TRACKING AIRCRAFT AROUND A TURN WITH WIND EFFECTS

By

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B.S., Aerospace Engineering
Boston University, 1991

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degrees of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1993

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ABSTRACT

Nowadays, radar trackers used for Air Traffic Control (ATC) purposes perform very satisfactorily during straight line flight segments but their performance tend to deteriorate during maneuvers. The introduction of the SSR Mode S system would make the transmission of the aircraft state information possible. In order for the ground tracker to perform efficiently around a turn, the minimal state information that can be down-linked is a signal which indicates the aircraft is in a turning mode.

In this research, a new turn tracker algorithm is devised using bank angle of the aircraft larger than 10 degrees as the criterion for switching on the turn signal. The algorithm is implemented in the terminal area air traffic control simulation (TASIM) developed by the Flight Transport Associates, Inc. (FTA). The performance of the new turn tracker is compared with a typical ATC tracker in the industry, the Track Oriented Smoother (TOS). Actually, the straight line tracking process of the TOS is used to track the aircraft in the straight line flight segments. Whenever the turn signal is on, the turn model is employed.

The results of the research prove to be a success for the new turn algorithm. Future research directions are suggested to improve the efficiency of tracking the aircraft around a turn to enhance the automation of ATC in the terminal area.

Thesis Supervisor: Professor Robert W. Simpson
Director.
Flight Transportation Laboratory
Acknowledgments

It has been a great opportunity for me to work in Flight Transportation Laboratory. This research is made possible by Professor Robert W. Simpson whose invaluable advice and expertise in the area are the key factors leading to this thesis. He deserves every piece of this work. He is not only a great advisor but also a very nice and kind person who has tremendous patience and is always willing to help. It is just a unique and unforgettable experience for me to work with Professor Simpson.

I would also like to thank all my good friends in FTL. They are always there to help me.

Last but not least, I would like to thank my family for their support and love.
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Chapter 1

Introduction

1.1 Objective of the Thesis

Advances in technology has helped to increase the efficiency of Air Traffic Control. In order to reduce the workload of the ATC controllers therefore, the impact of human errors on ATC, various automated decision support processes, (like Hazard Alerts, Automated Spacing Advisories and Conformance Monitoring) have been proposed. However, the successful implementations of all these automated decision support processes all rely heavily on a very accurate ground estimate of current position, ground speed and track direction of the aircraft. This is the reason why an extremely accurate radar measurement system and a highly efficient tracking algorithm are the ultimate goals in the ATC area.

There is always a limit to the accuracy of the radar measurement of the aircraft. Factors, like the background noise and other imperfections, interfere with the correct radar measurement giving the 'ground' a piece of uncertain information on the range and bearing of each aircraft. Primary and secondary radar surveillance systems in civil aviation scan at rates which provide this position measurement once every 5 or 12 seconds. They do not measure ground speed or track direction. As a result, radar
tracking processes, or tracking algorithms, have to be devised to estimate ground speed and track direction from recent radar measurements. They also provide a better estimate of the current position of the aircraft.

Civil aircraft, unlike their military counterparts, maneuver in a more predictable and slower fashion. Actually, there are a limited number of trajectories which are used by aircraft flying in the ATC system due to their performance limitations and their normal modes of flight. This makes the tracking of civil aircraft a much easier task. Current ATC tracking processes perform very well when the aircraft is flying a straight line, but they suffer severe transient errors whenever the aircraft maneuvers, (i.e. changes its speed drastically or its direction) as is the case in terminal airspace when arriving or departing from airports. In particular, there is a large transient error when the aircraft is making a turn. This error is mainly caused by the "straight line" logic in the tracking process. Unlike measurement errors which are random in nature, the transient errors are biased and therefore, will add up over successive scans during the turn. (See figure 1.1) Within few radar scans, the position error can easily exceed one nautical mile, the heading error can exceed 60 degrees, and the ground speed error can exceed 60 knots. There are large errors and ATC controllers currently do not display the output of radar tracking processes because of these transient errors from turns and deceleration.

Today, a new type of secondary surveillance system called "Mode S" is being developed. It provides a data-link which can send a message to the ground whenever the aircraft maneuvers. In the future, it will be possible to send a "Turn Signal" to the ground which can eliminate the transient errors of the current ATC tracking processes.
Figure I-1: Transient position error due to the tracking logic during a turn

The objective of the thesis is, therefore, to study a method which is able to track the aircraft more accurately if a very simple Turn Signal is sent to the ground.
1.2 Structure of the Thesis

In chapter 2, we will have a brief review on radar tracking processes. We will introduce the jargon of tracking and talk about the basic principles of radar tracking processes. The concept of radar ellipses, the pattern of surveillance errors and multi-radar coverage will be explored. In particular, we will look at the α-β tracker and the track oriented smoothing (TOS) tracker.

In chapter 3, we will have a look at the terminal area air traffic control simulation program (TASIM). TASIM is a computer simulation written in Turbo Pascal 6.0 developed by Flight Transport Associates, Inc (FTA). In TASIM, the TOS tracker is simulated. We will look at the general performance of the TOS tracker in TASIM.

In chapter 4, we will look at the development of the new "Turn Tracker" that is adaptive to the change in direction of the aircraft during a turn. We will investigate the choice of the 'state' of the aircraft to create the 'Turn Signal'. Then the turn transition tracking algorithm is developed and is implemented in TASIM.

In chapter 5, we will look at the performance of the new Turn Tracker as opposed the track oriented smoothing tracker (TOS).

