The Common ATM Information State Space – A unified data management system for the entire NAS resources based on an indexing system

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Abstract

The future Air Traffic Management system will allow all the participants to have access to the same data resulting in improved coordination and planning. Through advanced technology, high fidelity data will be available across the system allowing enhanced tools to be created to assist controllers and airspace users.

A fundamental requirement for such a scenario is the ability to provide a common information source that can maintain the state data and adapt as the information changes.

The FAA Office of System Architecture and Investment Analysis, and ISA Software have carried out a research project to develop a demonstrator of a common information source. The Common ATM Information State Space, CAISS, has been designed to manage all the different NAS resources using an advanced indexing mechanism and carefully elaborated algorithms. The resulting prototype demonstrates a system that is capable of storing and maintaining all of the NAS resources and providing access to the latest state information in a timely and efficient manner.

This paper describes the CAISS and the indexed airspace approach, and presents results from experiments to develop client applications that illustrate the utility of the approach.

Introduction

Considerable efforts on both national and international scales are already underway to define future systems and procedures that will cater for the anticipated demand growth in air traffic services. In the scope of programs such as the US National Airspace Redesign or the European ATM2000+, focus is placed on the introduction of innovative technologies and new airspace procedures. However, increased capacity utilization and better efficiency will not be achieved through technology alone. This requires solutions and procedures that are integrated into a seamless and efficient transportation system.

The key to achieving these levels of service lies in the ability to deliver high quality and useful information to all airspace participants. Data transparency for all users of the system, access to common information, and timely delivery of critical state data such as the movement of adverse weather areas or congestion updates will allow us to fully exploit all available capacity through real-time resource management - a capability previously unavailable due to the fragmented nature of the existing system.

Recognizing the important role of the information infrastructure in the success of the future Air Traffic Management system, research has been carried out to identify how a global information structure might be achieved and the associated information used. The Common ATM Information State Space (CAISS) is an early demonstrator of a Common ATM information system capable of managing ATM system and state data for the whole of the National Airspace System (NAS).

CAISS: Common ATM Information State Space

To overcome the constraints of the present day system in which the static and state data remain separate, a common information structure with a unified set of data (both static and dynamic) is required. As users come to terms with the information explosion, new application areas that make use of the wealth of available information are becoming commonplace. Geographic Information Systems (GIS), Image Processing Systems, Advanced Graphics Applications, Computer Vision or Environmental Systems are readily available to support our engineering needs. These applications have one thing in common – they use and maintain spatial data to support their solutions.

NAS components have geometric and temporal aspects. Components can range from the extremely static terrain, through the functionally static radar and associated coverage, to the very dynamic protection volumes associated with aircraft. Data is often associated with other useful information that is non-spatial, such as an identifying name of a radar resource, the closure schedule for a Special Use Airspace (SUA) or the current heading of a flight moving through the system. By combining static and dynamic system and state data through a unique indexing mechanism, CAISS provides a highly efficient data management facility for the NAS.

CAISS is fine tuned to provide the ideal data management, search and retrieval facility for future ATM applications. It processes vast quantities of geographic and 4-D aviation and ATM data in extremely low execution times. Client applications have rapid access to system-wide information stored in CAISS making it possible to utilize information from across the entire airspace system, even if it is outside of the current visual area. CAISS can continually update and modify information to maintain accurate and up-to-date dynamic state data.

To ensure the utility of a common information source, when dealing with the common data, all users must respect a standard reference system, regardless whether they choose to visualize or utilize the data from a different point of tangency. In keeping with this paradigm, CAISS has been implemented using a standard reference system, namely Latitude, Longitude, Altitude and Universal Time Coordinates. This renders the power and flexibility of a unified data source available for future Air Traffic Management systems.

To support the CAISS research and development, several client applications have been developed to illustrate a variety of uses from different viewpoints, including those of the ATC Service Provider, Cockpit-based facilities and Airline/Airspace planning facilities. These client applications illustrate how a system-wide standard data management component can be used to manage all of the ATM state-space information: Addition, retrieval, modification and removal of information is carried out for the whole area in a fast and efficient manner; Client applications access CAISS to extract or deposit the information that is relevant to their own needs.

