GEO-REFERENCING RADAR PLOT DATA FOR THE TRAFFIC INFORMATION SERVICE BROADCAST

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Abstract

The Federal Aviation Administration (FAA) has gained some significant early operational experience with the Traffic Information Service Broadcast (TIS-B), both on the East Coast of the United States, and in the Anchorage, Alaska area. TIS-B, for the first time, puts geo-referenced radar data directly in the cockpit where, for a number of reasons, the customer can be more sensitive to inaccuracy and other anomalies than the traditional user (i.e., the air traffic controller).

The Broadcast of Automatic Dependent Surveillance (ADS-B) is the air-to-air transmission of aircraft position and velocity information. In order for ground surveillance radar data and ADS-B data to integrate seamlessly in the cockpit, a "truly geo-referenced" radar alignment technique is needed for radar to ADS-B correlation. Successful synergy between ADS-B and radar requires accrued radar registration. Incorrect geo-referencing can result in a number of anomalies that can be difficult for both designers and pilots to deal with appropriately.

This paper describes the process of geo-referencing radar data, describes some real world limitations of the radar sensors, the anomalies that can be encountered and their cause, techniques for mitigating these anomalies, and finally, this paper discusses one of the radar alignment techniques used for the system providing TIS-B in Anchorage for the FAA's Capstone program.

This paper will attempt to bridge the gap between the ground systems and airborne systems. Given the insight into the processing performed on the ground, the avionics developers may adapt or create new ways to overcome these issues.

Background

ADS-B and TIS-B

The FAA is enhancing the legacy radar surveillance system with ADS-B. ADS-B provides Global Positioning System (GPS) positions of aircraft for separation by controllers. It also provides the unique capability of displaying surveillance data received air-to-air on a cockpit display for use by the pilot. During the initial period of ADS-B equipage, the FAA plans to supplement this cockpit display capability with TIS-B. TIS-B is the ground-to-air uplink of primarily radar derived surveillance data. Supplementing ADS-B with TIS-B will allow the ADS-B equipped pilot to see the remaining aircraft that have not yet equipped with ADS-B. In short, the cockpit display will depict both ADS-B air-to-air and TIS-B (derived from RADAR) from the ground uplink. Other sources of TIS-B exist, such as the rebroadcast of ADS-B and multi-lateration. These non-radar sources of TIS-B are beyond the scope of this paper.

Need for Geo-Referencing Radar Data

Radar measurements consist of range and azimuth (ρ, θ) plots. Range, or rho, is the distance from the radar antenna which is derived from measuring the time between the transmitted and received radio frequency (RF) pulses. Azimuth, or theta, generally, is the direction the antenna sail is facing. Pressure altitude may also be available in the Mode C reply to a radar interrogation. Rho, theta, pressure altitude (ρ, θ, h) coordinates, relative to a radar, are very different from the ADS-B GPS coordinates depicted in latitude, longitude, and both geometric and pressure altitudes.

Simple geometry is used to convert from the radar centric polar coordinate system to the WGS-84 coordinate system used by ADS-B. However, many subtleties exist in both physical and temporal dimensions. These subtleties are overcome through massaging the conversion algorithm with learned values in order to get the radar plot data as close to truth as possible. These variables are defined in the "radar alignment technique" section of this paper.

Radar Alignment is the process of obtaining the radar specific geographic attributes used to geo-reference the radar plot data. From an avionics and pilots perspective, radar alignment is the process used to determine the parameters necessary for converting radar plot data to the same coordinates as used by ADS-B. From a ground infrastructure and Air Traffic Control (ATC) perspective, radar alignment is what enables adjacent radar plots to be correlated as well as correlating the plot data with ADS-B. This correlation process is what allows an ATC tracker to maintain a single track from multiple surveillance sources, such as, adjacent overlapping surveillance radars and ADS-B sensors

