Robust Method for Universal Beacon Code Assignment

Vivek Kumar, Lance Sherry, and Richard Jehlen

This paper describes a method for assignment of Beacon Codes for secondary surveillance that eliminates the need for code "reassignments". As a result, the controller and pilot workload is reduced, and there is an increase in safety margins. The method, Space-Time Adjacency (STA) algorithm, assigns unique codes to flights by exploiting the temporal and spatial opportunities in individual flightplans. Simulations of 2007 NAS (National Airspace System) traffic using this method demonstrated that *zero* reassignments are required. The method is robust for peak day operations in all seasons in the presence of temporal and spatial variations in flightplans.

INTRODUCTION

Secondary surveillance utilizes Beacon Codes to uniquely identify aircraft. Due to the limitations of a four digit octal code and assignment of codes for military use, only 3,348 are available for civil aviation in the U.S.

Beacon Codes are assigned to flights to ensure unique identification of flights in the same surveillance Air Route Traffic Control Center (ARTCC). Each ARTCC is assigned a finite set of codes, with duplicate sets of codes assigned to ARTCCs with a low probability of interacting traffic. Ideally, flights could fly from their origin to destination using the same code for the entire flight duration. However, as the volume of traffic has grown and the route patterns have changed, the probability of hand-offs requiring a Beacon Code "reassignment" (due to codes already being used in the same ARTCC) has grown to an average of 12% each day. This phenomenon increases controller and flightcrew workload and reduces safety margins. This phenomenon is also not sustainable as air traffic continues to grow and routes continue to evolve.

This paper describes a method for universal assignment of Beacon Codes (Kumar, 2011). The method, Space-Time Adjacency (STA) algorithm, exploits the temporal and spatial opportunities available in the flightplans to assign unique codes valid for the entire flight duration to all flights in the NAS. Simulations of 2007 NAS traffic using this method demonstrated that *zero* reassignments are required and that the method is robust for peak day operations in all seasons in the presence of delays and variations in flightplans.

BACKGROUND

The primary purpose of Air Traffic Control (ATC) is to prevent collisions between aircraft operating in the National Airspace System (NAS), organize and expedite the flow of traffic, and to provide support for National Security and Homeland Defense (Nolan, 2007). Primary and secondary radars are used for surveillance.

Beacon codes are used to uniquely identify aircraft. For this reason, every aircraft within an ARTCC boundary must have a unique code assigned to it. Positive identification of the primary radar returns for individual aircraft is achieved through a system of interrogation and identification known as Air Traffic Control Radar Beacon System (ATCRBS). The transponders (Figure 1) located in aircraft respond to interrogations from ground stations with four digit codes, known as Beacon Codes (hereafter referred to as BC or codes). Each of these four digits is octal resulting in a total of 4,096(8^4) possible combinations, with 748 codes assigned to the military or reserved for other special use. As a result, 3,348 codes are available for civil aviation use in the U.S. (DOT/FAA, 2009).

Figure 1: A typical ATCRBS transponder (located in cockpit)

Figure 2: The 20 ARTCCs in the CONUS (Google Earth Representation)

The Contiguous United States (CONUS) is subdivided into twenty ARTCCs (Figure 2). The current process of Beacon Code allocation is ARTCC-centric. Each of the 20 ARTCCs in the CONUS is allocated a static subset of codes as per the DOT/FAA Order (DOT/FAA, 2009). The number of codes allocated to each ARTCC is not equal, and is dependent on the expected traffic (Figure 3). The center with the least allocation of codes is ZKC (Kansas City) with 601, while ZMA (Miami) has the most with 1,559.

Ideally, flights could fly from their origin to destination using the same code for the entire flight duration. However, codes are limited (3,348) and as a result the code subsets allocated to individual ARTCCs have overlapping sets of codes as shown in Figure 4. For example, there are 975 codes which are shared by four centers. As a result of the code sharing, it is possible (with about 12% likelihood) that when a flight enters a new ARTCC enroute to its destination, its current code is already in use by another flight. To maintain unique identification for that flight, the new ARTCC must "reassign" Beacon Codes to that flight from its own code subset. Every such reassignment requires human intervention which makes it vulnerable to errors. An undetected error may lead to misidentification of flights which can result in reduced safety margins. The current allocation method is also subject to transient short-term code shortages as the volume of air traffic grows.