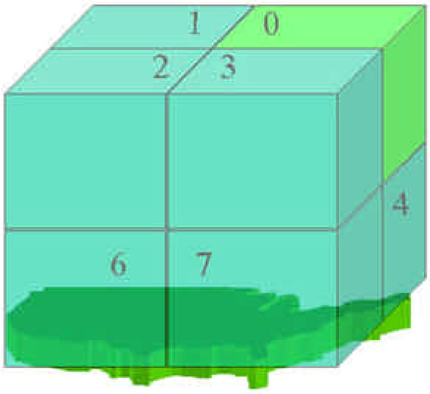
The CAISS Algorithm

The implementation of CAISS is based on ideas and concepts proposed by the FAA chief scientist for Architecture and NAS Development in the paper describing the Geographic Information System Based Airspace Concept[1] *[Bradford – Feb 2000]*. CAISS applies the Hierarchical Octree Space Partitioning (HOSP)[2] algorithms that are commonly found in geo-spatial data management systems, 3D medical information systems, n-body simulation in astronomy and molecular modeling. The basic principle of the Octree approach is to cover a region of interest by a cubic volume then recursively partition the cube into smaller cubes until each cube contains a suitably uniform subset of the input. The octree data structure was chosen, as it supports efficient, hierarchical organization and access of spatial data[3,4]:

CAISS Implementation Strategy – « Divide and Conquer »

The implementation of the CAISS prototype exploits the power of the Octree algorithm by applying it to the Airspace being considered:

1: Define a volume that contains the whole of the National Airspace System and divide it into a hierarchical set of airspace grid elements:



CAISS volume superimposed over NAS[5]

- Superimpose a hierarchical 3-D grid into the National Airspace System (NAS)
- Identify each grid element using a unique grid ID to support rapid access and retrieval of information
- Sub-divide each grid element as necessary to form a series of smaller grids (using eight equally sized sub-elements) to match the fidelity of the requirements. Each Grid/Sub-Grid is a 3-Dimensional volume of airspace
- Identify each sub-element using a sub-index in the same manner as before

[1] Geographical Information System Based Airspace Concept – Bradford, FAA/ASD-130, Feb 2000

[2] The Design and Analysis of Spatial Data Structures - Hanan Samet. Addison--Wesley, 1990.

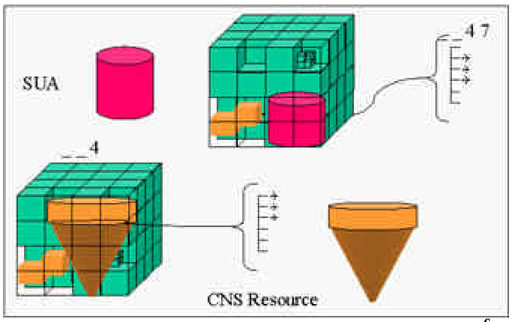
[3] Carlbom, Ingrid, Indranil Chakravarty, David Vanderschel. A hierarchical data structure for representing the spatial decomposition of
3-d objects. IEEE Computer Graphics and Applications, Vol.5, April 1985, pp. 24-31.

[4] Building a Registered Volume Database: an Object-Oriented Octree Program , Lynn W. Jones, Virginia Polytechnic Institute – ACM 1997

[5] Image source - Geographical Information System Based Airspace Concept – Bradford, FAA/ASD-130, Feb 2000

2: Register the airspace resources and known constraints (Sectors, CNS coverage, Special Use Areas (SUA), Weather Cells etc.):

- Sector information is registered in the 3-Dimensional gridded airspace
- Register Communication, Surveillance and Navigation (CNS) coverage information
- Register Weather cells and known SUA information



CNS Resource and Flight information registration[6]

3: Register flight information:

