Spatial & Temporal Distribution Metrics for Airspace Design with a Complexity Constraint

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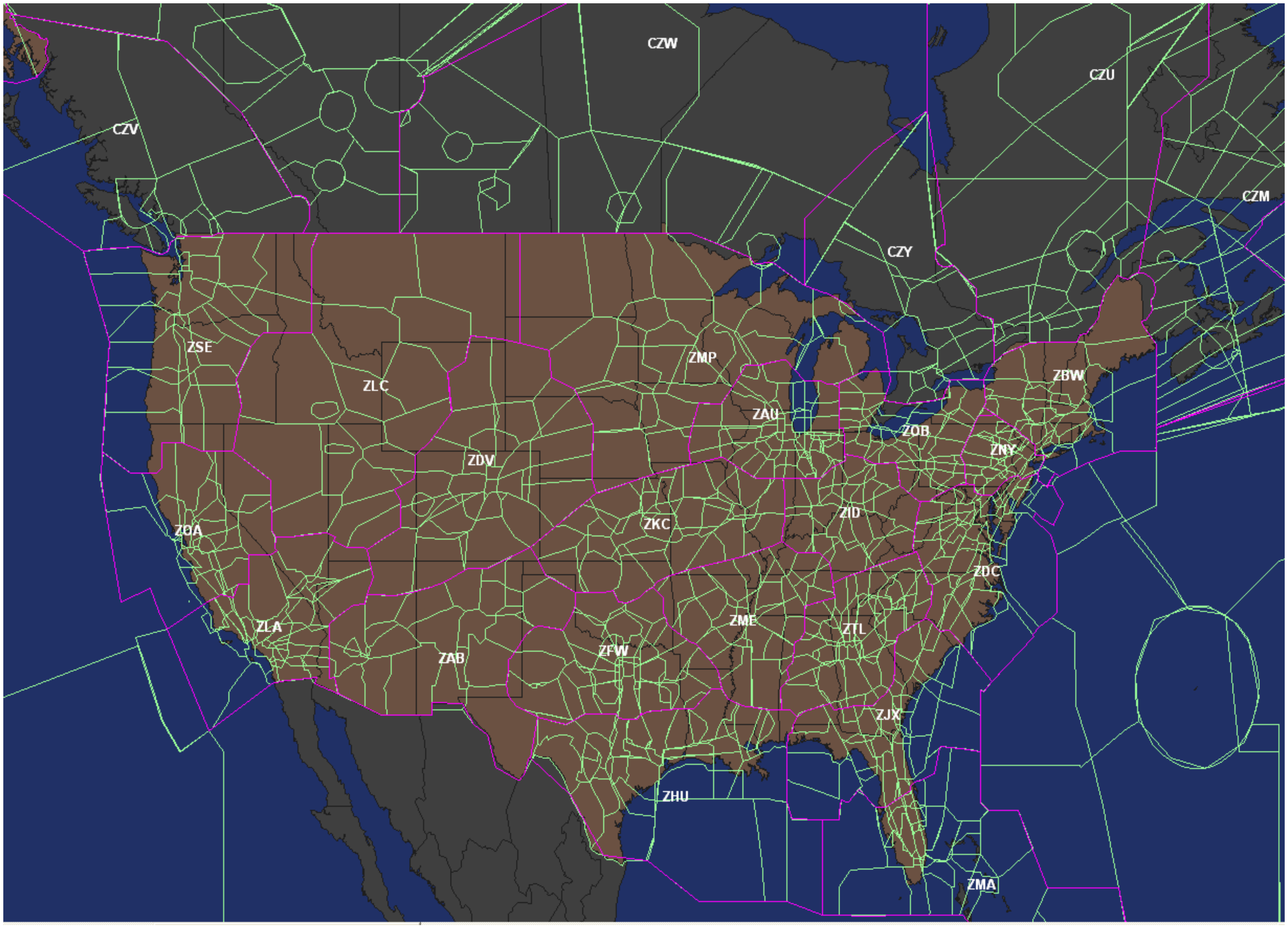
Outline

- Motivation for Research
- Definitions of Sector Workload and Complexity Index Metrics
- Comparison of Ranked Sector CI to Actual Traffic Flows in NE
- Application of Methodology to Optimum Sector Design
  - Define Building Block unit of Sectors (Hex-Cells – 24)
  - Compute Dynamic WL and CI for CONUS and 45,000 Flight Plans
  - Directions for Future Work
- Observations on Research to Date

Motivation

- **~85 percent of US ATCs (14,000) will be eligible for retirement over the next decade (*Bureau of Labor Statistics)* & lack of an adequately skilled workforce may lead to future capacity or safety problems.**
- **Available radio spectrum for controller-pilot communication is limited.**
- **Current airspace sectorization is not the most efficient design.**
- **Establishment of baseline airspace metrics is Required for evaluating any changes resulting from new ATC systems or procedures.**

Current Sectorization has Historical – Not Analytic Origins



Background

- **Current Lack of Widely Accepted Intrinsic Metrics for airspace capacity and complexity:**
  - **Number of aircraft passing through a sector DOES NOT capture the real airspace complexity, *(Sridhar et al., 1998)*.**
- **ATC workload depends on Both Qualitative and Quantitative parameters.**

Recent Related Work

- **Perceived complexity of an air traffic situation, (Pawlak et al., Wyndemere Inc., 1996).**
  - **Related to the cognitive ATC workload with or without the knowledge of aircraft intent.**
  - ***Human oriented and subjective.***
- **Dynamic Density (Laudeman et al, NASA ARC, 1998)**
  - **More quantitative and based on the flow characteristics.**
  - **Sridhar et al., 1998, developed a model to predict the evolution of this metric in the near future.**
- **Delahaye et al., 2000:**
  1. **Geometric approach: Based on the properties of aircraft relevant position and speed.**
  2. **Airspace system as a dynamical system: model the history of air traffic as the evolution of a hidden dynamic system over time.**
- **Impact of structure on cognitive complexity, (Histon et al., 2002).**
- **Much more ...**

Airspace Complexity

- **Critical factors contribute to sector Workload and Complexity (assuming good weather conditions):**
  - **Coordination factors: required coordination actions for conflict resolution, level of aircraft intend knowledge, …**
  - **Geometrical and geographical factors: sectors geometry & volume, airports, proximity of SUAs, # of neighboring sectors, # of hand in/off points, …**
  - **Traffic factors: # of altitude changes, # of crossing altitude profiles, # of intersecting routes, sector transit time, fleet mix, …**
  - **Encounter factors: conflict convergence angle, conflicting aircraft relative speed, separation requirements, flight phases, …**
- **A Fundamental Question:**
  - ***"Is there a set of computable or measurable metrics that reflect the most critical factors that contribute to the sector complexity"***

Sector Density & Transit Time are NOT SUFFICIENT

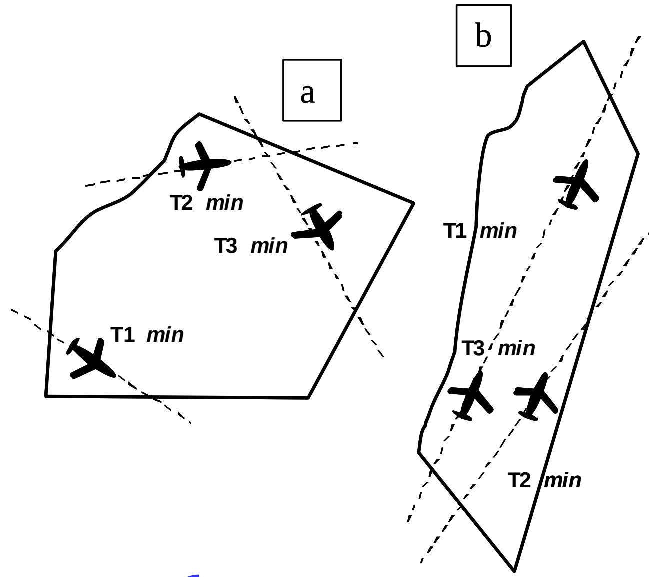
$$\text{Total Transit time} = \sum_{i=1}^{n} T_i \Big/ \text{Sector} \quad \text{[minute/sector]}$$

Where:

T_i = Transit time for aircraft i in the sector.

n = Total number of aircraft passing through the sector during any given time interval.

Density = Number of aircraft passing through a sector during any given time interval [aircraft/sector]



$$\begin{cases} den_a = den_b = 3 \\ Trans_a \neq Trans_b \end{cases}$$

a: More conflicts due to route intersection

b: More control time due to longer routes

Neither of these metrics, alone, adequately estimates the level of controller activity.

