SYSTEMS ENGINEERING PRINCIPLES AND METHODS FOR IMPROVING AIR TRAFFIC CONTROL USING RADAR REGISTRATION ERRORS ANALYSIS PROCESS (RREAP)

By

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ABSTRACT

This thesis examines systemic target position errors that occur among networked surveillance systems in the FAA controlled high density National Air Space (NAS). The FAA NAS currently uses a radar-based system to locate aircraft in its air traffic control (ATC) system. The problems associated with using a radar-network is in its inherent inability to accurately track and exactly locate the aircraft at the same location. Implementing the capabilities associated with surveillance networks has not come about without technical obstacles, one being the difficulty associated with registration of multi-sensor data, from which two or more radars produce separate tracks of the same target. This paper identifies a source of registration errors and a method for reducing the error associated with it, thereby producing a more accurate location point for the aircraft. For purposes of this paper, the process I have developed is called the Radar Registration Errors Analysis Process (RREAP).

Addressing registration problems can be approached in one of two different ways. A continuously adjustable filter such as a Kalman filter, which takes into account the aircraft's dynamic response, could be used and a weighted average of the different positions plotted. This would, in essence, mask the errors and provide a single target for

display. Modern (ATC) systems use filters of this and other similar types in multi-sensor fusion processes to improve the quality of track data. A second approach would be to develop a tool to identify the source of the errors and try to correct them. The purpose of this thesis is to take the second approach and try to develop a tool to discover the source of the errors. The impetus for this study is to identify potential biases in mathematical calculations, geodetic surveys references, and target tracking information transmitted by both aircrafts and secondary surveillance radars that may affect registration alignments between netted radars in overlapping coverage areas. These target position biases (errors) are clearly identified when a single aircraft observed from two or more radar systems does not appear at the same place when plotted with reference to a fixed point on a tangent plane. The second part of the research utilizes the tool developed to integrate live traffic data into a 3D Google Earth model from which targets exhibiting registration errors could be demonstrated and individual targets could be selected in high density traffic and analyzed for registration errors. The analysis technique developed translated each target's local coordinates into WGS-84 global coordinates providing an ability to compare the performance of each sensor's data against other sensors within a common three-dimensional model. By identifying the systemic variables that cause systemic errors, specific corrections could be simulated and bias corrections could be globally tested using the analysis tool. The effects of relatively small, commonly overlooked system bias errors were given significance when depicted in a live world air traffic presentation. The study eliminated the mathematical calculations used by the FAA as a possible source of systemic registration error. In addition, the study revealed significant

error in magnetic variation. The study and the RREAP tool revealed that specific bias corrections in magnetic variation improved the systemic registration by 150%-1380%. This makes the radar technology more reliable and will improve the FAA ATC systems using radar by making the systems more accurate, efficient, and most importantly, safe.

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LIST OF NOTATIONS / SYMBOLS

Θ	Theta

ACRONYMS

ADS-B	Automatic Dependent Surveillance- Broadcast Information
ARTCC	Air Route Traffic Control Center
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
Az	Azimuth
CRAD	Composite Radar Data Processing
CSV	Comma Separated Variables
DDD.MM.SSSS	Degrees.Minutes.Seconds
Ecc	Earth's Eccentricity
ECEF	Earth Centered Earth Fixed
EWR	Newark Sensor
FAA	Federal Aviation Administration
FTP	File Transfer Protocol
GPS	Global Positioning System
HPN	White Plains Sensor
ID	Beacon Identification Code by Secondary Radar
ISP	Long Island Islip Sensor
JFK	John F.Kennedy Sensor
KML	Keyhole Markup Language
La	Latitude
Lo	Longitude
NOAA	National Oceanic and Atmospheric Administration
MSSR	Monopulse Secondary Surveillance Radar
NAS	National Air Space
R	Range
RBAT	Radar Beacon Analysis Tool
RF	Radio Frequency
RREAP	Radar Registration Errors Analysis Process

TRACON	Terminal Radar Approach Control

1.0 INTRODUCTION

Today's Air Traffic Control (ATC) systems depend on surveillance systems to provide life-critical situational awareness of aircraft. Because of the problems associated with a radar-based system and its inability to accurately pin-point the exact location of aircraft within the NAS, greater separation standards between aircraft have to be maintained, which thereby lower the efficiency of busy airports and cause congestion and delay. Improvements made to surveillance capabilities will enhance current levels of safety, capacity, and efficiency. To effectively network and combine multi-sensor surveillance data into a universal picture, it is critical that raw data from each sensor in the surveillance network contribute accurate target information.

Typically, target position errors occur when multiple radars combine information in overlapping coverage areas to form a picture. For example, if two radars track the same target but produce two separate tracks of the same target, then there is a registration problem. Failure to identify the cause of these errors can introduce track estimation bias that degrades the performance of a netted surveillance system such that multiple redundant tracks are displayed for a single target. At worse, the level of degradation due to biasing errors can negate the usefulness of the surveillance network such that a single radar sensor is used to track air traffic.

The ability to detect and display exactly one track for each aircraft by at least one radar sensor in the network is the most valuable attribute of surveillance networks. The fundamental problem with tracking targets in airspace that is monitored by multiple sensors is determining if the track reports from two or more sensors represent a common target or two or more targets.

To effectively identify target position errors in these surveillance networks, it is critical that each radar sensor be correctly referenced and displayed in an absolute global coordinate system. Any biases in the reported sensor survey positions will translate into biases in the reported track of the aircraft. These target position biases (errors) are clearly identified when a single aircraft observed from two or more radar systems does not appear at the same place when plotted with reference to a fixed point on a tangent plane. Additionally, any reported bias in azimuth or range by a specific sensor in a network will be reflected as a tracking misalignment and the target's global position estimate will be skewed. A major obstacle to achieving accurate multi-sensor overlapping coverage is identifying the source of these errors. These ambiguities, referred to as registration errors, can compromise the utility of multi-sensor networks. Identifying the sources of these registration errors will improve the net-centric surveillance information provided to the Air Route Traffic Control Centers (ARTCCs) by limiting the creation of redundant targets when only a single target exists.

1.1 BACKGROUND

The FAA's National Airspace System (NAS) surveillance network utilizes both Primary and Secondary surveillance radar systems. A typical ATC Radar network correlates target track data used to monitor and maintain separation between aircraft. Target detection processing, signal processing, and track data processing all occur at the radar site. Geometrically, Primary radar measurements consist of a sequence of range and azimuth (r, θ) in a polar coordinate system. Primary radar range measurements, or rho, are calculated by measuring the time between transmitted and received radio frequency (RF) transmission pulses. Azimuth, or theta, is the direction the radar antenna is facing. Secondary radar reads coded radar responses that aircraft transmit in response to signals received. Secondary transponders function similar to modems configured with one modem located in the aircraft and the other modem located at the radar site. The atmospheric pressure altitude measurement is also packaged in the Mode C reply radar interrogation along with distance and direction, Rho-theta, and pressure altitude (r, h, Φ) measurements. The pressure altitude must be transformed into an elevation angle (θ) to produce the position in spherical coordinates. This transformation is outlined in Appendix 5.A. In either case, the origin of reference is measured relative to a radar antenna. Secondary radar systems have the capability to digitally communicate non-positional data such as aircraft's identification. Each radar system in a surveillance network provides available surveillance data from their respective air space.

The NAS depends heavily on the use of Secondary radar to monitor and control air traffic. Most aircrafts are "cooperative", equipped with transponders or beacon systems that transmit an encoded message though the surveillance network to the ARTCCs This information allows controllers to track the location, identification, and altitude of the aircraft. "Non-cooperative" aircraft are tracked using primary radar, this is a non-standard operation that may occur when an aircraft transponder fails or in the case of 9-11 when a pilot wants to remain undetected. The focus of this thesis is secondary radar data that provide digitized position reports to the ARTCC central track processor through the surveillance network. Surveillance data is then converted from radar plots, filtered, and oriented to the ARTCC local system plane by the central tracking processor before it is sent to the ATC displays. Accurate data registration is a prerequisite for multi-sensor networking [Bar m-m90]. The data used in this project is the raw secondary surveillance position report estimates received from the sensor networks to the Center prior to being filtered by the central processor. The output of the central processor is designed to produce an estimated single target position report track from the multi-sensory inputs.

1.2 RESEARCH MOTIVATIONS AND SCOPE

The accuracy and management of surveillance data networks are key ingredients to quantitatively evaluate real time surveillance data reporting. Registration errors are problems that are inherent to surveillance networks that can be addressed in one of two ways. A continuously adjustable filter such as a Kalman filter, which takes into account the aircraft dynamic response, has been developed with a weighted average of the different positions plotted. This, in essence, will mask the errors and provide a single target for display. Filters of this and other similar types have been developed and are being used. A second approach would be to develop a tool to identify the source of the errors and try to correct them. The purpose of this thesis is to take the second approach and try to develop a tool to discover the source of fixed errors. By crafting a tool that allows you to systemically manipulate computationally challenging geometric variables used in multiple sensors, the effects and source of fixed registration errors can potentially be identified. By combining the data from multiple sensors a universal picture of the overall air situation is presented.

The scope of this effort will involve transforming a ARTCC's network of secondary surveillance target track data into an Earth Centered Earth fixed (ECEF) three-dimensional live world traffic flow presentation. The iterative development process requires a series of secondary surveillance track data reports from the NAS New York TRACON. The data needs to be organized in a specific order to decouple the target track information from multiple sensors tracking similar and independent targets. The process development includes the mathematics used to translate each sensor into a common coordinate system, for example, a Least-Squares Estimation technique was applied using the site specific data from each sensor for target registration. There are a number of algorithms used for tracking targets, but few if any tools provide a world-view presentation that correlates a complete network of sensor inputs before being filtered. By modeling all the track data inputs, specific target track biases can be identified and manipulated. The intent of the tool is to identify the source of fixed registration errors by improving the understanding of how registration errors affect surveillance networks.

1.3 DOCUMENT OVERVIEW

Chapter Two reviews the literature of previous methods used to analyze multi-sensor registration.

Chapter Three describes the three primary approaches used to combine multi-sensor data. In addition, systemic and random registration errors are defined and specific error sources that contribute to target misalignments are established.

Chapter Four describes the tool development and mathematical procedure used to analyze and simulate track data within a 3-Dimensional earth centered model. The development tool serves as an effective means of selecting specific targets of interest that exhibit registration errors in a netted surveillance system from which specific aircraft and radar track data variable can be extracted.

Chapter Five uses the simulation tool, developed in the study, to display the results of the mathematical analysis used to systemically model and correct specific errors in target registration. Track data registration between four radars tracking one target within the surveillance network is analyzed before and after position biases are identified and corrected.

2.0 LITERATURE REVIEW

The current trend for solving registration errors has geometrically evolved from a relative to absolute environment. Initially, registration errors were identified and adjusted for by selecting a well calibrated radar, designated as the master radar, in a netted radar sensor environment. The other sensors were referenced relative to this master radar. The mathematical calculation used to identify and adjust all the radars in the network utilized only two-dimensional (x, y) parameters, provided by the radar plot reports. This registration identification process required a significant number of target reports organized in a specific order to decouple the azimuthal and target range errors [1]. In low-density traffic areas this registration method was very time consuming due to low sample rates between radar observations.

