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PTM Along Track Algorithm to Maintain Spacing During Same Direction Pair-Wise Trajectory Management Operations

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1. Introduction

Pair-wise Trajectory Management (PTM) is a cockpit based operation where the controller clears an aircraft to maintain spacing from one or more designated aircraft. On-board PTM tools will aid the flight crew in implementing the PTM spacing. The tools are expected to consist of a traffic display, decision support to accept or reject a PTM clearance, speed guidance to maintain spacing, conflict detection, alerting and resolution logic, ADS-B in capabilities, and CPDLC communications.
There are two types of PTM operations:
1. One-dimensional in-trail where the PTM aircraft maintains spacing from aircraft in front and/or behind;
2. Two-dimensional where the PTM aircraft maintains spacing from crossing aircraft and can maneuver laterally or longitudinally.

This paper describes an algorithm that will generate speed guidance for the flight crew to maintain spacing from a designated aircraft during one-dimension, same direction[1], PTM operations. The speed guidance will be in the form of a range of Mach speeds.

2. Algorithm

The algorithm takes the following parameters as input:

- Latitude and Longitude of the PTM aircraft (ownship)
- Velocity vector of the PTM aircraft (ownship)
- Latitude and Longitude of the Designated aircraft
- Velocity vector of the Designated aircraft
- Flight level or altitude of the ownship
- Velocity vector of the wind
- Base Mach of the pair, string or chain operation[2]
- Air temperature
- The order (leading or trailing) of the PTM aircraft with respect to the Designated aircraft
- Whether or not the ownship is a designated aircraft for another PTM operation

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[1] Same direction means aircraft with headings whose angular difference is less than 45 degrees. Same course is defined in FAA JO 7110.65 and same track is defined ICAO Doc. 4444 ATM/501. For the purposes of the algorithm in this paper, same direction, same course and same track are synonymous.
[2] PTM aircraft can operate in sequences of aircraft, which are following the same route. These sequences are called pairs, strings, and chains depending on the rules they are following. See reference [1] for more details.

The algorithm produces the following output:

- Lower and upper range Mach guidance.

2.1. Coordinates Mapping

The first step in the PTM along track algorithm is to map the latitude and longitude coordinates into Cartesian coordinates. The latitude is mapped to the y-axis and the longitude to the x-axis. Figure 2.1 shows an example of two locations with aircraft ac1 at 44 degrees north, 43 degrees east and aircraft ac2 at 45 degrees north and 45 degrees east.

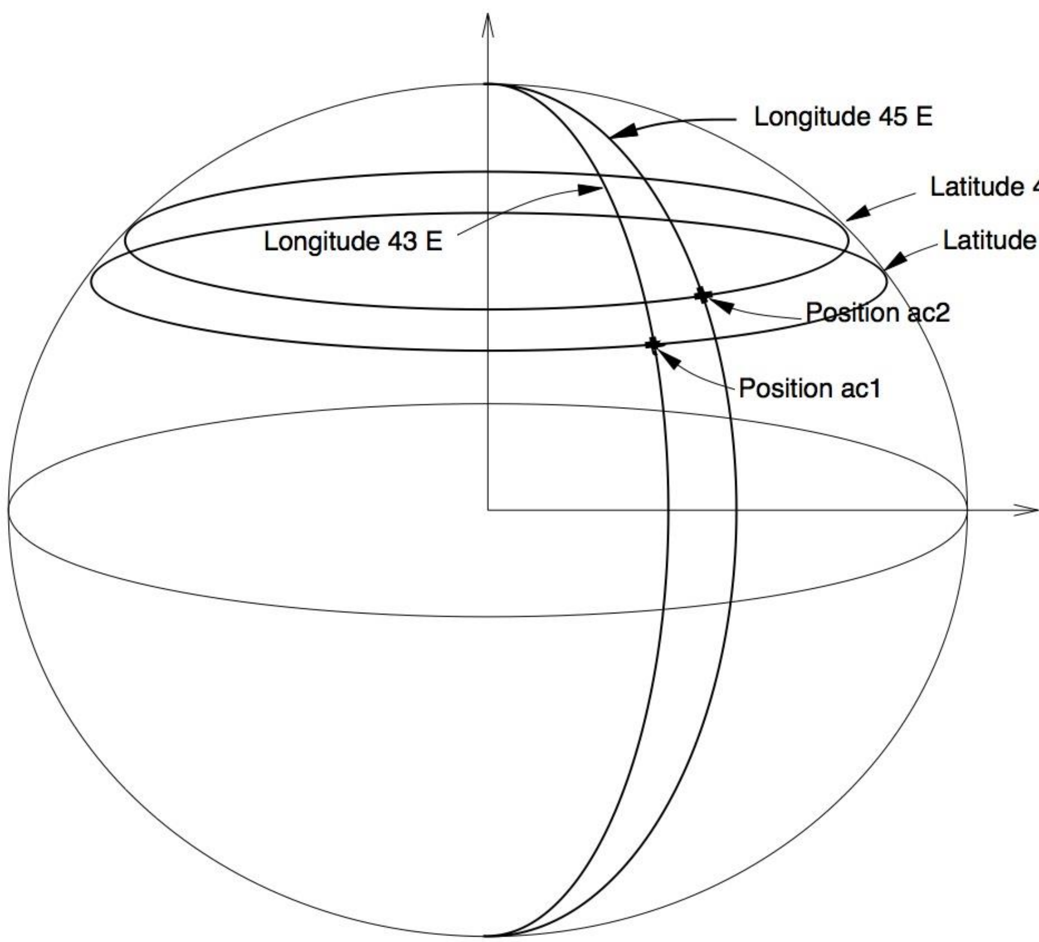

Figure 2.1. Example Coordinate Positions

In the example shown in Figure 2.1, aircraft ac1 is defined as the PTM aircraft (ownship) and aircraft ac2 as the designated aircraft (traffic). The ownship is set at the origin of the Cartesian coordinate system, as shown in Figure 2.2.