Hypothesis: ATC Workload Metrics Can Be Adequately Simulated for Optimum Sector Design

- **Use a Combination of High Fidelity Model Simulations and ATC workload metrics to Test Hypothesis**
- **Use a Model that Computes Human WL Metrics (TAAM) and Compare Results to Actual Flight Data**
  - **Total workload: 4 parameters (11 Sub-Parameters):**
    1. **Horizontal Movement Workload (WL_{HM})**
    2. **Conflict Detection and Resolution Workload (WL_{CDR})**
    3. **Coordination Workload (WL_{C})**
    4. **Altitude-Change Workload (WL_{AC})**
- **In each sector or group of sectors, the summation of these four parameters may represent the total workload.**
  - **Linear Assumption, MAY be NON-LINEAR**

$$\text{Total WL} = \sum (WL_{HM} + WL_{CDR} + WL_{C} + WL_{AC})$$

ATC Workload Simulation *(cont.)*

- **Movement or basic workload (*WL_{HM}*)** is determined by the number of aircraft in a sector (sector density) and average transit time.

$$WL_{HM} = F_{HM} \times (N_{HM} \times T) \quad \text{where:}$$
$$F_{HM} = \text{Adjustment factor for horizontal movement}$$
$$N_{HM} = \text{Number of aircraft passing through the sector}$$
$$T = \text{Average Flight Time}$$

- **The altitude-change workload *(WL_{AC})*** is determined by the type of sector altitude clearance request for level off, commence climb and commence descent.

$$WL_{AC} = F_{AC} \times N_{AC} \quad \text{where:}$$
$$F_{AC} = \text{Altitude clearance factor}$$
$$N_{AC} = \text{Number of aircraft with this clearance}$$

ATC Workload Simulation *(cont.)*

- **The conflict detection & resolution workload (*WL_{CDR}*)** is based on conflict detection using the conflict type and conflict severity.
  - The ***conflict type*** is determined by the tracks of the aircraft (succeeding, crossing or opposite) and the flight phases (climbing, cruising, or descending). For each type there is an adjustment factor ***T_{CT}*.**
  - The ***conflict severity*** is the percentage of available separation. For example if 100-120% or 80-100% of minimum separation is available. For each conflict severity, there is an associated adjustment factor defined as ***T_{CS}*.**

$$WL_{CDR} = F_{CDR} \times (T_{CDR} \times T_{CS} \times N_{CDR}) \quad \text{where:}$$

F_{CDR} = Adjustment factor based on conflict type

T_{CT} = Conflict type factor

T_{CS} = Conflict severty factor

N_{CDR} = Number of aiircraft with this conflict type and severity

ATC Workload Simulation *(cont.)*

- **The coordination workload (WL_C)** is determined by the type of coordination action including:
    - Voice Call
    - Clearance issue
    - Inter facility transfer
    - Silent transfer
    - Intra facility transfer
    - Tower transfer
  - For each of them there is a factor that reflects the complexity of that action

$$WL_C = F_C \times N_{CA} \quad \text{where :}$$
$$F_C = \text{Cordination action factor}$$
$$N_C = \text{Number of aircraft with this coordination action}$$

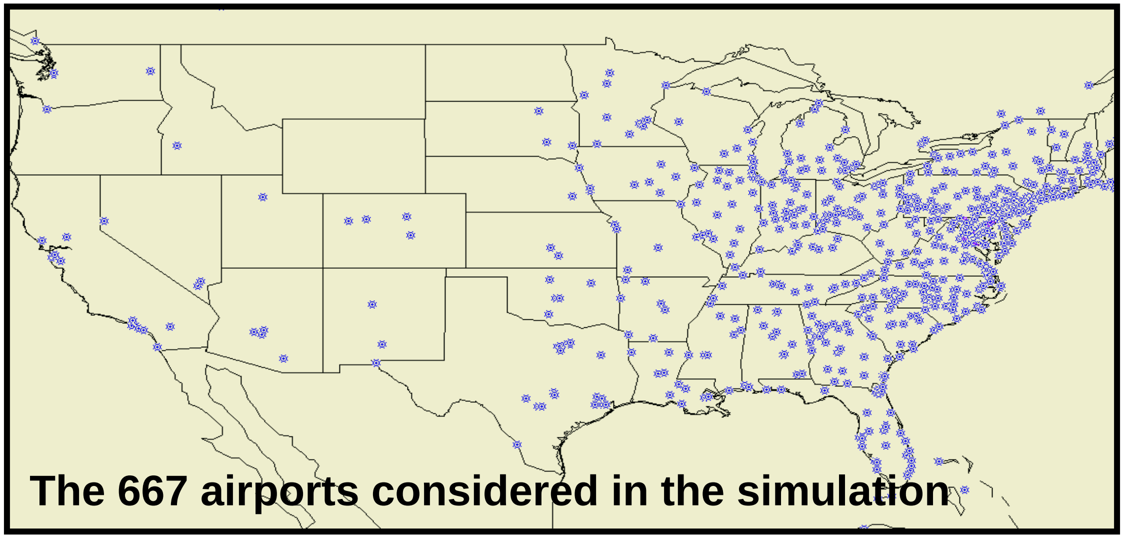
Airspace Complexity Quantification

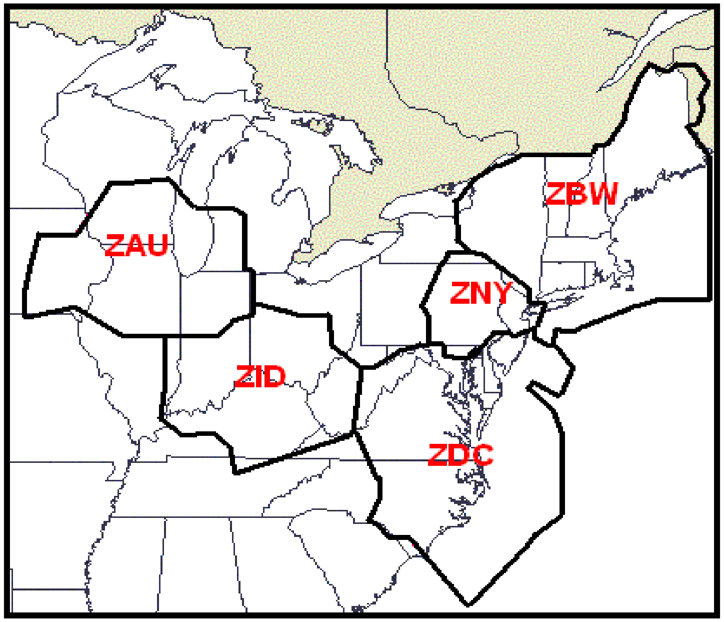
- **Aircraft in each sector, based on the sector complexity, create different workload levels.**
- **For each sector, *Complexity Index (CI)* is defined as the average workload per each aircraft.**
  - **For a given time epoch:**

$$CI = \frac{\text{Total Workload}}{\text{Total Number of Aircraft}} = \frac{\sum (WL_{HM} + WL_{CDR} + WL_{C} + WL_{AC})}{\text{Total Number of Aircraft}}$$

- **CI reflects critical factors that Linearly contribute to the sector complexity.**
  - **Could be Represented as a Non-Linear Combination**
  - **Could be Converted to a Cost Metric**

Test Case: Simulating 5 NE Centers – 162 Sectors and 667 Airports





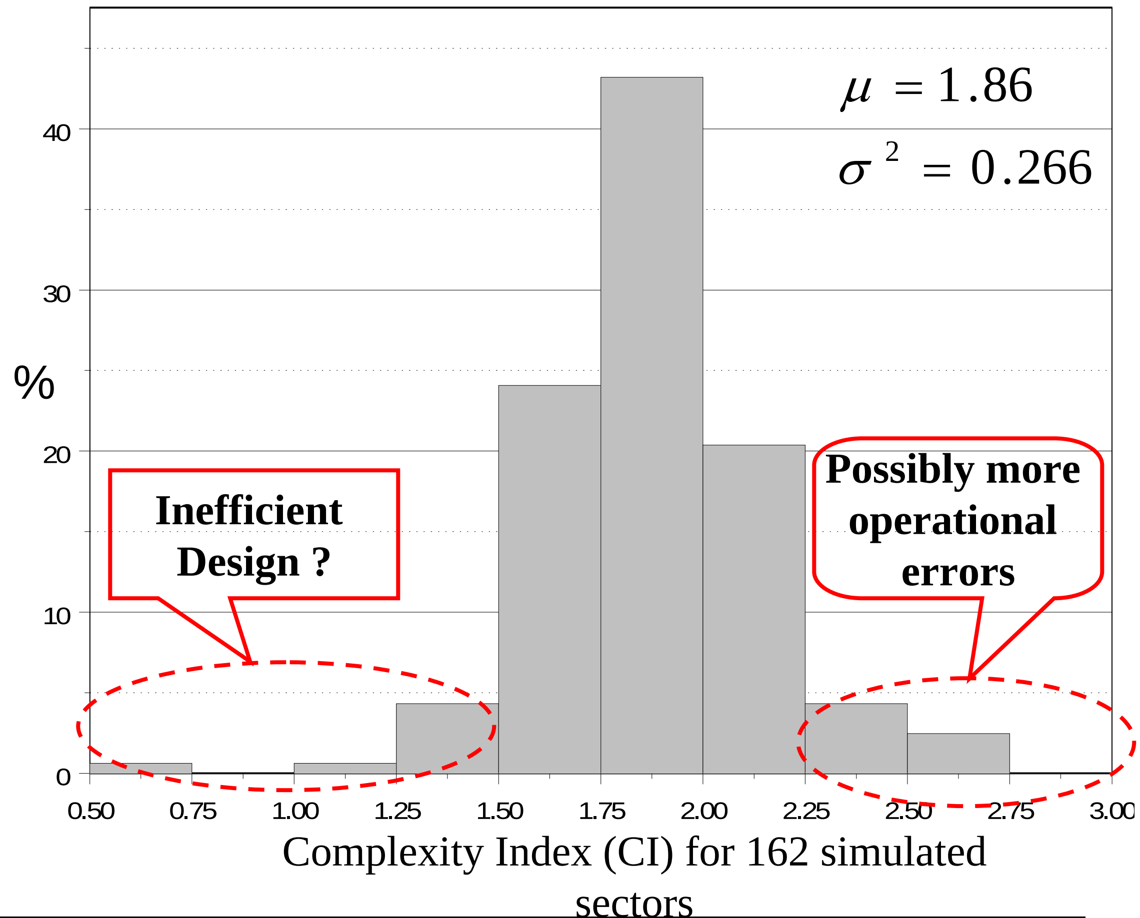
ARTCC	Number of Sectors
ZDC	43
ZNY	25
ZID	34
ZBW	19
ZAU	41