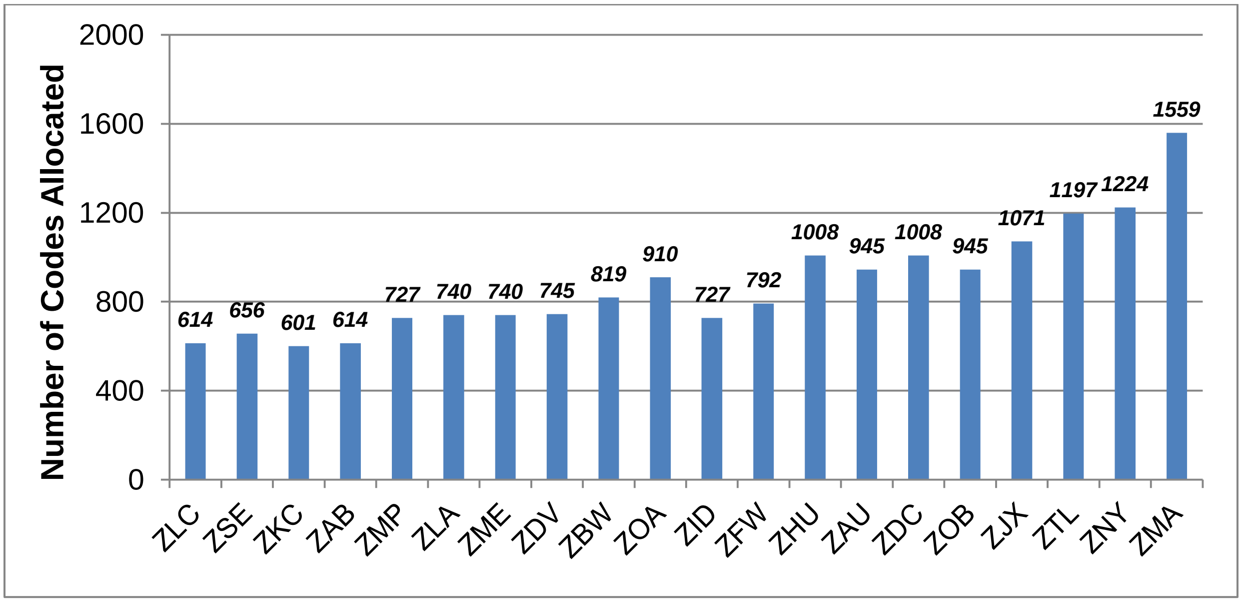


Figure 3: Distribution of total number of Beacon Codes allocated to 20 ARTCCs in the CONUS as per the National Beacon Code Allocation Plan (DOT/FAA, 2009)

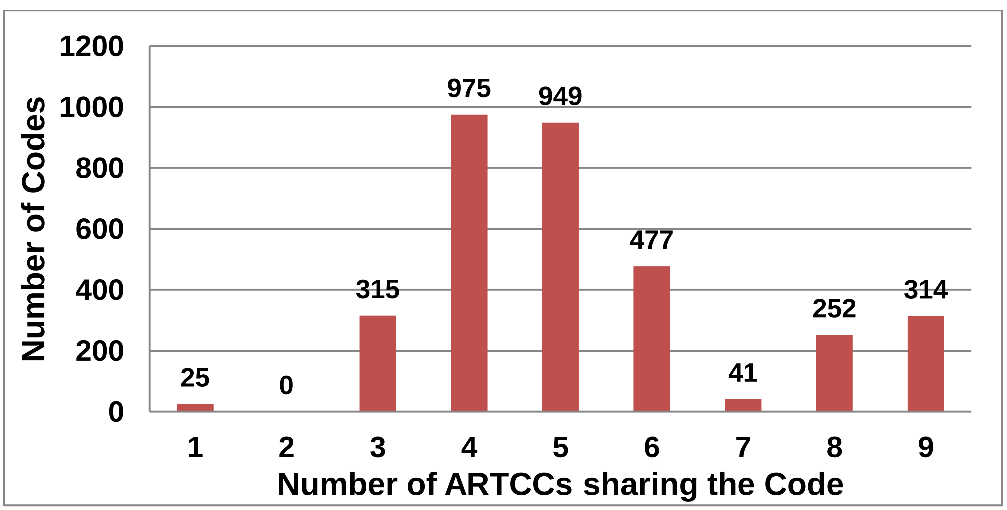


Figure 4: Histogram of Code-Sharing among the 20 ARTCCs in the CONUS derived from (DOT/FAA, 2009).