In chapter 6, we conclude and will talk about some recommendations from the simulation and some future research directions.
Chapter 2

A Review on Radar Tracking Processes

2.1 ATC Surveillance Radars

There are two types of surveillance radars: (1) Primary surveillance radar (PSR) and (2) Secondary surveillance radar (SSR). The replacement of ATCRBS with Mode S in the SSR system greatly increases the accuracy of SSR, by a factor of 4 in range and a factor of 6 in azimuth. The old system of SSR obtains information via ATCRBS transponder on aircraft identity (Mode A) and altitude (Mode C). The new system of SSR receives information of the aircraft via Mode S. The typical accuracy of the PSR are 100 feet in range and 0.5 degrees in azimuth while those of the new SSR are 30 feet and 0.04 degrees respectively. As a result, there is a tendency for ATC to rely on the SSR.

Both the PSR and the SSR will provide one radar measurement of range and azimuth for each aircraft on each radar scan while the SSR is also able to provide data on altitude. As a matter of fact, it is possible for the Mode S transponders to transmit a variety of accurate aircraft state information, like bank angle, turn rate, current heading or track direction, vertical rate, next intended heading/track or next intended altitude. This new capability to send aircraft state information to the ground is the crucial factor that makes the design of a new Turn tracker possible.
Since there are the presence of background noise and other imperfections, radar measurement is by no mean the correct measure of the actual target position. Actually, radar measurement is like drawing a sample point from a normal distribution with the actual target position as the mean and the radar accuracy as the standard deviation. If, hypothetically speaking, a target were stationary and its position repeatedly measured by a radar, the result would be a cluster of closely-spaced plots.\footnote{Dan Varon. \textit{Journal of ATC}. "On the Use of Tracks Versus Plots in ATC Systems", January—April-June 1991. p.36} With the regular samples of radar measurements, it is possible to obtain the best estimate of the aircraft's position, and also the best estimates of ground speed and track direction of the aircraft by track data processing. There is always a time lag in displaying the latest position of the aircraft due to the processing time of the radar and track data. One should bear in mind that the controller never sees the correct instantaneous position of an aircraft.

2.2 Radar Ellipses and the Pattern of Surveillance Errors

Since the accuracy of the surveillance radar is characterized in terms of both range and azimuth, the position error of the aircraft is characterized by an radially oriented error ellipse. The radar ellipse is used to describe the correct position of the aircraft within a 95\% confidence interval if the two standard deviations of the range and azimuth errors are used. As the aircraft flies away from the radar site, the tangential major axis of the error ellipse, which is due to the error in azimuth and the actual range of the aircraft from the radar site, is generally much larger than the radial minor axis of the error ellipse, which is due to the error in range. The radial minor axis of the ellipse should be almost a constant
during the motion. The pattern of the error ellipses is illustrated in figure 2-1. The particular pattern of error ellipses or orientation is very important to the development of the new turn tracker logic.

![Diagram](image)

**Figure 2-1. Radial error pattern**

Since the errors of radar measurement are being characterized by radial oriented error ellipses, the directions of the aircraft before and after a turn affect the turn tracking performance. It is possible to characterize two turning cases for a horizontal turn at constant speed: First, a "Radial Turn" from a radial to tangential direction; and secondly, a "Tangential Turn" from tangential to radial direction. See figure 2.2
Figure 2.2 The orientation of the error ellipses during a Radial turn and a Tangential turn

In case (1), the initial speed along the track will be accurately estimated by the ATC tracker but it will be more difficult to detect a turn away from track since the azimuth errors are larger.

In case (2), it will be easier to detect the turn away from track but the uncertainty in measuring the ground speed before the turn is larger.

The scenarios for testing the new tracker algorithm consist of both Radial turns and Tangential turns at different distances from the radar site. As a result, we are able to observe how well the new tracker will perform under different types of scenarios.
2.3 Multi-radar coverage

Today, the aircraft's ATCRBS transponder antenna is normally mounted on the bottom of an aircraft and is unable to send a strong return to the SSR during turns. There may be missing measurements during a turn. When this happens the aircraft’s track cannot be updated and must be coasted. This can be overcome if there is multiple coverage of the aircraft by ground radars.

The advantage of having multi-radar coverage is that the probability of having a missing radar measurement from all the radars at the same time is very slim. But there is a problem of choosing the best available radar measurement from all the radar reports. There are in general three methods for a system to obtain the most accurate measurement:

1. Compute a weighted average of target’s multiple plots and then treat it as the best smoothed position.
2. Let each radar maintain a local track and average the smoothed positions and velocity of the local tracks
3. Uses all the incoming reports to update a track more frequently rather than a single radar.

All these methods are satisfactory only if radars are of comparable accuracy and the aircraft is non-manoeuvering. "More sophistication does not necessarily lead to better systems". This research will assume that only single radar coverage is available and will ignore the issue of missing reports. In the future, aircraft with Mode S transponders will have antenna on both the top and bottom on the fuselage.

---

2.4 Simple Straight Line Tracking

Radar tracking is a process which derives an estimate of an aircraft's current speed, direction and vertical rate from recent history of position reports. During each scan, the difference between the latest radar measurement and a predicted position (which is derived from the last smoothed velocity vector) is obtained. This residual is the sum of two inseparable components: (a) the error between the predicted and the actual position and (b) random measurement noise which causes an error between the measured and actual position. A fraction of the residual is then added to the prediction in order to produce the best smoothed estimation of position. The displacement from the previous best smoothed position to the latest best smoothed position, together with the time increment between radar plots gives a rough estimate of the ground speed and direction.