Radar Processing for ATC Use

Historically, each Air Route Traffic Control Center (ARTCC) receives radar plots from the available radars in their respective air space. This data is then converted to the local system plane for tracking, flight plan association, and controller display. With this technique, the radar alignment parameters would only be adjusted enough for smooth transition between the adjacent radars that provide coverage for one ARTCC. The radars are aligned to each other and not to truth. The ATC display context is a little more forgiving than what is needed for TIS-B on a cockpit display. A pilot using the cockpit display to visually acquire crossing traffic 1 mile ahead using a 5 mile range scale will generally be more sensitive to latency and positional errors than an air traffic controller separating traffic at 3 miles using a 30 mile (or larger) range scale. Furthermore, due to the coarseness of the surveillance radar plot resolution, the alignment process does not need to be completely thorough. It only needs to be good enough to fall within the radar error in measurement. This is completely acceptable, since all of the data is still accurate relative to adjacent radar plots. If one is off, relative to the ATC automation system plane, they all are off by the same amount and there is no separation concern.

With the advent of ADS-B, two fundamental changes will take place:

1) The plot data will now needs to be truly geo-referenced for the first time, matching the capability inherent in ADS-B as defined by WGS-84.

2) Discontinuities at ARTCC boundaries cannot be tolerated. All surveillance radars must be truly geo-referenced across ARTCC bounds.

Limitations and Anomalies

TIS-B is used primarily for an aid to visual acquisition. TIS-B will give a pilot access to a wealth of powerful information. This means that pilots will want to use this information as part of their decision making processes, even though, they make these decisions without TIS-B today. This can be beneficial during instances, such as maintaining traffic awareness in an airport traffic pattern. It can also be a detriment. If this advisory information was misleading, it might lead a pilot to deviate course inappropriately to avoid traffic that is not really there. ATC controllers are trained to identify such anomalies when they occur. They also have the benefit of large scale displays. For the pilot however, this is new territory. Both avionics designers and pilots may encounter several anomalies, including:

Shadows

A "shadow" is the term used when a TIS-B report is up-linked representing a target that has already transmitted its ADS-B position. The avionics display depicts two targets flying in close proximity. The aircraft generating the ADS-B position receives its own TIS-B report which might be interpreted as an immediate danger.

The TIS-B service will not contain messages that represent a target that has already transmitted its ADS-B position. If implemented perfectly, this will eliminate the existence of shadows. It will also ease the transition from primarily radar surveillance to ADS-B surveillance. As aircraft equipage of ADS-B reaches completion, there is significantly less need for the TIS-B service. Therefore as time progresses, the load on the data-link channel will smoothly migrate from a majority of TIS-B messages to a majority of ADS-B messages. This transition will keep the data-link channel utilization consistent in time.

Pop ups

A "pop up" occurs when a non ADS-B target climbs into coverage of a ground RADAR. The ground tracker will initiate its first track and start transmitting. To the avionics this target will appear out of the blue. It is possible for this target to annoyingly appear and disappear while on the fringes of radar coverage

Non-Transponder Equipped Aircraft

At least in the near-term, TIS-B service will not include radar returns without mode-C (altitude) or radar returns only from primary, skin paint, radar. This means the pilot may find themselves near another aircraft that does not appear on the avionics display.

If primary only, or non Mode C, returns are included in the TIS-B service, the accuracy of the position will be severely reduced. This means that, at close range, the target might be incorrectly depicted on the display. It also means that the targets depiction of altitude will be incorrect or unknown. In any event, TIS-B will not provide a complete surveillance scenario because of the presence of aircraft without Mode C transponders.

Stitching (Jitter)

Radar resolution in azimuth decreases with range and errors are inconsistent from scan to scan. For long range Air Route Surveillance Radars (ARSR), the error in azimuth can currently be greater than 1.5 nautical miles *(refer to "radar accuracy" in the "Causes" section of this paper.)* This means if the TIS-B target has only one ARSR as its source the target may not have a stable trajectory and appear to "jump around" on the display. This error in azimuth will be compensated for through the noise filtering attributes of the trackers, but can not be eliminated completely.