Market segment	Number of daily flights
- Non-GA including Commercial, GA and Cargo (IFR) extracted from the Flight Explorer	22764
- General Aviation traffic (IFR and VFR) generated using economic activities between OD	7051
Total	**29815**

Total daily flights used in the simulation

CI Distribution for 5 NE Centers

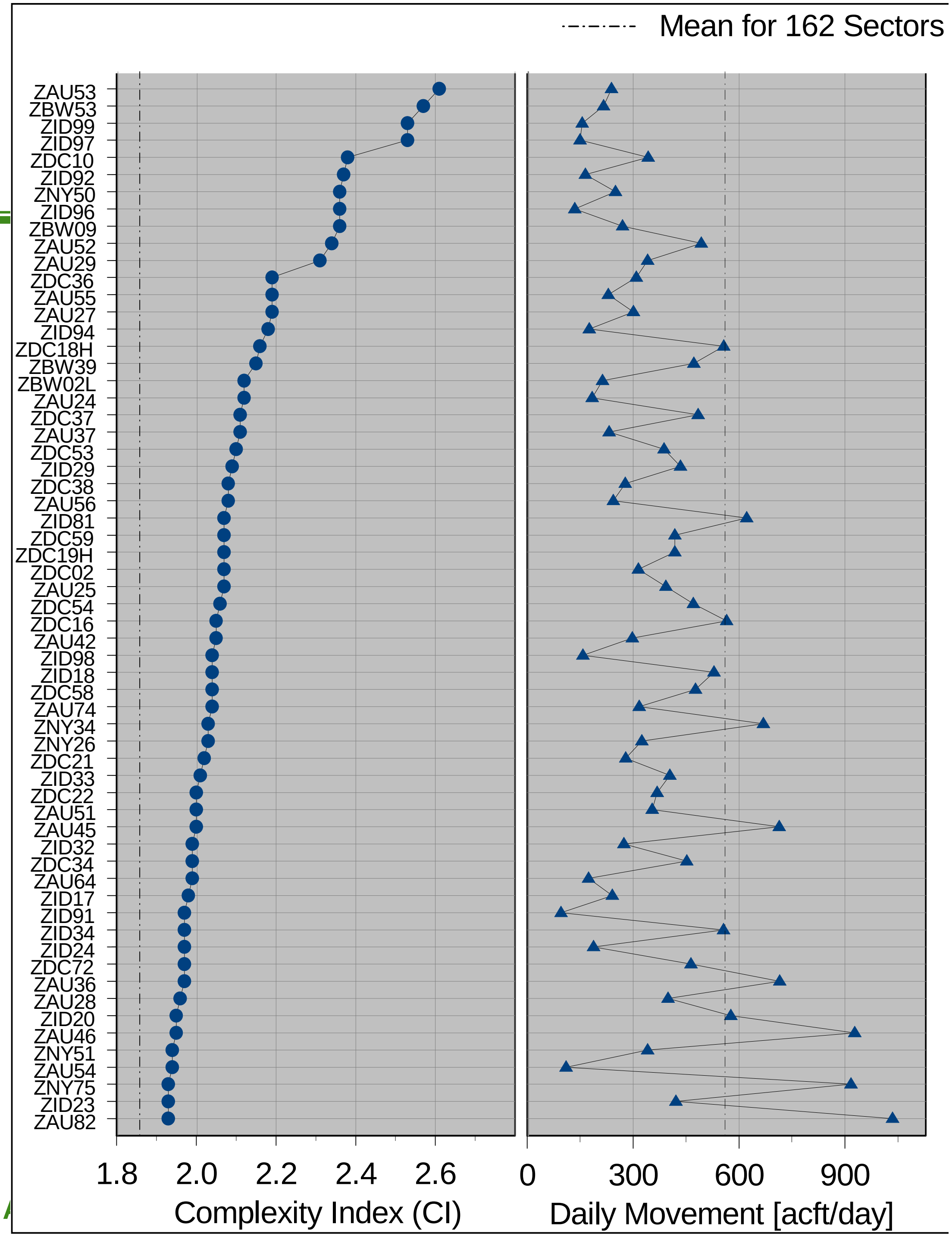
- **Large Variation of CI among all Sectors**
- **Inefficiency in sectors with low complexity?**
- **More Operational Errors may occur in HIGH or LOW complexity sectors**



***Hypothesis:** An efficient airspace sectorization should Approach a uniform distribution of the complexity among all sectors.*

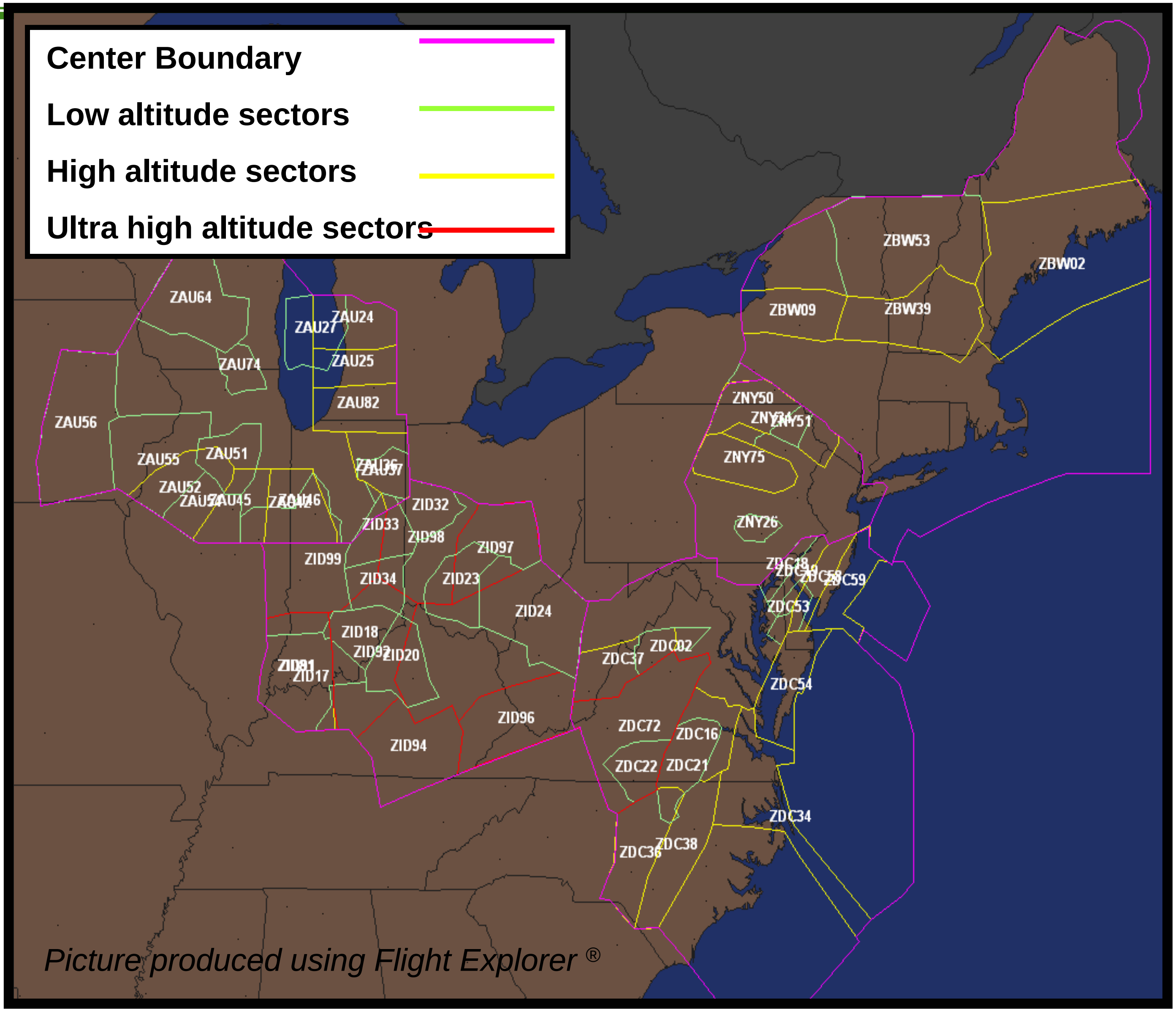
Result: Sector Rank by CI

- **50 (out of 162) most complex sectors in NE corridor**
  - **Although not rigorous, overall, less complex sectors have higher traffic volume.**
  - **Intuitively it can be interpreted as a good design (less complex sectors are capable to accommodate more aircraft without exceeding the controller workload thresholds).**