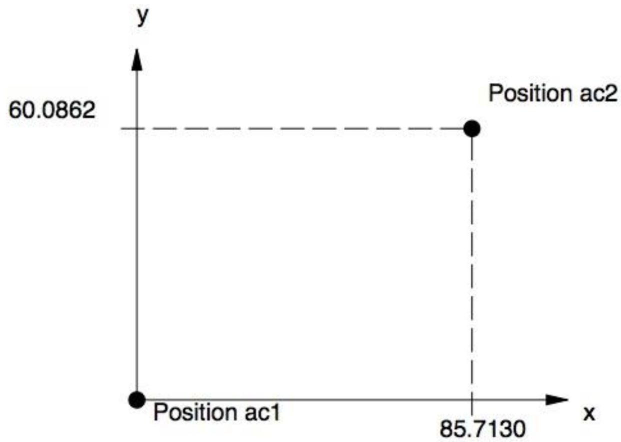

Figure 2.2. Location of aircraft in Cartesian Coordinates

The location of aircraft ac2 is relative to ac1. The y component of the location of ac2 is the difference in latitude between the two aircraft. The x component of the location of ac2 is the difference in longitude of the two aircraft at the average latitude. That is, the distance for the y component is the distance between longitude 43 degrees east and 45 degrees east at the average latitude of 44.5 degrees north.

The distance for the latitude is calculated by determining the difference in latitude angle between the aircraft and multiplying the angle by the radius from the center of the earth. The radius is the average radius of the earth plus the aircraft altitude. For the example shown in Figure 2.1, the latitude difference in distance is given by,

$$y = 1 \times \frac{2\pi}{360} \times (3437.74677 + 4.93746) \text{ nautical miles} \qquad (1)$$

where,

3437.74677 is the average radius of the earth in nautical miles,
4.93746 is an altitude of 30,000 feet in nautical miles.

The distance for the longitude is calculated by determining the difference in longitude angle between the aircraft and multiplying by the radius of a plane normal to the earth axis that dissects the earth at the average latitude, as shown in Figure 2.3. For the example shown in Figure 2.1, the longitude difference in distance is given by,

$$x = 2 \times \frac{2\pi}{360} \times (3437.74677 + 4.93746)\sin(90 - ave\_latitude) \text{ nautical miles} \qquad (2)$$

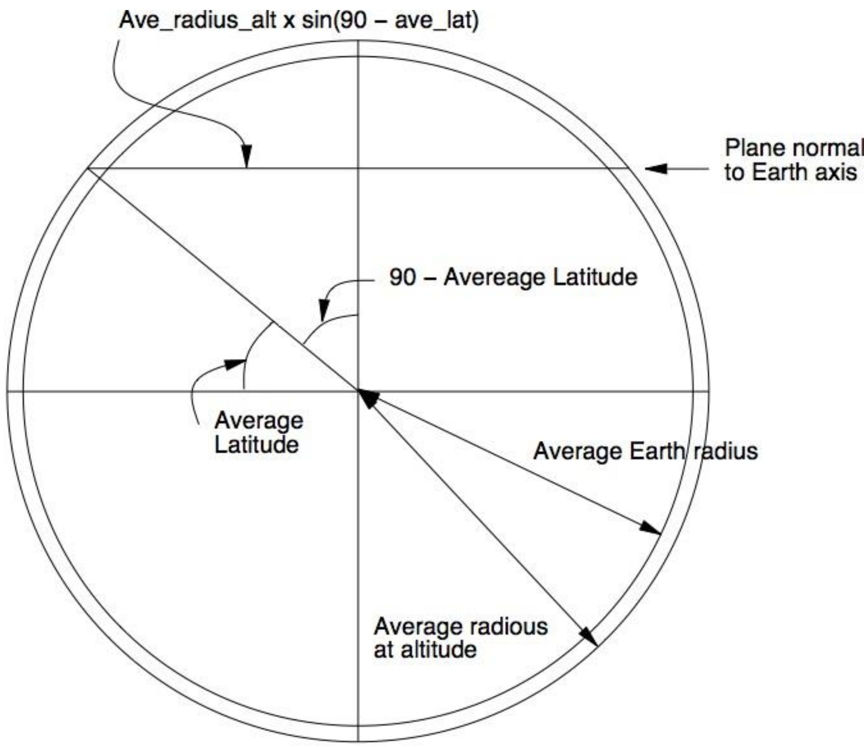

Figure 2.3. Calculation of Longitudinal distance at Average Latitude

2.2. Velocity Vectors

The velocity vectors of the aircraft are mapped to the Cartesian coordinates system with the north component to the y-axis and the east component to the x-axis. Figure 2.4 shows an example of velocity vectors and utilizes the position of the example of Figure 2.2. The velocity vector for aircraft ac1 is 333.75 knots north and 333.75 knots east. The velocity vector for aircraft ac2 is 286.08 knots north and 381.43 knots east. Aircraft ac1 and ac2 speeds are 472.0 knots and 476.79 knots, respectively.

