

# A Method for Universal Beacon Code Allocation

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## Abstract

Beacon codes or squawk codes are a set of limited National Airspace System (NAS) resource. The Air Traffic Control Radar Beacon System (ATCRS) was deployed for civilian use by FAA after World War II. With the increase in demand for codes resulting from the growth in air traffic, the current system of beacon code allocation leads to code reassignments which are inefficient. Also, the current system is vulnerable to code shortages as the traffic grows. This paper describes a new algorithm of beacon code assignment that eliminates the need for “reassignment” and is also more scalable to increasing traffic in the NAS. The method, Space-Time Adjacency (STA) algorithm, assigns unique codes to flights by exploiting the temporal and spatial opportunities in individual flightplans. Five high traffic volume days across different seasons of 2007 were used to test the algorithm performance and robustness. The results show that this method of code assignment required *zero* reassignments.

**Keywords** – Beacon Code, Squawk Code, ATCRBS, En-route traffic, NAS, Air Traffic Controller workload.

## Introduction

ATCRBS is an acronym for Air Traffic Control Radar Beacon System. It is an outgrowth of the Identify Friend or Foe (IFF) technology developed during World War II. It is a system used in ATC to enhance surveillance radar monitoring and separation of aircraft [1][2][3].

The ATCRS uses Beacon Codes as flight identifiers. In order for the controller of a given Air Route Traffic Control Center (ARTCC) to uniquely identify and address each aircraft, it is necessary to ensure that all aircraft flying within that ARTCC are uniquely identifiable. In other words, each aircraft within that Center has a unique beacon code. 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 [4]. This phenomenon increases controller and flightcrew workload and reduces safety margins (details in Section II of the paper). This phenomenon of beacon code reassignment is also not sustainable as air traffic continues to grow and routes continue to evolve.

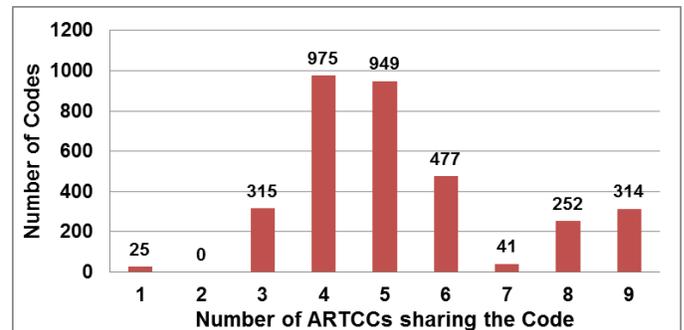
This paper describes a method for universal assignment of Beacon Codes [4]. The method, Space-Time Adjacency (STA) algorithm, exploits the temporal and spatial opportunities available in the flightplans to assign unique codes valid for the entire flight duration to all flights in the NAS. Simulations 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.

This paper is organized as follows: background, data sources and preprocessing, method of analysis, experimental setup, results, and conclusions.

## Background

The ATCRBS consists of transponders (in aircraft) and Secondary Surveillance Radar (SSR) which is co-located with the Primary Surveillance Radar (PSR) on the ground. The SSR located at the ATC site, transmits interrogations and listens for replies. Transponders located on the aircraft receive interrogations, decode it and respond with requested information (mode 1,2,3/A,C). ATCRBS interrogator at the ATC facility on ground periodically interrogates aircraft on a frequency of 1030 MHz. Aircraft receiving this interrogation reply with the requested information (altitude and/or identification) after a 3 micro second delay. The interrogator then decodes the reply and identifies the aircraft.



**Figure 1: Histogram of Code-Sharing among the 20 ARTCCs in the CONUS derived from (DOT/FAA, 2009)**

When an aircraft receives a mode 3/A interrogation, the reply expected is a Beacon/Squawk code. Current mode 3/A transponders installed on aircraft are designed to transmit four octal digits, resulting in a total of  $8^4 = 4096$  possible beacon codes. 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. [4]. The National Beacon Code Allocation Plan (NBCAP) established by DoT/FAA order 7110.66D allocates these 3,348 codes to the ARTCCs of the CONUS [5]. Many Beacon Codes are shared by multiple Centers. The level of code-sharing among ARTCCs that exists in the current distribution of code is shown in the form of a histogram in Figure 1. For example, there are 975 codes that are shared by exactly 4 centers.



