Temporal and Spatial Distribution of Airspace Complexity for Air Traffic Controller Workload-Based Sectorization

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We develop an Air Traffic Controller (ATC) workload-based methodology for airspace sectorization. As an initial step, we partition the US National Airspace into three layers with different altitude ranges. The range of each layer is based on the operational levels in low, high, and ultra-high airspace. Each layer is further tiled to 2,566 hexagonal cells (hex-cells) with 24 nautical mile sides. These hex-cells are assumed to be the finite elements of airspace and ATC workload is modeled for each hex-cell using various airspace metrics. We simulate a one-day scenario of the entire National Airspace System (NAS) and calculate the ATC workload for each hex-cell. Furthermore, we apply new visualization techniques to analyze the temporal and spatial distribution of the controller workload. Having the workload values for each cell for the entire day, we develop clustering algorithms using optimization theory to cluster cells and construct sectors. Our effort concentrates on simulation as a means to evaluate cognitive workload for the elements of airspace regardless of current sector and center boundaries.

Nomenclature

TotalWL = total ATC workload for a sector or group of sectors during a given time interval
WLHM = horizontal movement workload
WLCDR = conflict detection/resolution workload
WLC = coordination workload
WLAC = altitude-change workload
WL_t = ATC workload function at time t
n = number of sectors
s = side of hex-cell in nautical mile
f = generic function
t = time index
lat = latitude in degree
lon = longitude in degree

I. Introduction

AIR travel in the U.S. grew at a rapid pace until 2001, expanding from 172 million passenger enplanements in 1970 to nearly 615 million in 2000. However, over the next 4 years, a combination of factors—the events of September 11th, 2001, an economic recession, and other factors—combined to reduce the traffic back to 1995 levels. Never-the-less, air travel remains one of the most popular modes of transportation and it is projected to grow with a rapid pace[1]. A combination of many factors limit the National Airspace System (NAS) capacity and it is expected that current system capacity could not maintain a high quality of service for the future demand. The limited airspace capacity is already imposing significant en route delay in the congested areas of the NAS[1].

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A. Capacity limitations and the role of Air Traffic Controllers (ATCs)

The capacity of the nation's air transportation system has not kept pace with the growth in demand. Thus costs in terms of lost time and extra fuel consumed continue to grow rapidly for society and business[2]. Capacity of the NAS is constrained by many factors including number of runways, aircraft separation requirements, and the Air Traffic Controller (ATC) workload limitations. Future increasing demand could result in under utilization of the airspace system due to controller workload constraints. In congested areas of the NAS, the ATC workload limitation is a critical capacity constraint which generates significant en route delay and increased Operational Errors (OE)[5]. The controllers often enforce Miles in Trail (MIT) restrictions or they may reroute the aircraft or deny access into a sector to avoid high workload situations. Without effective improvements to reduce the ATC workload in congested areas, airspace capacity could not be maintained up to a level which satisfies the future growth.

Airspace sectorization has a direct impact on the amount of workload that controllers experience and an efficient sectorization could ease the workload even in the complex traffic situations[3,4, and 6]. The current airspace sectorization is not based on a comprehensive and system-level study of demand profiles and route structures. The majority of sector boundaries have a historical, not an analytical background[3,4,7,& 19]. Currently, modifications and airspace redesigns are often conducted within Air Route Traffic Control Centers (ARTCC) and the system-wide effect of any change to the entire NAS is not usually studied. Throughout the years sectors in the congested airspace have been divided into smaller sectors to lower the aircraft density. However the available frequency spectrum for controller-to-pilot and controller-to-controller communication eliminates the achievable number of sectors in the NAS[8].

The ATC workload is directly related to the controllers' situational awareness[9]. Structured air traffic reduces the system dynamics and enables the ATC to develop mental abstractions to reduce the cognitive complexity of traffic situation. This complexity reduction results in airspace capacity improvement[10,11]. Current air traffic patterns in the U.S. contains highly structured routes that are favorable for the controllers. However current airspace sectorization is not often in accordance with these structured routes and ATCs are not able to take full advantage of this existing highly structured traffic. For example, an aircraft destined to ORD from LAX may cross up to 15 different sectors while en route. Such a decentralized system produces significant amount of controller-to-controller and pilot-to-controller coordination workload and this results in system inefficiency.

Recent advances in Air Traffic Management (ATM) technology are changing operating conditions of the ATC. Today, with the use of advanced data links, one controller could be able to track an aircraft and communicate with a pilot all the way from origin to destination. Advanced navigation equipment and data links such as Global Positioning System (GPS), Airborne Separation Assurance System (ASAS), Automated Dependent Surveillance Broadcasting (ADS-B) and Cockpit Display of Traffic Information (CDTI) enable pilots to provide separation assurance. Hence the ATC functions could become more strategic in nature.

B. Lack of trained ATCs and excessive number of ARTCCs

The Federal Aviation Administration (FAA) currently employs approximately 15,272 controllers out of which, more than 7,000, *almost half the workforce*, are expected to retire in the next nine years[12]. The FAA has proposed to raise the retirement age to help deal with an unprecedented number of retirements. But this temporary solution does not address the issue in the long term. The retirement issue in addition to the increasing demand for air traffic exacerbates challenges facing the ATM system. The Air Traffic facilities in continental U.S. are located in 20 ARTCCs across the country. As shown in Fig. 1, the overall traffic is not uniformly distributed among the Centers. There are many administrative employees in each ARTCC other than the controllers. Such a decentralized system results in inefficiencies in terms of providing unnecessary infrastructure and staffing requirements. Reducing the number of centers could result in significant savings. The FAA has initiated the National Airspace Redesign (NAR) project, which in part aims for a more optimal sectorization by balancing the traffic load and sectors' capacity[13]. The NAR project also proposes a reduction in number of Centers. In this venue, a comprehensive methodology that analyses the temporal and spatial distribution of airspace complexity and provides a scientific, yet *practical*, technique for airspace sectorization is needed to guide the decision makers.