Velocity Lag

This is probably the most recognizable of the radar tracking anomalies. Currently, trackers perform noise filtering and position estimation on raw data. For trackers that do not have access to Doppler velocity, such as ATC trackers, this filtering process can not keep up with aircraft accelerations. Even a simple turn is acceleration in one dimension. Current ATC Tracker filters treat acceleration as noise. This anomaly manifests itself as a lag in the velocity vector and the reported track position is in error tangential to the turn. The figure below shows an exaggeration of this condition.

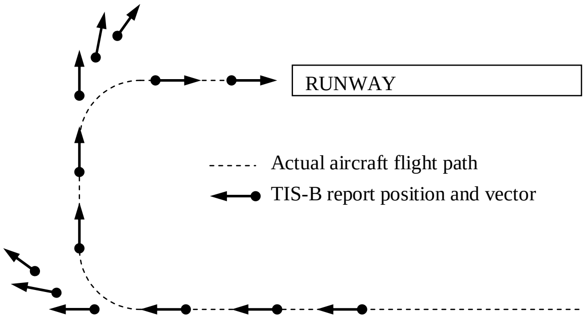

Figure 1. Tracker positional lag in a turn

In extreme cases this anomaly can result in substantial position errors that could be seen by a pilot. The example above is a tight turn in the pattern on approach. The avionics display will show the aircraft arcing well beyond the approach corridor then suddenly jumping back in place once the turn is complete. In a tight turn, it is possible for the tracker to loose track association and initiate a new track for the same target.

Identification swapping

When an ADS-B to radar correlation has been determined, the ADS-B address will be carried along through out the life of the track. When the ADS-B aircraft flies beyond the coverage of a ground sensor, the now radar-only track will still have the correct address. In rare cases, a neighboring radar return can be attributed to the track in question. This address will now be erroneously propagated throughout the second aircraft's track life. One example is when an ADS-B correlated track lands and a radar only track takes off from the same airport on parallel runways at the same time. This may not be an important issue for pilots; but coupled with the rest of the anomalies, it may be another factor limiting user confidence in the system.

Causes

There are many contributing factors that influence the introduction of TIS-B positional errors and anomalies. Some of which are described below. As with most modern day deployments, TIS-B is a system of systems. Any slight hiccup along the path can result in positional error in a TIS-B report. Anomalies can be caused by any or all of the following.

Noise filters

The time tested accepted means of noise filtering and position estimation in the NAS is the Kalman filter. Regardless of the filtering technique, you are in effect compressing subsequent plots into a track. This track represents a blend of the historic plots. This blend is what enables bad positions to be ignored and trend information to be deduced. Using this analogy, one can easily see that the resultant data from a filter may or may not always be the best. In extreme circumstances it can actually be wrong.

Latency

Variable latency will affect TIS-B report accuracy because it makes it difficult to derive an accurate plot time of applicability (TOA). Having poor radar plot TOA decreases the accuracy of the position estimate made by the tracking systems. Since the radar does not assign the exact time to the plot measurement, one must be derived. Listed are three contributors to this variable latency. 1) Out of the radars own interface, the latency is variable. This is caused by unknown fluctuations in traffic loads. Generally, radar interfaces have limited bandwidth and reports can be backed up prior to receipt. 2) Multiple plot reports from overlapping sensors may arrive at the tracking system out of order in time. This disorder is due to variable latencies in the ground telecommunications. The Kalman filter expects the data to be ingested in the order it was sensed. In systems with sensors distributed over a WAN, or even with direct serial connections, the radar data will obviously be received asynchronously with ADS-B. 3) Finally, residual latency biases represent a known constant delay and are not so much a problem. Since, this trend can be measured and accounted for.

Radar Accuracy - Range versus Azimuth

As discussed in the “anomalies” section, azimuth resolution is problematic at range to the radar. The range measurement however is fairly consistent. There exists 4096 possible azimuth measurements from all Secondary Surveillance Radars (SSR.) These are called Azimuth Change Pulses (ACPs). Using the ARSR with a 250 nmi range as a worst case, the resolution is the circumference at 250 nmi divided into 4096 segments which is about 0.38 nmi. [1] Given the possible error associated in measurement could be +/- 2 ACPs the total distance in azimuth can be greater than 1.5 nmi from one report to the next.