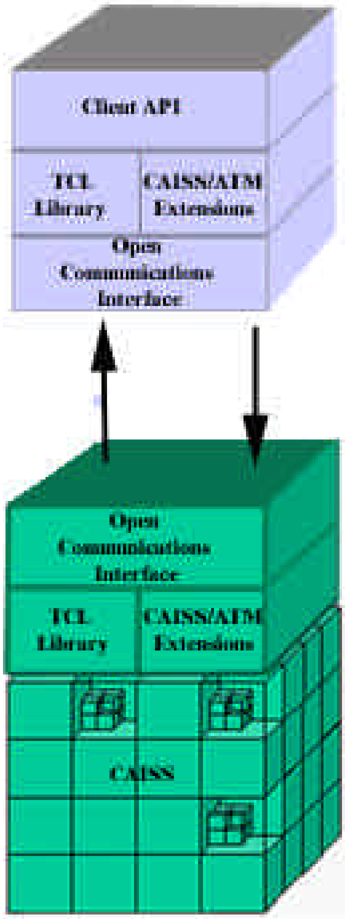
- The 4-Dimensional aircraft trajectory (historic or projected) is registered in the grid

Querying the ATM State Space

Having created a flexible 3-D data management system, a formal mechanism through which data can be found, filtered and rendered available to a client application is required. ATM Data in particular is spatial in its characteristic and highly dynamic – changing rapidly and sometimes unpredictably at a moments notice (e.g. weather, flight delays, conflict resolution actions, SUA activity etc). The data also contains a lot of contextual information: information that describes the interactions between its different data elements. Therefore, Careful consideration of the nature of the data and the target applications of CAISS has been made to ensure the best approach to information collection and distribution.

We recall the objectives for a query system in CAISS:

1. To provide a formal query mechanism, where the user has the ability to formulate dynamic queries against the CAISS database
2. To provide facilities through which data can be rapidly registered or retrieved, either directly or in a filtered form, and
3. To support creativity and ease-of-use on the user side



CAISS Query Interface

The approach taken in the design of the CAISS query mechanism makes use of a readily available formal language, and provides ATM and CAISS specific additions to that language. It is based on the Tool Command Language (TCL)[7][8] library with domain specific extensions.

TCL is a time-proven, highly portable scripting language that has been successfully used in many applications around the world. The CAISS/ATM extensions to TCL are used to register CAISS commands while the TCL engine deals with error checking and execution.

Through this approach, the client/user can exploit all the power associated with a highly developed scripting language, TCL, combined with specific CAISS/ATM built-in commands

6 Image source - Geographical Information System Based Airspace Concept – Bradford, FAA/ASD-130, Feb 2000

7 TCL and the Tk Toolkit – J. Ousterhout. Addison-Wesley 1994

8 Practical Programming in Tcl and Tk – Brent B. Welch. Prentice-Hall 1997

to produce sophisticated queries on the fly without any need to modify CAISS.

In addition to the interactive TCL scripting interface, a set of standard library functions has been created and is available as a library of helper utilities. These utilities can be linked directly into a client application to provide direct access to all of the query functionality in CAISS.

The library encapsulates the Open Communication Interface layer, OCI, thereby rendering the CAISS communications layer transparent to the end user / client application. In this way it can be easily enhanced to use alternative communications protocols such as HTTP or HLA without compromising client applications.

The CAISS Prototype – Technical Information

The CAISS prototype was delivered to FAA in September 2001 and illustrates the use of an indexed airspace approach to data management of NAS system resources. The prototype includes full support for the registration of ATC centers and sectors, CNS resources and flight data processing in the CAISS.

The objective of the prototype was to illustrate that the concept can be used and that by the careful design and implementation of efficient data management and retrieval algorithms, system resource and flight data covering the whole of the NAS can be stored without the need for specialized computing equipment. In addition, the prototype serves to illustrate that retrieval and modification (or removal) of state space information is both easy and very rapid, even when the gridded airspace is heavily populated.