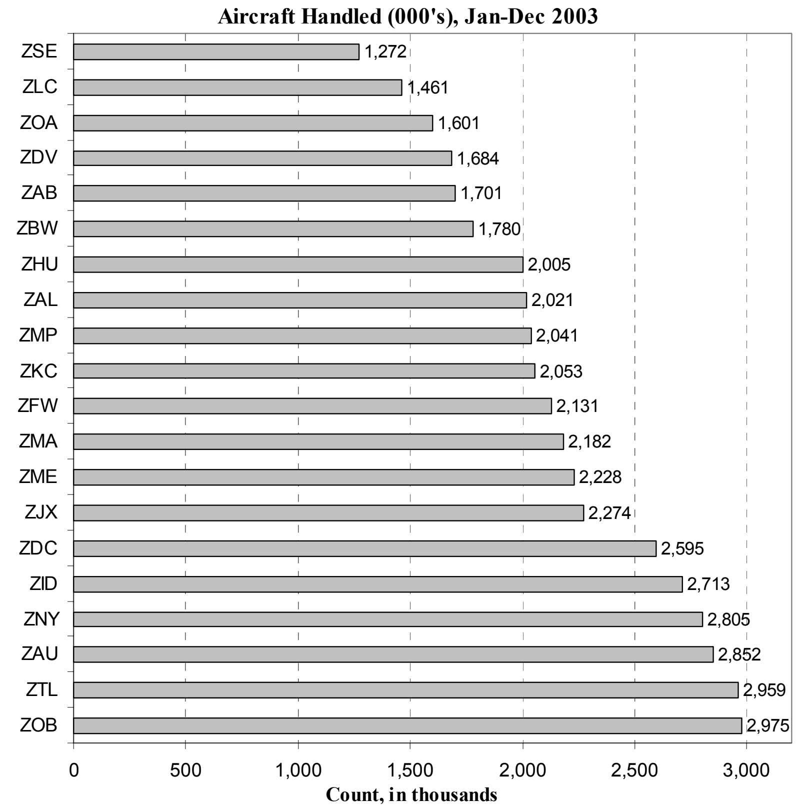

Figure 1. Annual air traffic distribution among CON U.S. ARTCCs. Source: FAA Factbook, March 2004. URL: *http://www.atctraining.faa.gov/factbook.*

C. Deficiencies of previous research

The ATC workload is the major factor in designing the sector and center boundaries. The current heuristic approaches for airspace design have reached the limit of their acceptability. To explore more automated and systematic methodology, researchers have tackled the airspace partitioning problem in separate efforts. Various mathematical methodologies like graph theory, genetic algorithm, computational geometry, and constraint programming are applied to solve the portioning problem[14-18]. In general, these approaches do not consider standalone metrics that reflect *all* the factors contributing to the ATC cognitive workload. Instead, they tried to represent the workload by some simplified metrics that capture *some* of the contributing factors to the ATC workload. In addition, to our knowledge, none of the proposed mathematical models has been *practical enough* for designing the *actual* sector boundaries using *real* operational data. The previous approaches take the existing sector boundaries as a basis and try to optimize them *locally*. In other words, the workload has its meaning in the context of *existing* sector boundaries. The vertical movement of the aircraft is not usually considered and the proposed models are representations of the airspace in 2-D.

II. ATC Workload Modeling

Research in controller workload has been motivated by a desire to understand occupational stress, eliminate operational errors, enhance safety, and improve controller training. Surprisingly there is no globally accepted definition for ATC Controller workload –"controller workload is a confusing term and with a multitude of definitions, its measurement is not uniform"[19]. Workload measurement in ATC is often based on several parameters measured at the same time. As workload cannot be measured directly, it has to be *inferred* from quantifiable variables. [19-35]. Researchers have traditionally estimated workload through four basically different categories of measures:

- Physical interaction of ATC with control devices like number of key strokes and communication tasks,

- Physiological state of the ATC like heart rate and blood pressure,
- Psychological state of the ATC as the amount of cognitive demand that is generated by traffic situations,
- Traffic characteristics have been quantified through measurable constraints pertaining to the task and its environment: total number of aircraft monitored during a work shift, number of coordination actions, availability versus restriction of airspace, number of conflict points per hour, etc. Individually or combined, they are seen as indicators of controller's workload.

All of these metrics are measured during the actual operation or using real time simulations assuming that sector boundaries are already designed. These measures have meaning in *the context of already designed sector boundaries*. For the purpose of workload-based sectorization, the ATC workload needs to be modeled for any given volume of airspace given a certain traffic pattern. In other words, when we are interested in designing the airspace, there is no existing sector that conventional methods could be applied for workload measurement. Instead, a large scale simulation is essential to calculate variety of airspace metrics such as aircraft density, number and geometry of conflicts, number of coordination actions, altitude changes, communication actions, etc. The simulation must be able to calculate all the mentioned airspace metrics for *generic* and uniform sector *building-blocks*.

Ref. 36 discuses an analytical method for workload modeling based on the traffic characteristics and sector complexity. The ATC workload is divided into four variables:

1- Horizontal Movement Workload (*WLHM*),
2- Conflict Detection and Resolution Workload (*WLCDR*),
3- Coordination Workload (*WLC*),
4- Altitude-Change Workload (*WLAC*).

In each sector or group of sectors, the summation of these four variables gives the total workload, Eq.(1).

$$TotalWL = \sum (WLHM, WLCDR, WLC, WLAC) \tag{1}$$

The horizontal movement workload (*WLHM*) is determined by the number of aircraft in a sector (sector density) and the average flight time. The Conflict Detection/Resolution (CDR) workload (*WLCDR*) is based on the conflict detection using the type of conflict and the conflict severity. The coordination workload (*WLC*) is determined by the type of coordination action including: voice call (coordination between two controlled airspace), clearance issue (i.e. for changing the course), inter-facility transfer (coordination between two sectors from different ARTCCs), silent transfer (coordination from controlled to uncontrolled airspace), intra-facility transfer (coordination between sectors within an ARTCC), and tower transfer (coordination between Tower and TRACON ATC). The altitude-change workload *(WLAC)* is determined by the type of sector altitude clearance request for level-off, commence-climb and commence-descent.

The Total Airport and Airspace Modeler (TAAM) has been utilized in order to calculate the variables in Eq.(1). TAAM is a large-scale fast-time ATM simulator that simulates the aircraft performance in all phases of flight (gate-to-gate), airport operations, and ATC's decision-making. TAAM counts and records different actions that controllers take as well as the number of aircraft passing through each sector[37]. TAAM output tables are used to calculate each of the four variable in Eq.(1). For detailed formulation and validation refer to Ref. 36.