Extrapolation

An early architectural decision was made that over-the-air bits were not to be spent on encoding the position’s time of applicability (TOA) for ADS-B messages. TOA is instead inferred by the receiver from the time of message receipt and the TOA assignment rules used by the data link.

In order to generate and format an over-the-air TIS-B message for transmission by the ADS-B data link, the position encoded in the message must be valid at the time expected based on the link TOA assignment rules prior to the actual transmission opportunity. For example, if the message is to be valid at the beginning of the UTC second prior to transmit and the last position report from the tracker contributing to this message is more than a second old then the position needs to be extrapolated out to that UTC epoch. However this approach is not without shortcomings. Current surveillance trackers cannot provide velocity and acceleration values accurate enough to extrapolate with any confidence over this period of time. Well behaved aircraft flying in a rich surveillance environment should extrapolate with no problem. The rest will not.

Poor Radar Alignment

Several parameters are needed to convert from radar reported coordinates to WGS-84 coordinates. These parameters are described below in the “Radar Alignment Technique” section. Poor radar alignment is probably the biggest contributor to positional errors in TIS-B.

Atmospheric Interference and Refraction

Slant range is commonly considered the straight line distance directly from a radar to an aircraft. It is actually the distance of a very slightly curved line influenced by the refractive index of the atmosphere. The curvature of this line is usually modeled using a simple 4/3 earth radius. However, climate and meteorological conditions can change the refractive properties of the atmosphere. For measuring distance, the difference in length between this arced line and a straight line are negligible. However, these changes also affect how far a radar's "line of sight" extends beyond the horizon. This sometimes results in radar coverage in one area one day and not the next.

Techniques for mitigating TIS-B Errors

For the most part, there is little that can be done to defend against the introduction of positional error due to the causes outlined above. Paying attention to the little things can mitigate a lot of the problems but there is no perfect solution.

Kalman filtering techniques

Several variations of the Kalman filter have been developed to fight these issues. [4] With the introduction of networked sensors and the accessibility to compute platforms that are far more advanced than were available back when the Kalman filter was created, other means of position estimation and noise filtering should be explored. Specifically, obtaining better measurements or tracking models for velocity and acceleration will greatly enhance the current trackers capabilities.

Determining better TOA

As the FAA migrates away from serial communication interfaces toward a networked solution the effects of latency will continue to compound. Even though modern networks provide better throughput, their complexity makes it difficult to determine latency characteristics. Simple serial connections, though limited in bandwidth, are easily characterized. By developing ways to better assign time of applicability to radar plots, the effects of latency can be reduced.

Assignment of Integrity and Accuracy Values

By assigning the confidence in the position estimate and the likelihood that it is correct, the user of the data can determine if it is acceptable to act on. We may find that in certain circumstances some TIS-B report may not meet minimum accuracy and integrity to even be included as part of the service.

Limit Service to Radar Rich Environments Needed for Higher Levels of Service

One way to combat a good portion of the causes of error is to only provide TIS-B services in areas of rich overlapping radar coverage. The disadvantage would be a severe reduction in service areas of interest, such as coastal areas and Alaska. More demanding TIS-B applications will definitely require the use of this technique.

Proper Radar alignment

Next to the actual filtering and correlating algorithms in the tracker, radar alignment is the single most important process needed for minimizing positional error. Radar alignment needs to be a periodic or pseudo real time process that can adapt to physical and load induced changes in the radar as soon as possible. The following section identifies one approach for radar alignment for geo-referencing radar plot data.

Radar alignment technique

This radar alignment technique was developed for use by the FAA's Alaskan Capstone TIS-B system. It derives eight highly coupled values which are defined below. If these values were mutually exclusive it would be possible to solve the system mathematically. It is however highly unlikely for this problem due to the variable's interdependencies. Most of the values are constant terms such as location. Some of the values have linear components.