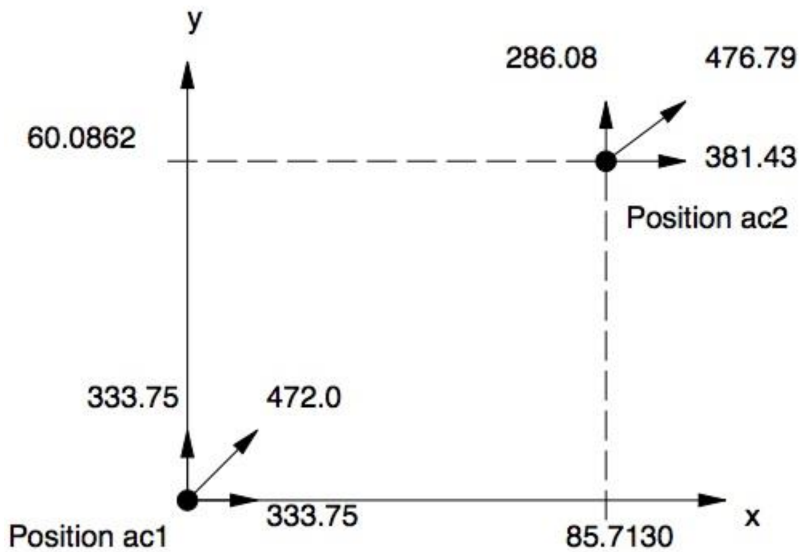

Figure 2.4. Example of Velocity Vectors on the Cartesian Plane

2.3. Intersection and Parallel Routes

The one dimensional PTM operations are based on "along track" distance. To determine the along track distance between the aircraft, the intersecting point of the aircraft tracks is determined. Figure 2.5 shows the intersecting point for the position and velocity vector example.

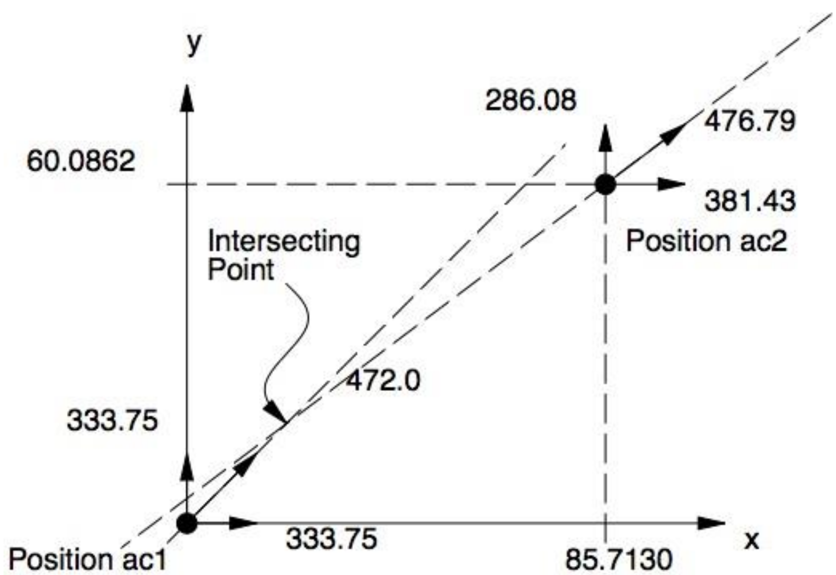

Figure 2.5. Intersecting Point of the Tracks

There are 4 cases when determining the relative location of the intersecting point with respect to the aircraft:

- Aircraft ac1 is after the intersection and ac2 is before
- Aircraft ac2 is after the intersection and ac1 is before (Example of Figure 2.5)
- Both aircraft are after the intersection point
- Both aircraft are before the intersection point

There is a possibility that there is no intersecting point between the tracks. This occurs when the velocity vectors are parallel.

2.4. Leading and Trailing Aircraft and Along Track Distance

Using the intersecting point of the tracks, the leading and trailing aircraft and the along track distance can be calculated.

Case 1. Aircraft ac1 is after the intersection and ac2 is before

When aircraft ac1 is after the intersecting point and ac2 is before, ac1 is the leading aircraft. The along track distance is the sum of the distances from each aircraft to the intersecting point.

Case 2. Aircraft ac2 is after the intersection and ac1 is before

When aircraft ac2 is after the intersecting point and ac1 is before, ac2 is the leading aircraft. The along track distance is the sum of the distances from each aircraft to the intersecting point.

Case 3. Both aircraft are after the intersection point

When both aircraft are after the intersection point, the aircraft with the longest distance to the intersection point is the leading aircraft. The along track distance is the difference of the leading aircraft distance minus the trailing aircraft distance to the intersection point.

Case 4. Both aircraft are before the intersection point

When both aircraft are before the intersection point, the aircraft with the shortest distance to the intersection point is the leading aircraft. The along track distance is the difference of the trailing aircraft distance minus the leading aircraft distance to the intersection point.

Parallel tracks

When the velocity vectors are parallel, there is no intersection point. A perpendicular vector to the velocity vector of ac2 to is calculated as shown in Figure 2.6.

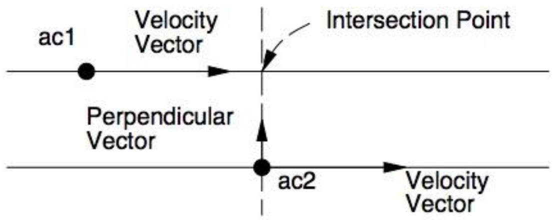

Figure 2.6. Aircraft on Parallel Tracks

The intersection point for the parallel tracks scenario is the point a-beam of aircraft ac2. When aircraft ac1 is before the projected intersection point, aircraft ac2 is the leading aircraft. When aircraft ac1 is ahead of the intersection point, ac1 is the leading aircraft. The along track distance is the distance between aircraft ac1 and the projected intersection point.