III. Temporal and Spatial Distribution of ATC workload

A. Airspace partitioning

Today's airspace over continental U.S. is divided into low, high, and ultra-high altitude ranges that cover controlled airspace in classes A, B, C, D, and E[38]. The operational environment of each altitude range is of different nature. Most of the General Aviation (GA) aircraft use the low altitude airspace whereas commercial operations take place in the high and ultra-high airspace depending on the flight range. Thus the traffic pattern in each altitude range has certain characteristics and for the purpose of airspace sectorization each altitude range should be treated differently. Keeping this in mind, we partition the continental U.S. airspace into three layers as follows:

- Mean Sea Level (MSL) to FL210, where short-hull turboprops tend to fly and Visual Flight Rule (VFR) operations take place.
- FL210 to FL 310, where most of the short to medium-hull jet aircraft fly. It is also transition layer from ultra-high jet routes to lower level airspace.
- Above FL310, where en route airspace and jet routes are located.

Each layer is further tiled to 2,566 hexagonal cells (hex-cells) which are assumed to be the finite elements of airspace. Figure 2 illustrates a view of airspace partitioning process. In such a partitioning, we disregard any existing sector or center boundary. We model the ATC workload for each hex-cell and describe how these cells could be clustered to construct sectors. The hex-cells need to be small enough to provide reasonable resolution also large enough to capture conflict scenarios for computation of conflict detection/resolution workload. Current minimum lateral separation in en route airspace is 5 nm and controllers often add a safety buffer to this minimum. Taking this into account, side of each hex-cell is considered to be 24 nm or 0.4 degree, which is enough to accommodate 3 to 4 aircraft along one route.

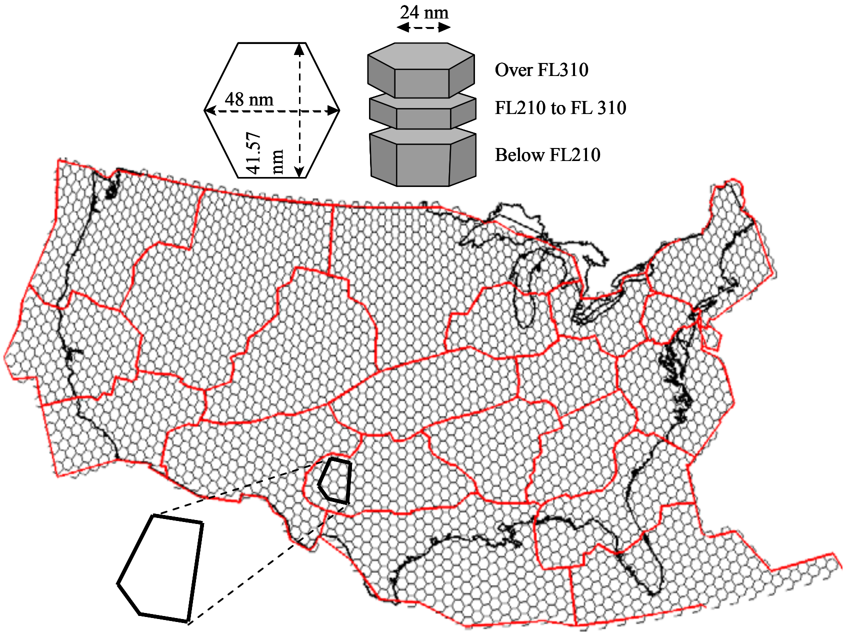

Figure 2. Airspace partitioning and the hex-cell structure.

Tiling a surface is possible by a triangular, rectangular, or hexagonal mesh. For the purpose of airspace sectorization the most suitable geometry seems to be a hexagonal mesh. Computationally, it is easier to cluster hex-cells in every direction. Figure 3 illustrates how hexagons can be clustered together in different directions in a plane. For the triangular and rectangular mesh, if we cluster two cells in diagonal directions, they touch each other in their edges and do not have a common side. So an aircraft cannot move from one cell to the other without leaving the cluster. It is only in a hexagonal mesh that all the cells have common sides for clustering in every direction. Also by using a hexagonal mesh, we avoid the acute and right angles in triangle and rectangle that may result to short transit times for aircraft passing close to the edges.

Our intention is to develop the *methodology* for a workload-based airspace sectorization and we have selected the described geometry for airspace layers and hex-cell mesh as an initial concept. One could divide the airspace to more than three layers with different ranges or tile each layer with smaller/larger cells.

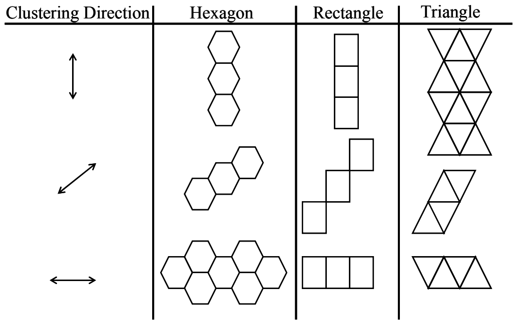

Figure 3. Comparison of different tiling methods.

B. Simulation and hex-cell workload modeling

We use TAAM to simulate a one-day scenario of entire NAS operations. Each hex-cell is treated as a sector and ATC workload is modeled using various airspace metrics that are calculated by TAAM. For each hex-cell the coordination workload in Eq. (1) is set to zero (WLC=0) because, in reality, there is no hand in/off when an aircraft moves form one hex-cell to the other. The required flight schedule and flight tracks are extracted from the Enhanced Traffic Management System (ETMS) database and converted into proper format for TAAM. In the ETMS flight-table there are few sets of flying tracks recorded for each flight ID. ETMS updates the recorded routes every time Airline Operation Centers (AOC) file a new flight plan. These updates are due to the FAA amendments and advisories or to avoid inclement weather along the previously filed route. We filter the last filed route, before the aircraft push back, as an input to the simulation model. In the ETMS, there are many flights with missing attributes like origin, destination, or departure/arrival time. Total number of flights that are retrieved from the ETMS is roughly 45,000 flights. So we are missing 5,000-15,000 flights per day. Figure 4 shows a view of TAAM simulation with hex-cells as sectors and actual flown tracks. TAAM output tables provide all the parameters for calculation of workload based on Eq. (1).

The hex-cell workload values during 15 minute bins are plotted in Fig.5. Each line represents one hex-cell and low and high altitude cells are separated into two graphs. The low altitude hex-cells generally have higher workload due to their larger altitude range. All the hex-cells follow a same trend throughout the day and there are few hex-cells with exceptionally high workload values. In the next sections we investigate the geographical location of these cells.