In addition to issues with reassignments, the current approach of allocating static set of codes to individual ARTCCs is not robust enough to accommodate changes in season fluctuation that may lead to localized code shortages. For example, Miami experiences heavy traffic in the winter which may lead to shortage of codes. When an ARTCC exhausts all the codes in its subset, then the controllers must assign non-discrete codes to flights. This process is workload intensive for the controllers and reduces the safety margin because a flight may respond to an ATC communication intended for another flight on the same Beacon Code.

QUANTIFYING THE ISSUES WITH BEACON CODES IN THE CURRENT SYSTEM

Historical data was analyzed from two data sources, Host data and Traffic Flow Management System (TFMS) data, to quantify the number of BC reassignments and establish a baseline. Days were chosen from different seasons to account for variation in traffic demand and route structure. The ratio of the number of BC reassignments to the total number of hand-offs generates the likelihood of a flight getting a code reassigned when it crosses an ARTCC boundary.

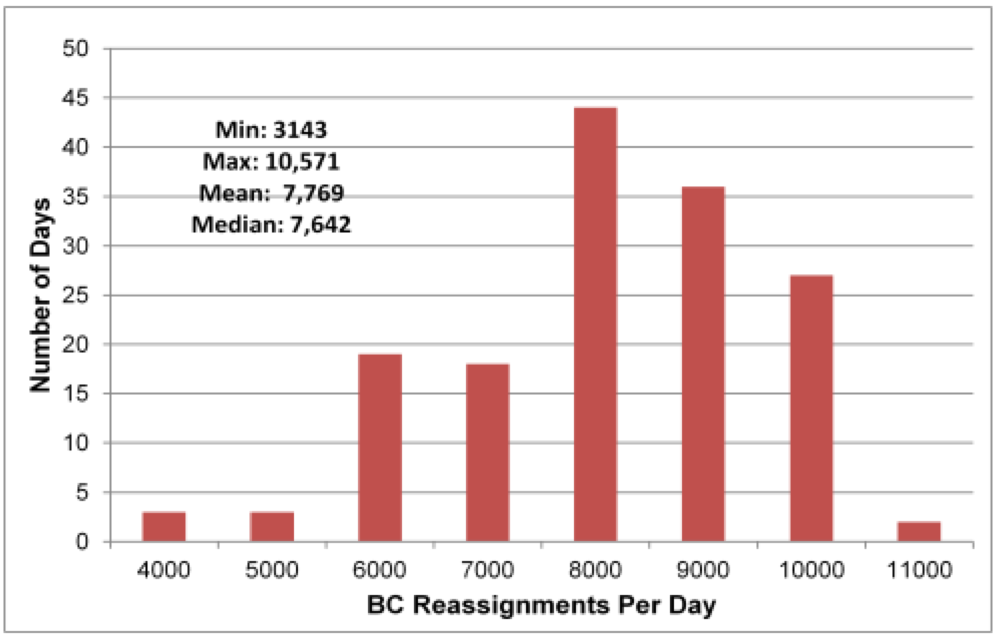
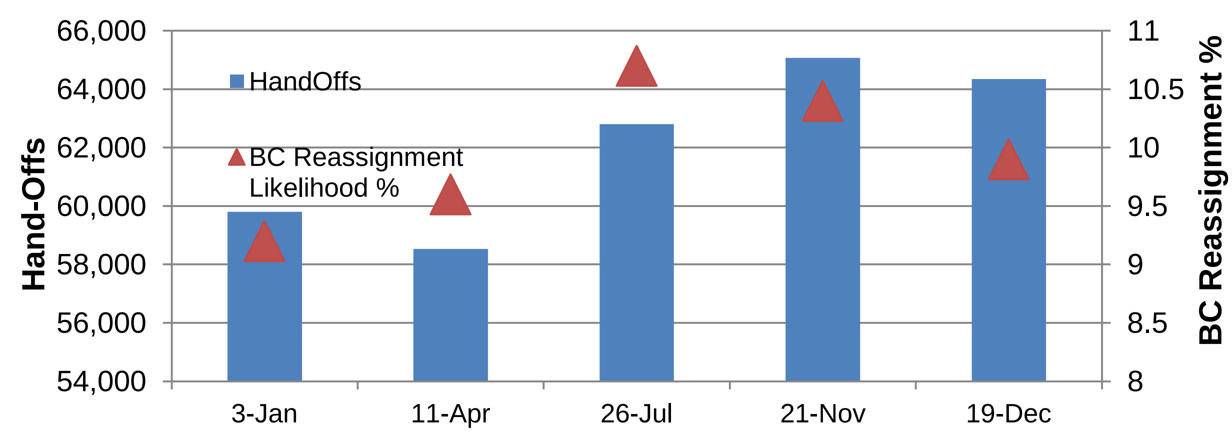


Figure 5: Histogram of BC Reassignments for 153 days of Host Data

The number of BC reassignments in NAS for 153 days of Host data analyzed over the period of 1st August 2007 to 31st December 2007 is shown in Figure 5. The average number of reassignments is 7,642 with a standard deviation of 1,451. This is equivalent to an average reassignment likelihood of 12.3 % (7,642/62,111).