Two other mathematically sophisticated methods have added to the study of registration errors. The first, by Fischer, Muehe, and Cameron [2] favored by Bar-Shalom [3] involves mathematically calculating a generalized linear least-squares estimation using cooperative targets or objects of known position. This registration method is for two-dimensional radar displays and requires the inversion of a 4X4 matrix. This method assumes that the errors are constant over time. Another two dimensional method that assumes errors are constant over time is used by Crowley, et al [4] and Dhar [5] to compute sensor biases.

Each of these methods has only been implemented in two-dimensional space, with a modified flat-earth model. Both methods perform poorly in low-density areas because they require 50-100 data point pairs. Neither method utilizes an ECEF coordinate system [6].

Today, the ATC system relies on surveillance networks to communicate target positions as a single track file in an imperfectly registered airspace. Properly relating the data received by multiple sensors in this surveillance network poses numerous problems, particularly when two or more individual sensors report the same target. The problem of having to identify the source of bias errors and accurately orienting multiple radars in a common reference system is an increasing challenge yet is often neglected [7]. New air traffic growth estimates, reduced target separation standards, and data fusion or processing requirements will all be affected by the accuracy in which aircraft position estimates are identified and reported. This problem has appeared in various literatures such as Multi-target-Multi-sensor Tracking [3], the difficulty associated with the registration of multi-sensor data [7-10], and the anomalies of geo-referencing radar data in a real world environment [1].

In this project, a number of target tracking algorithms and mathematical formulas have been applied or created to accept the target track reports from a surveillance system composed of multiple radars. A tool was developed to translate three dimensional tracking data in to a real world air traffic environment. Sensor data from any system in the surveillance network can be input into the analysis tool and evaluated in a three dimensional ECEF environment. The tool allows the user to change all the available variables used in the target tracking process and evaluate the effects that different spatial components (x, y, and z coordinates,) or target track pairs may have on the system environment. Unlike previous efforts in registration analysis, this tool does more than computations of three-dimensional track data. It provides a systemic means of manipulating real time target track data without impacting air traffic operations and potentially identifying the source of fixed registration errors.

3.0 INTEGRATING NETWORKS OF SURVEILLANCE TRACK DATA

Currently there are three primary approaches used to combine multi-sensor data. They are Mosaic Processing, "Tracker of Tracks" Processing, and Plot-Level Multi-sensor Data Processing. Mosaic Processing is the traditional method and utilizes sort boxes from which a single radar (primary) is designated to supply air traffic information to the center and the other sensors provide backup in case the primary fails. A second method, "tracker of tracks," processes air traffic information by having each sensor in the network develop independent tracks of each target in the coverage area. From which the sensor that is believed to provide the best track based on the relative accuracy of each is used by the controllers to manage and direct air traffic. The third approach, Plot-Level Multi-Sensor Data Processing, combines all the sensor information into a single estimate weighted according to the relative accuracies of all the sensors being used to track the target. [6] Each of these multi-sensor processing approaches is designed to minimize the effect that registration errors have on target tracking system.

3.1 SOURCES OF SYSTEMIC REGISTRATION ERRORS

The FAA's surveillance system depends on different combinations of multi-sensors to provide a systemic picture of air traffic. However, data used to create situational awareness from surveillance radars generally operate in a stand-alone configuration. Accurately merging multi-sensor information, though an attractive performance goal, is difficult to achieve due to registration errors. For example, when a single sensor tracks multiple aircraft, the information acquired with respect to the range and azimuth positions of the targets are relative to the radar and therefore there are no offsets. However, when multiple sensors are netted and provide overlapping coverage of the same targets the situation is quite different due to measurement errors between sensors. These errors or biases between sensors can be grouped into two main causes: random errors and systemic errors.

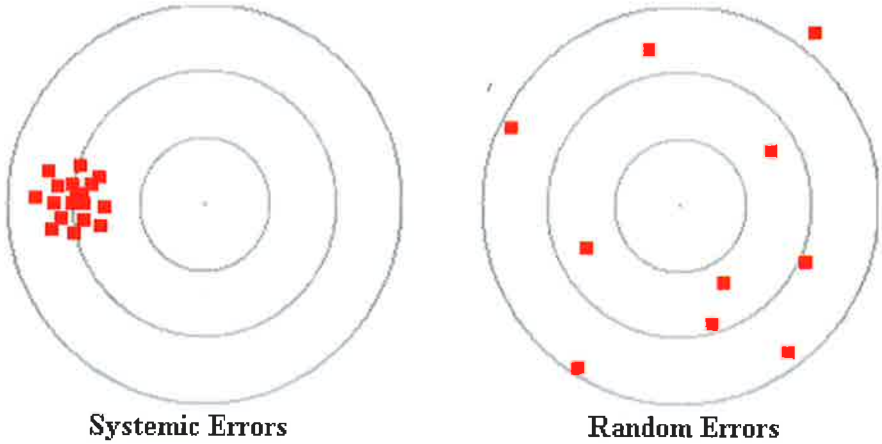

Figure 1: Systemic and Random Registration Errors

Systemic errors are not determined by chance, but are introduced by an inaccuracy in the system that is predictable. These errors are harder to detect then random errors because the mean of many separate measurements differs significantly from the actual value of the measured attribute. These errors are all measurements made in a common way by each radar and tend to be constant in magnitude or direction. Therefore, accuracy can be improved by additive or proportional corrections. Additive corrections involve adding or subtracting a constant adjustment to each measure. Proportional corrections involve multiplying the measure(s) by a constant.

Random errors are caused by unpredictable or unknown changes that can distort a target observation on any given occasion. They can be the result of the equipment used to track and process radar information or from changes in environmental conditions. Filtering or finding the average (arithmetic mean) usually provides the most accurate measured position. Registration is the process of eliminating such things as time, survey, azimuth, and calculation errors that result in redundant target tracks in a multi-sensor network when only one exists. Systemic registration errors that result in miles of offset between two or more sensors may not necessary be completely eliminated but can often be improved. To address the problem various registration error sources can contribute to the offset between reported target positions. The following errors are variables that contribute to misalignments between netted radar:

- **Timing Errors** - Occur when the timing of an aircraft position report varies between sensors. Sensors tracking similar targets may be offset in time between each other as a result of differences in scan rates. Also, there is no current method for accurately synchronizing each netted sensor report time. Instead, each sensor's target report is time stamped independently by the local radar computer system, resulting in track reports running at different rates, fast or slow. Presently, the time an aircraft position is detected is communicated over secure networks to the ATC centers. Network latency issues may also contribute to variations in report times.
- **Survey Errors** – May occur when surveyed sensor locations are in error (e.g. the radars latitude, longitude, height above the ellipsoid, and differences in the earth model referenced). The determination of radar's location is critical to net centric registration process, since it incorporates radar's spherical measurements relative to other radars or with respect to a reference location, such as the earth center. With the integration of Global Positioning System (GPS), it is practical for the FAA to position radar platforms with greater accuracy.

- **Azimuth Errors** - May occur due to incorrect alignment of the radar antenna with the north mark or from misalignment of the antenna's axis of rotation with the local vertical. If there is an offset between where the physical antenna points north and where the radar software indicates north, then an error can occur. Furthermore, antenna tilt can cause azimuth errors. For two-dimensional radars, non-height finding surveillance, the entire azimuth bearing may be tilted due to the position of the antenna or the azimuth bearing may be level but the electrical axis of the antenna may be tilted. Both tilts produce errors proportional to the tangent of the elevation angle of the target.
- **Calculation Errors** – Can result from inaccuracies in the process of converting target coordinates to system coordinates if traditional approximations are made and all corrections are not included. Therefore, translating local sensor track information into a common coordinate system is important. The positioning data used to integrate a net centric surveillance system contribute to track accuracy and are important when determining the accuracy of a networked traffic control system.

If any of these systemic errors, individually or in combination become significantly large, then the accuracy value of the information provided by the multiple radars in the surveillance network will be less accurate than a single radar tracking report. If registration errors become extreme, they can result in a failure to correlate multiple radar measurements from a common aircraft on the same track. This in turn will reduce the system's effectiveness to a single radar system or lead to multiple tracks from the same aircraft. Because the fundamental objective of a networked surveillance network is to provide the most accurate seamless surveillance coverage, registration errors can defeat or diminish the very purpose of a multiple radar system. Systemic problems require elaborate filtering technologies to estimate target track estimations to account for registration errors.

4.0 REGISTRATION ERROR TOOL DEVELOPMENT METHOD

A mathematical procedure was needed to convert the radar measured target Azimuth (Az) and Range (R) coordinates into Earth Centered Latitude (La_r) and Longitude (Lo_r) coordinates. The FAA already had a mathematical procedure in place. My study looked at this procedure for correctness, and a new mathematical procedure was developed during this study to check the accuracy of FAA data.

In order to display radar targets on a Google Earth map, it is necessary to convert the measured radar coordinates that are referenced to the radar position on the surface of the earth to the earth-centered Latitude (La_t) and Longitude (Lo_t). It is also important to note that the term "radar" generally means secondary radar which has the capability of transmitting aircraft ID and barometric altitude in addition to the usual target information. The barometric altitude is needed to compute an estimate for the target's physical altitude above a tangent plane centered at the radar's position on the earth's surface. The targets' ID are necessary to filter the data files so that a particular aircrafts data may be operated upon.

4.1 SIMULATION INFORMATION

The raw data files contain the following information that will be used in this analysis.

- Time of Day of the observation.
- Beacon Code (This is the target's ID transmitted by the secondary radar).
- The terms MSSR (Monopulse Secondary Surveillance Radar), Beacon, Secondary Radar, Beacon Interrogator and Mode S are synonymous and the term radar will be used throughout this paper.
- Range (in Nautical Miles).
- Azimuth (in Degrees, corrected for magnetic variation).
- The magnetic variation is obtained from a separate data base which also lists the radar sites latitude, longitude, height, and sometimes the earth reference model and method of survey.[1]
- Altitude[2]
- Site ID (This is a 3 letter identifier for the particular radar site). Example, EWR signifies the Newark airport ASR-9 radar and Mode S.
- Latitude[3]

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[1] It is also important to note that several different databases exist for the radar site data and there are sometimes small but significant differences in the data.

[2] This is Barometric Altitude, not physical height above the earth's surface but an estimate of altitude obtained by using the measured barometric pressure as a parameter in an equation representing the standard atmosphere as defined by NOAA.

- Longitude[4]

Table 1: MAGNETIC DECLINATION FOR SELECTED RADAR SITES

National Geophysical Data Center July 25,2007	EWR NGDC	JFK NGDC	ISP NGDC	HPN NGDC
LATITUDE (N)	40 40 24 N	40 38 22 N	40 48 23 N	40 40 24 N
LONGITUDE (W)	74 11 09 W	73 45 59 W	73 06 44 W	74 11 09 W
MAGNETIC DECLINATION	13. 0 W	13. 14 W	13. 39 W	13. 23 W

Explanation of the remaining parameters is given in Table 1.

[3] This is the target's latitude computed by the FAA from the radar measured Azimuth, Range and the transmitted Barometric Altitude along with the radar sites Latitude, Longitude, and Height above the ellipsoid.

[4] This is the targets Longitude computed by the FAA from the radar measured Azimuth, Range and the transmitted Barometric Altitude along with the radar sites Latitude, Longitude ,and Height of the ellipsoid.