Another important aspect of the prototype is to illustrate that, through the gridded airspace concept, the basic functions that are required to promote enhanced automation can be achieved. The CAISS prototype provides full functional support for all of the requirements that have been identified as necessary to support the gridded airspace concept, namely:

- The capability to catalogue the geographic features for a very large airspace region (the entire NAS)
- The ability to identify relationships and interactions between different data within the gridded airspace (Sector Entry/Exit, Projected Loss of Separation, Sector Loading etc.)
- Provision of ultra-rapid and accurate geographic information upon request

In addition to the CAISS prototype, a CAISS Demonstrator Interface client has been built to permit users to visualize the data that is registered in CAISS. Within the interface client, support is provided to commit CAISS queries through which data in the CAISS can be added, interrogated, modified or removed. Several other client applications have been built that make use of the CAISS, but these remain outside the scope of this paper.

CAISS Prototype - Benchmarks

A major objective during the design and development of the initial CAISS prototype has been to produce a very efficient and portable system for the management of NAS-Wide data. To ensure that this is the case, all of the development has been carried out using standard algorithms and the most efficient standard C++ library implementation – STL, the Standard Template Library.

Using a standard office personal computer configured with a single 800MHz Pentium 3 processor, 256 MB RAM and a 20GB hard drive and running the Windows NT 4.0 operating system (a typical machine being offered by most hardware OEM's) CAISS has attained highly impressive performance benchmarks, some of which are illustrated below:

Benchmark	**Execution Time**
Registration of 350 3-D airspace volumes (sectors) for the entire NAS region	< 1 sec
Registration of 15000 4D flight trajectories and calculation of all of the sector intersections for the entire NAS region	10 sec
Retrieval of a sector profile for a given flight	Instantaneous
Retrieval of a 24 hour sector load projection for a given sector	< 1 sec
Retrieval of all 4D flight positional information in a user defined region (pseudo pilot view)	< 1 sec
Registration of 15 Radar resources covering the Kansas City ARTCC	Instantaneous
Retrieval of all Radars covering a 4D flight position	Instantaneous
Identification of CNS coverage for a given 4D flight plan	Instantaneous

Operational Case Studies Used to Test and Illustrate the Flexibility of the Indexed Airspace Approach

Recalling that one of the objectives of developing the CAISS prototype is to illustrate that the approach can be used in support of basic functions that are required to promote enhanced automation, a number of operationally oriented case studies have been carried out.

The following examples illustrate how CAISS can be used to improve system-wide automation through efficient data delivery and a unified access to common high-fidelity aviation information.

Case 1: Pre-Operational Support - Flight Planning

Flight planning is a 'pre-operational' task that is instigated in the US by the airspace user (e.g. Airline Operations Center (AOC)) and supported by the HOST computer system. The following processes characterize the flight planning activity:

- Airspace user files a preferred flight plan
- On receipt of the flight plan, the HOST calculates a theoretical 4D trajectory for the flight
- The theoretical trajectory is verified to see if CNS services can be guaranteed in the NAS for the whole route

Using the CAISS prototype, with the current CNS resources (Radars, Navigation beacons, Radio communications facilities etc) the client application files a 4D profile, which is registered in the CAISS, then commits a CAISS query to verify CNS availability.

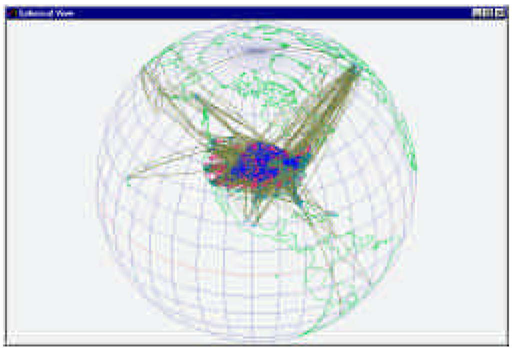
Any system that can generate a text based schedule and routing for a flight that is either semi-colon, comma, space or tab delimited can be used to provide the flight plan to the system[9].

For this particular demonstrator, the client application used was a combination of Microsoft EXCEL (to define the flight schedule, aircraft type and planned route) along with a flight plan parser and 4D Profiler tool (based on the RAMS Plus ATC Simulator profiling algorithms).