TAAM Simulation: 50 Most Complex Sectors - Observations

- **Most of the complex sectors are located next to the center boundaries.**
- **Includes all altitude ranges.**



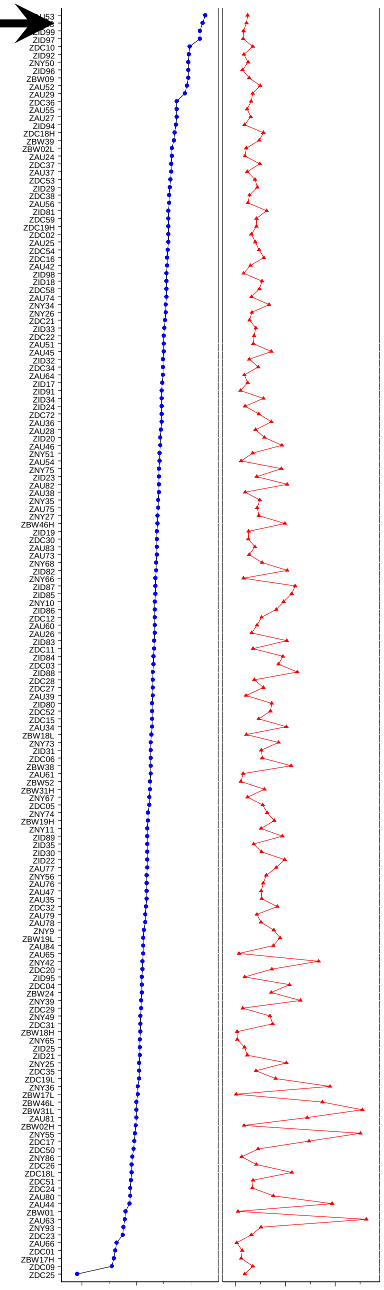
Picture produced using Flight Explorer ®

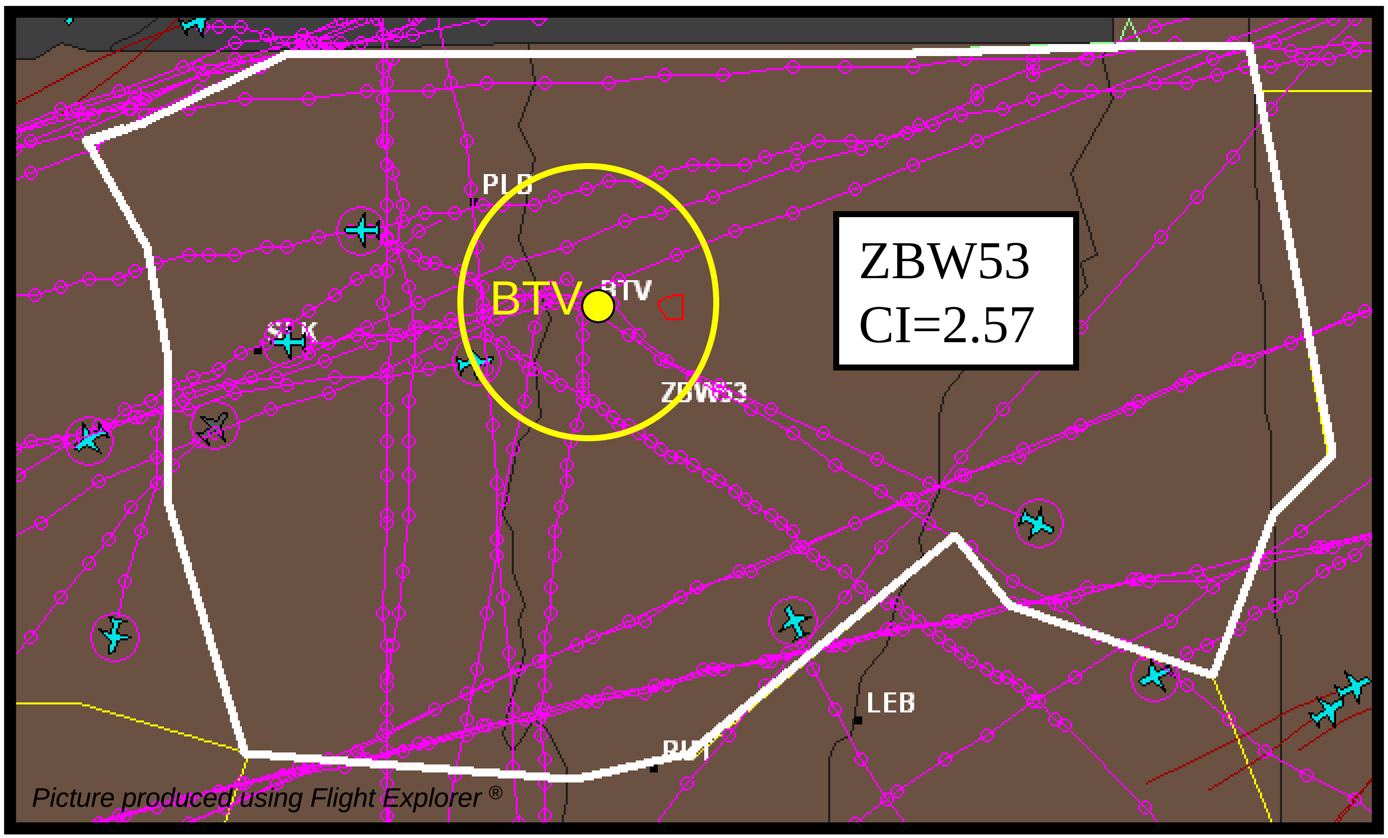
- Low altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Burlington INTL Airport
- Many level changes for flights operating out of BTV
- Short sector transit-times at the edges

Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order: 2/162



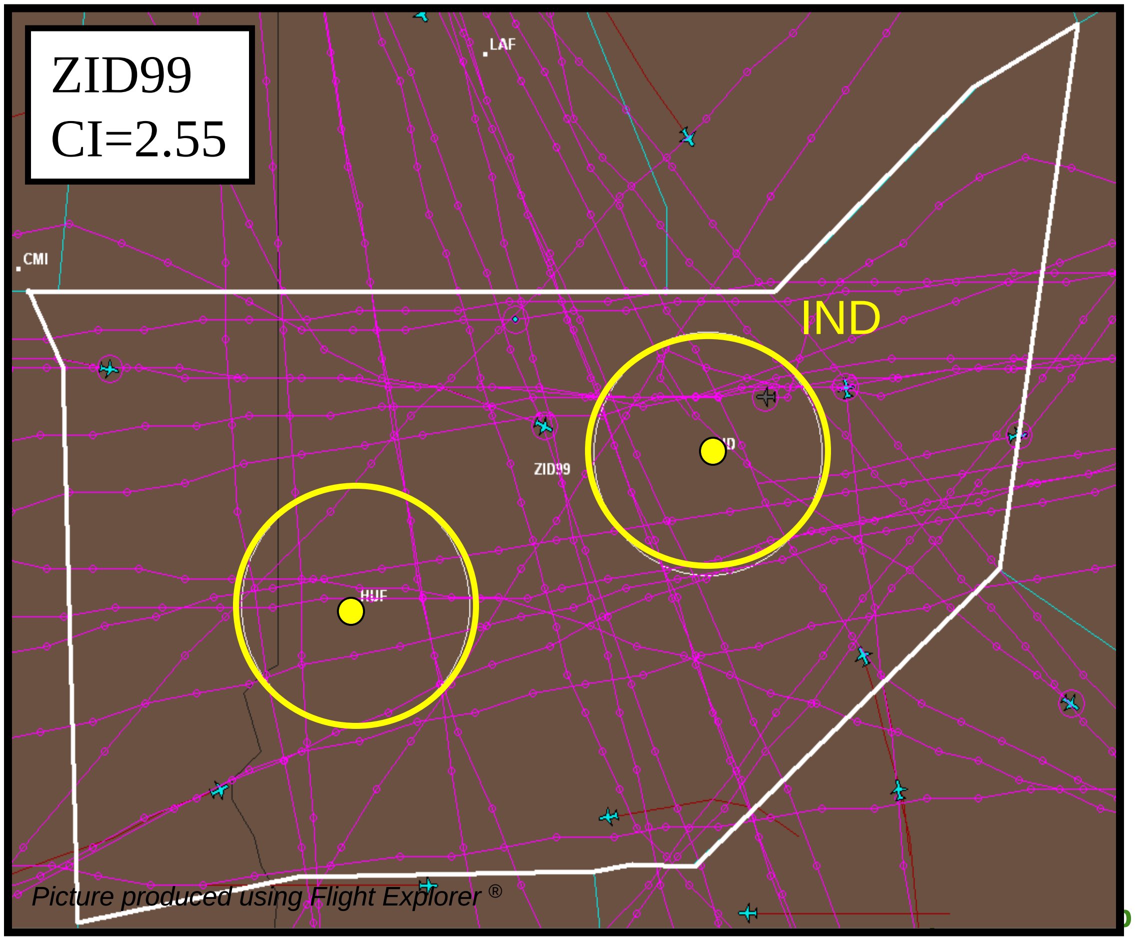


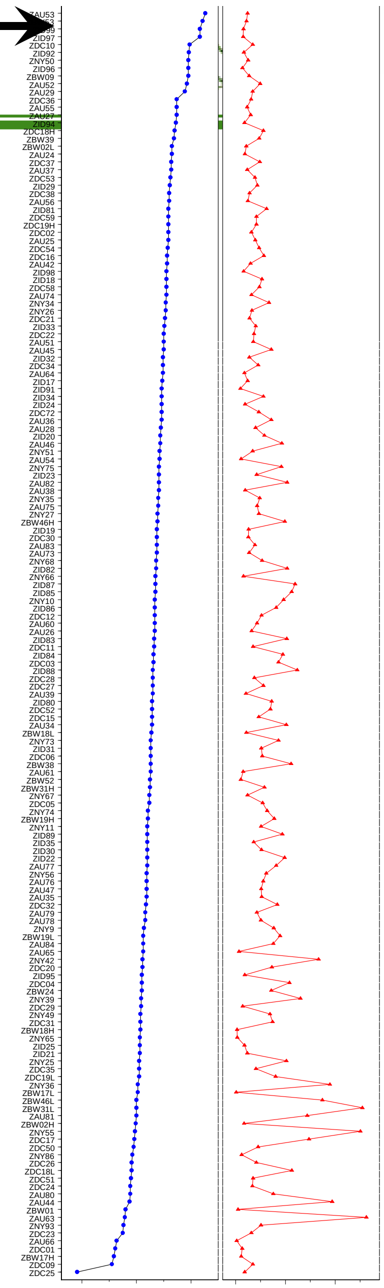
Picture produced using Flight Explorer ®

- High altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Indianapolis INTL & Terre Haute INTL Airports
- Many level changes for flights operating out of IND

Daily movement
CI: mean=1.86, max=2.61, min=0.7

Complexity order: 3/162

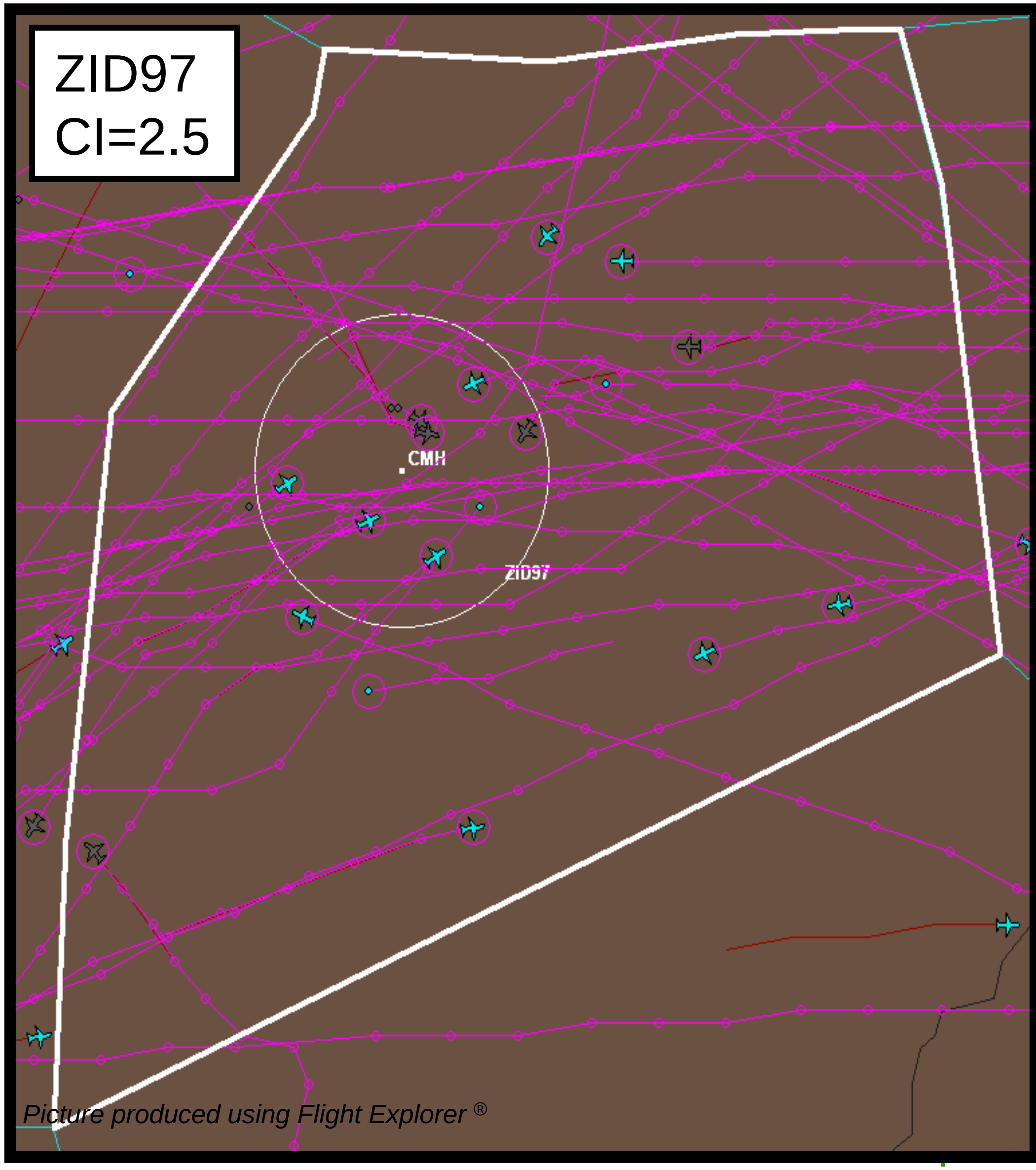




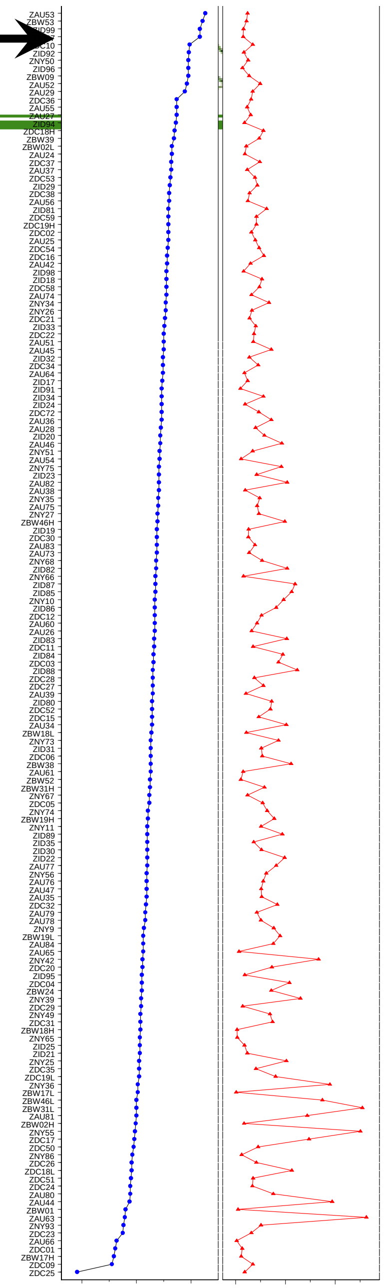
Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order: 4/162



- Ultra high
- Non-structured traffic
- Many inter-sector handoff points
- Many track intersections