2.5. Speed Guidance for the PTM (ownship) Aircraft

The objective of the algorithm is for the PTM (ownship) aircraft to maintain spacing from the designated aircraft in a safe and efficient manner. The spacing is the sum of a separation standard and buffer distance. The algorithm gives speed guidance to achieve the spacing. That is, if the along track distance is greater than the spacing, the algorithm will give speed guidance such that the along track distance can be reduced. When the along track distance is at or near the spacing, the algorithm will give speed guidance to maintain the spacing. The algorithm will give speed guidance such that the PTM aircraft can increase the along track distance if the PTM aircraft is not a designated aircraft for another PTM aircraft in a string. See examples 1 and 2 which illustrate a PTM pair and a PTM string and the speed guidance associated with these operations.

The following parameters are used in the computation of the speed guidance:

- Separation standard distance – a minimum distance that shall never be infringed upon. The range between the aircraft shall never be less than the separation standard distance.
- Buffer distance – a distance used to achieve the operational goal of the separation standard
- Spacing – the sum of the separation standard distance and the buffer distance.
- Along track distance – The distance between the aircraft along the flight path of the aircraft over segments that might include turns at waypoints.

- Wind velocity – the velocity vector of the wind at the ownship location.
- Base Mach – the speed that has been assigned to the designated aircraft.
- Time to achieve spacing – the time used to calculate the speed guidance and to achieve spacing.
- Time to achieve spacing when loss of spacing – the time used to calculate the speed guidance to achieve spacing when the along track distance is less than the spacing.
- Maximum Mach – The maximum Mach that the algorithm will give as an upper bound. This value depends on the type of the aircraft. This maximum Mach does not mean that the aircraft can actually achieve this speed. It is a bound put on the algorithm guidance output.
- Minimum Mach – The minimum Mach that the algorithm will give as the lower bound. This value depends on the type of the aircraft. This minimum Mach does not mean that the aircraft can actually achieve this speed. It is a bound put on the algorithm guidance output.

The speed guidance is calculated starting with the ground speed of the aircraft. A new ground speed is calculated for the PTM aircraft. When the PTM aircraft is leading, the new ground speed is,

$$new\_gs = gs_d - \frac{D_{AT} - spacing}{T_s} \text{ knots} \tag{3}$$

where,

gs_d is the ground speed of the designated aircraft,
D_{AT} is the along track distance between the aircraft,
T_s is the time to achieve spacing.

When the PTM aircraft is trailing, the new ground speed is,

$$new\_gs = gs_d + \frac{D_{AT} - spacing}{T_s} \text{ knots} \tag{4}$$

From the new ground speed, a new True Air Speed (TAS) is calculated taking into account the wind velocity vector at the ownship location. The vectorial components of the TAS are calculated from the new ground speed.

$$tas_x = new\_gs \times \sin(heading) - wind_x \tag{5}$$

$$tas_y = new\_gs \times \cos(heading) - wind_y \tag{6}$$

The magnitude of the TAS is calculated from the vectorial components.

$$TAS = \sqrt{tas_x^2 + tas_y^2} \tag{7}$$

In order to calculate the Mach speed, the speed of sound is calculated by,

$$s_{sound} = \frac{3600}{1852} \times 331.3 \times \sqrt{1 + \frac{temp}{273.15}} \quad \text{knots} \tag{8}$$

where *temp* is the temperature of the air in degrees Celsius.

The new Mach number is the new True Air Speed divided by the speed of sound at altitude,

$$new\_Mach = \frac{TAS}{s_{sound}} \tag{9}$$

The new Mach speed is rounded to the nearest one hundredth of a Mach. The speed guidance is determined from the new Mach speed, the maximum and minimum Mach, whether the ownship is leading or trailing the designated aircraft, and whether the ownship is a designated aircraft for another PTM operation.
When the ownship is leading and not the designated aircraft for another PTM operation, the guidance is,

Lower Mach = New Mach
Upper Mach = Maximum Mach

When the ownship is leading and is designated aircraft for another PTM operation, the guidance is,

Lower Mach = New Mach
Upper Mach = max(Base Mach, New Mach)

When the ownship is trailing and not the designated aircraft for another PTM operation, the guidance is,

Lower Mach = Min Mach
Upper Mach = New Mach

When the ownship is trailing and is the designated aircraft for another PTM operation, the guidance is,

Lower Mach = min(Base Mach, New Mach)
Upper Mach = New Mach

Where the function max(a, b) gives the greater of the two numbers a and b and the function min(a,b) gives the lesser of the two numbers a and b.

2.6. Non linearity to account for Incremental Nature of Guidance

The speed guidance in units of Mach speed is given to the flight crew in 0.01 Mach increments. This is the typical resolution of the Mach command in the flight control panel. That is, Mach guidance in thousandth of Mach increments cannot be selected in the flight control panel of the aircraft. For example, a Mach guidance of 0.834 would not be possible to implement in a typical aircraft flight control panel.
To be able to achieve spacing closer to the desired spacing objective, a non-linear characteristic is designed into the algorithm.