[9] alternative client applications can also be developed to deal with specific data formats should this be necessary

The flight plan is entered into an Excel spreadsheet and saved in delimited (csv) text format. The resulting flight plan is parsed and passed to the profiler which is used to generate the projected 4D flight plan based on the performance characteristics of the given aircraft type. The 4D trajectory is then registered in CAISS using the CAISS query facility.

For a typical cross country flight from JFK to SFO, calculation and registration of the new 4D flight profile in a heavily populated CAISS was achieved in under 0.5 seconds (from saving the EXCEL defined flight plan to confirmation that the flight is registered in CAISS) the majority of which was associated with the parsing of the flight plan and the generation of the 4D Profile.



CAISS Interface showing populated ATM resources

Once the proposed profile is registered in CAISS, the flight planner can query CAISS to verify that CNS coverage is available for the entire flight plan. With this information easily at hand the user can decide whether the requested profile is acceptable or not (i.e. whether CNS coverage is available for the entire route).

Having filed a flight plan, it is important that the service provider is able to assure that sufficient CNS resources are available across the complete routing being requested. Using a unified indexed approach as demonstrated by CAISS, each and every filed flight plan can be automatically surveyed to ensure that full CNS coverage is available throughout the projected trajectory.

Furthermore, as the flight progresses through the NAS, and modifications or updates are made, they are registered in the CAISS and similar queries can be made to continually monitor the availability of essential resources.

Case 2: Strategic Operations – Planned Airspace Non-availability using Time-based Special Use Areas

In the second operational case study, the flight planning operation is considered at a strategic level. It is still carried out by the airspace user, but information regarding SUA activity (Prohibited Airspace Areas) is returned for the requested flight plan. In this scenario, the user has filed a flight plan and verified the availability of CNS resources. At this point, the user checks to see if any known prohibited areas are encroached upon. Based on this information, the user can request further information regarding the proposed airspace closures, for example the closure / reopening times for a given area. With this additional knowledge, the user may decide between several strategies for example:

1. Re-plan the route to avoid the SUA by diverting around it
2. Plan a completely different route that may be considered more suitable for the users requirements
3. Re-plan the flight to use the desired routing earlier (or later) to exploit a window when the SUA will be unrestricted
4. File at risk – i.e. they are expecting the flight to arrive at the restricted area close to it's limit of activity and are willing to take the risk that the area will be available for use on arriving there

CAISS Interface showing close-up of SUAs

To model this operational scenario, the following (CAISS) actions are carried out:

- 4D profile is registered in CAISS
- A CAISS Query is executed to return information about CNS availability
- A second query is executed to retrieve information regarding prohibited areas (e.g. SUAS) that might affect the proposed flight plan
- Where airspace is temporarily unavailable, a further CAISS query is used to discover the characteristics of the prohibited area, and in particular, its opening and closing times

With information regarding the infringement of restricted areas easily at hand, the client can make informed decisions to allow more efficient options to be considered.

The second operational scenario illustrates how additional CAISS queries can be used to enhance the strategic support to the pre-flight planning function, and distribute additional NAS resource information to the airspace user.

Expanding further along the lines of this approach by extending the reasons for registering temporary airspace restrictions or areas/volumes that should be avoided: With the appropriate information registered in CAISS, flights and route planners can easily project when bad weather, high turbulence or possibly over congested areas may be encountered further into the flight plan and provide contingency to avoid these problems at an early stage.

Case 3: Tactical Operation – Unforeseen Outage of an Airspace Resource

In the third operational case study, we consider the use of the indexed airspace approach to cater for tactical operations that might be necessary in response to a sudden loss of a valuable resource. Situations of this kind occur regularly in the airspace system, and despite contingency planning, these unforeseen outages can have a significant impact on the traffic. It is not long since the US press reported problems due to critical failure to the ASR-9 terminal radar systems (which are installed at over 134 major US airports). These failures resulted in total loss of these facilities. In one particular incident at Logan airport, hundreds of departure flights had to be cancelled as a result. In a similar incident at JFK, 110 aircraft suffered significant delays up to a day later than the incident occurred[10].