	3-Jan	11-Apr	26-Jul	21-Nov	19-Dec
HandOffs	59,797	58,529	62,805	65,076	64,348
BC Reassignment Likelihood %	9.2	9.6	10.7	10.4	9.9

Figure 6: Beacon Code Hand-Off and Reassignment Likelihood from TFMS Data

The number of ARTCC boundary crossing instances (hereafter called hand-offs) for a typical day in the NAS is 62,111 (obtained from analysis of TFMS 4-D trajectory data for the 5 days as shown in Figure 6). The average number of BC reassignments for this time period is 6,208. The range for reassignment likelihood is 9.2%-10.7% with an average of 9.96% and a standard deviation of 0.6%.

A previous study of Beacon Code reassignments using traffic data from days ranging from year 2001 to 2004 showed that the mean number of code reassignments for a period of 17 days was 8,809 (Lucic, 2005). The minimum and maximum numbers of Beacon Code reassignments reported were 7,014 and 9,865 respectively.

The analysis of the two independent data sets yielded similar results and the range of BC reassignment likelihood was established to be 9.2% to 12.3%. This implies that in the current system, per 2007 traffic, there is a one in ten chance of a flight getting its Beacon Code reassigned whenever it crosses an ARTCC boundary enroute to its destination. This range serves as the baseline for comparing any new proposed Beacon Code assignment method.

SPACE-TIME ADJACENCY (STA) ALGORITHM FOR UNIVERSAL BEACON CODE ASSIGNMENT

The purpose of the Space-Time Adjacency (STA) algorithm is to assign BC to flights by exploiting the spatial and temporal opportunities of the flight schedules and routes. The goal of STA algorithm is to be able to assign codes to all the flights in the NAS using less than 3,348 codes such that there are *no reassignment instances*. In other words, every flight is assigned a single BC for its entire flight duration.

The STA algorithm comprises of the following steps: (Figure 7)

Step 1: Flights with filed flight-plans are ordered by departure time in ascending order.

Step 2: The ARTCC crossing times for all flights are then generated using their filed flightplans and added to the flight list. This ordered list of flights along with their predicted ARTCC crossing times is called the “Master List”.

Step 3: All the flights that are *active* (need Beacon Codes) in the current planning-window are removed from the “Master List” and exported into a new list called “active flights” list for the current planning-window. A flight from the “Master List” is deemed *active* in a given planning-window if its schedule departure is *no later than* DSPI (Departure Strip Printing Interval) minutes after the end of the window (typically = 30 minutes for all ARTCC).

Step 4: The “active flights” list and their predicted ARTCC crossing times are then used to generate the Space-Time Adjacency (STA) Matrix. This matrix identifies flights that are predicted to be in the same ARTCC at the same time.

Step 5: The list of overlapping flights is generated which consists of flights that are predicted to be *active* beyond the end of the current planning window.

Step 6: Based on the STA matrix and the codes timed out by overlapping flights of the previous planning-window, all the flights in the current planning window are assigned BC.

Step 7: A code Time-Out Matrix (TOM) is then generated for the following planning-window using the codes assigned to overlapping flights of the current window.

Steps 1 through 7 are repeated until all the flights have been assigned BC.