The same method of smoothing position is then applied to that of speed and direction to obtain new best estimates. In general, if the aircraft is not maneuvering, it is an advantage to display the smoothed position because it has a smaller standard deviation than the radar measurements. However, it takes several scans for the ground speed to "settle in" to optimal values. Uncertainty in ground speed will decrease with increasing number of scans. There is a typical reduction in the uncertainty of the best estimate for a constant speed when averaging over the last n measurements. An illustration is given in figure 2.3.
Figure 2.3 - Uncertainty in Groundspeed after n Scans

2.4.1 The (α - β) Tracker

A tracking process must place emphasis on the measurements of the last n samples by virtually using weighting values on recent measurements which decay with age. The usual approach in ATC is to use a linear recursive filtering process called an (α, β) tracker. The generic staged process of radar tracking is shown in figure 2.4.
Figure 2.4 - The Common Radar Tracking Process

**Step 1:** Association or Correlation - Prediction Error

Aircraft at scan n-1 on a radial track is at an estimated range \( \hat{r}_{n-1} \). If its estimated speed is \( \hat{S}_{n-1} \), then the predicted range at scan n is

\[
\hat{r}_{pn} = \hat{r}_{n-1} + \hat{S}_{n-1} \times \Delta t
\]

where the scan interval is \( \Delta t \)

A measurement \( \hat{r}_{mn} \) is made at scan n, and the deviation between predicted and measured position is

\[
\Delta r_{mn} = \hat{r}_{mn} - \hat{r}_{pn}
\]

**Step 2:** Smoothing or Estimating Correct Track Data

Given the deviation, the smoothing equations to give an optimal estimate for range and speed at scan n for an adaptive (\( \alpha, \beta \)) tracker are:

\[
\hat{r}_n = \hat{r}_{pn} + \alpha_n \times \Delta r_{mn}
\]

where \( \alpha_n < 1 \) is the smoothing constant

\[
\hat{S}_n = \hat{S}_{n-1} + \beta_n \times \frac{\Delta r_{mn}}{\Delta t}
\]

where \( \beta_n < 1 \) is the smoothing constant,

where \( \alpha_n \) and \( \beta_n \) are a function of the recent history of deviation (i.e., a function of the accuracy of recent predictions)
These equations provide a better estimate of the actual range and speed for the aircraft than that obtained from the current measurements as long as the aircraft remains in straight line, unaccelerated flight. Notice that if $\alpha = \beta = 0$, the tracker will make no use of the current information to estimate position and speed, but instead it uses only smoothed data from prior samples. On the other hand if $\alpha = \beta = 1$, the tracker will believe in the measurement of the most current estimates of position and speed and make no use of the prior samples. The fact that $\alpha, \beta$ are changing constantly explains the adaptive nature of the tracker.

**Step 3:** Prediction

With current best smoothed position and velocity vector, a prediction of the next position can be made:

$$\hat{r}_{p(n+1)} = \hat{r}_n + \hat{S}_n \times \Delta t$$

**Step 4:**

The tracker awaits the radar measurement and repeat the steps starting from Step 1.

**2.4.2 Track Oriented Smoothing (TOS) for straight-line Flight**

The $\alpha$-$\beta$ tracker is based on an assumption that the flight is a straight line. A set of parameters are being used for smoothing position ($\alpha$) and speed ($\beta$). The set of parameters tend to optimize the performance of the tracker only if the aircraft is leading a straight line. However, this assumption is far from reality. Factors like wind always disturb the flight of an aircraft. Limitations are always present in the navigation system of an aircraft even though it is being controlled by an auto-pilot. The principle that the
guidance system works is to make sure that the aircraft flies within a 'channel' towards a predetermined waypoint. See figure 2.5.

![Diagram of flight path and channel]

- **waypoint**
- **ideal flight path**
- **actual flight path**
- **'channel' of the flight path**

**Figure 2.5 The actual flight path of the aircraft**

The aircraft actually 'wiggles' along a straight line. Since the $\alpha$-$\beta$ tracker is not adaptive to maneuver cases, for example, a turn) a second attempt has been made and it is called Track Oriented Smoothing (TOS) which uses two values of $\alpha$ and $\beta$ - one set for "along-track" smoothing, and the other for "across-track" smoothing.

TOS actually is an improvement of the $\alpha$-$\beta$ tracker even though the main idea of TOS is no different from the basics of tracking processes. The difference in predicted position and radar measurement is first obtained. A fraction of the difference is added to the
predicted position to give the best estimate of position. With the best smoothed value of
the latest velocity of the aircraft, the next predicted position of the aircraft is made.

One of the major difference of the TOS compared to the α-β tracker is the
establishment of a local "Track-oriented (p,q)" coordinate frame at the current aircraft
position. See figure 2.6. The current along track (ground track) direction is called the p-
axis. The local coordinate frame moves with the aircraft and rotates to remain oriented in
the current track direction. Note that the two axes are always perpendicular to each other.
The 'Smoothing' process are then carried out in the p,q directions. Ground speed \( \dot{S}_n \) and
track direction \( \dot{\psi}_n \) are used to estimate the next position at scan n+1.
Figure 2.6 - Coordinated Reference Frames For Tracking

The TOS is a much better algorithm than the α-β tracker in cases of maneuvers. It is usually more adaptive to the ground speed change, which caused by winds, and to the track direction change. However, there still exists large transient errors in speed, and ground track of the aircraft during a turn. The typical speed error can be up to 60 knots
while the heading error can be 60 degrees depending on the position of the aircraft with respect to the radar site.
Chapter 3

Terminal Area Air Traffic Control Simulation (TASIM)

3.1 Introduction

In order to investigate the performance of α-β tracker and TOS, the Flight Transport Associates, Inc. (FTA) has developed a simulation program called Terminal Area Air Traffic Control Simulation (TASIM). TASIM is written in Pascal and can be run in IBM compatibles with or without a math co-processor. The graphics representation of the terminal area makes use of the 'state of the art' object oriented programming which is made possible by the Turbo Vision application of Turbo Pascal 6.0 developed by Borland.