The non-linearity is added into the algorithm by determining if the along track distance is less than the spacing requirement or more than the spacing requirement plus a hysteresis parameter. If the along track distance is less than the spacing requirement, the Mach guidance is adjusted by 0.01 Mach to increase the distance between the aircraft. If the along track distance is more than the spacing requirement plus the hysteresis parameter, the Mach guidance is adjusted by 0.01 Mach to decrease the distance between the aircraft.

3. Performance of the Algorithm and Examples

This section presents three examples and what speed guidance is produced for a given set of parameters. The parameters used for the examples are shown in Table 3-1.

Table 3.1. Parameters Used for the Examples

Parameter	Value
Separation Standard distance	5 nautical miles
Buffer	1.5 nautical miles
Spacing	6.5 nautical miles
Hysteresis	0.2 nautical miles
Base Mach	0.82
Time to achieve spacing	30 minutes
Time to achieve spacing when loss of spacing exists	10 minutes
Minimum Mach	0.77
Maximum Mach	0.86

Example 1

Example 1 is a PTM pair where the PTM aircraft is trailing the designated aircraft as shown in Figure 3-1. In this figure, the black aircraft (A) is the PTM aircraft and the white aircraft (B) is the designated aircraft. Aircraft A is maintaining spacing from B.

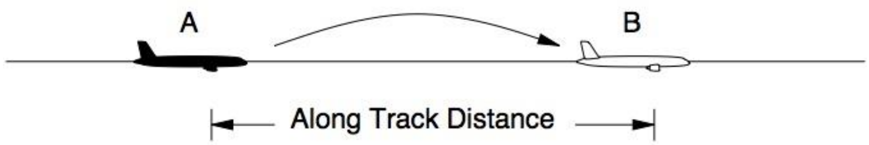

Figure 3-1. Example 1, PTM pair with PTM Aircraft Trailing

The speed guidance as a function of along track distance is shown in Figure 3-2.

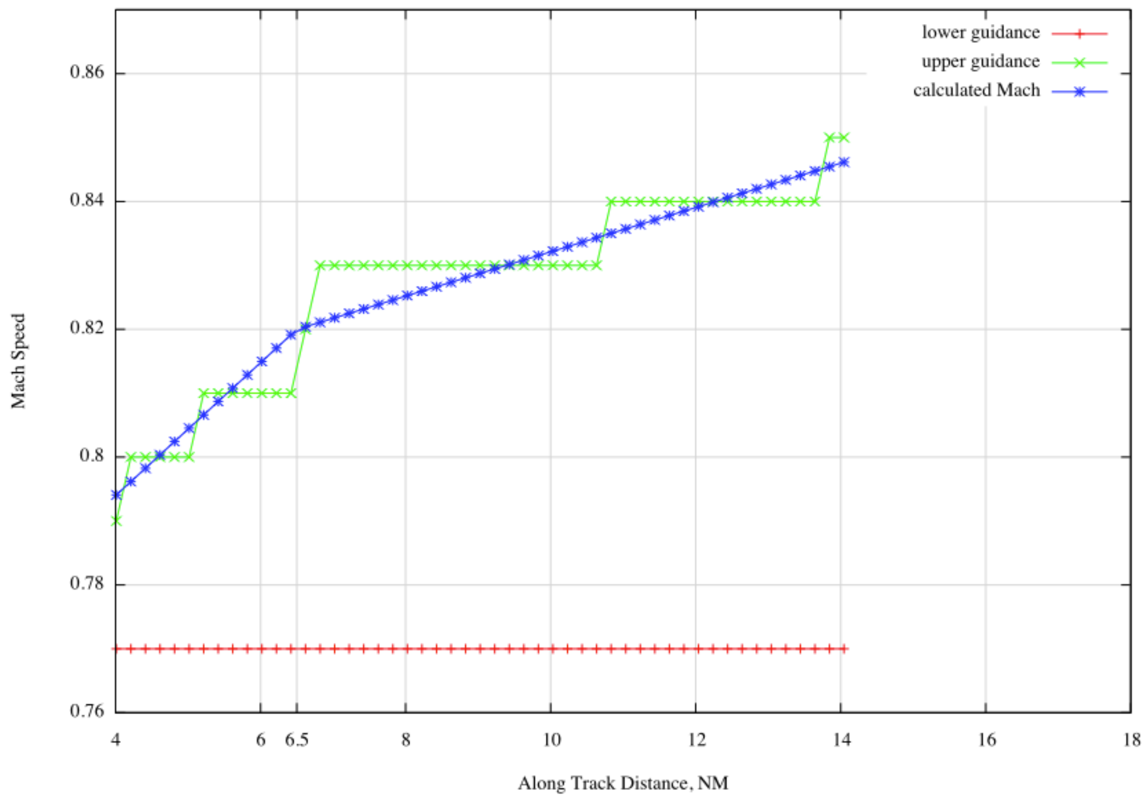

Figure 3-2. Mach Guidance for Aircraft A as a Function of Along Track Distance

When the along track distance is 6.4 NM, the algorithm gives a guidance of 0.77 to 0.81 Mach. The upper guidance is less than the base Mach which will increase the along track distance to achieve the desired spacing of 6.5 NM. When the along track distance is 6.6 NM, the algorithm gives a guidance of 0.77 to 0.82 Mach which will increase or maintain the present distance. When the along track distance is 6.8 NM, the algorithm gives a guidance of 0.77 to 0.83 Mach which allows for the PTM aircraft to go faster than the designated aircraft and reduce the along track distance. The flight crew also has the option of going slower than 0.83 Mach to maintain or increase the distance. When the along track distance is 14 NM, the algorithm gives a guidance of 0.77 to 0.85. The flight crew can decrease, maintain, or increase the along track distance.