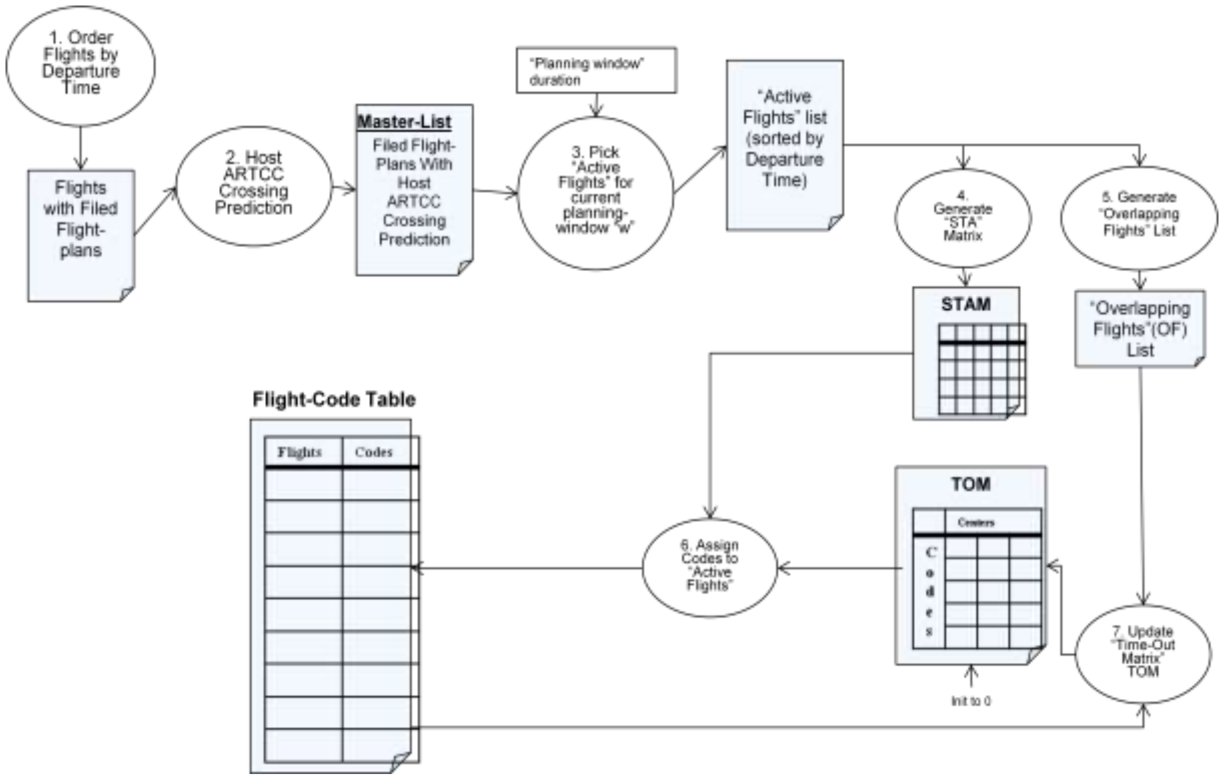


Figure 7: Description of STA Algorithm

Space-Time Adjacency Matrix

The Space-Time Adjacency (STA) matrix is a binary matrix which is referenced for every flight-pair. If an element of STA is 1, it signifies that the flight-pair corresponding to that particular position are predicted to be in the same ARTCC at the same time for at least one instance on their trajectories. This implies that the corresponding flight-pair must be assigned different codes. A flight-pair for which the corresponding value in the STA matrix is 0 may be assigned the same Beacon Code, as they are not in conflict at any point on their trajectories.

Overlapping Flights (OF) List and Code Time-Out Matrix (TOM)

The "Overlapping Flights" (OF) list for a given planning-window is the list of flight indices of flights that are "active" (need Beacon Code) beyond the end of the planning-window.

The code "Time-Out Matrix" (TOM) is a two dimensional matrix of 3,348*20 (=66,960) elements. The rows and columns correspond to "BC" and "centers" respectively. An element [i,j] of TOM represents the time *until* which code 'i' is timed-out in center 'j', i.e. it can't be assigned to any other flight in center 'j'. The code "Time-Out Matrix" (TOM) for the first planning-window is initialized to 0, i.e. all the elements of TOM at the start of the algorithm are set to 0. For the TOM example shown in Table 1, code 3 is timed-out for center 1(ZAB) until 7:00 AM. However, code 2 is available for assignment in center 1 because element [2,1] is 0.

Table 1: Time-Out Matrix (TOM) (3348 X 20 elements)

Center	1	2	3	.	.	20
Code Index	ZAB	ZAU	ZBW	.	.	ZTL
1	6:00 AM	0	0	.	.	.
2	0	7:00 AM	0	.	.	.
3	7:00 AM	0	0	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
3348	.	.	.	.	.	.

At the *end* of the current planning-window, the codes assigned (output of current run of STA) to each of the "overlapping flights" are *timed-out* in the centers that these flights are predicted to traverse after the end of the current planning-window.

At the *start* of the following planning-window, all the values in TOM that are less than the start-time of the planning-window are reset to zero. By doing so, all the codes whose time-out epoch expires before the start-time of the planning-window are made available for use.