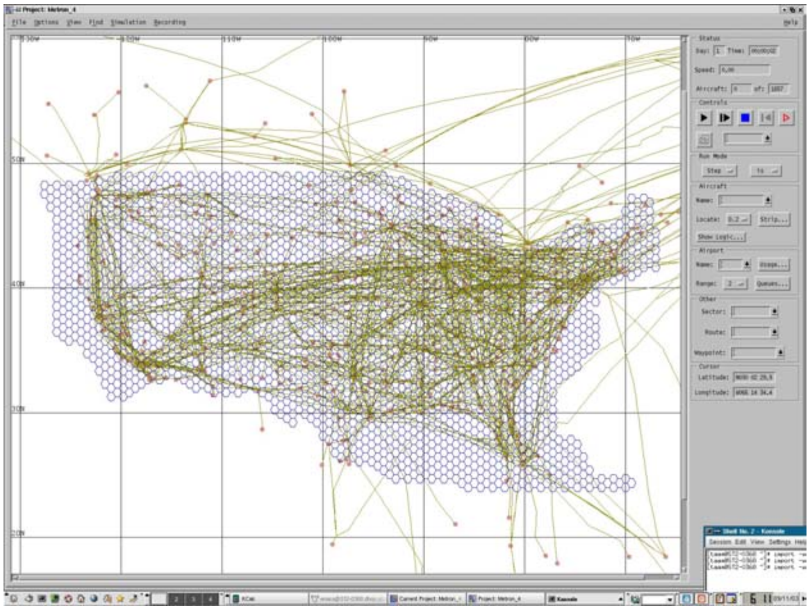

Figure 4. A view of TAAM simulation.

Figure 6 categorizes the high altitude hex-cells by their ARTCC for each hour of the day. Each bar represents one hex-cell and height of the bars indicates the total workload during one hour intervals. The New York Center (ZNY), the smallest Center in the NAS, contains the most complex hex-cells whereas in larger Centers like ZLC and ZMP there are hex-cells with very low workload values. A comparison of Centers located in east and west coasts points out the time lag between operational peaks in each side of the country. For instance, in ZLA, the peak workload starts at 15:00 Zulu whereas in ZDC, workload begins to grow at 11:00 Zulu.

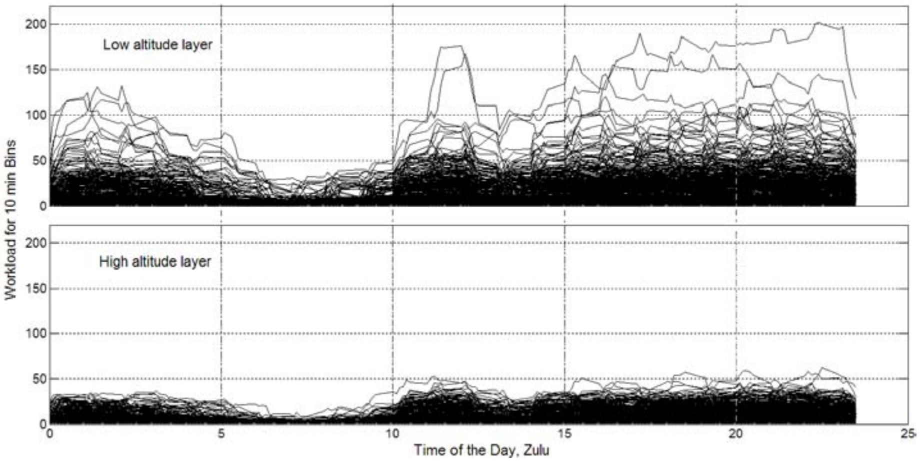

Figure 5. Workload trend of each hex-cell during one day for low and high altitude layers.

Currently there are 20 ARTCCs that cover the whole continental NAS. The NAR project proposes a reduction for number of ARTCCs. Reducing the number of Centers may potentially enhance the system efficiency in terms of necessary infrastructure and staffing requirements. The methodology presented in this paper could be useful for designing more efficient ARTCC boundaries. The total hourly workload for a Center is simply the integral of workload values for all the cells. Figure 6 depicts the fact that current Center boundaries do not balance the airspace complexity among all the Centers. Centers like ZLC, ZMP, and ZDV cover large areas of the NAS but they contain very small portion of overall traffic complexity. These low workload Centers could be expanded to cover larger areas.

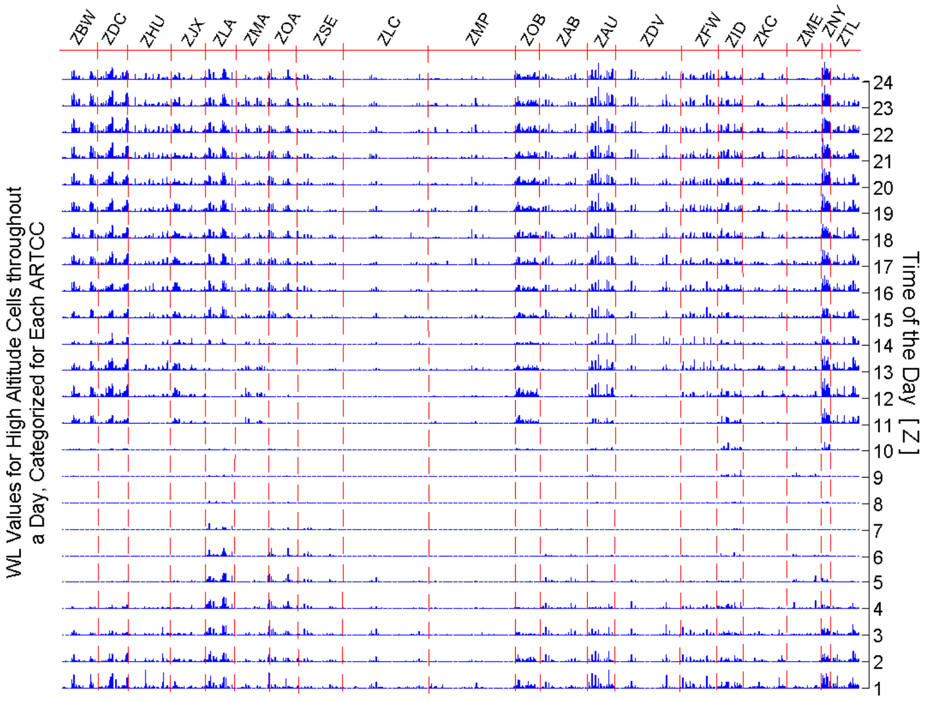

Figure 6. Workload values for high altitude hex-cells categorized by their ARTCCs.