Radar location is the three dimensional position of the radar antenna in a geographic coordinate: latitude, longitude, and elevation. Often times, surveyed locations of radars are inaccurate at best. An up-to-date database of GPS measured radar sensor locations does not seem to exist.

Azimuth bias is a constant additive value applied to the radar plot azimuth measurement. This is the angle from North in a clockwise direction. This generally corrects for a physical shift in the desired antenna position.

Additive range bias is a constant value added to the radar plot range measurement from the sensor. This generally corrects for inaccurate range measurements due to latencies from the antenna to the processing that calculates the range.

Multiplicative range bias is used to scale the range for any number of reasons. Some possible explanations are to negate any inaccuracies in the computer algorithms used to convert from radar-centric polar coordinates to geographic coordinates, or to modeling the curvature of the RF waveform due to atmospheric conditions.

Plot timestamp bias is an additive value used to correct a trend in miscalculating radar plot time of applicability (TOA). Latencies from the radar sensor to the process responsible for assigning TOA exist and introduce error in the measurements.

Scan period is the average time it takes the radar to complete one full rotation or scan. The nominal value of 4.6 seconds seems to be a general guideline and not the actual period for terminal radars. This parameter will affect the capability of a tracker to correct and/or derive accurate time of applicability for radar plot measurements.

Depending on how sophisticated the registration process needs to be, some of these biases can have both constant and linear components. One could even go as far as modeling exponential components for some of these biases. This would, however, probably yield minimal if not negligible effects. The Constant azimuth bias may be a good candidate for a linear component. This linear scaling function with respect to azimuth could model the effects of wind load on the antenna sail or possibly model the effect of the slope of the geoid relative to the WGS-84 ellipsoid.

Radar alignment steps

Step 1) coarse radar registration using a graphical tool

Utilizing a graphical tool designed to overlay radar plot data and ADS-B position data, allows the user to “click and drag” the radar plot symbols over the ADS-B position symbols. The user iteratively massages the radar location, azimuth and range biases until these initial registration parameters are close enough to establish correlations in a tracker.

Step 2) generation of plot data to ADS-B position report correlations

A tracker is configured to apply the coarse registration parameters from step one. The same set of data used in step one is fed into this tracker which is tailored to output a list of all correlated ADS-B reports and raw radar plot data. Upon completion, a file is generated and contains a mapping between all plot data and ADS-B reports that share a common track.

Step 3) AI learning algorithm

A) The correlation file generated in step 2 is read into memory and stored.

B) A truth value is determined for each track at every time a radar measurement is present. To accomplish this, least squares curves are fit to all the ADS-B reports, in three dimensions, that correlate to a given radar plot. Then a position solution is interpolated from this curve at the time of radar sensor measurement. This position represents the true geographic position of the corresponding radar plot. By using the least squares method, most of the 30 feet of measurement noise from the GPS position in the ADS-B message should be filtered out and a more accurate position will result [2, 3].

C) A natural selection algorithm is implemented to operate on a population of agents over many generations. Each agent contained 8 DNA strands which represent the value of the 8 alignment parameters. Each generation, random mutations are applied to the agents’ DNA. The radar plot data is then converted to geographic locations using the registration parameter values contained in the DNA. A fitness value is calculated by comparing the converted plot data positions to the truth positions interpolated from ADS-B. The average of all the distances calculated is assigned to each agent’s fitness value. The good performers are retained and the poor performers are eliminated. Then this process is repeated for the number of desired generations. Upon completion, the best performing agent's DNA is obtained and the alignment parameters are ready for use. [5]

No seed is required to converge on a solution. By employing an iterative technique, the user can manipulate the range of the DNA strands to perform specific analysis on individual alignment parameters.

The applications used in the steps outlined above can be used in a real time fashion. This would enable a system to monitor the state of the radar alignment and generate alarms for service technicians when the radar goes out of alignment, as well as, provide feedback to the tracker in real time to potentially update its registration values automatically.