Example 2

Example 2 is a PTM string where 2 PTM aircraft are in trail of the designated aircraft as shown in Figure 3-3. Aircraft B is the designated aircraft for aircraft A and aircraft A is the designated aircraft for aircraft C. Aircraft A is maintaining spacing from aircraft B and aircraft C is maintaining spacing from aircraft A.

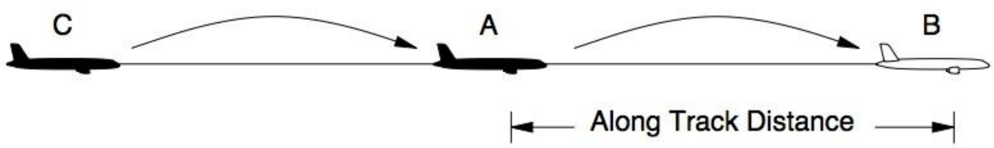

Figure 3-3. Example 2, PTM String with PTM aircraft Trailing

The speed guidance for PTM aircraft A as a function of along track distance between aircraft A and B is shown in Figure 3-4.

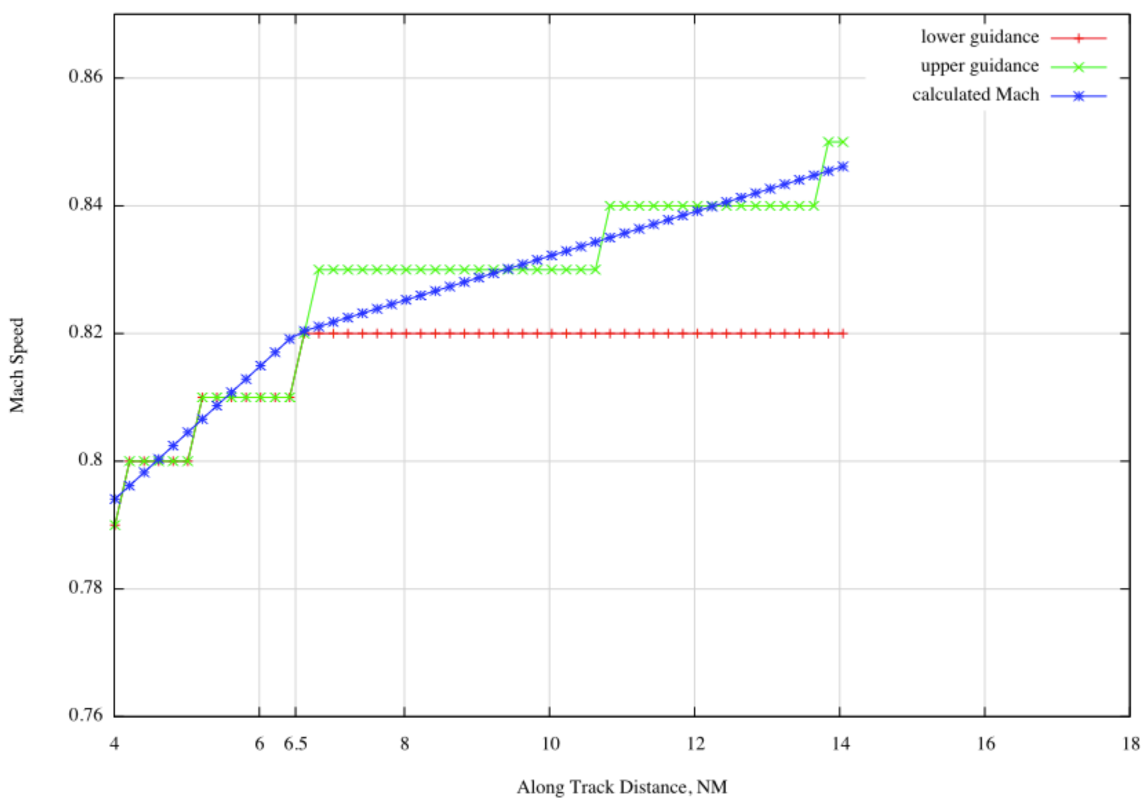

Figure 3-4. Mach Guidance for Aircraft A as a Function of Along Track Distance

Table 3.2 shows the distances and times for Example 1 when the PTM aircraft follows the upper guidance speed and the Time to Achieve Spacing parameter is set to 30 minutes. When the initial distance is 14 NM and the PTM aircraft follows the upper guidance, the aircraft will achieve spacing in 57.4 minutes.

Table 3.2. Time and Distance Between the PTM and Designated Aircraft, with Time to Achieve Spacing set at 30 minutes

Time	Distance	PTM aircraft speed	Closure rate
0 minutes	14 NM	0.85 Mach	17.3 knots
1.4 minutes	13.6 NM	0.84 Mach	11.5 knots
17.1 minutes	10.6 NM	0.83 Mach	5.8 knots
57.4 minutes	6.7 NM	0.82 Mach	0 knots

Table 3.3 shows the distance and times for Example 1 when the PTM aircraft follows the upper guidance speed and the Time to Achieve Spacing parameter is set to 15 minutes. When the initial distance is 14 NM and the PTM aircraft follows the upper guidance, the aircraft will achieve spacing in 38.6 minutes.