C. Airspace Complexity Visualizer (ACV)

To explore the geographic location and daily workload trend for each hex-cell we have developed the Airspace Complexity Visualizer (ACV). The ACV color codes the hex-cells based on their workload and displays a sequence of 144 frames of entire NAS for 10 minute bins during the day. Figures 7 and 8 illustrate two frames of ACV for high and low altitude hex-cells during 18:10 to 18:20 Zulu. As we expect for the low altitude airspace, hex-cells

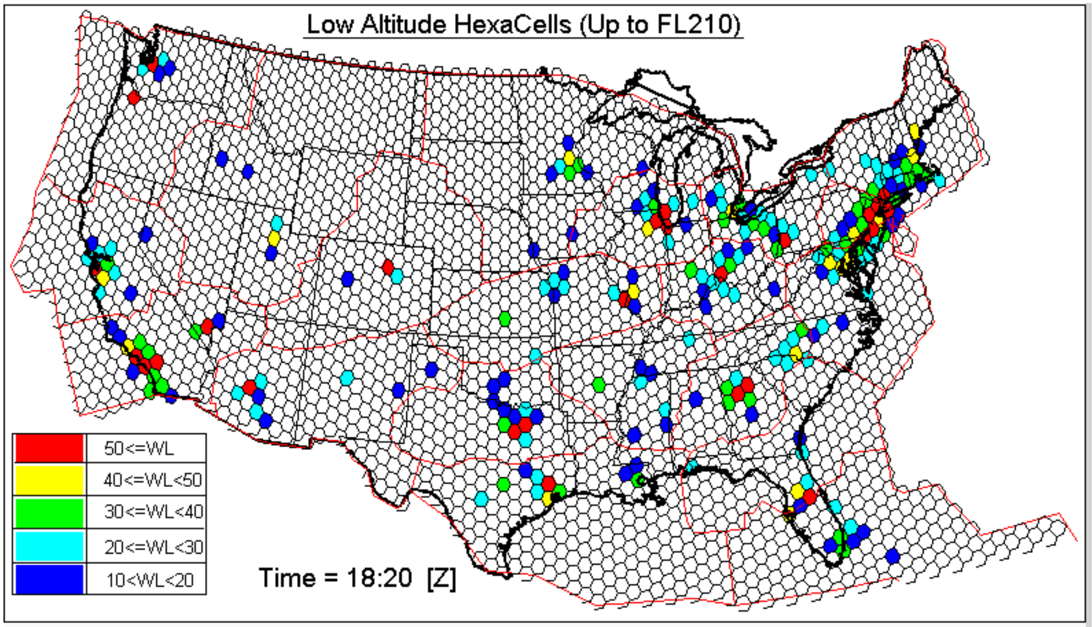

Figure 7. One frame of ACV for time bin of 18:10 to 18:20 Zulu. Low altitude hex-cells are color-coded based on their workload values.

with high workload are located in vicinity of large airports and densely population areas whereas in the high altitude airspace the complex airspace is further out the airports in the en route airspace.

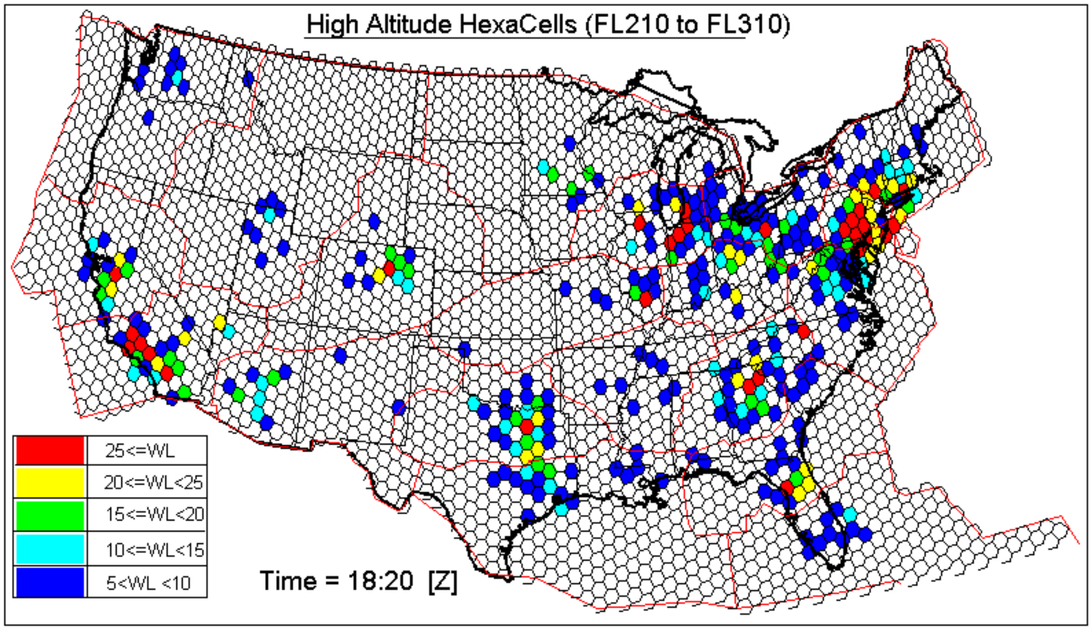

Figure 8. One frame of ACV for time bin of 18:10 to 18:20 Zulu. High altitude hex-cells are color-coded based on their workload values.

Unfortunately it is not possible to include more frames of ACV in this paper. Running the ACV for the entire day displays how the airspace complexity propagates throughout the NAS. Congested areas grow in a very structured fashion between airports and the routing structure is clearly identifiable.

IV. Airspace Sectorization

In this section we discuss an optimization-based methodology for clustering the hex-cells and construct sectors.

A. Requirements for an optimum airspace secotrization

We identify the top-level requirements for an efficient sectorization system as follows:

The system shall;

1. be bounded by the Canadian & Mexican borders as well as the boundaries between oceanic airspace and current ARTCCs,
2. be developed independent from the inland ARTCC and sector boundaries,
3. be implemented in accordance to the operational flight levels,
4. focus on the en route airspace. The Terminal Radar Approach Control (TRACON) areas shall not be included in the system,
5. minimize the overall coordination workload,
6. balance the spatial distribution of overall workload among all the sectors,
7. provide reasonable average sector transit time and avoid very short sector transit times,
8. avoid highly concave sectors.