Real World Limitations

Poor range resolution from Anchorage ASR-8:1/8 nautical mile – Increasing the resolution of the ASR-8 can be accomplished by reconfiguring the device used to digitize the analog radar data. This will decrease the expected error, aid in the registration process, and increase the accuracy of the up-linked TIS-B data.

Unknown radar antenna elevation – surveying the antenna elevation eliminates one variable from the problem making it twice as easy. Geometric ellipsoidal elevation can be greatly different from the mean sea level (MSL) elevation at the radar. This means you can have wild values for radar elevation when converting to GPS coordinates.

Since this radar alignment technique relies on geometric altitude reported in the ADS-B positions, an accurate geometric elevation of the radar sail is needed.

The results of this radar alignment technique show that the antenna elevation needed to have a greater degree of flexibility. There are two possible explanations for this. 1) The difference between surveyed geoidal elevation (MSL) and WGS-84 ellipsoidal elevation are significant in many regions of the earth. 2) There probably exist some deficiencies in the equations used to convert from radar coordinates to WGS 84 coordinates. These deficiencies, however, should have been minimized by the multiplicative range bias component. For systems that do not have the ability to adapt by a range factor, the antenna height can act as a multiplicative range adjustment to a degree.

Mapping pressure altitudes to geographic altitudes induces several feet of vertical error – Although this has nothing to due with aligning the radar. Now that radar alignment is made you still have to map between pressure altitude and geometric altitude for generating non ADS-B TIS-B reports. This problem is beyond the scope if this paper.

The ADS-B geometric altitude was used in place of the Mode C altitude for all plots. Since Mode C altitude is not really a radar sensor measurement, this simplified the algorithm greatly.

rho-theta to geographic coordinate equations may differ from system to system – trackers often track on local coordinate systems prior to converting to geographic positions. If ATC automation systems are used to generate the TIS-B data, a common coordinate system needs to be standardized for ATC The automation system planes should be replaced with WGS-84 and the display systems should utilize the recent advances in graphics technology, such as OpenGL.

Number of generations limited by time and processing capacity – This severely limits the ability of registration techniques to operate in real time. Honing in on an exact solution requires a powerful compute platform. Deriving values close enough for our use can be accomplished with inexpensive commercial hardware.

Limited targets of opportunity – The absence of ADS-B equipped aircraft severely limits the ability to perform radar registration in real time.

Poor plot time of applicability – Currently the ability to accurately timestamp radar plot measurements is poor at best. There exist techniques to correct the plot time of applicability. One of which is discussed below.

Deriving accurate radar plot Time of Applicability (TOA)

Characterization of radar plot data with respect to time of receipt reveals several deficiencies in the current state of TIS-B. Historically, the North sector mark has been used to synchronize time and derive TOA for plot data. Since the North sector mark has a higher priority than plot data, it is received as soon as possible. This allows the ground system to derive TOA based upon azimuth and scan rate. Unfortunately, the North mark still has variable latency associated with it. An unknown amount of the previous plot will still be transmitted before the North mark can start. This is further compounded, if the North mark is not immediately time stamped at the radar site prior to transmission on a ground network. For these reasons using the North mark may still be error prone.

This paper's alignment technique shows one way for accurate radar plot TOA calculations. Strict use of the azimuth of the plot will yield a relative TOA no less accurate than 2 ms in quantification error. This simple approach allows the tracker to utilize two registration variables for calculating the plot TOA: 1) scan period, and 2) plot time stamp bias. Basically, plot TOA is equal to the scan period threshold added to the time it takes to traverse the plots azimuth in degrees added to the plot timestamp bias:

TOA = T * N + T/360.0 * theta + bias

Where T is the period of the radar scan, N is the number of scans elapsed since some reference time (t0), theta is the azimuth of the plot in question, and bias is the residual time left over for lining up t0 with the North azimuth. This residual time is also affected by the average latency of the plot data prior to time stamping.