4.2 CALCULATIONS REQUIRED

The following steps outline the procedure used to develop the necessary mathematical equations for calculating target Latitude and Longitude from radar Range, Azimuth, and Barometric Altitude. The Latitude and Longitude that are generally supplied in degrees, minutes, and seconds format are converted to decimal form (DDD.MM.SSSS) by the following equations, where the *x* represents the latitude or longitude. The DDD represents the degrees; the MM represents the minutes; and the SSSS represents the seconds and decimal seconds to whatever precision is available.

$$h1(x) = 100(|x| - floor(|x|)) \tag{1}$$

$$h2(x) = \frac{floor(h1(x))}{60} \tag{2}$$

$$h3(x) = \frac{h1(x) - floor(h1(x))}{36} \tag{3}$$

$$h(x) = \frac{x}{|x|(floor(|x|) + h2(x) + h3(x))} \tag{4}$$

The earth's semi-major axis (a) and flattening factor (f) for the Earth model chosen (WGS-84) are entered.

$$a = 6378137\ meters$$
$$f = \frac{1}{298.257223563} \tag{5}$$

The Earth's eccentricity (ecc) is computed from the flattening factor (f).

$$ecc = \sqrt{f(2 - f)} \tag{6}$$

The Range (R_n), which is the length of the normal to the ellipsoid at the radar site terminated by the ellipsoid's minor axis, is calculated from the ecc and the radar sites Latitude.

$$R_n = \frac{a}{\sqrt{1 - ecc^2 \sin(La_r)^2}} \tag{7}$$

The Earth centered coordinates of the radar (X_r, Y_r, Z_r) are computed from the radar's Latitude (La_r), Longitude Lo_r, Height (Ht_r), R_n and eccentricity (ecc).

$$X_r = (R_n + Ht_r)\cos La_r \cos Lo_r \tag{8}$$
$$Y_r = (R_n + Ht_r)\cos La_r \sin Lo_r \tag{9}$$
$$Z_r = ((1 - ecc^2)R_n + Ht_r)\sin La_r \tag{10}$$

The Elevation angle is then computed from the earth's semi-major axis (a), the target's barometric altitude (b), and the target's Range (R_t).

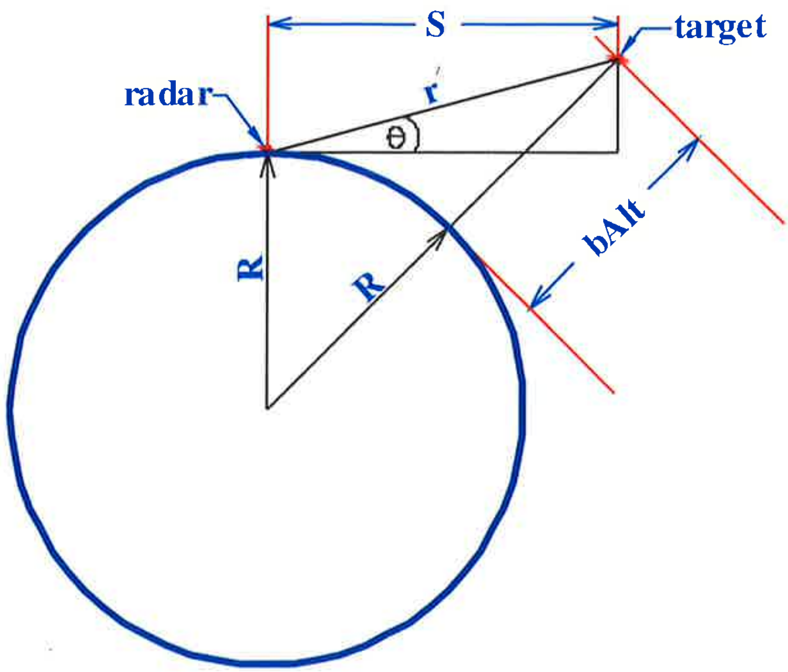

Figure 2: Parameters for converting target Azimuth, Range, and Barometric Altitude to Latitude and Longitude.

$b = barometric\ altitude$

$$(a+b)^2 = a^2 + R_t^2 - 2aR_t\cos(90+\theta) \quad (11)$$

$$\cos(90+\theta) = \frac{(a+b)^2 - a^2 - R_t^2}{-2R_t} \quad (12)$$

$$El_t = \cos^{-1}(90+\theta) - 90 \quad (13)$$

The distance from the radar site and the target projected on the tangent plane centered at the radar site (S_t) is calculated from the target range (R_t), and the Elevation angle (El_t).

$$S_t = R_t \cos El_t \quad (14)$$

The target X_t, Y_t, and Z_t coordinates are computed from the spherical Range (R_t), Azimuth (Az_t), Elevation (El_t) coordinates and the distance from the radar site and the target projected on the tangent plane centered at the radar site (S_t).

$$X_t = S_t \sin Az_t \quad (15)$$
$$Y_t = S_t \cos Az_t \quad (16)$$
$$Z_t = R_t \sin El_t \quad (17)$$

Vectors (V_t) and (V_r) are formed from the target X_t, Y_t, Z_t and the radar site's X_r, Y_r, Z_r.

$$V_t = \begin{matrix} X_t \\ Y_t \\ Z_t \end{matrix}$$
$$V_r = \begin{matrix} X_r \\ Y_r \\ Z_r \end{matrix}$$

A rotation Matrix (C) is formed from the radar site's Latitude and Longitude. This matrix will rotate the vector (V_t) so as to align itself with the radar's X_r, Y_r, Z_r coordinates.

$$[C] = \begin{bmatrix} -\sin Lo_r & -\cos Lo_r \cdot \sin La_r & \cos Lo_r \cdot \cos La_r \\ \cos Lo_r & -\sin Lo_r \cdot \sin La_r & \sin Lo_r \cdot \cos La_r \\ 0 & \cos La_r & \sin La_r \end{bmatrix} \quad (18)$$

The vector (T) representing the earth centered Cartesian coordinates of the target is obtained by adding the vector (V_t) multiplied by the Matrix [C] to the vector (V_r).

$$T = V_r + [C] \cdot V_t \quad (19)$$

Calculate the target's Longitude (Lo_t) from the X_t and Y_t components of the vector T.

$$Lo_t = \tan^{-1}\left(\frac{T_1}{T_0}\right) \quad (20)$$

Calculate P and U which will be used in the equations for the target's Latitude (La_t).

$$P = \sqrt{T_0^2 + T_1^2} \quad (21)$$
$$U = \tan^{-1}\frac{T_2}{P(1-f)} \quad (22)$$

Calculate the target's latitude (La_t) from P, U, ecc, f , a and T_2.

$$La_t = \tan^{-1}\left(\frac{T_2 + \left(\frac{ecc^2}{1 - ecc^2}\right)a(1 - f)\sin U^3}{P - ecc^2 a\cos U^3}\right) \quad (23)$$

Finally use the following routine to convert decimal degrees to degrees, minutes and seconds. This is necessary to compare data and also is the form used to enter latitude and longitude in the Google Earth program.

$$p1(x) = floor(|x|) \quad (24)$$

$$p2(x) = 60(|x| - floor(|x|)) \quad (25)$$

$$p3(x) = 60(p2(x) - floor(p2(x))) \quad (26)$$

$$p(x) = \frac{x}{|x|}\left(p1(x) + \frac{floor(p2(x))}{100} + \frac{p3(x)}{10000}\right) \quad (27)$$

In the above equation the decimal degrees are substituted for x and the resulting latitude or longitude will be in the form of DDD.MM.SSSS.

After developing all the calculations used in processing a target's position, it was necessary to check the FAA calculations. Refer to appendix (a) for a sample of how the FAA calculations for Newark (EWR) radar sensor were confirmed. Both processes produced very good agreement, so the calculation process was eliminated as a possible source of registration error. The next step was to focus on the site data as a possible source of error. From the site variable, Latitude, Longitude, Height, and Magnetic Variation I felt that the best candidate for errors was magnetic variation, so I focused on this as the first parameter to evaluate.

4.3 ASSUMPTIONS

A number of assumptions are asserted in order to simplify the development of this registration error simulation model.

4.3.1 Single Target Sample

A single target is assumed in this analysis, and the influence of biases applied on a single target will also apply for multiple targets.

4.3.2 Time Errors Due To Multi-Sensor Radar Rotation Sampling

Radars do not normally measure a moving target at a fixed interval of time unless the target paths are strictly radial. I eliminated the offset of timing errors between single sample observations by concentrating the analysis on track data.

4.3.3 Tracks

A track is the information a platform acquires from a specific target over time. It is developed through the use of onboard aircraft sensor equipment and radar surveillance processing. Each track is assigned a unique identification code.

4.3.4 WGS84 Earth Model

The modeling assumptions are that the FAA's WGS84 target position accuracy are modeled correctly in Google Earth which also uses WGS84 datum for mathematically interpreting the earth's shape.

5.0 PROCEDURE

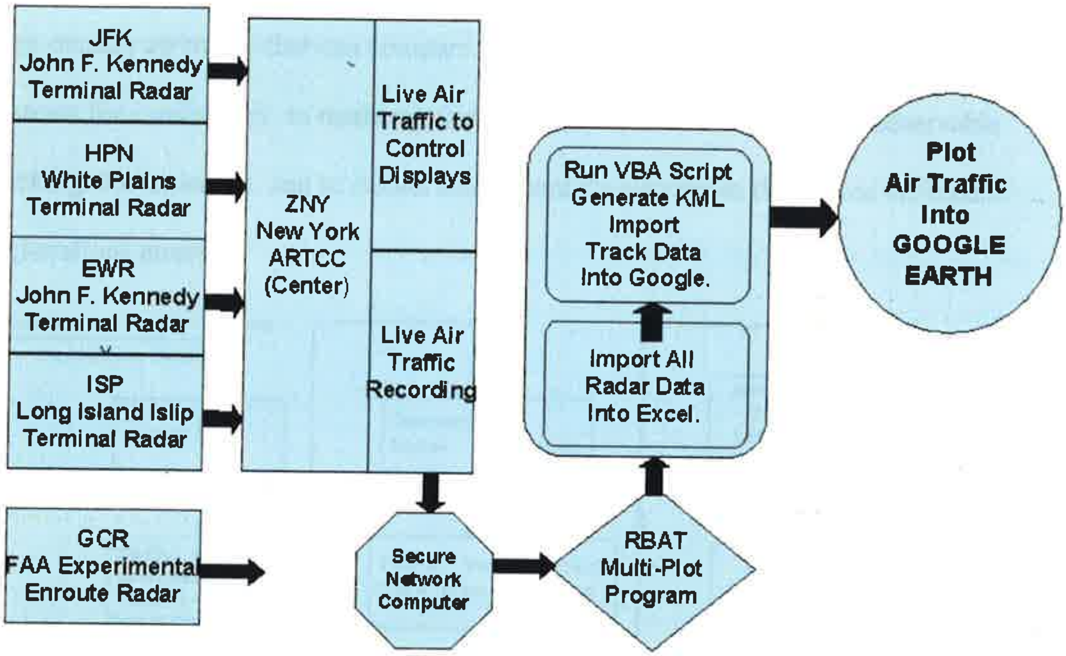

Figure 3: Data Collection and Evaluation

The design of the study employs raw data from the terminal radar sites that supply the New York TRACON with real time air traffic surveillance information. From this air traffic surveillance database, the analysis was centered on four specific sensors: John F. Kennedy (JFK), White Plains (HPN), Newark (EWR), and Long Island Islip (ISP), all of which provide critical data to the Center for controlling and managing air traffic.