Table 3.3. Time and Distance Between the PTM and Designated Aircraft, with Time to Achieve Spacing set at 15 minutes

Time	Distance	PTM aircraft speed	Closure rate
0 minutes	14 NM	0.86 Mach	23.1 knots
6.8 minutes	11.4 NM	0.85 Mach	17.3 knots
11.6 minutes	10.0 NM	0.84 Mach	11.5 knots
18.9 minutes	8.6 NM	0.83 Mach	5.8 knots
38.6 minutes	6.7 NM	0.82 Mach	0 knots

Example 3

Example 3 is a PTM chain where a PTM aircraft is between two designated aircraft as shown in Figure 3-5. Aircraft B and C are the designated aircraft for aircraft A. Aircraft A is maintaining spacing from aircraft B and C.

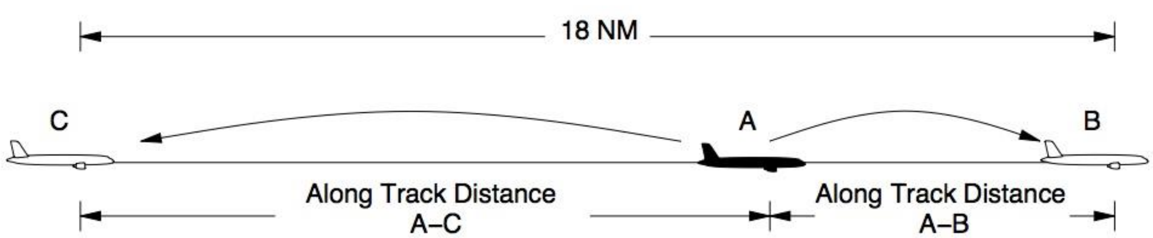

Figure 3-5. Example 3, PTM Chain

The speed guidance for PTM aircraft A as a function of along track distance between aircraft A and B and between aircraft A and C is shown in Figure 3-6.

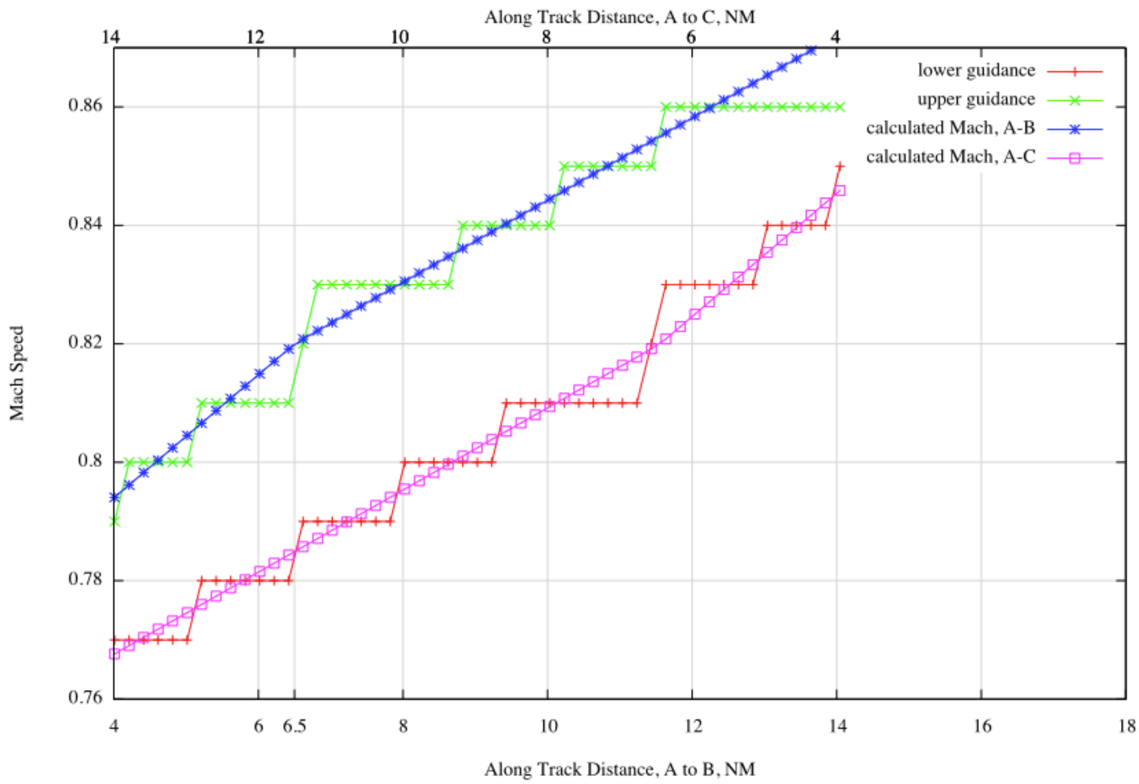

Figure 3-6. Mach Guidance for Aircraft A as a Function of Along Track Distance between Aircraft A and B, lower x axis, and Aircraft A and C, upper x axis

4. Accuracy, Errors, and other Considerations

Radius of the Earth

The calculations of distances from one position to another are performed using the average radius of the Earth. Because the Earth is not a perfect sphere, this can result in calculation errors of distance. The radius of the Earth at the equator is taken for WGS84 as 3,443.918466 nautical miles. The radius at the pole is 3,432.371660 for WGS84. The average radius used in the calculation of along track distance is 3437.746771. When calculating the distance between two aircraft, which are approximately 15 nautical miles apart, an error of up to 0.0269 nautical miles or 49.87 meters could result. The error increases as the distance between the aircraft increases and decreases as the distance between the aircraft decreases, where it is more critical. At 5 nautical miles apart, the maximum error will be 0.00898 nautical miles or 16.62 meters. A function to estimate the Earth radius as a function of latitude has been added which makes this error negligible.