Planning-Window Duration

The STA algorithm is implemented for a finite duration of time known as the planning-window. Ideally, all the flights for the entire day would be allocated codes in one "run" of the STA algorithm. In that case the duration of the planning-window, denoted by 'T' would be 24 hours. However, setting the 'T' to 24 hours is impractical due to the following two reasons:

(1) *Storage*: The number of "active flights" in each planning-window increases with 'T'. If the value of 'T' is 24 hours, then on a typical day in NAS (26^{th} July 2007) with 48,721 flights, the number of elements required to be stored in STA matrix is 1,186,843,560 (Based on n*(n-1)/2). Due to the non-linear increase in memory requirement with respect to the number of flights, the planning horizon needs to be curtailed.
.
(2) *Weather prediction*: The prediction of boundary crossing times of the flights depends on accurate forecast of weather and the resulting capacity of the constrained resources in NAS. Due to randomness in weather and the resulting inaccuracy of weather forecasts, creating a plan for routes for the entire day is not realistic (Michalek, D., Balakrishnan, H., 2004). The state-of-the art in convective weather forecast is MIT Lincoln Laboratory's Convective Weather Forecast product (Wolfson, M., et al., 2004) which provides accurate prediction of weather in the 0-2 hour range.

Due to the combination of the two factors mentioned above, the typical duration of a planning-window is set to 60 minutes. As a result, the day is divided into 24 non-overlapping and sequential time-windows, each of 60 minutes duration. Each planning-window 'w' has a start and end time represented by α_w and $\Omega_{w.}$ As the windows are non-overlapping but continuous, $\Omega_w = \alpha_{w+1}$, i.e. start-time of the following window corresponds with the end-time of the current window.

TESTING SCENARIOS

The STA algorithm for code assignment was tested using 5 high volume days of 2007 that represent different seasonal traffic patterns in time and space. These days are January 3, April 11, July 26, November 21 and December 19. The traffic statistics for these days are summarized in Table 2.

Table 2: Statistics of Traffic in the CONUS for the 5 days of 2007 used as input for STA

Days(2007)	Total Flights	Start of Peak Quarter-Hour (UTC)	Number of Operations in Peak Quarter-Hour	Average Number of Flights per Quarter-Hour
3-Jan	43,649	17:30	4,897	3,033
11-Apr	43,966	21:30	5,019	3,013
26-Jul	48,721	21:15	5,302	3,277
21-Nov	46,202	18:30	5,541	3,228
19-Dec	47,145	22:15	5,355	3,219

The *actual* departure time for each flight is used as a proxy for its scheduled departure time. Also, the actual center-crossing times are used as a proxy of host-prediction of center crossing times. Algorithms for computation of crossing times, host-prediction are described in detail in the dissertation (Kumar, 2011).

The construction of Space-Time Adjacency (STA) matrix is based on the filed flightplans and the *host-prediction* of ARTCC crossing times of the flights. Due to the delays and/or flight route changes induced by the stochastic influences of weather and airline operations, there is a temporal as well as spatial uncertainty associated with the flightplans.

Temporal uncertainty in flight trajectories

A flight may be delayed either at the origin airport or enroute due to operational or tactical reasons. As a result, the actual ARTCC boundary crossing times of the flight may be different from the crossing times predicted from the original flightplan. This type of temporal shift in flight trajectory may also result from rerouting (including holding pattern) within the ARTCCs on the original flightplan of the flight.

The robustness of the STA algorithm against this category of uncertainty was tested by blocking a time-window of buffer minutes (+ and -) around each of the *predicted* boundary crossing instances. The duration of the time-window was varied to 0, 15, 20, 25 and 30 minutes for this analysis. A *host-prediction* uncertainty value of 0 minutes represents *perfect information* about the center crossing time of each flight in the system.

For the example shown in Figure 8, flight AAL123 traveling from JFK (John F. Kennedy Airport, New York) to DCA (Ronald Reagan National Airport) is predicted to cross the ZNY-ZDC ARTCC boundary at 12 Noon. A host-prediction uncertainty of 15 minutes implies that the flight is considered *active* (for the purpose of STA matrix creation) in ZNY up to 1215 Hours and also *active* in ZDC from 1145 Hours onwards. As expected, higher *host-prediction* uncertainty buffer values leads to higher demand for codes.

