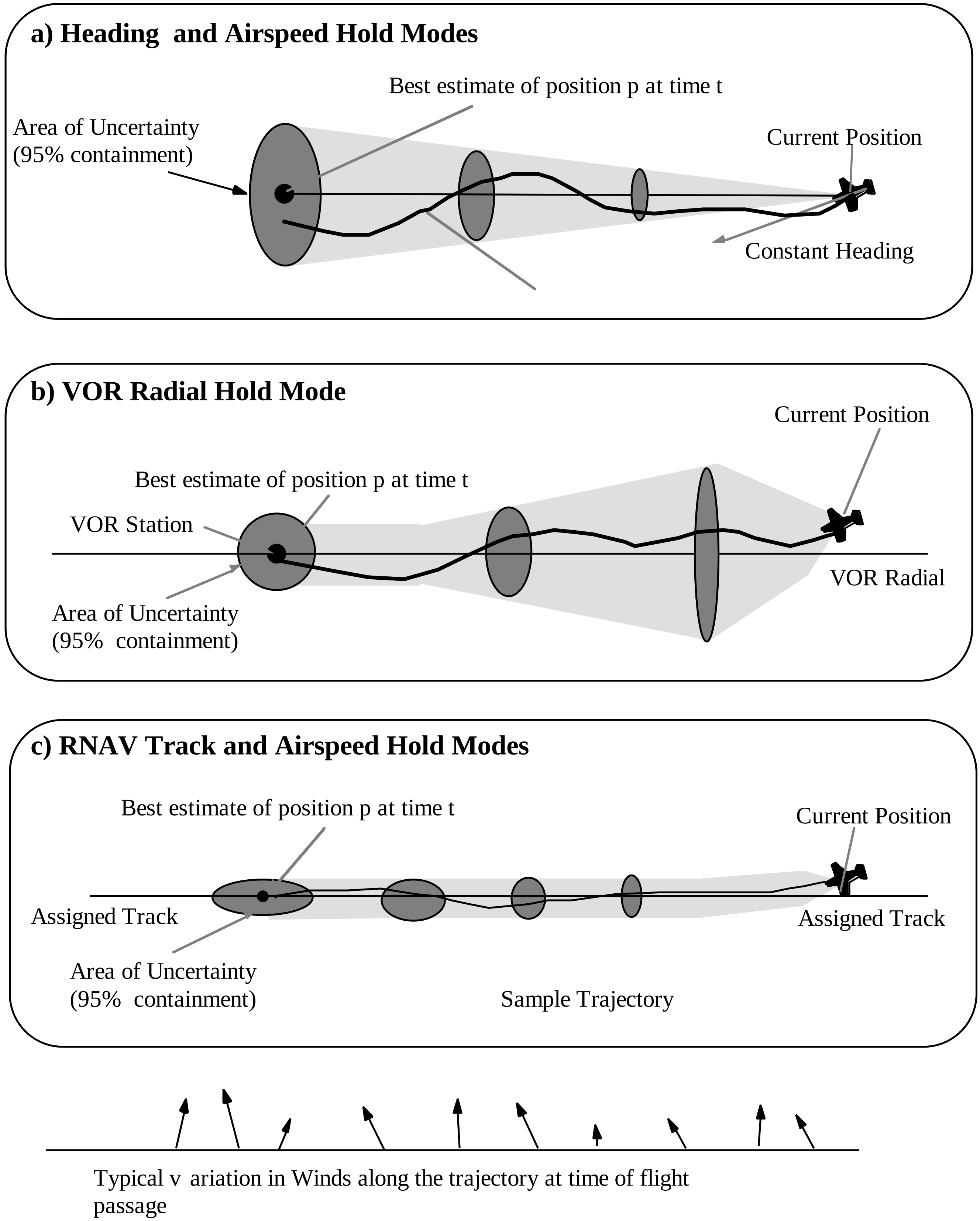
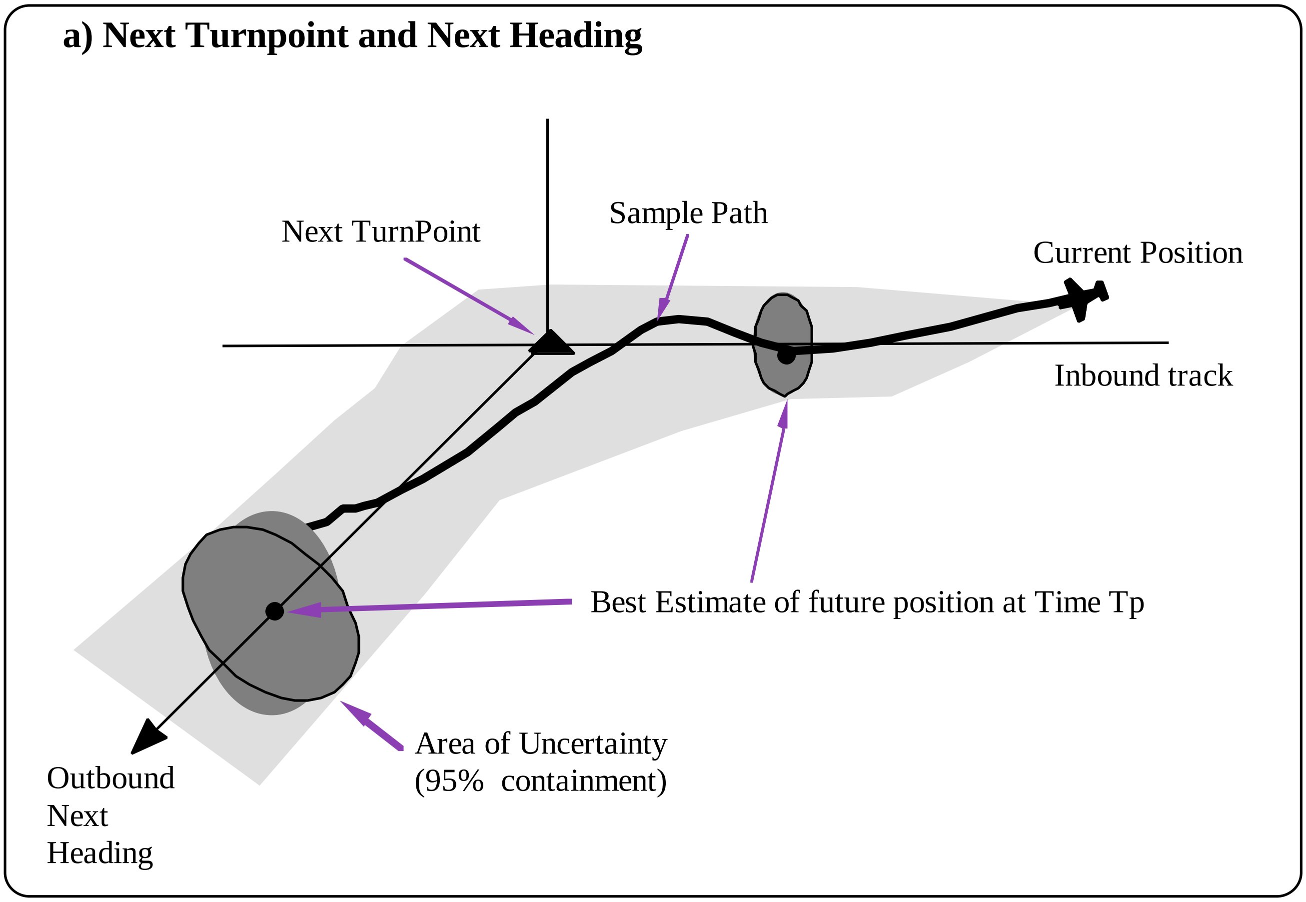