This process, developed to analyze surveillance networks for registration errors, utilized both aircraft target position report data and site-specific radar survey data. The compilation of techniques applied here can be applied to model any TRACON with high-density air traffic. As digital images are one of the major sources of monitoring and controlling traffic, Google Earth software was integrated into the process to effectively model 3D air space. The objective of the procedure is to develop a framework model of high-density air traffic that can compare identical target track data from multiple radar systems for consistency, to mathematically assess track data with clearly observable tracking discrepancies, and to isolate and potentially determine the source of fixed registrations errors.

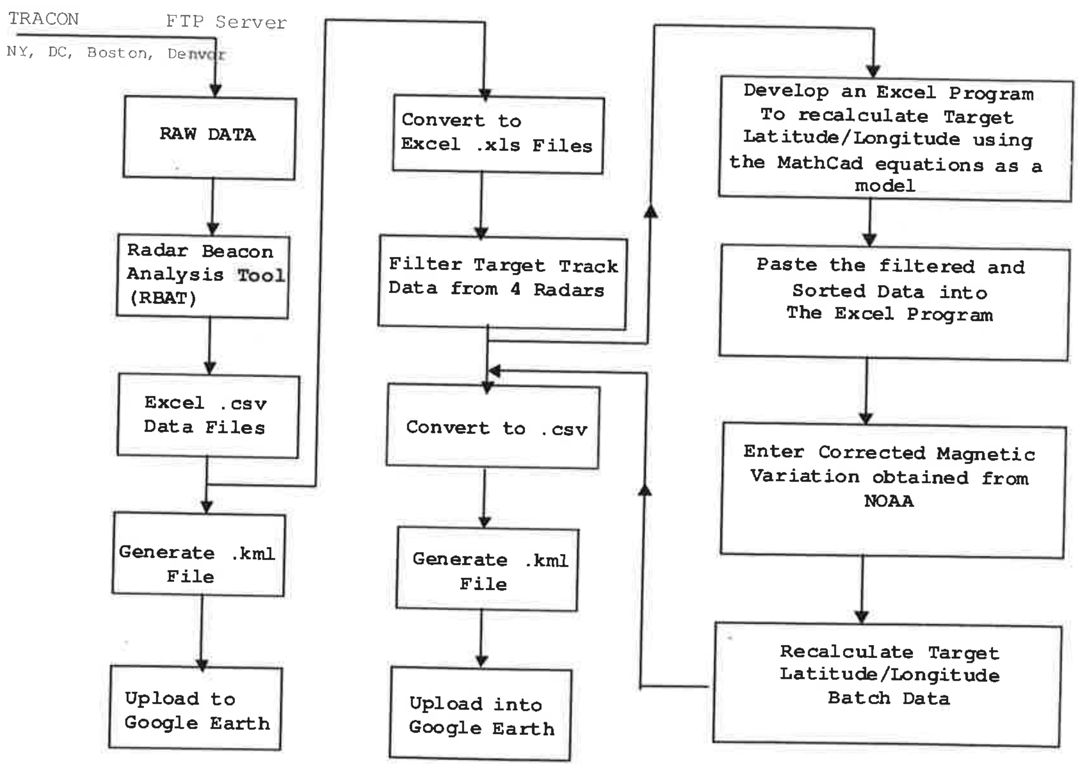

Figure 4: Simulation Model Block Diagram Description

The first step in the process was to extract a 30-minute data recording from the New York TRACON using an FAA approved computer program called Radar Beacon Analysis Tool (RBAT), (see Appendix 2C, Table 2). This software tool is capable of importing live traffic data being delivered to the Center over a secure network in File Transfer Protocol (FTP) format and converting it into an Excel database. This experimental database is the primary source or master database from which this study was developed. The tracking information imported from the surveillance networks has not yet been processed for the purpose of ATC.

TimeOf-Day	Type	Code	Mds-Id	Range	Azimuth	Alt	Site	Lon	Lat	Hdg
19:35:51.313	S	1141		57.734	244.072	26700	JFK	-74.731980	40.027406	51
19:35:54.086	S	1141		45.891	226.670	26700	EWR	-74.731993	40.036772	54
19:35:56.016	S	1141		57.156	244.072	26800	JFK	-74.722318	40.033627	51
19:35:56.297	S	1141	aafc11	28.773	0.088	26975	GCR	-74.697332	40.063071	621.611
19:35:58.688	S	1141		45.344	226.406	26800	EWR	-74.721685	40.042581	54
19:36:00.516	S	1141		56.578	244.160	26800	JFK	-74.713881	40.040939	51
19:36:03.281	S	1141		44.781	226.318	26800	EWR	-74.713787	40.049878	54
19:36:05.211	S	1141		56.016	244.160	26900	JFK	-74.704462	40.046981	47
19:36:05.844	S	1141	aafc11	29.594	2.000	27075	GCR	-74.676125	40.076562	312.704
19:36:07.883	S	1141		44.234	226.143	26900	EWR	-74.704847	40.056389	48
19:36:09.813	S	1141		55.438	244.160	26900	JFK	-74.694804	40.053175	47
19:36:12.477	S	1141		43.688	225.879	26900	EWR	-74.694761	40.062316	45
19:36:14.414	S	1141		54.875	244.248	26900	JFK	-74.686569	40.060275	49
19:36:15.484	S	1141	aafc11	30.430	3.450	27075	GCR	-74.658962	40.090033	0.000
19:36:17.070	S	1141		43.141	225.615	27000	EWR	-74.684734	40.068327	49
19:36:19.016	S	1141		54.297	244.248	27000	JFK	-74.676869	40.066473	47
19:36:21.672	S	1141		42.578	225.439	27000	EWR	-74.675824	40.075166	51
19:36:23.617	S	1141		53.734	244.248	27000	JFK	-74.667452	40.072487	48
19:36:25.133	S	1141	aafc11	31.289	5.032	27075	GCR	-74.639307	40.103418	0.000
19:36:26.273	S	1141		42.031	225.264	27000	EWR	-74.667150	40.081818	50
19:36:28.211	S	1141		53.156	244.336	27000	JFK	-74.658898	40.079711	49
19:36:30.961	S	1141		41.484	225.088	27000	EWR	-74.658532	40.088506	48
19:36:32.914	S	1141		52.578	244.336	27000	JFK	-74.649202	40.085880	47

Table 2: TRACON data sample

The size of the master database recording is 8.68MB and reflects approximately two minutes of live air traffic being networked into the Center from multiple radar systems. The master database consists of approximately 8,600 target reports. Each radar generates one target report per scan for each target. To translate the raw target reports from each surveillance network into a 3D geographical working model, the recorded data was imported into a Google Earth program as shown in Figure 5.

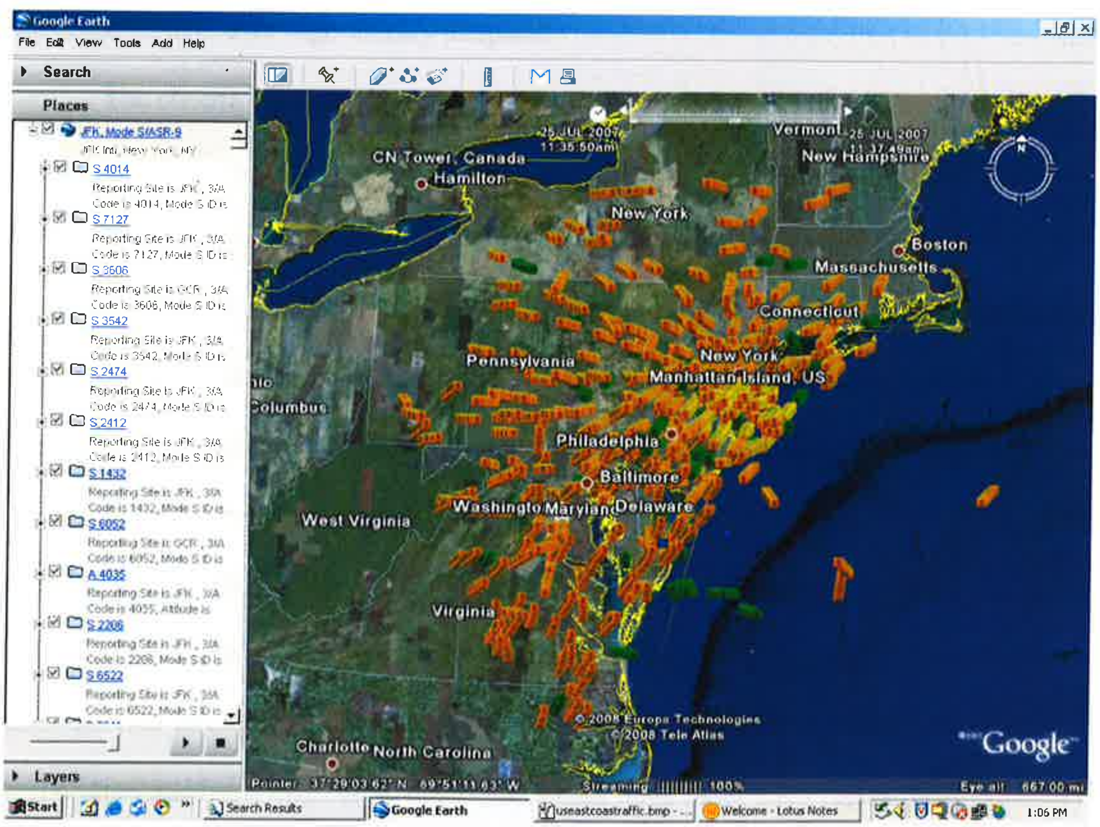

Figure 5: Live TRACON Data

The layering capability of the Google Earth program has the capability of intricately relating the complexity of overlapping surveillance data. The program is utilized in the Radar Registration Errors Analysis Process (RREAP) as a means of overlaying overwhelming amounts of unprocessed surveillance data into a 3D presentation. It is simple to navigate and functions as a virtual hand when gaining perspective on specific tracks of target information that reflect registration errors across hundreds of miles of controlled airspace. More specifically, this modeling process provided a means of zooming in and isolating surveillance tracking biases and the significance that registration errors have on accurately positioning and processing netted surveillance data over high-density airspace.

The criteria used to select and evaluate a target for registration errors typically started by overlaying the entire airspace network available to the New York ARTCC systemic data from the top-down. Then for this analysis, the tracks were selected and examined in detail to look for registration offsets (See Figure 6). To operate the program you could either select a target ID from the Google Earth Places menu or manually zoom in on a specific region of air traffic. For example, by selecting target ID 3542 from the Places menu, the program automatically repositions the viewing window over the specific target of interest and the track data being used to process the multiple surveillance systems tracking target 3542 can be extracted, analyzed, and compared. In this example there are four terminal radars tracking the same target, each track is clearly offset in registration making it difficult to determine which 3542 radar track report most accurately fits the target's actual position. This iterative process was used to select four specific targets with similar registration patterns. Each target being defined by four specific tracks of data generated by four different radar systems and spaced relatively equal apart in distance. The target registration data collected from the four targets was filtered and sorted out of the master database and saved as a separate file for further analysis (See Table 3).