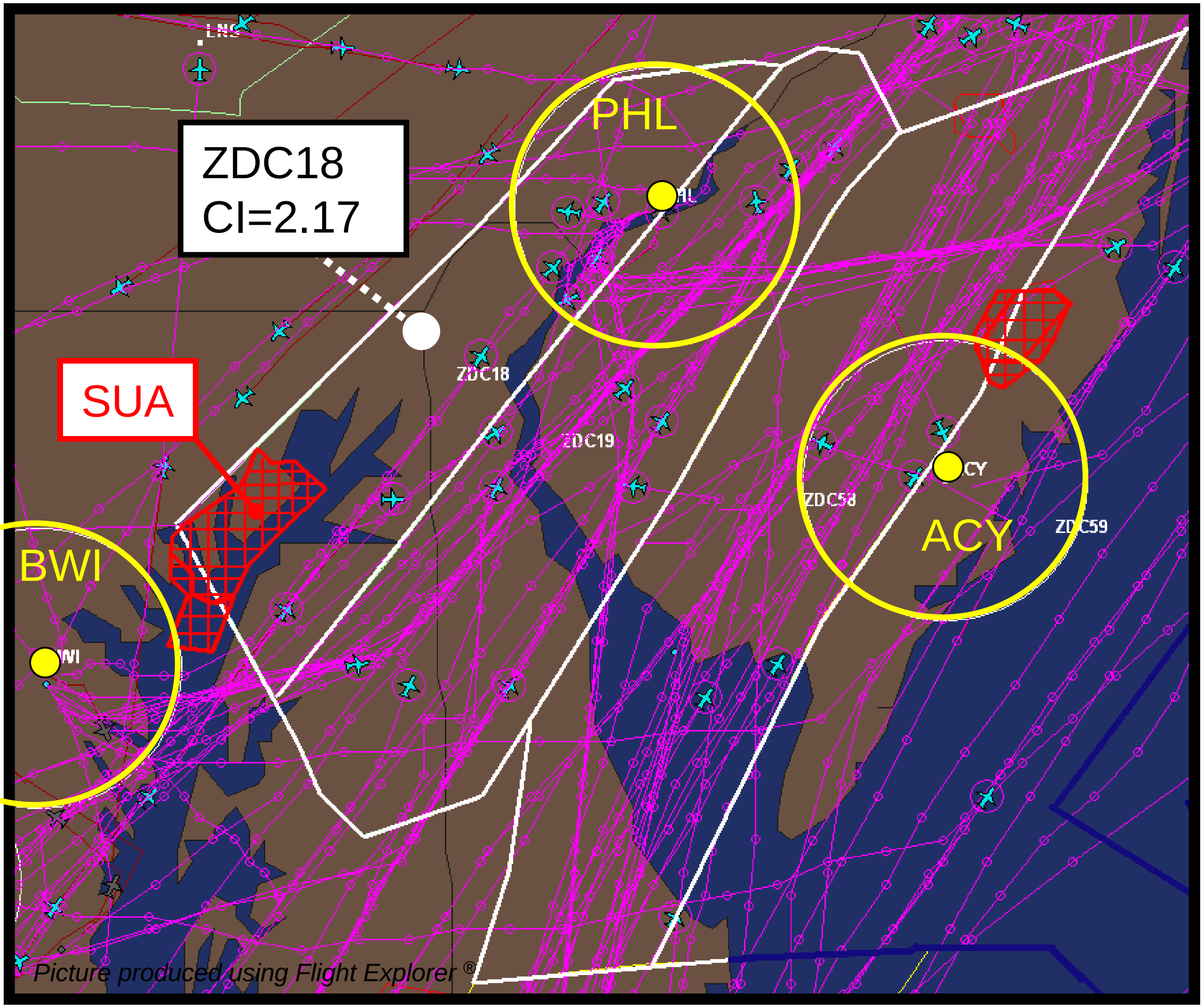


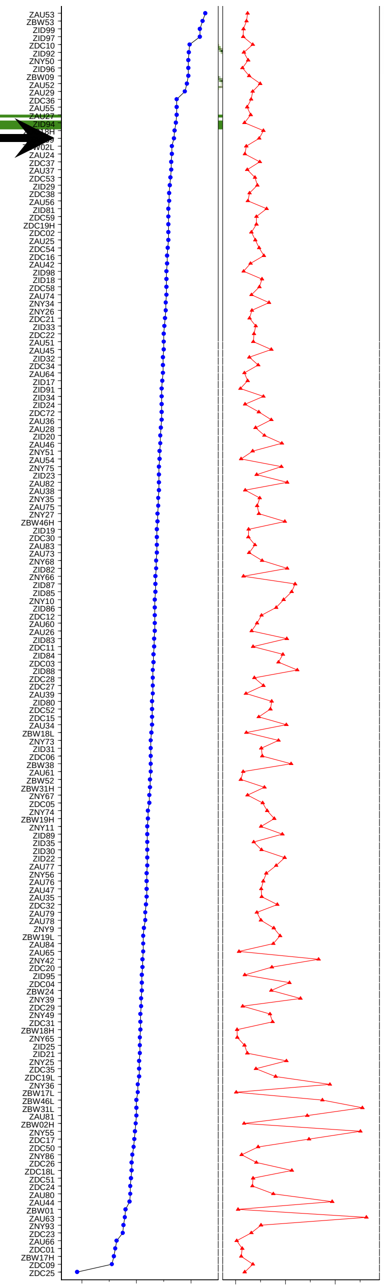
- Low altitude and small
- SUA blocks sector entrance
- Proximity of two large airports (BWI and PHL)
- Many altitude changes
- Almost structured but also many crossing traffic
- Short sector transit-times at the edges

Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order: 16/162



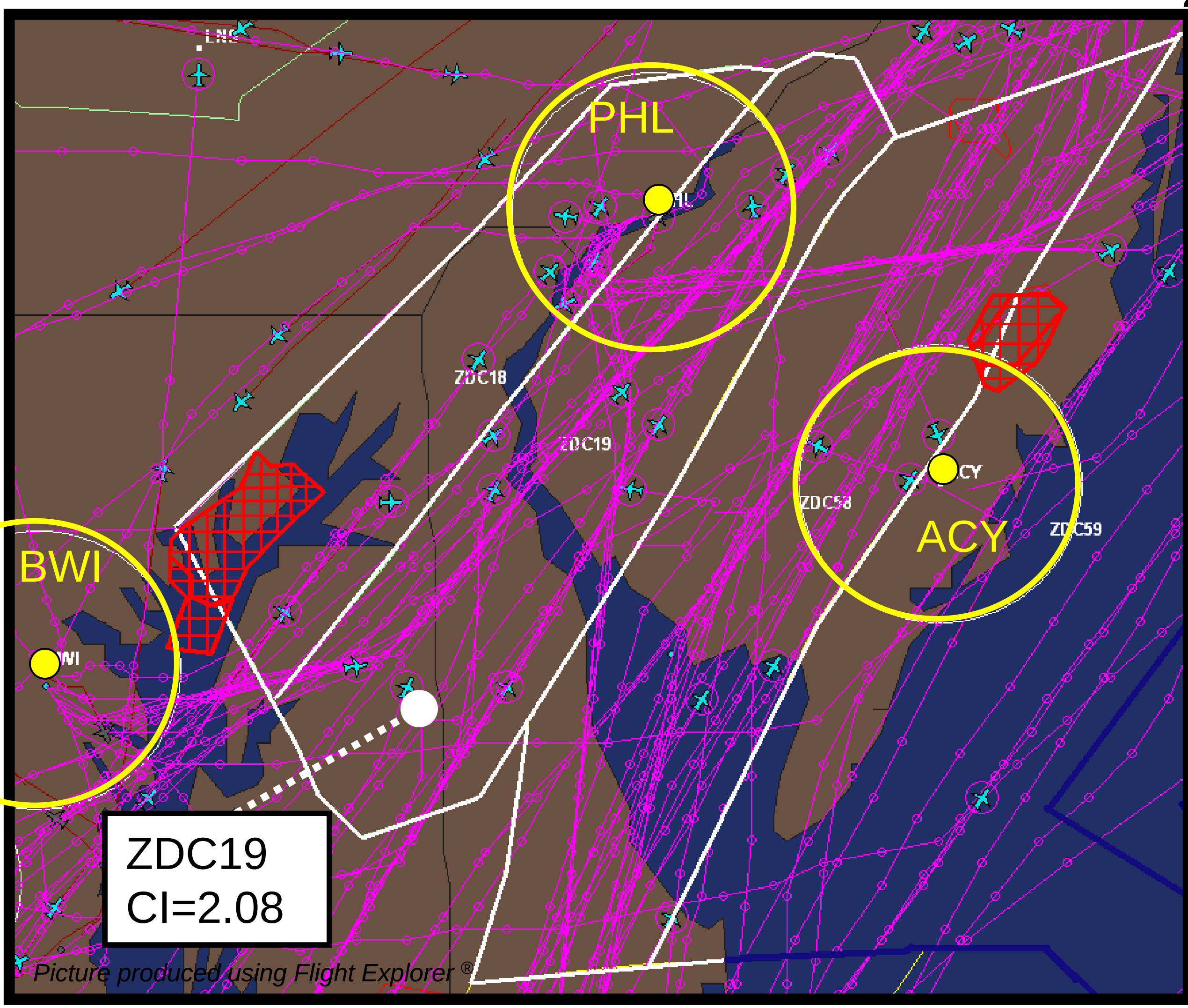


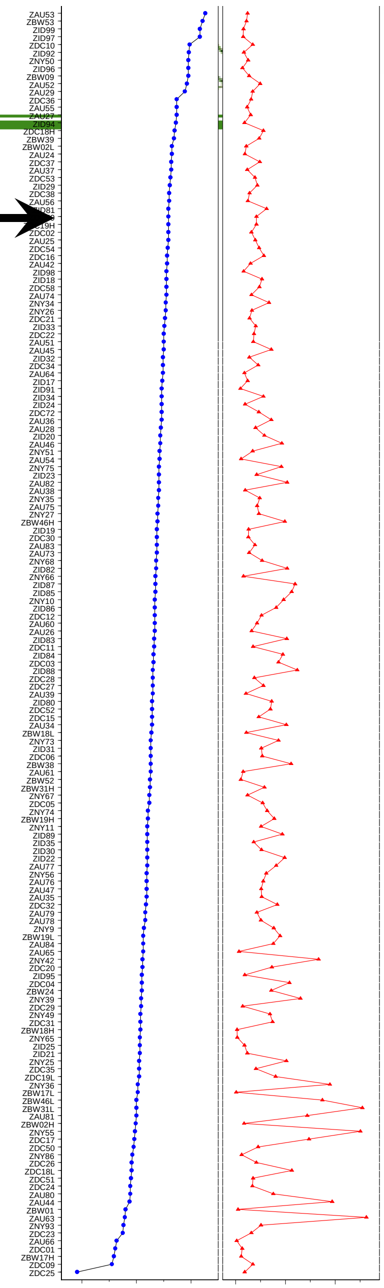
Daily movement

CI: mean=1.86, max=2.61, min=0.7

- Low altitude and small
- Structured but also many crossing traffic
- Proximity of three airports (BWI, PHL & ACY)
- Many altitude changes

Complexity order: 28/162

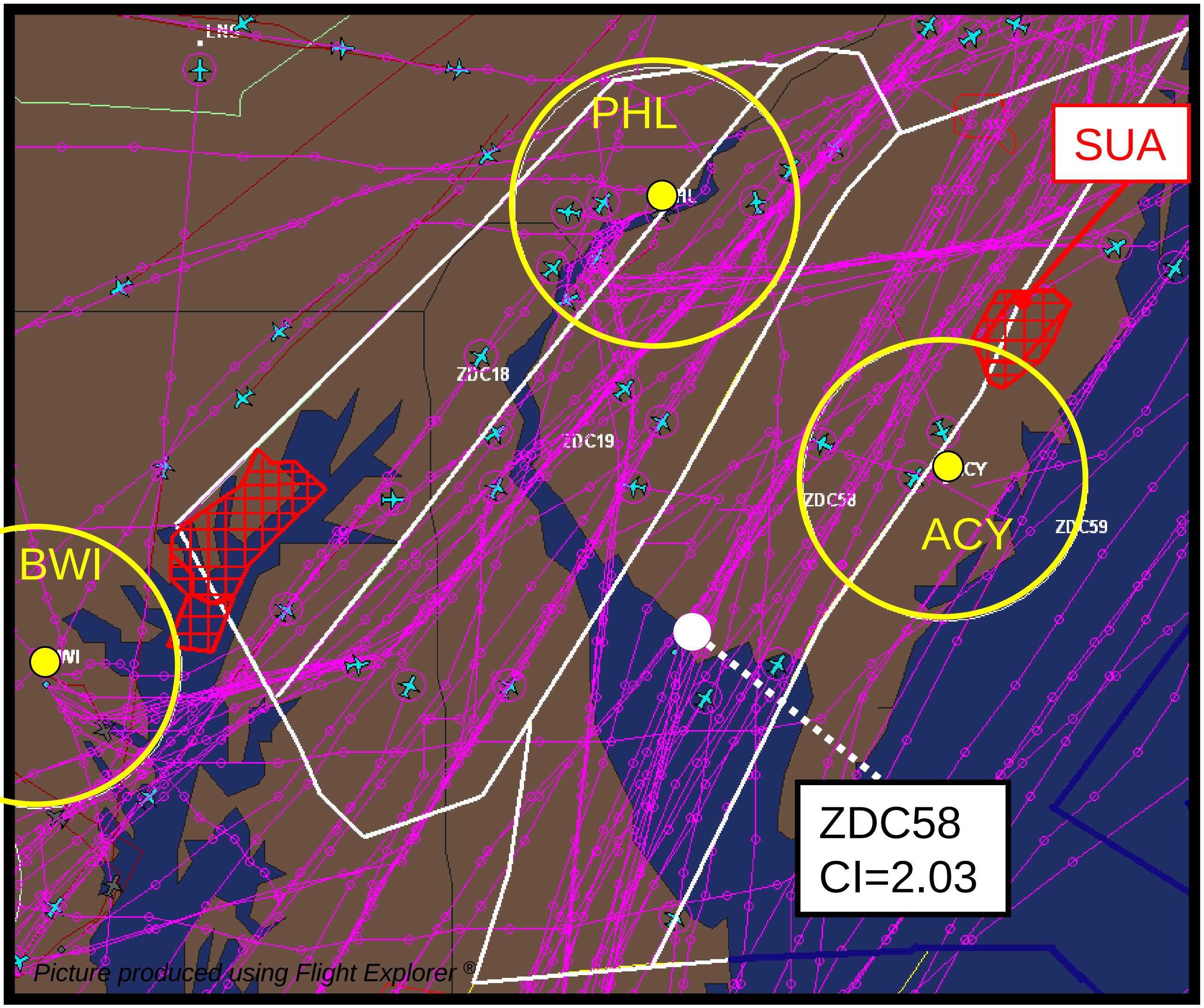


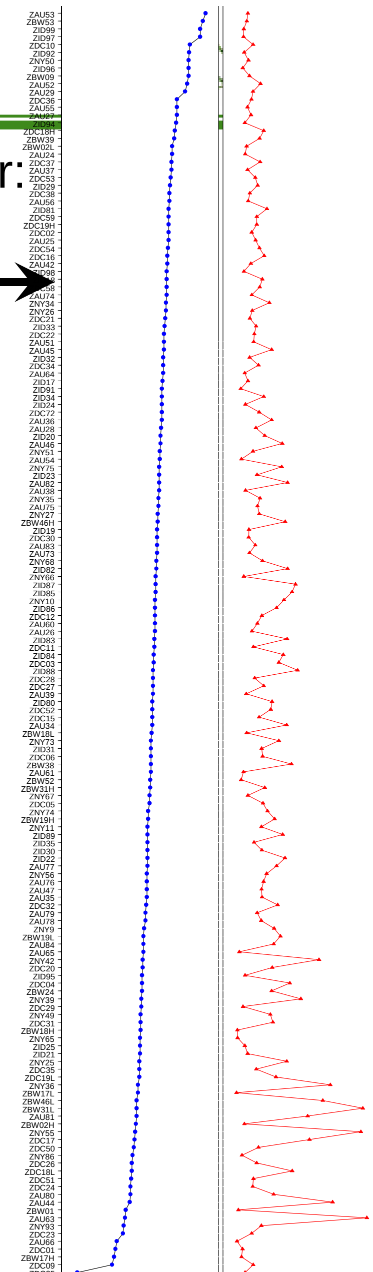


- High altitude
- Small volume
- Structured but also many crossing traffic
- ~~Proximity of two large airports (BWI and PHL)~~
- Proximity of SUA