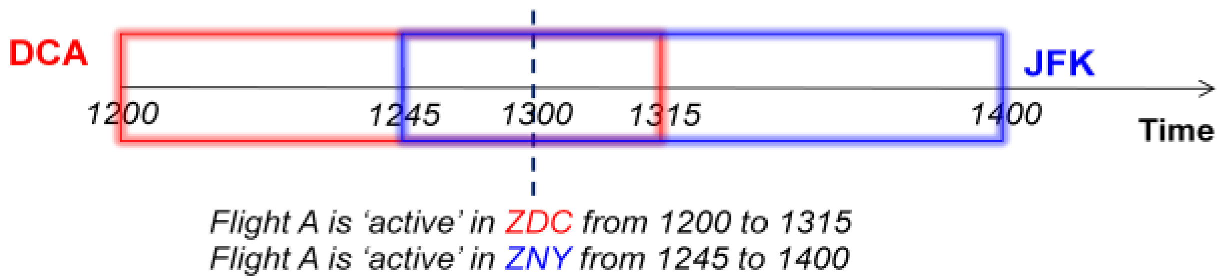


Figure 8: Temporal Uncertainty in ARTCC Crossing Time Prediction (Example of 15 minutes window)

Spatial (Lateral) uncertainty in flight trajectories

A flight may also be vectored for traffic or weather. The most common type of flight trajectory change is lateral path offset. To account for this type of uncertainty in the algorithm, every flight track was augmented by two parallel tracks on either side of the original flight track in the same altitudinal plane (Figure 9). The distance of these parallel tracks from the original track used to test the STA algorithm in this research are 5 nm and 10 nm.

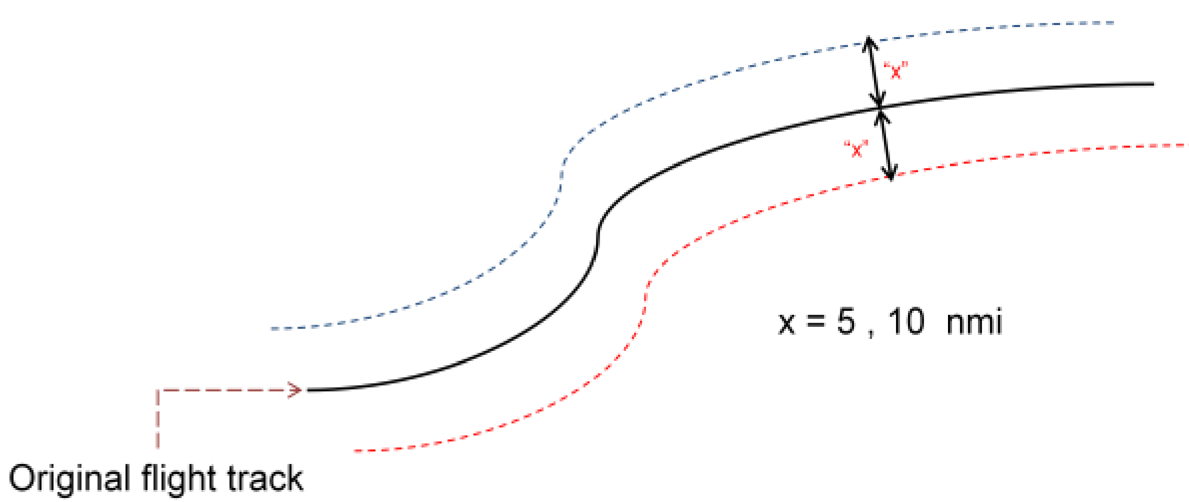


Figure 9: Lateral Uncertainty in Flight Route (Bird's-eye view)

RESULTS

When STA algorithm is used to assign codes to the 5 days of 2007 used in this research, there are *zero* instances of Beacon Code reassignments both with temporal and spatial uncertainties in flight trajectories.

When there is temporal-only uncertainty in flight trajectory (x=0 nmi), the maximum number of codes required in case of 30 minute host-prediction uncertainty of boundary crossing times is 70.5% (2,362 codes). This still leaves 986 (3348-2362) codes available for use. The percentage of codes used for the 5 days for different values of host-prediction uncertainty tested is shown in Table 3.

Table 3: Percentage of codes used by the STA algorithm in the presence of no lateral offset

	Temporal Uncertainty in "Host-Prediction"				
Date (2007)	0 min	15 min	20 min	25 min	30 min
3rd Jan	39	50	54	57	61
11th April	38	50	53	57	60
26th July	39	51	54	58	62
21st Nov	45	58	63	67	71
19th Dec	40	53	56	60	64

When the spatial uncertainty in flight trajectory (x = 5 and 10 nmi) is introduced, the maximum number of codes required in case of 30 minute uncertainty in host-prediction of boundary crossing times increases to 85%. The percentage of codes used when codes assignment is done using the STA algorithm for the 5 days with 10 nmi lateral offset is shown in Table 4.