TASIM is a rather complete simulation of the terminal area and it provides a useful testbed for testing the new tracker algorithm prior to full-scale integration into the system. There are several features of TASIM worth discussing. We are able to choose from the different kinds of radar: (i) Radar, (ii) Beacon and (iii) Exact. The 'Radar' option is a representation of the Primary Surveillance Radar, PSR while the 'Beacon' is a representation of the Secondary Surveillance Radar, SSR. Hence, a much better radar accuracy of the 'Beacon' option is expected. The 'Exact' option is present for the sake of comparison and it generate no radar error at all. A 'Wind' option is also available in the
TASIM. However, the direction and magnitude of the wind will be constant throughout the run. Iterative simulation runs of varying flight scenarios under a variety of tracker parameters are required. The resulting data is compiled in the form of a tracking report consisting the information of the 'state' of the aircraft which enables the easy identification of tracker error characteristics in maneuvers and on straight paths. The simulation is extremely useful in the analysis of the tracker performance.

3.2 The TOS tracker simulation in TASIM

The following three subfunctions of the TOS tracker are simulated in TASIM

(1) Track Cross Referencing

(2) Track Correlation

(3) Track Correction and Prediction

3.2.1 Track Cross Referencing

A primary and secondary bin are constructed around each active track's predicted position. The size of each bin is determined by the relationship between the track's firmness and track range, and by the characteristics of the radar. The primary bin is large enough to ensure correlation with the correct return, but small enough to reduce the probability of incorrect correlation. Secondary bins are approximately twice the size of primary bins and are used when no radar report are in the primary bin. The minimum and maximum range and azimuth limits of the bins are determined by the following formulae:
R +/- ER and A +/- EA (for primary bin)
R +/- 2(ER) and A +/- 2(EA) (for secondary bin)

R and A are the range and azimuth, respectively, of the predicted target position. ER represents the error in range and is equivalent to M×C1. C1 is the sum of the radar's error and the error in prediction (zero is used if the computation results in a negative value). M, a multiplier, is a system parameter. EA represents the error in azimuth which is equivalent to C2+(P×C3)/R. C2 is the radar error in azimuth. C3 is the error in predicted position and is a function of the track's firmness. P, another system parameter, is equal to 1.5.

3.2.2 Track Correlation

Upon initialization, a track is assigned a low (1-7) firmness value and classified as an initial track. Two correlations later, the firmness will have reached a value of 14 or larger after which the track is classified as a normal track. Firmness is an indication of the confidence in the track history. Larger values represent a high degree of stability in the track. Track firmness is updated every scan and changes dependent upon the success of correlation. However, if the track fails to correlate in its primary bin, but does correlate in its secondary bin, an additional track called a "deviation track" is created. The purpose of the deviation track is to detect and follow turning maneuvers of the original or "parent" track. On the first scan after the creation of a deviation track, an attempt is made to correlate the parent track. If correlation of the parent track is successful, the deviation track is dropped. However, if the parent track does not correlate and the deviation track
does, the parent track is dropped and the deviation track becomes the parent track. If both tracks fail to correlate, the deviation track is dropped and the parent track is placed into a coast status. Following a successful track correlation, correction (or smoothing) of the track's predicted position and velocity is accomplished.

3.2.3 Track Correction and Prediction

Track Correction consists of updating a track's data file with the information of the current scan. This includes track information updating and track smoothing. Smoothing creates an estimated position between the correlated plot's reported position and the track's last predicted position. This estimated value, along with a smoother value for track velocity, is used to predict the track's new position for the following scan.

Track-oriented smoothing is used in order to preserve the radar or geographic (X,Y) coordinate system. Smoothing occurs in a track-oriented system which allows different sensitivities to exist for along-track and cross-track deviations. The orientation of the current track is computed on each scan and deviations from along and across-track positions are determined. A separate firmness value for each deviation controls the degree of smoothing. The initial values of the smoothing parameters are formulated such that an approximate least-squares straight-line fit of a succession of plot positions is equivalent.

Track Prediction provides for whole or partial scan updates of track position on all tracks in each sector. All normal, parent, and deviation tracks are straight-line predicted from their current position to their expected position at the time of the next radar scan.
Figure 3.1 Information Flow - Tracker Unit of TASIM
3.3 The General Performance of the TOS Tracker

The tracker errors encountered whenever a simulated target is on a straight path are minimal. The simulation run gives further support to the large transient errors during the turn. The transitional errors occur in position, speed and track direction of the aircraft are large disregard of the types of flight path scenarios. What makes situation worse is that the errors are few times larger than those before the turn and takes more than ten measurements which is about a minute in time for the errors to come back to the stabilized values during straight line flight. All these errors being encountered during the turn will have significant effects to the ATC area. Unless these errors are suppressed, undesirable effects such as false alarms will be the result.

There are factors affecting the efficiency of the TOS tracker. Since the 'Beacon' (SSR) system provides a better accuracy than the 'Radar' (PSR) system, it is not surprising to see that the errors are larger for the 'Radar' (PSR) cases. The difference in radar accuracy however has a moderate and consistent effect. As a result, it does not really matter of what kind of radar system we choose for the testing of new tracker logic.

The magnitude and frequency of errors increase with range. As the confidence factor effecting the size of "bins" used to guide the predicted position of a target is a function of range, as is the amount of sensor/system error. Track direction also is a very important factor as explained in section 2.2.-radar ellipses and the pattern of surveillance errors. All these factors will lead to the devise of the different types of flight path scenarios for the thorough tests of the new tracker logic.
Chapter 4

The Development of the New Turn Tracker

4.1 The detailed description of the problem

In ATC operations, aircraft are asked to fly a sequential set of straight line segments. While current radar tracking processes provide better values for position, speed, and direction as long as the aircraft maintains a straight path, they will provide values which have very severe transient errors after and during a turn. It requires several measurements along the next straight segment before good values for position, speed, and direction are achieved. Since the usual scan rates are either 12 seconds for long range enroute radars, and 4.8 seconds for short range terminal area radars, this means that the ATC system is deprived of good information on speed and direction of an aircraft during a turn, and for roughly one minute after the turn is completed.