CAISS Interface showing Radar Coverage at FL350 for 4 Centers (ZDV, ZKC, ZOB, ZMP)

[10] Washington Post, March 19th 2001

The scenario we present in test case 3 considers actions that would be taken in response to a catastrophic failure of a given beacon, and illustrates some of the automated support facilities that might be useful to assist in the Airspace Management activities.
There are three levels of reaction, all of which can be easily supported using the indexed airspace approach:

- Action to deal with the immediate impact on the flights using the failed beacon
- Action to cater for the up-stream impacts on flights routing toward the failed beacon in a short time period
- Long term (strategic) impact to flight planning operations

CAISS demonstrates many useful facilities that can assist the service provider to deal with situations of this nature.
In reaction to the immediate impacts, information can be rapidly retrieved, via suitable CAISS queries, to identify:

- Lists of flights currently navigating via the failed beacon
- Nearest alternative beacons for each and every affected flight
- Availability and utility of the given beacon in respect to the current range, surrounding airspace restrictions etc

In this strategic scenario, the user interrogates CAISS to formulate not only strategic actions, but also to remove or discount options that are not operationally viable, for example, offering a heading toward an alternate beacon that is 'blocked' by a hot Special Use Area and therefore the given flight cannot navigate to the beacon from its current position.
To support decisions and remedial actions with regard to the upstream traffic, CAISS queries can be used to identify flights that are routing toward the failed beacon and are expected to use it in a given time. Based on the results of this query, the service provider can make informed decisions about the necessary actions.
To provide additional support to the Airspace planning function, CAISS queries executed in the flight planning operations example (as described in case 1). Through this capability, flight planners would automatically be made aware of the lack of navigation capability as an impact of the outage.

Case 4: Tactical Operation – Airspace reorganization in response to temporary obstacles

In some cases, it is necessary to re-assign small volumes of airspace in response to the need to divert traffic around a temporary obstacle, such as a large area of bad weather or a space launch. In the event where a large bad weather area is located close to the control boundary, and diversion is difficult or impossible within the existing boundaries, it may be necessary to re-assign part of the neighboring volume to help cater for the diverted traffic flow.
The indexed airspace approach can be used to help assess the impact of a temporary delegation of a small airspace region, though queries that can identify:

- How much traffic is affected by the obstacle, and needs to be diverted?
- Are there sufficient CNS resources available to the controlling sector to provide cover for the delegated area?
- How much traffic in the neighboring airspace would require diverting to permit a temporary delegation of the airspace?

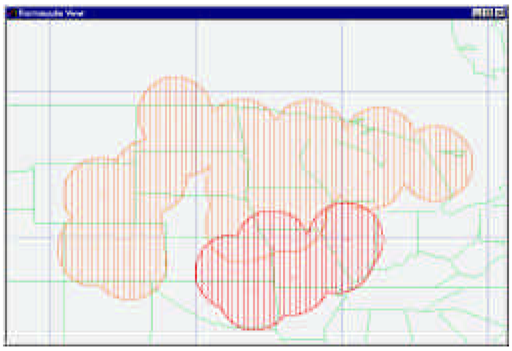
Once again, the client application in support of temporary delegation would be responsible for the formulation of suitable queries and presentation of relevant information

Design and Evaluation of Procedures using CAISS

In addition to providing support to daily ATM activities, CAISS can also be used as a support tool in the design and evaluation of ATM procedures. The following case study considers how CAISS can be used to assist in the design and validation of a contingency plan in reaction to a catastrophic failure of a given ARTCC.

Case 5: Contingency Planning – design and evaluation of a contingency plan for the total failure of an ARTCC

It is not uncommon that a specific center suffers a temporary loss of service. This could be for a number of reasons, for example total loss of power. In this event, although the CNS resources that support the ARTCC operations remain active, Communication and Surveillance facilities are rendered ineffective since there is no possibility of using the data being transmitted from those resources.
In the USA, this situation is called ATC Zero – where a given Center is unable to provide any ATC services for an unknown length of time.