Table 3: Sample of Sorted and Filtered Raw (Uncorrected) Data

Time-of-	Typ	Co	Ran	Azimu	Al	Sit	La	Lo
.27		354		155.6			40.257	-
19:35:50.		745		178.6			40.498	-
19:35:50.		354		215.0			40.251	-
19:35:51.		745		250.3			40.490	-
19:35:51.		261		227.1			40.210	-
19:35:51.		701		248.2			40.348	-
19:35:52.		745		129.7			40.495	-
19:35:52.		354		137.5			40.252	-
19:35:53.		354		176.0			40.251	-
19:35:53.		261		188.8			40.217	-
19:35:53.		745		193.6			40.495	-
19:35:53.		701		208.8			40.354	-
19:35:54.		261		213.8			40.218	-
19:35:54.		701		225.0			40.354	-
19:35:54.		354		156.6			40.250	-
19:35:55.		354		215.2			40.244	-
19:35:55.		745		180.6			40.494	-
19:35:55.		745		250.1			40.486	-
19:35:55.		261		227.1			40.219	-
19:35:56.		701		248.2			40.353	-
19:35:57.		745		130.4			40.492	-
19:35:57.		354		138.2			40.245	-
19:35:58.		354		176.5			40.243	-
19:35:58.		261		188.0			40.226	-
19:35:58.		745		193.9			40.491	-
19:35:58.		701		208.2			40.359	-

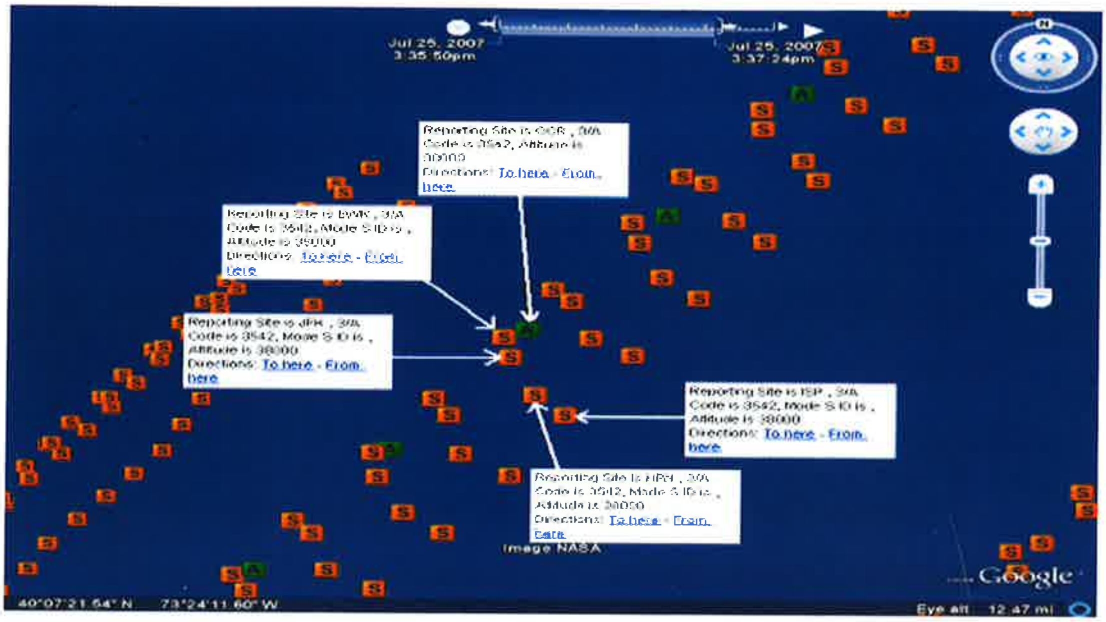

Figure 6: Expanded View of Expanded Track

The following outlines the procedure used to initially analyze the raw TRACON network database:

- Convert CSV file into KML file.
- Upload KML file into Google Earth to view air traffic in 3D WGS84 datum.
- Zoom in and identify targets that have multiple parallel Surveillance track or more specifically, registration errors.
- Select a target of interest with the criteria that it has four or more sensors with overlapping or parallel tracks and exhibits registration offset. Note the target ID code (3542) and reporting sites (JFK, EWR, ISP, HPN, GCR).
- [S] symbolizes a mode-s target from terminal radars.
- [A] symbolizes a mode-s target from Enroute radar located in Elwood, New Jersey.

- Perform an approximate measure of the registration error distance in nautical miles (nmi) units between sensors track position using the tools available in Google earth of the same target in relative time.
- Zoom in or out using the scroll wheel on your mouse, or click on screen minus/plus button to localize a specific target with multiple surveillance tracks.
- Select 1 target of interest being tracked by 4 different radars and record aircraft ID so that the target data can be filtered out of the working database.
- Perform this operation 4 different times using targets of opportunity.

Once the initial observation was complete, an Excel analysis program was created that was designed to analyze the registration tracking data isolated in the modeling simulations analysis. This Excel program was modeled after the MathCAD program developed earlier to assess the accuracy of the FAA target position calculations. The purpose for using MathCAD as the model for developing the Excel program is due to the fairly complicated process in Excel. Therefore, this complexity was eliminated by using the previously developed MathCAD program to model the excel program. This program accepted both the radar site information and the target information and is able to analyze each radar's information with regard to tracking data from specific targets (See Table 4). The tracking data provide by each radar tracking the same target in the surveillance network was evaluated to determine the potential source of the registration error. The FAA's William J. Hughes Technical Center's long range (Enroute) experimental radar was coupled into the analysis as an independent means of comparing and referencing the New York TRACON short range radars (Terminal) track data against data received and processed from an independent surveillance system. This technique was iteratively applied to multiple targets of opportunity with four or more non-merging, parallel tracks.

6.0 RESULTS

The first batch processing envolved cutting and pasting the original data into the new Excel program and recalculating the Latitude and Longitude with the original data to validate the program. This raw data reflect the mean and standard deviation of the original tracks with JFK being the reference. JFK was arbitrarily chosen as the reference because it was somewhat central to the other radar tracks.

After validating the program, I decided to make the first change to the original data by updating the magnetic variation. To do this, I went to the NOAA's National Geophysical Data Center (NGDC) site and downloaded the magnetic variation for each radar, tracking the filtered targets under observation. Then the new values where substituted in place of the original variations used by the FAA to process the target and the track data position was recalculated. Then I inserted the new magnetic variations into the Excel program and recalculated the target's Latitude and Longitude for each of the four targets as seen by each of the four radars. Next, I copied the recalculated Latitude and Longitude from the Excel batch program and pasted them into the original database and imported the new tracking data into the Google Earth to model and simulate the new target position tracks and noted significant registration improvement.

Table 4: Target Azimuth, Range and Barometric Altitude to Target Latitude and Longitude

Radar ID	JFK		SIN	COS										
Radar Lat DD.DDDD	40.63955600	0.70929406	0.65129825	0.75882184										
Radar Lon DDD.DDDD	-73.76644400	-1.28746733	-0.96013013	0.27955347										
Radar Ht ft MSL	29.00000000	8.83920000												
Radar Mag Var DD.DD	-13.26666667													
a semimajor axis (m)	6378137.00000000													
f flattening	0.00335281													
ecc eccentricity	0.08181919													
Rn tangential radius	6387212.28308865													
Er radars ECEF coordinate	1354929.37083061													
Fr radars ECEF coordinate	-4653523.08096673													
Gr radars ECEF coordinate	4132137.44939408													
C11, C12, C13	0.96013013	-0.18207268	0.21213128											
C21, C22, C23	0.27955347	0.62533107	-0.72856771											
C31, C32, C33	0.00000000	0.75882184	0.65129825											
Time		Beacon code			Range	Az (M)	Alt (ft)	Site ID	AZ (rad)	Alt (m)	R (m)	El (rad)	Recomputed Lon (DecDeg)	Recomputed Lat (Dec Deg)
19:35:50.273	S	3542			29.625	155.654	38000	JFK	2.485128	11582	54865.54	0.208503	-73.38205507	40.25668609
19:35:54.891	S	3542			29.766	156.621	38000	JFK	2.502005	11582	55126.67	0.207459	-73.38869535	40.24986392
19:35:59.492	S	3542			29.906	157.588	38000	JFK	2.518882	11582	55385.95	0.206433	-73.39553978	40.24311869
19:36:04.125	S	3542			30.078	158.467	38000	JFK	2.534224	11582	55704.50	0.205184	-73.40136167	40.23641713
19:36:08.750	S	3542			30.250	159.521	38000	JFK	2.552620	11582	56023.04	0.203950	-73.40900190	40.22892629
19:36:13.375	S	3542			30.422	160.488	38000	JFK	2.569497	11582	56341.59	0.202730	-73.41604967	40.22192002
19:36:17.992	S	3542			30.609	161.455	38000	JFK	2.586374	11582	56687.91	0.201419	-73.42312989	40.21476232
19:36:22.625	S	3542			30.797	162.334	38000	JFK	2.601716	11582	57036.09	0.200118	-73.42954862	40.20804879
19:36:27.227	S	3542			31.000	163.213	38000	JFK	2.617057	11582	57412.04	0.198730	-73.43598988	40.20116576
19:36:31.883	S	3542			31.203	164.092	38000	JFK	2.632399	11582	57788.00	0.197360	-73.44262758	40.19433375
19:36:36.539	S	3542			31.422	165.059	38000	JFK	2.649276	11582	58193.59	0.195902	-73.45020099	40.18694518
19:36:41.141	S	3542			31.641	165.850	38000	JFK	2.663082	11582	58599.18	0.194464	-73.45616538	40.18035100
19:36:45.789	S	3542			31.875	166.729	38000	JFK	2.678423	11582	59032.54	0.192949	-73.46309341	40.17321426
19:36:50.367	S	3542			32.109	167.607	38000	JFK	2.693747	11582	59465.91	0.191456	-73.47022329	40.16613777
19:36:54.984	S	3542			32.344	168.398	38000	JFK	2.707553	11582	59901.13	0.189979	-73.47660431	40.15944001
19:36:59.664	S	3542			32.594	169.189	38000	JFK	2.721358	11582	60364.13	0.188431	-73.48303558	40.15255559
19:37:04.258	S	3542			32.859	170.068	38000	JFK	2.736700	11582	60854.91	0.186815	-73.49051909	40.14515973
19:37:08.906	S	3542			33.109	170.859	38000	JFK	2.750505	11582	61317.91	0.185314	-73.49735274	40.13837711
19:37:13.500	S	3542			33.375	171.650	38000	JFK	2.764311	11582	61810.55	0.183742	-73.50424848	40.13139378
19:37:18.148	S	3542			33.656	172.441	38000	JFK	2.778116	11582	62330.96	0.182108	-73.51122715	40.12422456
19:37:22.773	S	3542			33.938	173.145	38000	JFK	2.790403	11582	62853.22	0.180495	-73.51737253	40.11737965
19:37:27.383	S	3542			34.234	173.936	38000	JFK	2.804209	11582	63401.42	0.178831	-73.52464385	40.11007015
19:37:31.953	S	3542			34.516	174.639	38000	JFK	2.816479	11582	63923.68	0.177271	-73.53115447	40.10331684
19:37:36.602	S	3542			34.813	175.342	38000	JFK	2.828748	11582	64473.72	0.175656	-73.53774329	40.09636605
19:37:41.227	S	3542			35.125	176.045	38000	JFK	2.841018	11582	65051.55	0.173988	-73.54442142	40.08921751
19:37:45.875	S	3542			35.422	176.748	38000	JFK	2.853288	11582	65601.59	0.172427	-73.55138646	40.08235849