- v. Ori – 3 or 4 letter ICAO code for origin airport. Eg: ORD
- vi. Dest – 3 or 4 letter ICAO code for destination airport.
- vii. Lat – Latitude of the aircraft at the corresponding time in minutes. Eg: 2906 represents 2906/60 ~ 48.43 degree North
- viii. Lon – Longitude of the aircraft at the corresponding time in minutes. Eg:3674 represents 3674/60 ~ 61.23 degrees West.
- ix. Alt – Represents the flight altitude level. Eg: 370 means the aircraft was at 370000 feet above MSL(mean sea level).

converted to a time ordered sequence of ARTCCs that the flight goes through enroute to its destination along with the entry and exit time of each ARTCC along the flight’s route. This section describes a set of algorithms that were developed to implement this conversion.

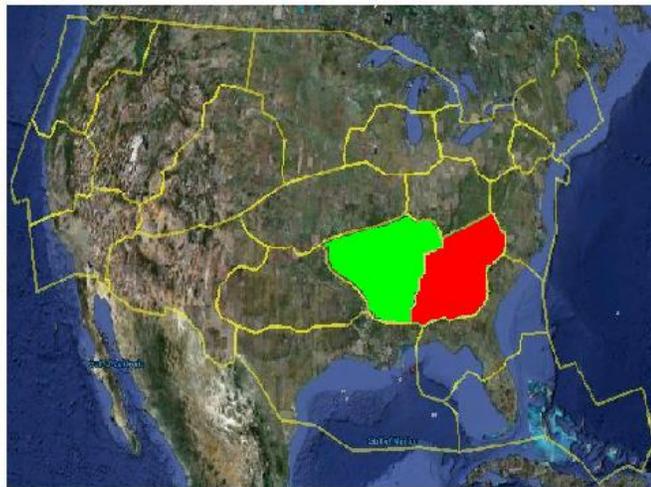
Firstly, the latitude/longitude format of the ETMS data is converted to the Cartesian coordinate system using the equations listed below. This step is required because the point-in-polygon algorithms (Ray-Casting Algorithm) operate in the Cartesian coordinate system. The formulae used for the conversion are as follows:

$$X = R * \cos(\text{longitude}) * \cos(\text{latitude})$$

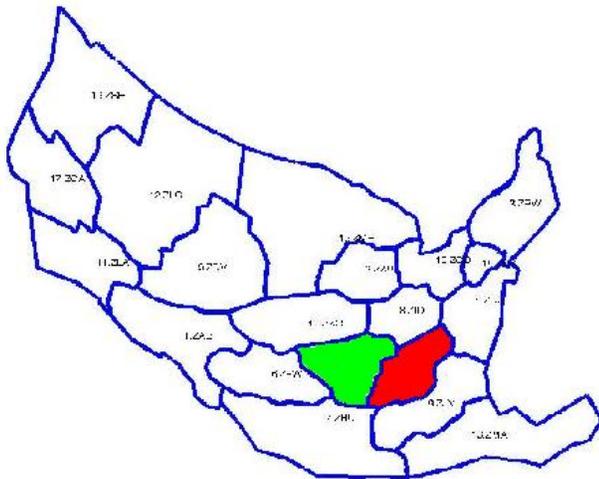
$$Y = R * \sin(\text{longitude}) * \cos(\text{latitude})$$

, where R = 6,378,100 metres (Average radius of Earth).

This method of conversion is based on projection of earth on a flat surface. Due to the curvature of earth, such a projection does not conserve the scale of the map, i.e. the actual distance between any two points on earth may not be the same as the distance between those points on the projected map. However, for the purpose of this research, we are only concerned about if and when the flights cross the ARTCC boundaries. As shown in Figure 4, the projection method being used here leads to a one-to-one mapping of each point on the earth’s actual surface (curved) to the projected surface. Similarly, the latitude/longitude boundary definition of each ARTCC is also transformed to the Cartesian coordinate system.



Actual (Latitude/Longitude)



Projection(Cartesian Coordinate)

**Figure 4: One-to-one mapping of Coordinate Transformation**

*Data Preprocessing: 4D Trajectory to Center-Path Conversion*

To test the proposed algorithm for Beacon Code assignment, the 4-D trajectory data obtained from ETMS for each flight is

**Method**

The algorithm for Beacon Code assignment developed during this research is called Space-Time Adjacency (STA) algorithm because it assigns 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:

**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.

### *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.

## Experiment Setup

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. 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. 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 example: If a flight 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.

### *Temporal 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. 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.

## 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 2.

**Table 2: Percentage of codes used by the STA algorithm in the presence of no lateral offset**

| Date (2007) | Temporal Uncertainty in "Host-Prediction" |        |        |        |        |
|-------------|---|--------|--------|--------|--------|
|             | 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 ( $x = 10$  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 3.

**Table 3: Percentage of codes used by the STA algorithm with a lateral offset of 10 nmi**

| Date (2007) | Temporal Uncertainty in "Host-Prediction" |        |        |        |        |
|-------------|---|--------|--------|--------|--------|
|             | 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 there 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 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.

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