CAISS Interface Showing Radar Coverage (4 centers) Following Critical Failure in ZKC

When developing a contingency plan for such a failure, it is useful to be able to ascertain which areas that are normally covered by the failed center are sufficiently covered by resources in the neighboring areas. Based on this information, a set of procedures can be set out to re-allocate active traffic to adjacent facilities to ensure continued service.

Using CAISS, and appropriate queries, catastrophic failure of a given center can be simulated, and secondary coverage from neighboring areas can be evaluated, using overlays of Communication, Navigation and Surveillance areas.

Additionally, using historic flight planning or radar data recordings, the contingency plan can be evaluated to see if the proposed procedures provide sufficient contingency to cater for typical traffic situations in the center.

Using future traffic forecasts to enhance the levels of traffic and by adding predictive or analytical capabilities, the service provider can also use the system to carry out predictive analysis on the future effectiveness of the contingency plan.

Applying standard modeling techniques, the effect of compound failures, where the problem cascades into neighboring regions can also be analyzed in regard to the contingency plans in place.

Conclusions

The CAISS prototype has already demonstrated that through the careful design and implementation of data management algorithms, the indexed airspace approach is highly suited to concept of a flexible and adaptable airspace. In the traditional Airspace Management Systems, dynamic modification of the airspace resource or reaction to system outage can result in heavy flight delays and huge reductions in the capacity of the airspace. The use of a unified data management facility that provides a highly efficient, reliable and rapid access to system-wide information such as that illustrated by CAISS is an important first step in improving flexibility. The CAISS prototype has been instrumental in provoking additional discussion and thoughts in regard to the gridded airspace concept.

Author Biographies

Ian Crook *has over 17 years experience in computing, specializing in the application of leading edge technologies to user oriented software systems. Specific skills include the use of Object Oriented methods, Artificial Intelligence, Discrete Event Simulation and Distributed Object Architectures.*
Having spent his formative years working in the aviation manufacturing industry, specializing in the development of on-board aircraft control software, Ian spent five years developing telecommunication systems, before returning to the aviation industry in 1991.
Since then, Ian has specialized in the design of ATM-oriented simulation systems.
Recent projects include the Eurocontrol Airspace Model (EAM), Capacity Analysis Facility (CAPAN), Reorganised ATC Mathematical Simulator (RAMS), Airspace-Airport Integrated Modeling System (AIMS), FAA RAMS-OPGEN dynamic link and the ISA Software/FAA ATMOS Weather server.

Diana Liang *works for the Office of System Architecture and Investment Analysis for the Architecture and System Engineering Division of the FAA. She is responsible for the development of the NAS Architecture Tool and Interface called CATS-I, directing analyses in support of NAS Concept Validation, and the development of Modeling Tools and Fast-Time Simulations to support that validation. This work includes several models she is developing jointly with NASA and cooperative efforts with Europe via Eurocontrol. Prior to working for ASD, Ms. Liang worked in the Office of Energy and Environment for two years as the lead for the Emissions and Dispersion Modeling System (EDMS), updated the FAA's Air Quality Handbook and reviewed Environmental Impact Statements related to emissions. Ms. Liang holds a BS in Computer Science and is currently attending George Washington University.*

Zak Tibichte *is chief software architect at ISA Software, specializing in the application of object oriented design methodologies and object management architecture with a focus on networking, communications and interoperability.*
For over 12 years, Zak has specialized in the design and implementation of ATM simulators and decision support tools. Responsible for the design and implementation of AMOC – an ATFM simulator built by connecting existing modeling tools including NASPAC, CASA and TACOT, Zak became involved in interoperable simulation techniques at an early stage.
More recently, Zak has been responsible for design and development of the FAA RAMS-OPGEN link, the ISA Software Open Communications Interface (OCI) and the Airport-Airspace Integrated Modeling System (AIMS) – an architecture that allows new and legacy simulation tools to operate interactively across a distributed network.
Zak is the principle engineer on the ISA-Software/FAA Common ATM Information State Space (CAISS) project.