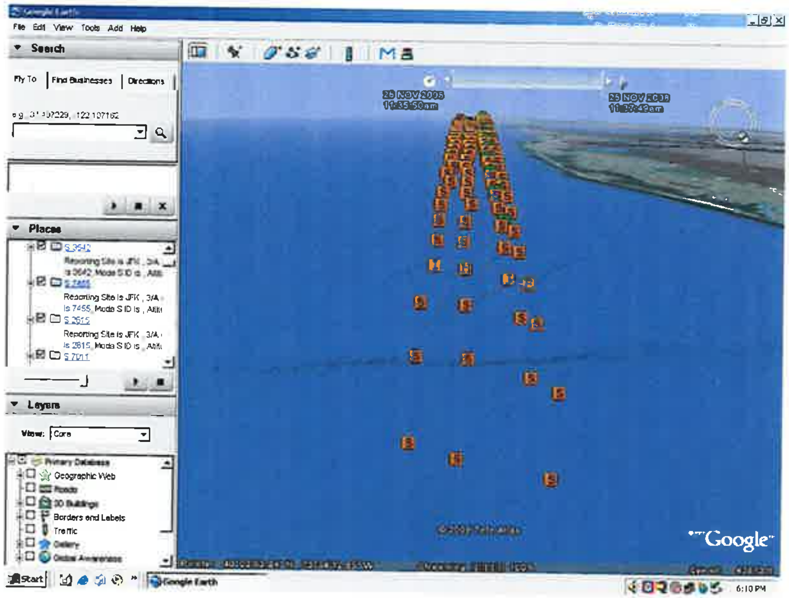

Figure 7. Raw Data capture of Target 3542 JFK VS. EWR

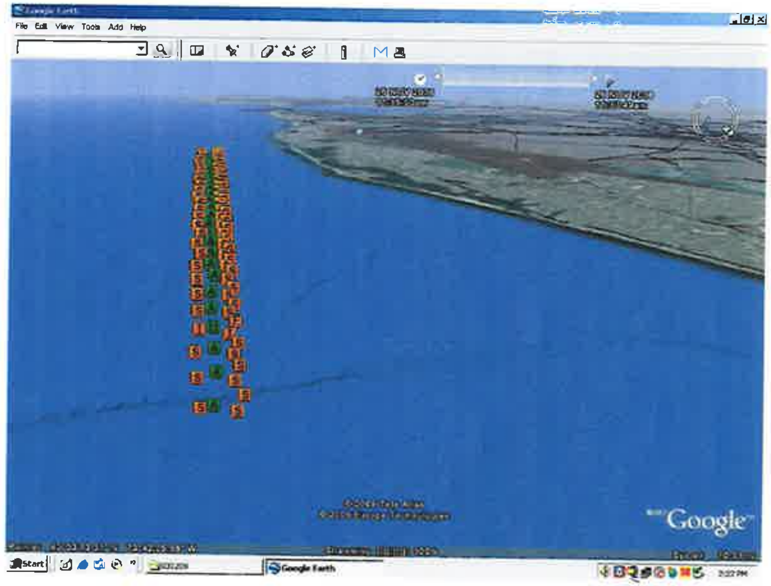

Figure 8. Corrected Bias Error of Target 3542 JFK VS. EWR

- The before and after modeling and simulation images developed using the RREAP.
- The track data in Figure 7 reflects four different radar tracks for aircraft code ID 3542 with the track distance between JFK and EWR depicted with a white line J-E in each image.
- The registration error bias between JFK and EWR radar track seen in Figure 7 is offset by 0.36 nautical miles.
- Magnetic variation correction are then applied in the RREAP and the distance between radar tracks JFK and EWR are depicted with a white line J-E in Figure 9. Reducing the offset to 0.21 nautical miles.
- RREAP provided a method to improve registration between JFK and EWR radars by 162% .

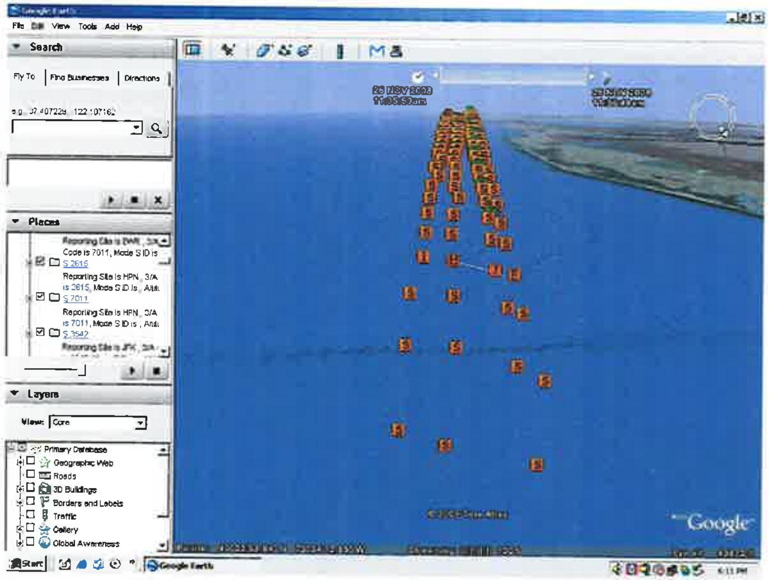

Figure 9 Raw Data capture of Target 3542 JFK VS. HPN HPN

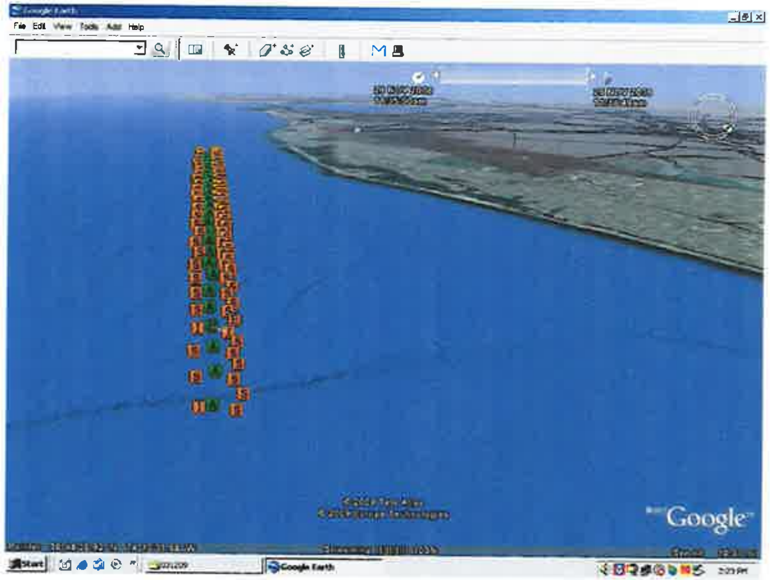

Figure 10. Corrected Bias Error of Target 3542 JFK VS.

- The before and after modeling and simulation images developed using the RREAP.
- The track data in Figure 9 reflects four different radar tracks for aircraft code ID 3542 with the track distance between JFK and HPN depicted with a white line J-H in each image.
- The registration error bias between JFK and EWR radar track seen in Figure 9 is offset by 0.44 nautical miles.
- Magnetic variation correction are then applied in the RREAP, and the distance between radar tracks JFK and HPN are depicted with a white line J-H in Figure 10. Reducing the offset to 0.033 nautical miles.
- RREAP provided a method to improve registration between JFK and HPN radars by 1381%

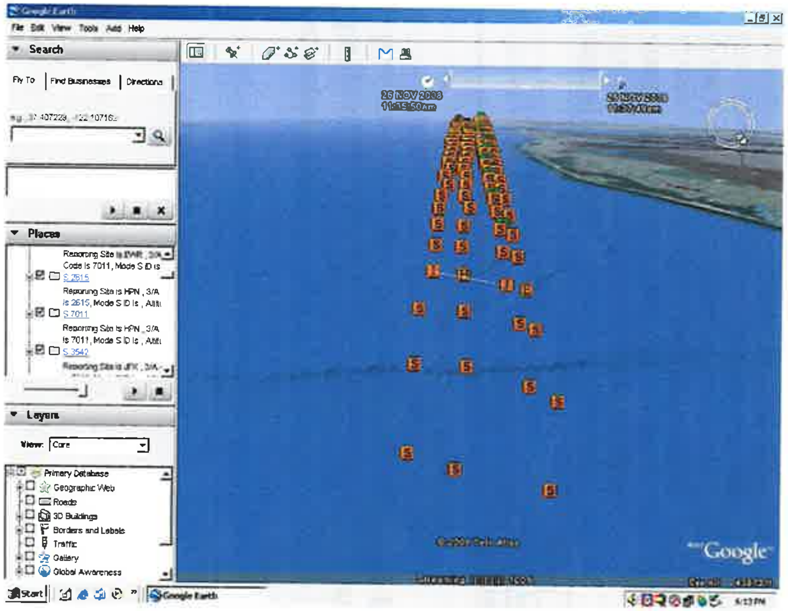

Figure 11 Raw Data capture of Target 3542 JFK VS. ISP

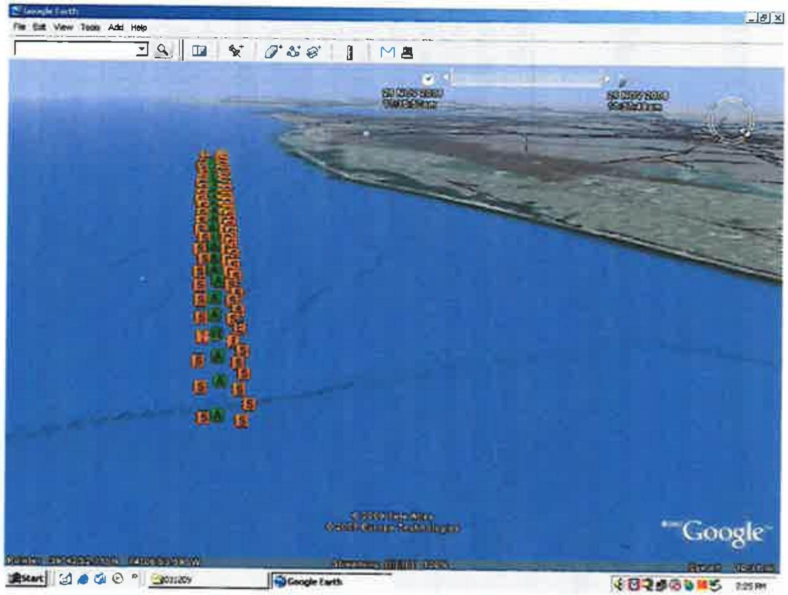

Figure 12. Corrected Bias Error of Target 3542 JFK VS. ISP

- The before and after modeling and simulation images developed using the RREAP.
- The track data in Figure 9 reflects four different radar tracks for aircraft code ID 3542 with the track distance between JFK and ISP depicted with a white line J-I in each image.
- The registration error bias between JFK and ISP radar track seen in Figure 11 is offset by 0.47 nautical miles.
- Magnetic variation correction are then applied in the RREAP and the distance between radar tracks JFK and ISP are depicted with a white line J-I in Figure 12. Reducing the offset to 0.04 nautical miles.
- RREAP provided a method to improve registration between JFK and ISP radars by 219%