Figure 4 - Patterns of Trajectory Uncertainty with Intention Information



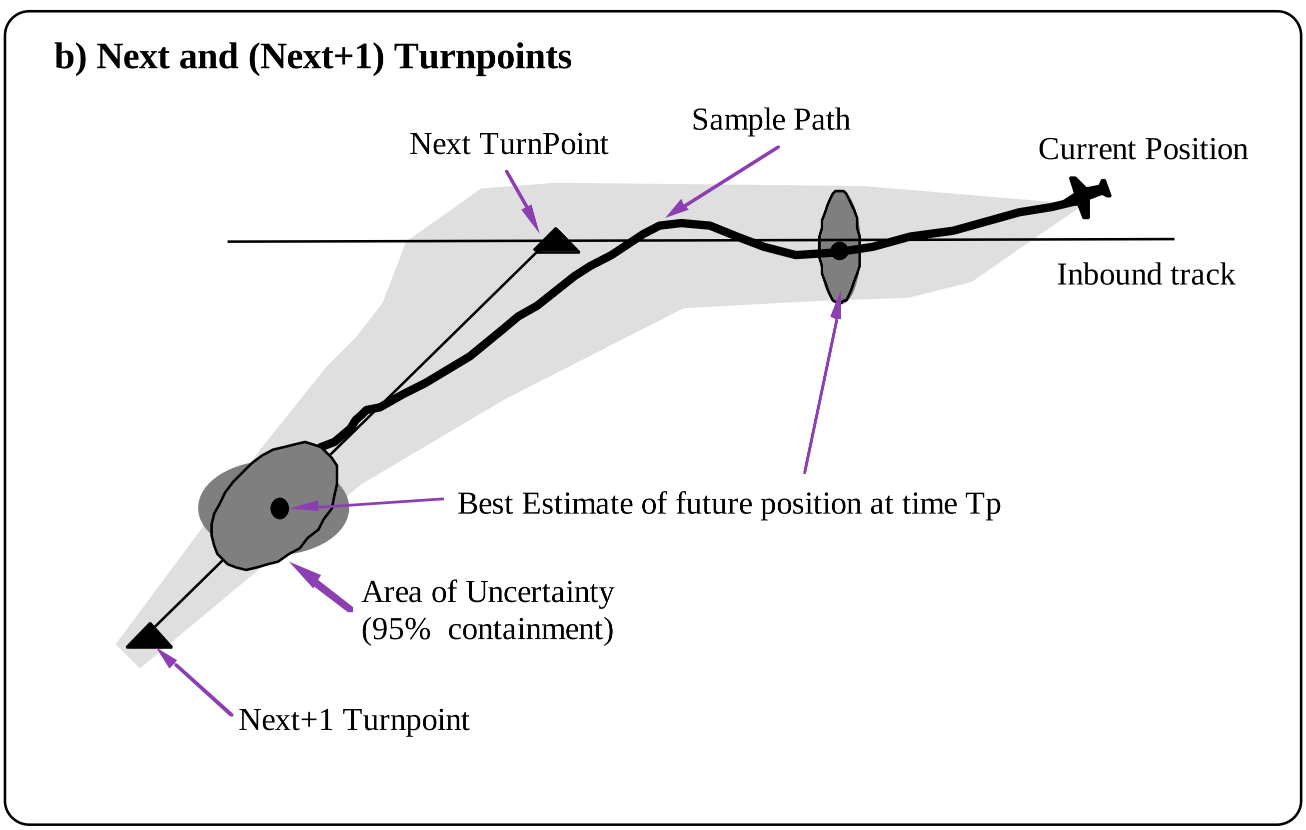


Figure 5 - TYPICAL OPERATION OF AN AUTOMATED SEPARATION ASSURANCE SYSTEM