These transient errors occur because the radar tracking process continues to believe that the aircraft is flying a straight line. When designing a tracker algorithm, one of the building blocks is the kinematics model of the tracked aircraft. Preferably, the model is of sufficient fidelity to reflect the aircraft true motion. However, neither the α-β tracker nor
the TOS tracker includes the turning motions of the aircraft in the kinematics model inside the tracker algorithm. As a result, the errors are of the order of 60 knots and 60 degrees, and even more depending on circumstances, and pose a problem for any future automated decision support systems for the ATC controller. Currently, all ATC controllers display the raw measurement data to avoid these turning transient errors.

The transient errors can be avoided if information that the aircraft is turning can be sent to the radar tracking process. "More sophisticated software (algorithms) cannot improve the tracking accuracy beyond a certain limit." With the advance in electronic technology, the 'intelligent' tracking process will be an imminent reality. This can be achieved using the data-link of the Mode S, secondary surveillance radar system if all aircraft were modified to send a simple "Turn Signal" on every radar scan which also indicated the direction of turn: right or left. This requires two pieces of information. One piece of the information would occupy a bit of memory with zero as 'no turn' and one as 'turn'. The second bit would indicate right or left. This would provide the information to stop the straight line tracking process, and avoid the transient turn errors by assuming a turn kinematics model. But this requires a definition of the state of "turning" for an aircraft. This might be stated in terms of "bank angle greater than X degrees for Y seconds", or "heading rate of change greater than P for T seconds. Of course, with modern digital flight systems, a transport aircraft’s current best estimate for ground speed and direction can be sent to the ground over the Mode S data-link which avoids using ground radar tracking, but this uses valuable capacity of the data-link and, most important of all, not all aircraft have digital flight systems.


This raises the issue of how to specify a simple, automatic ground tracking system which avoids the transient turning errors, and which minimizes the use of Mode S data-link capacity therefore the cost of modifying aircraft. That issue is the subject of this research.

It is possible to consider changing the ground tracking process from a "straight line" mode to a "turning" mode, and create a statistical filtering process which also estimates other parameters associated with the curving track such as wind speed and direction, rate of change of heading or track (which may not be constant), and the time at which the turn began (which is unknown since it can occur between scans). Unfortunately, turns are not of sufficient duration to estimate all these parameters statistically. Normally, turns are less than 90°, and therefore only 6 or less measurements are obtained from the 4.8 second scan time.

But even if it were possible, good values of position, track direction and ground speed during the turn are not of interest to ATC. The position for the start of the next segment, its direction, and the new ground speed are the values of interest. These are the initial conditions for resuming straight line tracking after the turn is finished. Thus, the goal of this study is to provide these initial values, not to provide continuous estimates around the turn.

Normally, the ATC system and the pilot will know the intended duration of the turn, or the intended new or "target" direction - but the radar tracking system will not know this unless the controller, or pilot/flight management system provides these intentions. The end of the turn will be signaled by the absence of the Turn Signal on some scan since it is inadvisable to use information on intentions in an automated ground tracking system. The use of intentions will remove the essence of tracking processes. Thus, it is assumed that
the ground tracking system does not know when the turn will stop and must be prepared for it to stop on any scan. Good estimates of the initial position, track direction, and ground speed of the next straight segment must be available on every scan during the turn. The straight line tracker will use these initial values to improve rapidly the best estimate of these quantities over the next few scans.

There are many alternatives to designing a system which improve the ground radar tracking processes when a turn occurs. In this research, it has been decided to investigate what can be accomplished with the simplest Turn Signal. It requires two bits of information on each scan to indicate that a turn is occurring and whether it is to the left or right. A simulation model of aircraft dynamics for navigation and guidance along a specified path in the face of winds was modified to create a turn signal whenever the bank angle exceeded 10 degrees for more than 2 seconds. This allows corrective guidance maneuvering to occur along a straight segment without creating a turn signal. Various algorithms were then investigated to produce good estimates for initial track direction and speed using the directions and lengths of the "chords" between measurements during the turn. These algorithms are called "Chord Processing" algorithms.
4.2 The choice of a 'State' of the aircraft to create the 'Turn' signal

There are two obvious aircraft state information which can be the possible candidate for constituting the turn signal. They are the heading and the bank angle of the aircraft.

Both seem to be a suitable parameter to make up the turn signal. However, in the code, an instantaneous value of the variable is being checked for detecting a turn. In this context, the bank angle seems to be a better candidate because as it is greater than 10 degree, we can declare a right turn. As it is smaller than -10 degree, a left turn can be declared. This is the 'Turn Signal' for the new turn tracker.

The same testing criteria cannot be applied using the heading measure, especially in cases of strong winds. The heading has to be pointed in a specific direction in order for the aircraft to fly in a straight line to 'fight off' the effects of strong winds. As a result, the detection of a turn using an instantaneous value of heading is not effective at all. This makes the heading measure an unsuitable aircraft state variable to constitute the turn signal.
4.3 The Turn Transition Tracking Process

The 'Turn' signal is clearly defined as in section 4.2. When the turn signal is on, the TOS tracker, which is the best straight line tracker, is being turned off. The procedure is being switched to a turn signal processor. The next task is to develop the algorithm of this turn signal process.