6.1 RESULTS OF CORRECTED VALUES

Table 6: Comparison of Corrected and Uncorrected Data for Aircraft Code 3542 and EWR, HPN, ISP and JFK Radars

EWR	HPN	ISP	JFK		JFK-EWR, nm	JFK-HPN, nm	JFK-ISP,nm
-73.386468	-73.380572	-73.378536	-73.382055		0.202845	-0.068175	-0.161758
-73.393283	-73.388472	-73.384780	-73.388695		0.210881	-0.010263	-0.179966
-73.399626	-73.394859	-73.391081	-73.395540		0.187794	-0.031288	-0.204915
-73.406657	-73.401351	-73.398594	-73.401362		0.243373	-0.000469	-0.127187
-73.412912	-73.407888	-73.404888	-73.409002		0.179727	-0.051186	-0.189091
-73.420158	-73.414613	-73.411374	-73.416050		0.188835	-0.066030	-0.214894
-73.428172	-73.423101	-73.417918	-73.423130		0.231771	-0.001334	-0.239572
-73.434191	-73.428276	-73.424518	-73.429549		0.213380	-0.058494	-0.231236
-73.440556	-73.435281	-73.432384	-73.435990		0.209858	-0.032589	-0.165748
-73.447463	-73.442348	-73.437874	-73.442628		0.222237	-0.012857	-0.218503
-73.455744	-73.447817	-73.445894	-73.450201		0.254750	-0.109597	-0.197954
-73.460925	-73.455120	-73.451469	-73.456165		0.218783	-0.048029	-0.215858
-73.469201	-73.462603	-73.458351	-73.463093		0.280734	-0.022553	-0.217976
-73.474311	-73.470091	-73.465274	-73.470223		0.187874	-0.006071	-0.227473
-73.481556	-73.475915	-73.472400	-73.476604		0.227574	-0.031686	-0.193235
-73.487890	-73.483709	-73.478130	-73.483036		0.223145	0.030944	-0.225486
-73.496211	-73.489683	-73.485222	-73.490519		0.261603	-0.038427	-0.243468
-73.502525	-73.497716	-73.492370	-73.497353		0.237728	0.016692	-0.229030
-73.508720	-73.503847	-73.498355	-73.504248		0.205533	-0.018455	-0.270891
-73.515009	-73.510161	-73.505585	-73.511227		0.173809	-0.048985	-0.259328
-73.523649	-73.516574	-73.513031	-73.517373		0.288487	-0.036706	-0.199528
-73.528826	-73.525003	-73.518984	-73.524644		0.192221	0.016511	-0.260123
-73.535237	-73.529638	-73.524965	-73.531154		0.187628	-0.069716	-0.284493
-73.542923	-73.536289	-73.532543	-73.537743		0.238093	-0.066847	-0.239026
				Mean	**0.219528**	**-0.031900**	**-0.216531**
				Stndrd Dev	**0.030319**	**0.033107**	**0.036483**
				% imprmnt	**162.828887**	**1380.934169**	**218.805160**

The percent improvement is the result of taking the difference of the latitude and longitude of the new magnetic declination and substituting the corrected values for the uncorrected values.

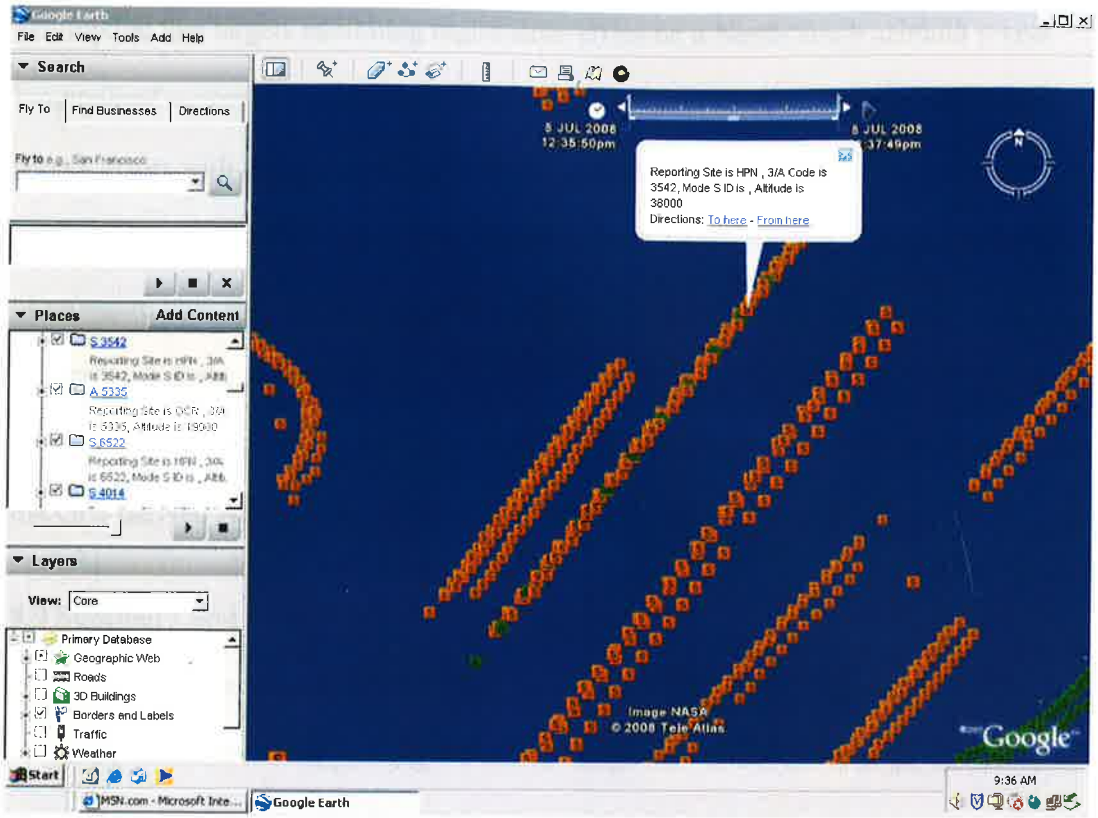

Figure 13: Top Down View of Registration Improvements using RREAP

7.0 Recommendation

- Incorporate the RREAP tool into a further investigation of improvements that can be made by carefully testing the latitude and longitude of FAA radar with respect to tracks generated in the surveillance network. If by perturbing the latitude or longitude improves target registration, it is reasonable to conclude that some error exists in the survey data of the radar(s).

- Incorporate the RREAP tool to evaluate two or more target tracks that exhibit registration errors running North-South or East-West. If possible one of the radars tracking the target should be relatively perpendicular to recorded tracks. Verify the assumption that targets exhibiting registration errors on a North-South azimuth reveal longitudinal survey errors and target traveling on an East-West azimuth reveal latitude survey errors with respect to the radars being evaluated.

- Investigate timing errors by selecting single targets from different radars for the same observation time and compare the target with available Automatic Dependent Surveillance-Broadcast information (ADS-B) data when available and perturb the observation times to the targets closest to the ADS-B position. The assumption being that the GPS derived ADS-B observation is the most accurate.

8.0 Summary and Conclusion

The process developed to analyze target registration proves that adjusting the magnetic variation (actually, using the correct magnetic variation) for each surveillance system location based on the date of the observation that significant improvements can be made to the overall registration.

The RREAP incorporated an Excel program and the Google Earth program, The Excel program provided a means to recalculate the positions of the targets with respect to netted radars observing the targets. The Google Earth program supported the transformation of the data and provided a unique approach to merging, separating, and viewing 3D traffic information while preserving the integrity of the data. Functionally, it opens the door to modeling ATC in 3D to the professional who manages the system as well as the customers who use the system. It provides a wide range of previously difficult problems to numerical system analysis.

Appendix 1A

NOAA Estimated Value of Magnetic Declination

The following data sheets from NOAA reflect the estimated values of magnetic declination from each of the radars used in Radar Registration Errors Analysis Process. The latitude and longitude position data coincides with flight recording used in this study.

Appendix 1A.1
John F. Kennedy (JFK) Radar Estimated Magnetic Declination

Estimated Value of Magnetic Declination

To compute the magnetic declination, you must enter the location and date of interest.

If you are unsure about your city's latitude and longitude, look it up online! In the USA try entering your zip code in the box below or visit the U.S. Gazetteer. Outside the USA try the Getty Thesaurus.
Search for a place in the USA: **JFK**

Enter Location: (latitude 90S to 90N, longitude 180W to 180E). See Instructions for details.

Latitude: 40.639556 N S **Longitude:** 73.766444 E W

Enter Date (1900-2010): Year: 2007 Month (1-12): 7 Day (1-31): 25

Compute Declination

Declination = 13° 16' W changing by 0° 2' E/year

For more information, visit:
Answers to some **frequently asked questions** | **Instructions** for use |

Appendix 1A.2
Newark (EWR) Radar Estimated Magnetic Declination

Estimated Value of Magnetic Declination

To compute the magnetic declination, you must enter the location and date of interest.

If you are unsure about your city's latitude and longitude, look it up online! In the USA try entering your zip code in the box below or visit the U.S. Gazetteer. Outside the USA try the Getty Thesaurus.
Search for a place in the USA: **EWR**

Enter Location: (latitude 90S to 90N, longitude 180W to 180E). See Instructions for details.

Latitude: 40.673222 N S **Longitude:** 74.185667 E W

Enter Date (1900-2010): Year: 2007 Month (1-12): 7 Day (1-31): 25

Compute Declination

Declination = 13° 2' W changing by 0° 1' E/year

For more information, visit:
Answers to some **frequently asked questions** | **Instructions** for use | **Today's Space Weather**

Appendix 1A.3
White Plains (HPN) Radar Estimated Magnetic Declination

NOAA > NESDIS > NGDC > Geomagnetism   comments | privacy policy

Estimated Value of Magnetic Declination

To compute the magnetic declination, you must enter the location and date of interest.

If you are unsure about your city's latitude and longitude, look it up online! In the USA try entering your zip code in the box below or visit the U.S. Gazetteer. Outside the USA try the Getty Thesaurus.
Search for a place in the USA: **HPN**

Enter Location: (latitude 90S to 90N, longitude 180W to 180E). See Instructions for details.

Latitude: 41.072778 N S **Longitude:** 73.715364 E W

Enter Date (1900-2010): Year: 2007 Month (1-12): 7 Day (1-31): 25

Compute Declination

Declination = 13° 26' W changing by 0° 2' E/year

For more information, visit:
Answers to some **frequently asked questions** | **Instructions** for use | **Today's Space Weather**

Appendix 1A.4
Long Island Mac Arthur (ISP) Radar Estimated Magnetic Declination

NOAA > NESDIS > NGDC > Geomagnetism comments | privacy policy

Estimated Value of Magnetic Declination

To compute the magnetic declination, you must enter the location and date of interest.

If you are unsure about your city's latitude and longitude, look it up online! In the USA try entering your zip code in the box below or visit the U.S. Gazetteer. Outside the USA try the Getty Thesaurus.
Search for a place in the USA: **ISP**

Enter Location: (latitude 90S to 90N, longitude 180W to 180E). See Instructions for details.