This technique utilizes the timestamp placed on the plot at the time it was received. This timestamp is different than the plot TOA. This timestamp is used for only one reason. It is used to calculate N in the equation above. The timestamp, in my opinion, is only accurate enough to determine which scan the radar is on relative the reference time (t0). Once N is found an accurate TOA is a simple matter of arithmetic. All variability in latency is no longer an issue.

There exists one operational deficiency. Any time the radar is disrupted for any reason will be cause for reconfiguration of the tracker. A new scan period and TOA bias will have to be determined in this event. A real time monitor of these biases would correct this problem.

Discussion on flight test route contributions to errors

A flight route consisting of one predominant range does not isolate the range biases and antenna elevation.

By flying at the same range to the radar for the entire flight test, three registration parameters can be manipulated to produce several solutions all with different values. Additive range bias, multiplicative range bias, and antenna elevation are all affected by the range calculation. In order to isolate each variable many different ranges have to be included as part of the flight route. Several range biases and radar elevation solutions can be found for any given data set.

A flight route consisting of one predominant direction about the radar does not isolate the azimuth bias.

Current flight routes only fly one direction around the radar at a constant speed. This means several plot timestamp biases and azimuth biases can be used for a given data set. It is not possible to mathematically isolate these variables in this case. A change in azimuth bias can manifest itself as a change in the radar plot timestamp bias and vise versa.

A flight route consisting of one predominant direction radially from a radar does not isolate the range bias.

Flight routes may only fly one direction around away from the radar and return to the radar at a different radial. This means several plot timestamp biases and range biases can be used for a given data set. It is not possible to mathematically isolate these variables in this case. A change in range bias can manifest itself as a change in the radar plot timestamp bias and vise versa.

Flight route enhancements

In order to isolate all the radar alignment variables, modifications need to be made in test flight routes.

Fly a round figure eight (snowman) with the intersection over the radar. Each loop of the figure eight snowman will cancel out the time dependency from the previous loop by providing subsequent radar plots traveling in different directions relative to the radar and radar rotation. The figure below represents one example of this type of flight path.

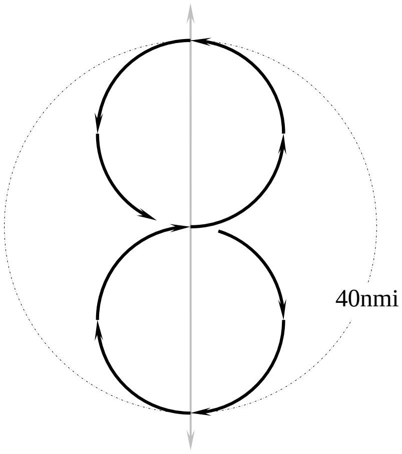

Figure 2. Proposed flight path designed to isolate registration parameters

This flight path will not have a noticeable effect on time and resources for executing the flight. The shape of the flight path will provide plot data in an even distribution of ranges, thus allowing the isolation of range biases and antenna elevation. It will capture radial data approaching and leaving the radar location, thus isolating range bias from radar plot timestamp latency bias. It will provide sufficient data points in all four quadrants of the radar. It will provide radar plot data for an even distribution of azimuths flying in differing directions relative to the radar, thus isolating azimuth bias and radar plot latency timestamp.

One surprising artifact of the figure eight flight is the additive range bias was found to converge on zero. This provides some evidence that the range bias used in most trackers for radar alignment should, in fact, not be additive but be replaced by its multiplicative component. Furthermore, the use of additive range bias is probably incorrect for all plots except the plots that reside at one half of the range of the average plot data.

Recommendation

The human eye is the best known tracker we have access to. By allowing avionics displays to subtly depict historic track information, the pilot can easily see what is real and what is caused by poor ground system implementation. Similar to many problems of the day, there are certain things the computer is not suited to do, and come naturally to the human brain. Keep the human in the loop, whether it is active controller vectors, or pilot interpretation of this data.

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