4.3.1 Processing at Scan 0

We are tracking an aircraft using a straight line tracker, and have the following quantities:
1. Best estimate of position \((\hat{x}_0, \hat{y}_0)\)
2. Best estimate of speed \(\hat{S}_0\)
3. Best estimate of track direction \(\hat{\psi}_0\)

We call this step the Scan 0. It is the last measurement before Turn signals are received.

4.3.2 Processing at Scan 1 (The first Turn signal is received)

We receive a turn signal showing that a turn is occurring with a known direction of turn at the same time as the position radar measurement. It may be obtained from aircraft's instrumentation in terms of a bank angle greater than 10 degrees holding for more than 2 seconds. In the simulation, the turn signal is created when the bank angle is larger than 10 degrees for any radar measurement and the direction of the turn is known.
We do not know when the turn started or how quickly bank has been applied. The turn signal indicates that the aircraft is no longer flying a straight line, and that the straight line tracker must be turned off.

We are not sure if the turn will be continued. Therefore, a Turn Tracking process is being created which "transitions" the aircraft into the straight line tracker whenever straight flight is resumed. We want a good estimate of speed and direction as the next straight segment is resumed. Therefore, there are always two predictions during the turn: (1) prediction T - if the turn continues on the next measurement, (2) prediction S - the turn has stopped.

The following procedure is called Scan 1.

(1) Set best estimate of position on Scan 1 as the newly measured position. We do not know when the turn started. In mathematics,
\[
\hat{x}_1 = \hat{x}_i,
\]
\[
\hat{y}_1 = \hat{y}_i
\]

The last predicted position prior to this radar scan was based on the assumption that the aircraft was flying a straight line. This piece of information is useless in this context. Hence no smoothing can be done to the radar measurement of position.

(2) Smoothing at Scan 1

Set smoothed speed to value on Scan 0,
\[
\hat{S}_1 = \hat{S}_0
\]

Set smoothed direction
\[
\hat{\psi}_1 = \hat{\psi}_i + \hat{\omega} \times \Delta t
\]

where \(\hat{\omega} = 3\) degree/second and \(\Delta t =\) scan interval.
Note that $\hat{\omega} = 3$ degree/second is the standard rate of turn for transport aircraft. It represents an initial guess at the turn rate in ATC operations.

We assume that turn direction information is available.

(3) Predictions at Scan 1

\[ M_{02}^p = 2S_1 \Delta t \]

measured and best estimate of position on Scan 1

Figure 4.1 Prediction of positions on Scan 1.
(i) Prediction \( T_{02} \):

If a turn signal is received on Scan 2, we predict the next "Turn" position by a vector at angle \( \theta_1 = \hat{\omega} \times \Delta t \) from \( \hat{\psi}_0 \) so that \( \psi_{02} = \hat{\psi}_0 + \hat{\omega} \cdot \Delta t \)

The distance between the next predicted position and \((x_0, y_0)\) is \( M_{02} = 2 \hat{S}_1 \cdot \Delta t \). Refer to figure 4.1. Notice that the prediction is based upon the smoothed position at Scan 0, not the current measured position.

(ii) Prediction \( S_{12} \):

If no turn signal is received, we predict the next "straight" position by a vector at angle \( \theta_1 \) from \( \hat{\psi}_0 \) and distance \( \hat{S}_1 \cdot \Delta t \) from the best smoothed position on Scan 1 \((\hat{x}_1, \hat{y}_1)\) which is equivalent to the radar measurement. The prediction of the next position is \( \hat{\psi}_{02} \) which is the best estimate for tangential direction at Scan 1. We shall call this tangential direction \( \hat{\psi}_1 = \hat{\psi}_{02} \). Also, if no turn signal is received, we have to switch the tracker back to the straight line TOS tracker using \( \hat{S}_1 \) and \( \hat{\psi}_1 \) as the direction for the next straight line segment.
4.3.3 Processing at Scan 2

Now we receive a second consecutive turn signal to compare with our predicted turn position from Scan 1.

\[ \hat{x}_0, \hat{y}_0 \]

\[ \theta_0 \]

\[ \theta \]

\[ \psi_{02} \]

\[ \psi_{m2} \]

\[ \Delta M_2 \]

\[ \text{measured and best estimate in Scan 1} \]

\[ \text{the new measurement on Scan 2} \]

\[ \text{Figure 4.2 The position radar measurement on Scan 2} \]

Let \( M_{02}^m \) be the distance from \( (\hat{x}_0, \hat{y}_0) \) to new measurement on Scan 2.

\[ M_{02}^p = \left[ (x_{02}^m - \hat{x}_0)^2 + (y_{02}^m - \hat{y}_0)^2 \right]^{1/2} \]

The prior estimate for the length was \( M_{02}^p = 2 \hat{S}_1 \bullet \Delta \hat{t} \)

The error, therefore, is \( \Delta M_2 = M_{02}^m - M_{02}^p \)

Let the direction to the measurement point be \( \psi_{02} = \tan^{-1} \left\{ \frac{x_{02}^m - \hat{x}_0}{y_{02}^m - \hat{y}_0} \right\} \)

The prior estimate for the direction was \( \hat{\psi}_{02} = \hat{\psi}_0 + \theta_1 \)

The error, therefore, is \( \Delta \psi = \psi_{02} - \psi_{02} \)
Smoothing on Scan 2

Values for $\alpha$, $\beta$, $\gamma$ are used to smooth the estimates for position $(x, y)$, speed $\hat{S}$, and turn angle $\hat{\theta} (\hat{\omega} \cdot \Delta t)$ respectively. A value of 0.5 is chosen as the initial guess for parameters $\alpha$, $\beta$, $\gamma$.