Coordinates Transformation

The transformation from latitude and longitude to Cartesian coordinates could result in a distance error. To map the east-west longitude to the x-axis, the average latitude is used. When the aircraft are 15 nautical miles apart, the worst error is 0.00006265 nautical miles or 0.116 meters. This error is negligible.

Range vs. Along Track Distance

A requirement for 1-dimensional PTM operations is that aircraft are same direction. Same direction aircraft are aircraft with headings whose angular difference is less than 45 degrees. The objective of the algorithm described in this paper is to maintain along track spacing. For separation standards and safety, the range between the aircraft is considered the metric of importance rather that the along track distance.
When the along track distance is, for example, 6.5 nautical miles and the leading aircraft turns 45 degrees at a waypoint, the range between the aircraft will become 6.005 nautical miles at the closes point of approach.

Round of Mach Guidance

The PTM Along Track algorithm will calculate Mach guidance to many digits of precision. However, it is not practical to give to the flight crew Mach guidance that is more than one hundredth of a Mach. For example, a Mach guidance of 0.82 to 0.823176 cannot be implemented in the flight control panel. The need for giving guidance no more precise than hundredths of a Mach results in the optimal spacing not being achieved. Table 3.1 shows that when the aircraft have an along track distance of 8.0 nautical miles, the base Mach is 0.82, and the spacing is 6.5 nautical miles, the guidance is 0.82 to 0.82. That means that with this guidance, the spacing of 6.5 nautical miles will not be achieved. On the other hand, if the along track distance is 6.0 nautical miles, which is less than the desired spacing of 6.5 nautical miles, the guidance is also 0.82 to 0.82. If the along track distance gets reduced to 5.9 nautical miles, and using the parameters of Table 3.1, then the guidance will be 0.81 to 0.81 to increase the distance.
The algorithm currently rounds the guidance to the nearest hundredth of a Mach. It is possible to modify the algorithm to round up or round down (truncate) to the nearest hundredth of the Mach. This modification will change the algorithm performance. If rounding up, the guidance will allow the aircraft to get closer together when the PTM aircraft is trailing and maintain the aircraft farther apart when the PTM aircraft is leading. When rounding up, the opposite effect will occur. The algorithm could also round depending on whether the PTM aircraft is trailing or leading and be designed such that the guidance will allow for the distances to be reduced further or the distances to remain longer.

Pressure Altitude vs. Geometric Altitude

The mapping of latitude and longitude to Cartesian coordinates take into account the aircraft altitude. The altitude is added to the radius of the Earth to determine distances. If the altitude used as input to the algorithm is the flight level of the aircraft rather than the geometric altitude, then an error will result. When the sea level barometric pressure is 29.92 inches of mercury (1013 hPa), the flight level is approximately the geometric altitude. Variations in atmospheric pressure will make the flight level and geometric altitude differ. To estimate the error, a lower atmospheric pressure than average is assumed. A lower atmospheric pressure will cause the aircraft to fly at lower geometric altitudes for a given pressure altitude. This in turn will result in a larger calculated distance than the actual distance. Assuming a barometric pressure of 25.10 inches of mercury (850 hPa), which is the lowest barometric pressure recorded on Earth, and the aircraft at FL350, the geometric altitude will be approximately 30,500 feet.
When the aircraft are at a distance of 15 nautical miles, the difference between flight level and geometric altitude for this worst case condition will result in an error of 0.003231 nautical miles or 5.98 meters.

GPS and ADS-B Position Errors

The algorithm accuracy will depend in the accuracy of the data being provided by the GPS data of the PTM (ownship) aircraft and the ADS-B data of the Reference aircraft. The source data of the ADS-B data of the designated aircraft is expected to also be GPS.
The distance calculation errors resulting from position errors will depend on the magnitude of the position errors and whether the errors are correlated between the PTM and designated aircraft (correlated bias errors) or independent errors.
The provision of 5 nautical miles separation in the U.S. National Airspace System using ADS-B requires a Navigation Accuracy Category for position of 7. This NACp level correspond to an accuracy of 0.1 nautical miles or 185.2 meters at a 95% level.

5. Summary and Conclusion

The PTM Along Track algorithm gives guidance to the flight crew of a PTM aircraft to maintain spacing from a designated aircraft during PTM operations. The spacing is the sum of a separation standard minimum distance and a distance buffer. The objective of the algorithm is to maintain safe and efficient PTM operations. Safe operations entail the range between the aircraft to never be less than the separation standard minimum. For efficient operations, it is desired that the along track distance is reduced as much as possible.

Due to the rounding of the Mach guidance given to the flight crew and other operational considerations, an exact spacing cannot be achieved. The algorithm must establish an optimal balance between maintaining high aircraft density during PTM operations and achieving the safety requirements.

6. References

[1] Carreño, V. and Graff, T.; Definitions, Theory and Operational Rules for Chains and Strings in the PTM Application, version 6, 2 September 2013.

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14. ABSTRACT
Pair-wise Trajectory Management (PTM) is a cockpit based delegated responsibility separation standard. When an air traffic service provider gives a PTM clearance to an aircraft and the flight crew accepts the clearance, the flight crew will maintain spacing and separation from a designated aircraft. A PTM along track algorithm will receive state information from the designated aircraft and from the own ship to produce speed guidance for the flight crew to maintain spacing and separation.

15. SUBJECT TERMS
Avionics; Delegated responsibility; Separation standard; Traffic management

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