Table 4: Percentage of codes used by the STA algorithm with a lateral offset of 10 nmi

	Temporal Uncertainty in "Host-Prediction"				
Date (2007)	0 min	15 min	20 min	25 min	30 min
3rd Jan	49	61	65	68	71
11th April	48	61	65	69	72
26th July	48	61	65	70	73
21st Nov	58	73	77	80	85
19th Dec	51	65	69	73	76

CONCLUSIONS

For the 5 high volume days of 2007, it was possible to allocate a code to all flights using STA algorithm without exceeding the available number of codes(3,348) such that were *no* instances of code reassignments in the CONUS. When the temporal-only uncertainty in host-prediction of ARTCC crossing time of 30 minutes was applied to each ARTCC crossing instance in the CONUS, it was still possible to allocate codes to all flights in the NAS using a maximum of 71% of available codes (21 November, 2007) without any code reassignments. When a 10 nmi spatial uncertainty in flight trajectories was also introduced, the maximum total number of codes required by STA algorithm was 85% of available codes (21 November, 2007).

Through this research, it has been demonstrated that the utility of a legacy system like ATCRBS in flight identification can be improved through software improvement without necessitating the need for any cost intensive hardware overhauls. Such software improvements would also help the NextGen modernization of NAS where newer technologies like WAM (Wide Area Multilateration) are still dependent on ATCRBS.

ACKNOWLEDGEMENTS

The authors would like to thank all who provided technical and management support of this research, especially Federal Aviation Administration's Pam Dees, Diana Liang, Geoffrey Barker, Paul Eure and John Guilding. The authors would also like to thank George Donohue, John Shortle, Alexander Brodsky, Karla Hoffman, and Akshay Kumar at George Mason University. Thanks also to Terrence Thompson, Arash Yousefi, Girish Sabhnani, and Chris Ermatinger at Metron Aviation Inc. We would also like to thank Ed Stevens at Raytheon.

ACRONYMS

ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
BC	Beacon Codes
CONUS	Contiguous United States
CRDT	Code Reassignment Delay Time
DCA	Ronald Reagan National Airport
DSPI	Departure Strip Printing Interval
FAA	Federal Aviation Administration
HCS	Host Computer System
JFK	John F. Kennedy International Airport
OF	Overlapping Flights
STA	Space-Time Adjacency Algorithm
TFMS	Traffic Flow Management System
TOM	Time-Out Matrix
WAM	Wide Area Multilateration
ZDC	Washington Center
ZNY	New York Center

References

DOT/FAA, 2009. DOT/FAA Order 7110.66D, National Beacon Code Allocation Plan

Kumar, V. (2011), "Methods for Universal Beacon Code Allocation", Ph.D. Dissertation. Advisor Dr. Lance Sherry. Center for Air Transportation Systems Research at George Mason University, Fairfax, Va.

Lucic, P. (2005), Geographic Beacon Code Allocation Optimization, CSSI Inc., Hyattsville, MD.

Michalek, D. and Balakrishnan, H. (2009), "Building a Stochastic Terminal Airspace Capacity Forecast from Convective Weather Forecasts," Proceedings for the Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, Phoenix, AZ.

Nolan, M.S. (2007), Fundamentals of Air Traffic Control, Wadsworth, Inc., Belmont, CA.

Wolfson, M., Forman, B.E., Calden, K.T., Dupree, W.J., Johnson Jr., R.J., Boldi, R.A., Wilson, C.A., Bieringer, P.E., Mann, E.B., and Morgan, J.P. (2004), "Tactical 0-2 Hour Convective Weather Forecasts for FAA," Proceedings for the 11th Conference on Aviation, Range and Aerospace Meteorology, Hyannis, MA.

Biographies

Vivek Kumar is a Research Assistant Professor in the Center for Air Transportation Systems Research (CATSR) at George Mason University. His research interests include air transportation systems engineer, air traffic management and the environmental impacts of aviation. He received his Ph.D. from GMU in 2012.

Lance Sherry is Associate Professor of Systems Engineering and Operations Research department at George Mason University. He serves as Director at the Center for Air Transportation Systems Research at GMU. He received a B.Sc. in Electrical Engineering from Brown University, and M.Sc. and Ph.D. in Industrial and Systems Engineering from Arizona State University. His research interests are in the system engineering of complex, adaptive systems.

Richard Jehlen is Director for the Systems Operations Services(SysOps), Planning and Performance (ATO) at the Federal Aviation Administration.