The following three subsections show the smoothing for position, speed, and turn angle (turn rate)

(i) Position

Figure 4.3 - Smoothing position between predicted & radar measurement
From figure 4.2, we can see that the smoothing is done in the following way:

\[ \Delta x_{2}^{mp} = x_{2}^{m} - x_{2}^{p} \]
\[ \Delta y_{2}^{mp} = y_{2}^{m} - y_{2}^{p} \]

The smoothed position on Scan 2 is therefore,

\[ \hat{x}_{2} = x_{2}^{p} + \alpha \cdot \Delta x_{2}^{mp} \]
\[ \hat{y}_{2} = y_{2}^{p} + \alpha \cdot \Delta y_{2}^{mp} \]

(ii) Speed

\[ \hat{S}_{2} = \hat{S}_{1} + \beta \cdot \frac{\Delta M_{2}}{2 \Delta t} \]

(iii) Turn angle (turn rate)

Let the smoothed estimate for \( \theta \) on Scan 2 be:

\[ \hat{\theta}_{2} = \theta_{1} + y \cdot \Delta \psi_{2} \]

Since \( \omega = \frac{\Delta \theta}{2 \cdot \Delta t} \)

therefore \( \hat{\omega}_{2} = \frac{\hat{\theta}_{2}}{2 \cdot \Delta t} \)

We now have smoothed estimates for \( (\hat{x}_{2}, \hat{y}_{2}) \), \( \hat{S}_{2} \) & \( \hat{\omega}_{2} \)

Actually, we could just smooth position and try to estimate speed, direction and turn rate. However, this could give us less adaptability of the estimates of ground speed, direction and turn rate of the aircraft in cases of wind. When there is a constant wind blowing from an unknown direction for an aircraft making a perfect circular path, the actual path will become a cycloid. The changes in speed, direction and turn rate of the aircraft as perceived from ground will be very different in the different parts of the cycloid.
Predictions on Scan 2: (for Scan positions)

Figure 4.4 - Iterative prediction of position from successive best smoothed positions.

From \((x_0, y_0)\) with all the states of the aircraft's information, we were able to make predictions for \((x_2, y_2)\). Similarly, all the state information of aircraft is known at \((x_1, y_1)\), so we can make predictions for \((x_3, y_3)\). The position \((x_1, y_1)\) now becomes the base for predicting the direction and length of the arc chord from \((x_1, y_1)\) to \((x_3, y_3)\).
Figure 4.5 Prediction of positions on Scan 3 from position on Scan 1

(i) Prediction $T_{13}$:

If a turn signal is received on Scan 3 we predict its next position by a vector at angle

$$\theta_2 = \hat{\omega}_2 \times \Delta t$$

from $\hat{\psi}_1$, so that $\psi_{13}^p = \hat{\psi}_1 + \hat{\omega}_2 \cdot \Delta t$

The distance between the next predicted position and $(\hat{x}_1, \hat{y}_1)$ is

$$M_{13}^p = 2 \hat{S}_2 \cdot \Delta t$$

Refer to figure 4.5.
(ii) Prediction $S_{23}$:

If no turn signal is received on Scan 3, we predict its position by a vector at angle $\hat{\theta}_2$ from $\hat{\psi}_1$ and distance $\hat{S}_2 \cdot \Delta t$ from the best smoothed position on Scan 2 ($\hat{x}_2, \hat{y}_2$).

The best estimate for tangential direction at Scan 1 is $\hat{\psi}_2 = \hat{\psi}_1^P$. Also, if no turn signal is received, we have to switch the tracker back to the straight line TOS tracker using $\hat{S}_2$ and $\hat{\psi}_2$ as the direction for the next straight line segment.

4.3.4 Processing at Scan 3

Once the aircraft started making a turn, the aircraft state information, (position, speed, track direction) is recorded during the turn. At this step, re-indexing occurs. The position and ground track direction data is being transferred from Scan 1 to Scan 0, Scan 2 to Scan 1 and Scan 3 to Scan 2 respectively. The exact same procedure as Scan 2 is carried out until the turn stops and the tracker algorithm is switched back to the straight line TOS tracker.

4.4 The implementation of the tracking algorithm

The algorithm in section 4.3 is being implemented together with the TOS tracker. The new code is called the new turn tracker. Figure 4.5 shows the simplified version of the flow chart.
* F is the firmness number of the track in the TOS.
F=11 means that the TOS is tracking the early stage of a new straight line segment.

Figure 4.6 - The flow chart of the new turn tracker algorithm. (Simplified version)

In order to find out the correct prediction of position of the aircraft from \((x_0, y_0)\). Transformations of the axes are carried out.
Chapter 5

Analysis of the performance of the New Turn Tracker Algorithm

5.1 The Flight Path Scenarios

Though Primary radar is a less accurate system than the Secondary Surveillance system, the difference in the accuracy is consistent. As a result, it is justified for us to test the new tracker algorithm using just one radar system. We choose the SSR system for all simulation runs. Its accuracy is represented as 30 feet in range and 0.04 degrees in azimuth.

There are two aspects: (i) the nature of turn and (ii) the location of the turn from the radar site to be tested. The effects of tracking of a tangential turn and a radial turn are discussed in chapter 2. As a result, four scenarios are being made as can be seen from figure 5.1. The aircraft is flying with a speed of 150 knots.
Figure 5.1 - The five test scenarios

The fifth scenario is the forth scenario with constant wind of 30 knots from 315º. It is to test on the performance of the new turn tracker in case of winds.
5.2. Comparison of the performance of the TOS and the New Turn Tracker

For each scenarios, ten sample runs are obtained for the new turn tracker algorithm and the old TOS. The maximum, total and the mean tracking deviation for the two trackers are tabled as followed. We can see an improvement of the performance of the new turn tracker algorithm in almost all the scenarios.