Requirements 1 to 3 are already considered in the process and we focus on the rest of the requirements. The operational environment in the TRACON area is different from the en route airspace[39]. The arrival/departure aircraft entering the TRACON are assigned Standard Terminal Arrival Routes (STAR), Standard Instrument Departure (SID) routes, and pre-defined holding patterns. In the TRACON, the minimum lateral separation is 3 nm versus 5 nm in the en route. The main task of TRACON controllers is sequencing assignment which is assigned based on the runway configuration, the structure of SIDs and STARs, and wake vortex separation standards. As a result, local considerations are necessary for TRACON sectorization. In this paper we focus on sector design out of the TRACON areas. The minimization of coordination workload is one of the main objectives in our methodology.

Coordination actions include controller-to-controller and controller-to-pilot communications for hand-off/hand-in and frequency assignments. This objective is satisfied if we minimize the hand-off/hand-in by decreasing the number of sectors. By balancing the distribution of workload among the sectors, we eliminate sectors with very high complexity as well as low complex sectors. This removes the airspace chokepoints which are one of the main sources of airspace inefficiencies. From the human perception point of view, it is important that aircraft remain in the sectors for long enough periods. Short transit times do not allow the controllers to comprehend the traffic situation and take necessary coordination actions. Short transit times typically occur in highly concave sectors where aircraft cross the sector close to the edges. Thus maintaining convex shapes for sectors is set as a requirement.

B. Sectorization Algorithm

1. *Defining a design period*

We model the workload as a varying function of time. Any clustering algorithm produces different sector boundaries for each period of the day. But human factor studies suggest a *constant* sectorization allowing the ATCs to sketch the traffic patterns in their mind[10,11,&40]. The ATCs memorize the enter/exit points and they often know at what time which traffic is entering their sector, where are the potential conflicting areas, and what are the necessary resolution actions. They develop *abstract* mental models of the traffic pattern. If we change the sector boundaries dynamically throughout the day, ATCs will not be able to develop such abstract models. This decreases the situational awareness and imposes high operational stress on the ATCs. Therefore we define a representative *design-period* that captures the workload dynamics throughout the day. In Fig. 9, total workload for each center is calculated by integrating the workload values for all hex-cells within each ARTCC. Each line represents the percentage of maximum daily workload for each center during different time bins. It can be observed that at time 21:00 Zulu all the centers are operating above 80 percent of their maximum daily workload. It means that despite the time lag for operational peaks, at 21:00 Zulu most of the high altitude airspace is very congested. As an initial phase, we select this time as the *design-period* and apply clustering algorithms based on the hex-cells' workload during 20:00 to 21:00 Zulu. Future research may suggest other methods for defining this design-period to capture the system's dynamics more rigorously.

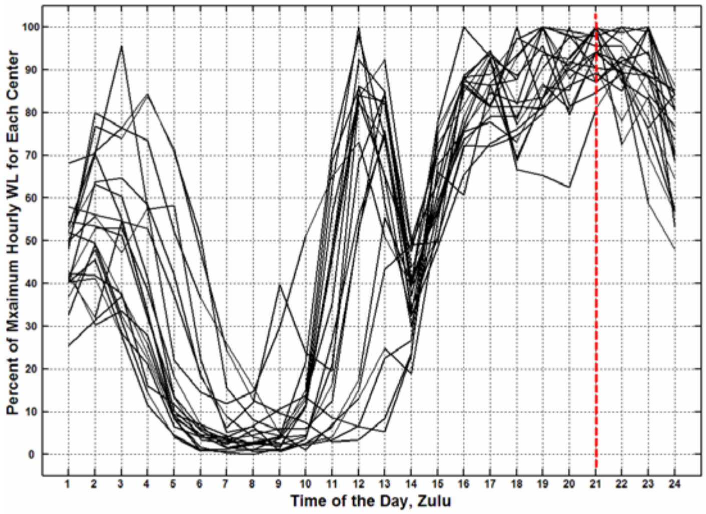

Figure 9. Percentile of high altitude workload for each ARTCC in one hour increments. At time 21 Zulu all the centers are operated with over 80 percent of their maximum daily workload.

2. *Geometry of the clustering algorithm*

So far, we have 2,566 hex-cells that need to be clustered into *n* sectors. We define a set of potential centers for sectors on top of the hex-cell mesh. It means that the clusters start to grow from these potential centers. The geometry of centers for potential sectors is illustrated in Fig. 10. Parameter '*S*' denotes the side of the hex-cells which is set to 24 nm.

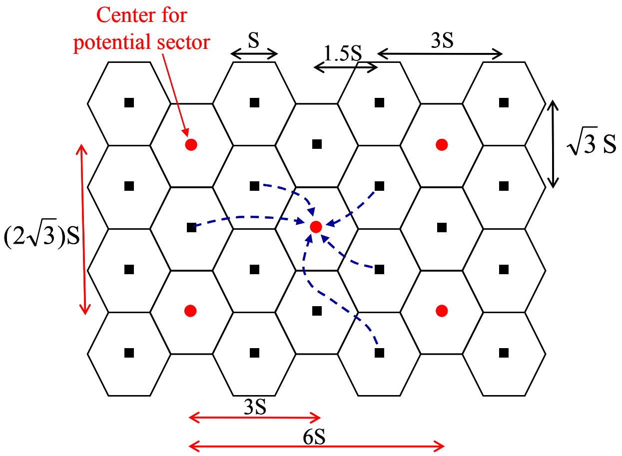

Figure 10. The geometry of clustering algorithm. Potential centers for sectors are shown in red circles. The side of each hex-cell is *S*=24 nm.

The number of potential sectors is large enough that it does not restrict the clustering process. In other words, the clustering algorithm has enough flexibility to open sectors and assign hex-cells to achieve the optimum solution.

3. *Clustering algorithm*

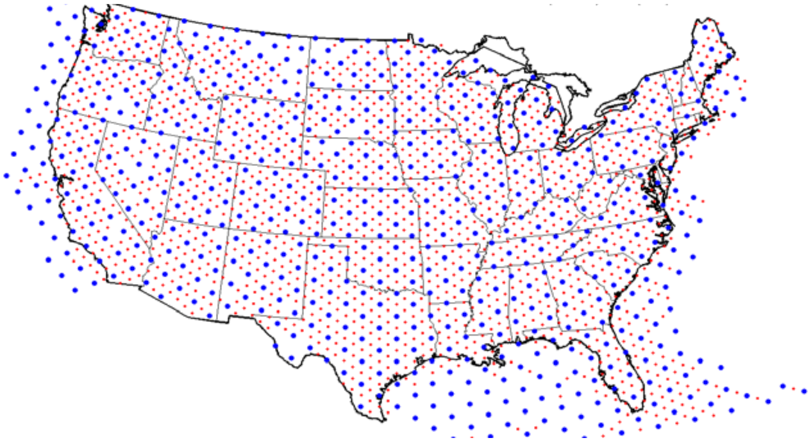

Figure 11. Potential centers for sectors are shown in blue and centers for non-zero workload hex-cells are shown in red.