Latitude: 40.806456 N S **Longitude:** 73.0955131 E W

Enter Date (1900-2010): Year: 2007 Month (1-12): 7 Day (1-31): 25

Compute Declination

Declination = 13° 42' W changing by 0° 2' E/year

For more information, visit:
Answers to some **frequently asked questions** | **Instructions** for use | **Today's Space Weather**

Section 2. COMPOSITE RADAR DATA PROCESSING (CRAD) SERVICE

Parameter	Reference Paragraph	Standard	Tolerance/Limit	
			Initial	Operating
3-5. CRAD PROCESSING.	TI 6110.110, TI 6110.111, TI 6110.112			
a. Primary Channel Radar Data Surveillance Processing.				
(1) Narrowband .... Site Coverage.	5-14d, 5-15, 5-21, 5-31, FAA-4306M, FAA-4306U, and NASP-5201, Vol. II	Satisfactory cover-age as determined using the operational program or offline support program(s) such as RARRE and QARS as needed	Same as standard	Same as standard
(2) Range .... and Azimuth Accuracy.	5-14d, 5-15, 5-22, 5-26, 5-27, and 5-31	Site registration with no correct-ions applied to either site OR Search and bea-con PE coordin-ates within ± 1/8 nmi and ± 2 ACPs. This may be verified by the target symbol appearing within the adapted GMLSDA map box for the PE OR Radar system with no available search PEs, uti-lizes beacon PEs with same toler-ance as stated above and a search reinforce value greater than 80%	±1/8 nmi and 2 ACPs	±1/8 nmi and ±2 ACPs

Section 2. COMPOSITE RADAR DATA PROCESSING (CRAD) SERVICE (Continued)

Parameter	Reference Paragraph	Standard	Tolerance/Limit Initial	Tolerance/Limit Operating
→ (8) Radar Data Transfer.	5–14d, 5–15, 5–30, and 5–31	Satisfactory system operation (absence of RTQC error printouts during program operation)	Same as standard	Same as standard
(9) ARTS–NAS Registration.	5–32 and FAA–4306R			
(a) Total environment mean position error (Z).		Within 0.40 nmi	Same as standard	Same as standard
(b) Hemisphere mean position error.		Within 0.50 nmi	Same as standard	Same as standard
(c) Total environment 5–percentile class interval (95% Z).		Within 0.75 nmi	Same as standard	Same as standard
(10) Quick Analysis of Radar Sites (QARS).				
(a) Offline QARS.	5–27, FAA–4303 and NASP–5201, Vol. II			
1 BEACON.				
BLIP/SCAN		99%	99% minimum	96% minimum
SCH–REINFOR.				
ARSR–4		85%	85% minimum	80% minimum
ARSR 1/2/3		70%	70% minimum	60% minimum
Other		60%	60% minimum	50% minimum

NOTE: Those systems using longer Beacon range than Search range shall be computed using the Search range as maximum range.

Appendix 3A
Sample Equations of Radar Registration Errors Analysis Process
The mathematics applied in this sample equation incorporates the magnetic variation used to define vectors for the radar and target coordinates.

Enter radar site three letter ID, Latitude (DD.MM.SSSS), Longitude (DDD.MM.SSSS) and Height (meters). Then enter target aircrafts Azimuth (DD.DDDD), Range (nautical miles) and barometric altitude (feet).

EWR

$Lo_r := -74.11084($

$La_r := 40.40236($

$Ht_r := 20.2$

$Az_t := (137.549 - 13.1) \cdot deg$

$R_t := 44.875$

$bAlt := 3800($

Enter constants (earths semi major axis - a in meters and flattening factor - f).

$a := 637813$

$f := \frac{1}{298.25722356}$ $\quad f = 0.00335281$

Enter conversion, h(x), from DDD.MM.SSSS to DDD.DDDDDD

$h1(x) := 100(|x| - floor(|x|))$

$h2(x) := \frac{floor(h1(x))}{60}$

$h3(x) := \left(\frac{h1(x) - floor(h1(x))}{36}\right)$

$h(x) := \frac{x}{|x|} \cdot (floor(|x|) + h2(x) + h3(x))$

$La_r := h(La_r) \cdot deg$ $\quad La_r = 40.67322222 deg$ $\quad \sin(La_r) = 0.65174401$ $\quad \cos(La_r) = 0.75843902$

$Lo_r := h(Lo_r) \cdot deg$ $\quad Lo_r = -74.18566667 deg$ $\quad \sin(Lo_r) = -0.96214985$ $\quad \cos(Lo_r) = 0.27252095$

Convert Rt and bAlt to meters.

$R_t := R_t \cdot 6076.12 \cdot 0.3048$ $\quad R_t = 83108.561748$

$bAlt := bAlt \cdot 0.3048$ $\quad bAlt = 11582.4$

$ecc := \sqrt{f \cdot (2 - f)}$ $\qquad ecc = 0.08181919$

$$R_n := \frac{a}{\sqrt{1 - (ecc \cdot \sin(La_r))^2}} \qquad R_n = 6387224.73650551$$

Calculate Earth Centered Earth Referenced Coordinates E, F, and G.

$E_r := (R_n + Ht_r) \cdot \cos(La_r) \cdot \cos(Lo_r)$ $\qquad E_r = 1320182.99209872$

$F_r := (R_n + Ht_r) \cdot \cos(La_r) \cdot \sin(Lo_r)$ $\qquad F_r = -4660976.93762238$

$G_r := \left[\left(1 - ecc^2\right) \cdot R_n + Ht_r \right] \cdot \sin(La_r)$ $\qquad G_r = 4134981.02958438$

Calculate Elevation.

$$El1_t := \frac{\left[(a + bAlt)^2 - a^2 - R_t^2 \right]}{-2 \cdot a \cdot R_t}$$

$El2_t := \operatorname{acos}(El1_t)$

$El_t := El2_t - \frac{\pi}{2}$ $\qquad El_t = 7.64160553\,\text{deg}$

Calculate the target X, Y, and Z local coordinates.

$S_t := R_t \cdot \cos(El_t)$ $\qquad S_t = 82370.49459723$

$X_t := S_t \cdot \sin(Az_t)$ $\qquad X_t = 67925.18346496$

$Y_t := S_t \cdot \cos(Az_t)$ $\qquad Y_t = -46594.71892224$

$Z_t := R_t \cdot \sin(El_t)$ $\qquad Z_t = 11051.45491007$

Construct a matrix that rotates the target X, Y, and Z coordinates to align them with the radars ECEF coordinates.

$$C := \begin{pmatrix} -\sin(Lo_r) & -\cos(Lo_r) \cdot \sin(La_r) & \cos(Lo_r) \cdot \cos(La_r) \\ \cos(Lo_r) & -\sin(Lo_r) \cdot \sin(La_r) & \sin(Lo_r) \cdot \cos(La_r) \\ 0 & \cos(La_r) & \sin(La_r) \end{pmatrix} \qquad C = \begin{pmatrix} 0.96214985 & -0.1776139 & 0.20669052 \\ 0.27252095 & 0.6270754 & -0.72973199 \\ 0 & 0.75843902 & 0.65174401 \end{pmatrix}$$

Define vectors for the radar and target coordinates.

$$V_t := \begin{pmatrix} X_t \\ Y_t \\ Z_t \end{pmatrix}$$

$$V_r := \begin{pmatrix} E_r \\ F_r \\ G_r \end{pmatrix}$$

$$T := C \cdot V_t + V_r \qquad T = \begin{pmatrix} 1396097.29770875 \\ -4679748.90426335 \\ 4106844.49625142 \end{pmatrix}$$

$$Lo_t := \text{atan2}(T_0, T_1) \qquad Lo_t = -73.38871659\,\text{deg}$$

$$P := \sqrt{(T_0)^2 + (T_1)^2} \qquad P = 4883557.87020321$$

$$U := \text{atan2}[P \cdot (1 - f), T_2] \qquad U = 0.70087335$$

$$La_t := \text{atan2}\left[P - ecc^2 \cdot a \cdot (\cos(U))^3, T_2 + \left(\frac{ecc^2}{1 - ecc^2}\right) \cdot a \cdot (1 - f) \cdot (\sin(U))^3\right] \qquad La_t := La_t \cdot \frac{180}{\pi}$$

Enter conversion, p(x), from DDD.DDDD to DDD.MM.SSSS

$$La_t = 40.25160692$$

$$p1(x) := \text{floor}(|x|) \qquad p1(La_t) = 40$$

$$p2(x) := 60 \cdot (|x| - \text{floor}(|x|)) \qquad p2(La_t) = 15.09641515$$

$$p3(x) := 60 \cdot (p2(x) - \text{floor}(p2(x))) \qquad p3(La_t) = 5.784909$$

$$p(x) := \frac{x}{|x|} \cdot \left(p1(x) + \frac{\text{floor}(p2(x))}{100} + \frac{p3(x)}{10000}\right) \qquad p(La_t) = 40.15057849$$

$$Lo_t := Lo_t \cdot \frac{180}{\pi} \qquad Lo_t = -73.38871659$$

$$p(Lo_t) = -73.23193797$$

REFERENCES

[1] Yaakov, Bar-Shalom Ediitor, Registration: A Prerequisite For Multiple Sensor Tracking, Multitarget-Multisensor Tracking: Advanced Applications, Chapter 5, pp. 155-185 (1990)

[2] Fischer et al, Registration: Errors in a Netted Air Surveillance System, Massachusetts Institute of Technology, Lincoln Laboratory, pp. 1-77 (Sep. 1980)

[3] Klein, Lawerence, Sensor and Data Fusion Concepts and Applications. Ed. Donald C.O'shea. Bellingham, WA: SPIE Optical Engineering press, 1993

[4] Crowley, D.C.,and Saffai, B. Registration in multi-sensor data fusion and tracking. In proceedings of the American Control Conference, San Francisco, CA. pp.1333-1335

[5] Dhar, S. Application of a recursive method of registration error correction in tracking with multiple sensors. In proceedings of the American Control Conference, San Francisco,CA.pp.869-874, June 1993.

[4] Yaakov, Bar-shalom and W. Blair, "Multitarget-Multisensor Tracking: Applications and Advances Volume III", Norwood, MA: Artech House, 2000

[5] Hall, D." Mathematical Techniques in Multisensor Data Fusion", Artech House, 1992

[6] Gad A., Farooq M., Serdula, J. and Peters, D. "Multitarget Tracking in a Multiplatform Environment" Royal Military college of Canada, pp 1-8, 1996

[7] Abel,J. and Chaffee, J(1991): "Existence and Uniqueness of GPS Solutions, IEEE Transactions on Aerospace and Electronic Systems, Vol.27, No.6 pp. 952-956

[8] D. Reid, "An Algorithm for Tracking Multiple Targets" IEEE Trans. On Automatic Control, AC-24, pp. 843-854 Dec. 1979

[9] Gad A., Farooq M., "Tracking Highly Maneuvering Targets in Clutter using Interacting Multiple Model Fuzzy Logic Based Tracker" SPIE, vol 4729, April 2002

[10] Farrell J. and Barth, M. "The Global Positioning System and Inertial Navigation" 1999

[10]Stout, D. and Mulholland, R." Approximation of Corrected Slant Range in a Radar Surveillance System" IEEE Transactions on aerospace and electronics systems Federal Aviation Administration Technical Center, vol. AES-17, NO.5 Sep.1981

[11] Abel,J. and Chaffee, J(1991): "Existence and Uniqueness of GPS Solutions, IEEE Transactions on Aerospace and Electronic Systems, Vol.27, No.6 pp. 952-956