<table>
<thead>
<tr>
<th>Deviation in nm</th>
<th>Max Deviation</th>
<th>Total Deviation</th>
<th>Average Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tracker</td>
<td>0.104</td>
<td>13.703</td>
<td>0.019</td>
</tr>
<tr>
<td>Old Tracker</td>
<td>0.129</td>
<td>15.825</td>
<td>0.022</td>
</tr>
<tr>
<td>Scenario 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tracker</td>
<td>0.211</td>
<td>16.274</td>
<td>0.023</td>
</tr>
<tr>
<td>Old Tracker</td>
<td>0.118</td>
<td>18.343</td>
<td>0.026</td>
</tr>
<tr>
<td>Scenario 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tracker</td>
<td>0.143</td>
<td>25.144</td>
<td>0.035</td>
</tr>
<tr>
<td>Old Tracker</td>
<td>0.242</td>
<td>29.733</td>
<td>0.041</td>
</tr>
<tr>
<td>Scenario 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tracker</td>
<td>0.126</td>
<td>21.529</td>
<td>0.030</td>
</tr>
<tr>
<td>Old Tracker</td>
<td>0.184</td>
<td>26.117</td>
<td>0.037</td>
</tr>
<tr>
<td>Scenario 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tracker</td>
<td>0.131</td>
<td>22.410</td>
<td>0.030</td>
</tr>
<tr>
<td>Old Tracker</td>
<td>0.205</td>
<td>25.609</td>
<td>0.034</td>
</tr>
</tbody>
</table>

The time series of average position errors, speed errors and ground track errors of the 10 random runs are presented in the following pages.
Figure 5.2 The time series of the typical errors of the new turn tracker (Scenario 1).
Note: □ -- New tracker
Figure 5.3 Comparison of the time series of errors of the new turn tracker and the TOS. (Scenario 1)

Note: ■ -- New tracker  ■ -- TOS tracker

Comparison of the performance of the old TOS and the new TOS

Comparison of the performance of the old TOS and the new TOS

Comparison of the performance of the old TOS and the new TOS
Figure 5.4  Comparison of the time series of errors of the new turn tracker and the TOS. (Scenario 2)

Note: ■ -- New tracker □ -- TOS tracker
Figure 5.5  Comparison of the time series of errors of the new turn tracker and the TOS. (Scenario 3)

Note: ■ -- New tracker  □ -- TOS tracker

Tangential turn at 40nm away from radar

Tangential turn at 40nm away from radar

Tangential turn at 40nm away from radar
Figure 5.6  Comparison of the time series of errors of the new turn tracker and the TOS. (Scenario 4)

Note: ■ -- New tracker  □ -- TOS tracker
Figure 5.7 Comparison of the time series of errors of the new turn tracker and the TOS. (Scenario 5-with wind effects)

Note: ■ -- New tracker  □ -- TOS tracker

Scenario 4 with 30 knots wind

Scenario 4 with wind

Scenario 4 with 30 knots constant wind
Chapter 6

Concluding Remarks

In this research, we have looked into the problem of tracking aircraft around turns in the ATC terminal area with and without wind effects. We have made up a new algorithm for tracking aircraft around turns and successfully implemented the algorithm in Turbo Pascal 6.0 in the TASIM. The simulation is able to run satisfactorily in terms of tracking and gives us valuable tracking reports to analyze. This research provides typical research procedures for future testing of new ideas in tracking in the ATC area.

The implementation of the turn signal as a turn detector for the aircraft, makes the so-called 'intelligent tracking' possible. It is able to improve the performance of the traditional tracker performance significantly. This is a major contribution of the research. However, further improvements can be made both in terms of the tracking algorithm and the simulation.

6.1 Insights and recommendations from the simulation

The down link of the aircraft's state information through the Mode S system will definitely improve the performance of the tracker during a turn. This makes automation in the ATC area more practical.
From this research, it is concluded that two pieces of information are needed to down link from the aircraft to the ground. They are respectively the turn signal and the direction of the turn. We do not want to send down intentions of the pilot because that would 'destroy' the essence of the automatic tracking processes.

The improvement in tracking efficiency of the new tracker in the algorithm is expected because it involves the processing of the turn information. The simulation, on the other hand, gives us a solid proof of the increase in efficiency and demonstrate the superior performance of the new algorithm.

6.2 Further Research Directions

In the code, we have used 2 pieces of information (i) turn signal, (ii) turn direction, to enhance the efficiency of detection and the tracking performance. However, this is not the minimal information. We might want to find out whether just one piece of information, (i.e. the turn signal only) is enough to provide the necessary tracking performance. This is one of the future research directions.

Also, we have used bank angle as our turn signal. We have not investigate the effects of using other aircraft state information (such as turn rate or heading) to constitute the turn signal. That may lead to an easier detection of turn and can further increase the efficiencies of the algorithm.

There are other chord processing algorithms which were considered. For example, one which makes use of the three latest best smoothed positions to predict the next position
has not been tested thoroughly. Tests can be carried out for various chord processing algorithms. A comparison can be made with the new turn track algorithm presented here.

In the TASIM, the old aircraft guidance option has been used. This is not a realistic guidance option because the aircraft's bank angle tends to increase instantaneously to 20 degrees and the actual flight path without wind effect tends to follow the flight legs exactly. In reality, the aircraft would actually deviate from the actual flight legs and wonder around them. This suggests the use of the new path guidance option which would represent the performance of an autopilot in following a specified track.
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- C.C. Lefas. "Using Roll angle measurements to detect and track maneuvers in advanced ATC tracking systems", Ministry of physical planning, Housing and environment, Greece.