One can think of the clustering problem as a standard facility location problem, where we have a set of customers that need to be assigned to facilities. Sectors are assumed to be the facilities and the customers are the hex-cells. Not all the facilities have to be opened so as for the sectors. For the entire NAS, we create 649 potential centers for sectors. We also filter out the hex-cells with zero workload during the design period. These zero-workload hex-cells do not have any impact in the clustering algorithm and they can be assigned to any sector after the clustering is finished. At the end, we have 2,031 customers and 649 potential facilities as shown in Fig.11. For visualization purposes from this point on, we represent the hex-cells by their center points. The facility location problems are extensively studied by operation researchers[41] and there is a wealth of knowledge in this area. However constraints for avoiding concavity or sector contiguity are not necessary in general facility location problems. We develop a linear integer minimization program to solve the clustering problem. The algorithm is summarized in Table 1.

MINIMIZE *(variation of workload among sectors)*
SUBJECT TO:

- *sector contiguity*
- *avoiding highly concave sectors*
- *number of sectors is limited*
- *avoid extremely large sectors*
- *some other ordinary constraints*

Table 1. Summary of minimization problem.

The objective is to minimize the variation of workload among sectors. In other words, we cluster the hex-cells into sectors in such a way that balances the distribution of workload among the sectors. The detailed mathematical formulation of minimization problem is a long discussion and beyond the scope of this paper.

4. *Clustering example*

Our intention is to apply the clustering algorithm for the entire NAS at the same time. But, as an initial step, we select the high altitude layer in Chicago Center (ZAU) to test the algorithm. The centers for hex-cells and potential sectors for ZAU high altitude layer are illustrated in Fig. 12. There are 70 hex-cells and 16 potential sectors. So the minimization algorithm needs to solve $(70 \times 16) = 1,120$ combinatorial variables to assign the hex-cells to sectors. The maximum number of sectors to be opened is a given parameter to the minimization problem. In the case of ZAU we assign the maximum number of sectors to 6. So 70 hex-cells will be assigned to maximum 6 opened sectors. The minimization problem is solved using CPLEX solver and the results are shown in Fig. 13. As illustrated in this figure, 6 sectors are opened and they are all convex and continuous. However one needs to pay attention that the ZAU center boundaries do not form a convex polygon. In Fig. 13, the indented sector sides are due to the concave shape of the ZAU Center itself.

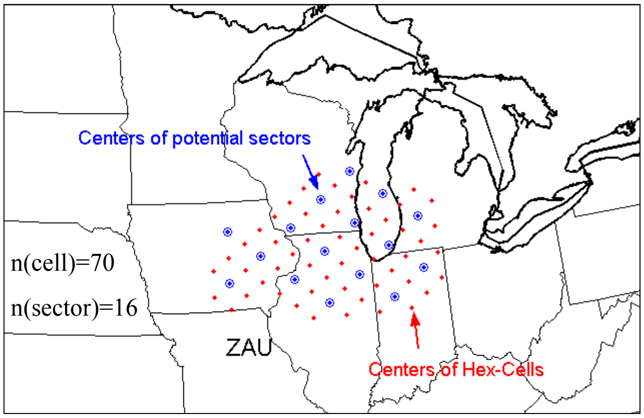

Figure 12. Center-points of potential sectors and center-points of hex-cells in high altitude layer of ZAU center.

5. *Problem complexity*

In the ZAU example there are $(16\times 70)=1{,}120$ combinatorial variables to be solved. The CPLEX run-time in a Pentium-M 1.6 GHz processor, with 1 GB RAM was less than a minute. But the complexity of problem increases non-linearly w.r.t the number of hex-cells and sectors. For each altitude layer of entire NAS we have $(649\times 2031)=1{,}318{,}119$ variables. This is an extremely large scale optimization problem. We are currently working on the efficiency of the algorithm. Another approach could be to reduce the problem size by dividing the NAS into *East-West Mississippi* or *Atlantic-Pacific* segments, or splitting the NAS using the *time-zones*. Then apply the clustering algorithm for a smaller population of hex-cells and sectors.

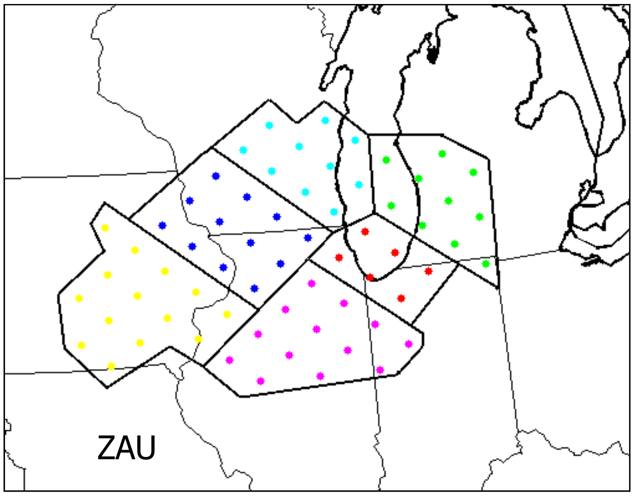

Figure 13. Sectorization of high altitude airspace in ZAU Center. Maximum number of opened sectors is assigned to 6.

D. An alternative approach; workload as a continuous function of time, latitude, and longitude

As explained before, the hex-cells have to be large enough to capture the conflicting scenarios. This eliminates the resolution of hex-cell mesh. To achieve higher resolution, we linearly interpolate the workload values between centers of the hex-cells. For each time bin, the linear interpolation yields a continuous workload surface which is a function of time, latitude, and longitude, Eq. (2).

$$\begin{aligned} &WL_t = f(lat,lon)\\ &where:\\ &\qquad f \quad \text{is a generic function}\\ &\qquad t \quad \text{denotes the time interval} \end{aligned} \tag{2}$$

The workload function is indexed by time intervals, for example WL_{1440} denotes the workload function during 14:30 to 14:40 Zulu. Figure 14 illustrates the projection of a workload surface into a plain for time interval of 14:30 to 14:40 Zulu (WL_{1440}). The ACV also animates these surfaces and visualizes the propagation of airspace complexity throughout the NAS continuously. The existing jet routes between congested airports are clearly identified and it is possible to study the evolution of high workload areas throughout the day.

We also calculate iso-workload contours for each WL_t. These contours are shown in Fig. 15. The partial derivative of WL_t, w.r.t latitude and longitude yields the gradient vector $\nabla\hat{W}L_{1440}$. The gradient vectors are perpendicular to the iso-workload contours and their length indicates the magnitude of the gradient, Eq. (3).

$$\nabla\hat{W}L_{1440} = \frac{\delta WL}{\delta lat}\hat{i} + \frac{\delta WL}{\delta lon}\hat{j} \tag{3}$$

For our next approach, we will make an analogy with the world of physics and crystal growing. To grow a crystal, one begins by heating the raw materials to a liquid state. This molten material is then slowly cooled, until the crystal structure is frozen in. If the temperature is decreased too quickly, flaws in the crystal can be locked in. Slow temperature decrease allows these flaws to *work themselves out* forming a much better crystal. This process is called annealing.

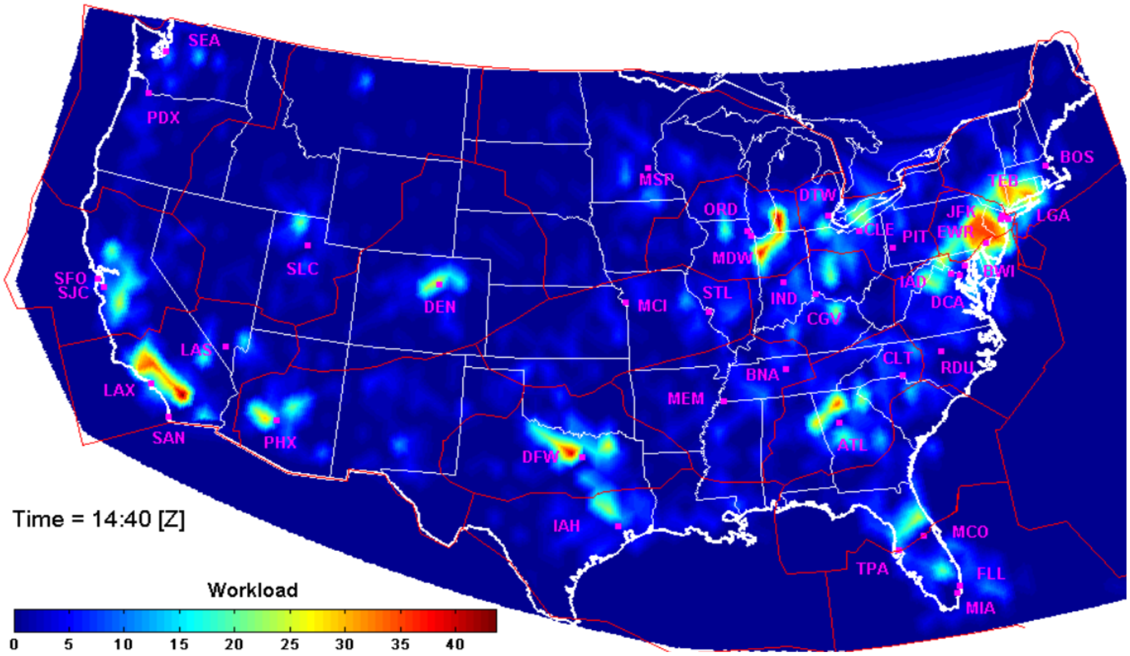

Figure 14. Planar Projection of the high altitude WL_{1440} surface. Large airports and center boundaries are illustrated in magenta and red.

One can think of the final state of a crystal as a local optimum: no small movement of the molecules can decrease the total energy content. A perfect crystal contains the minimum energy content of all the final possibilities. Because molecules only move locally, the laws of physics only require that some local optimum be found. But if annealing creates better solutions, perhaps we can simulate this annealing process.

We propose that the sectorization could be modeled as an annealing process to calculate the global optimum in terms of ATC workload distribution. By constructing continuous functions for workload, we transform the problem domain so that we can apply Simulated Annealing (SA) techniques for the sectorization process. The discussion of sectorization by SA is beyond the scope of this paper and we leave this methodology for the future work.

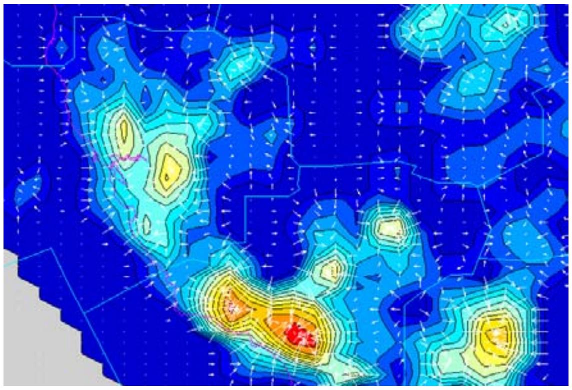

Figure 15. Iso-workload contours and gradient vectors of WL_{1440} for the high altitude layer.

V. Conclusion

An ATC workload-based methodology is discussed to solve the airspace sectorization problem. ATC workload is modeled using large scale simulation for elements of airspace regardless of current sector and center boundaries. Hexagonal cells are assumed to be the building blocks of sectors and these building blocks are clustered to construct sectors. Initial results for sectorizarion of a single ARTCC is promising. We are currently working on efficiency of the clustering algorithm and applying the methodology for the entire NAS. We define the design-period as the time period that most of the NAS is congested. To include the impact of weather related disruptions, it is possible to simulate the workload for few bad-weather days and define the design period for combination of different days including when the inclement weather interrupts the operations. We use TAAM to calculate the required airspace metrics for workload modeling. The presented methodology is general and other ATM models could be used for workload measurement and validation of TAAM outputs.

As an alternative approach we model the workload as a continuous function of time, latitude, and longitude of each point in the NAS. Accordingly we propose to use Simulated Annealing techniques for designing the sector boundaries. This could open new venues for development of alternate clustering algorithms.

The presented methodology for analysis of tempo-spatial distribution of ATC workload could also be used to determine the optimum number and location of ARTCCs.

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