Daily movement
CI: mean=1.86, max=2.61, min=0.7

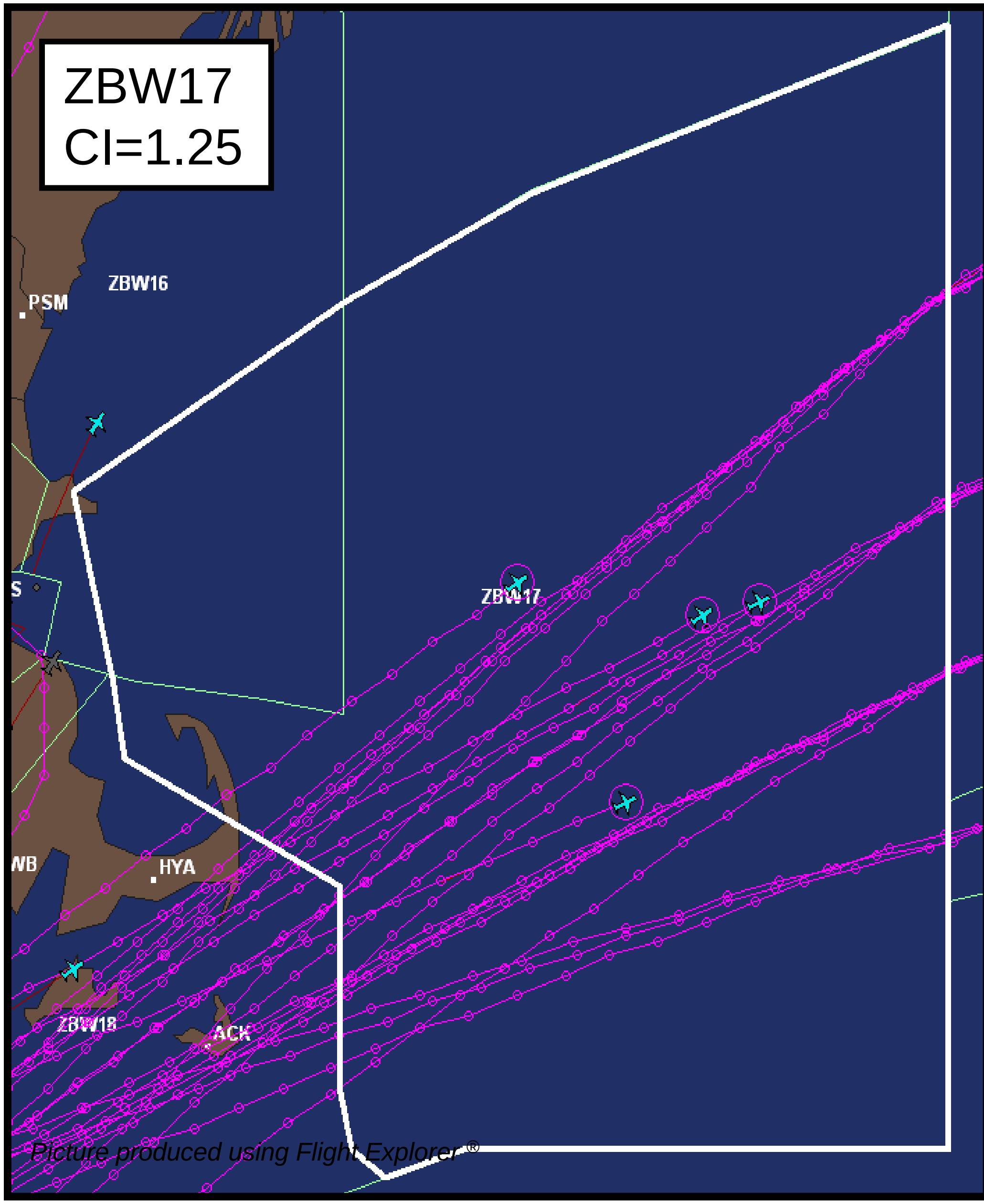
Complexity order:
36/162



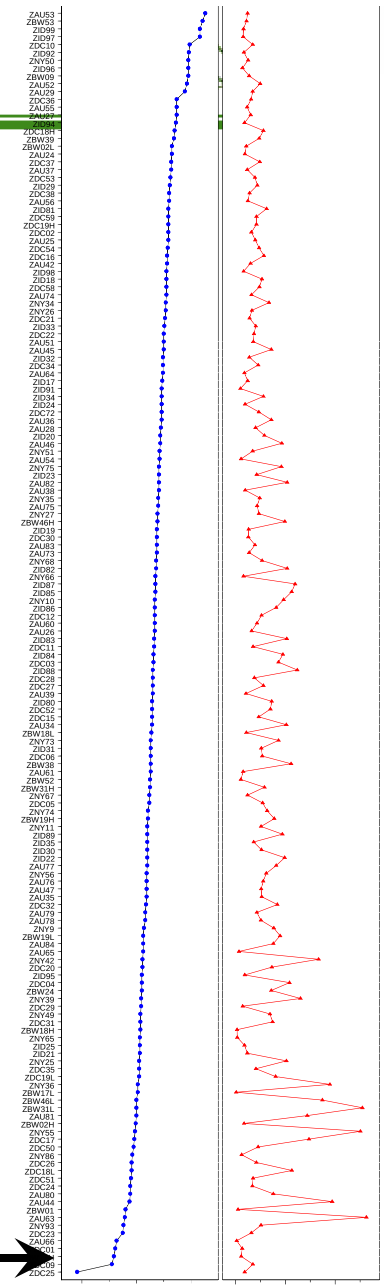


Daily movement

CI: mean=1.86, max=2.61, min=0.7



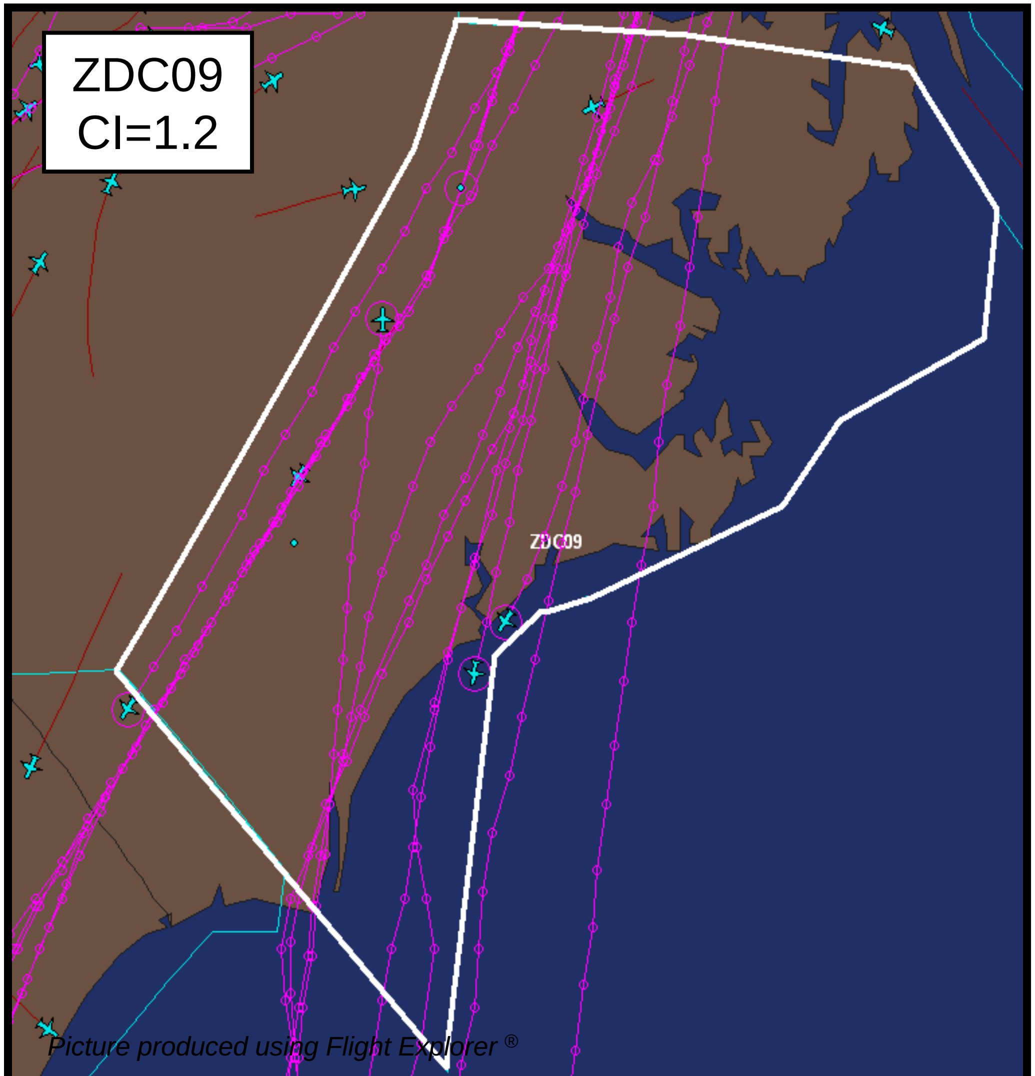
- High altitude
- Highly structured
- Inter-sector handoff points are concentrated



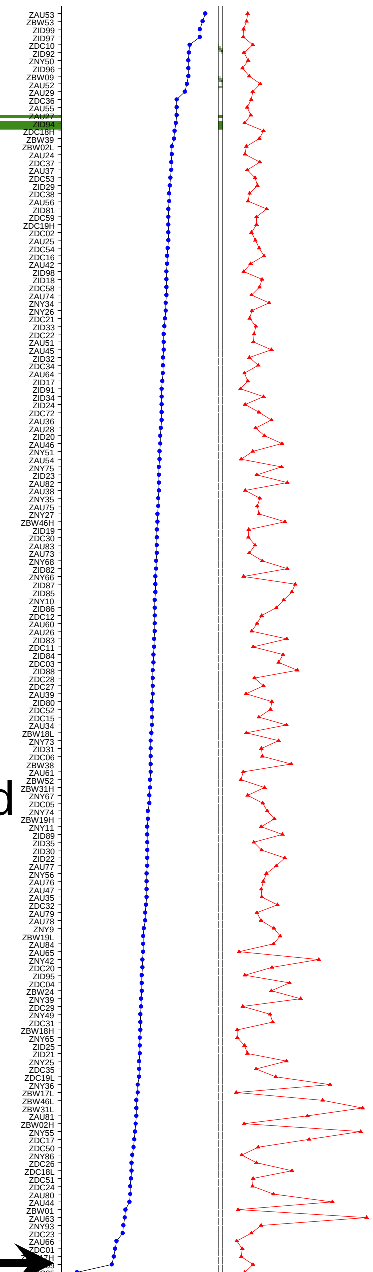
tion Lab

Complexity order: 160/162

Daily movement
CI: mean=1.86, max=2.61, min=0.7



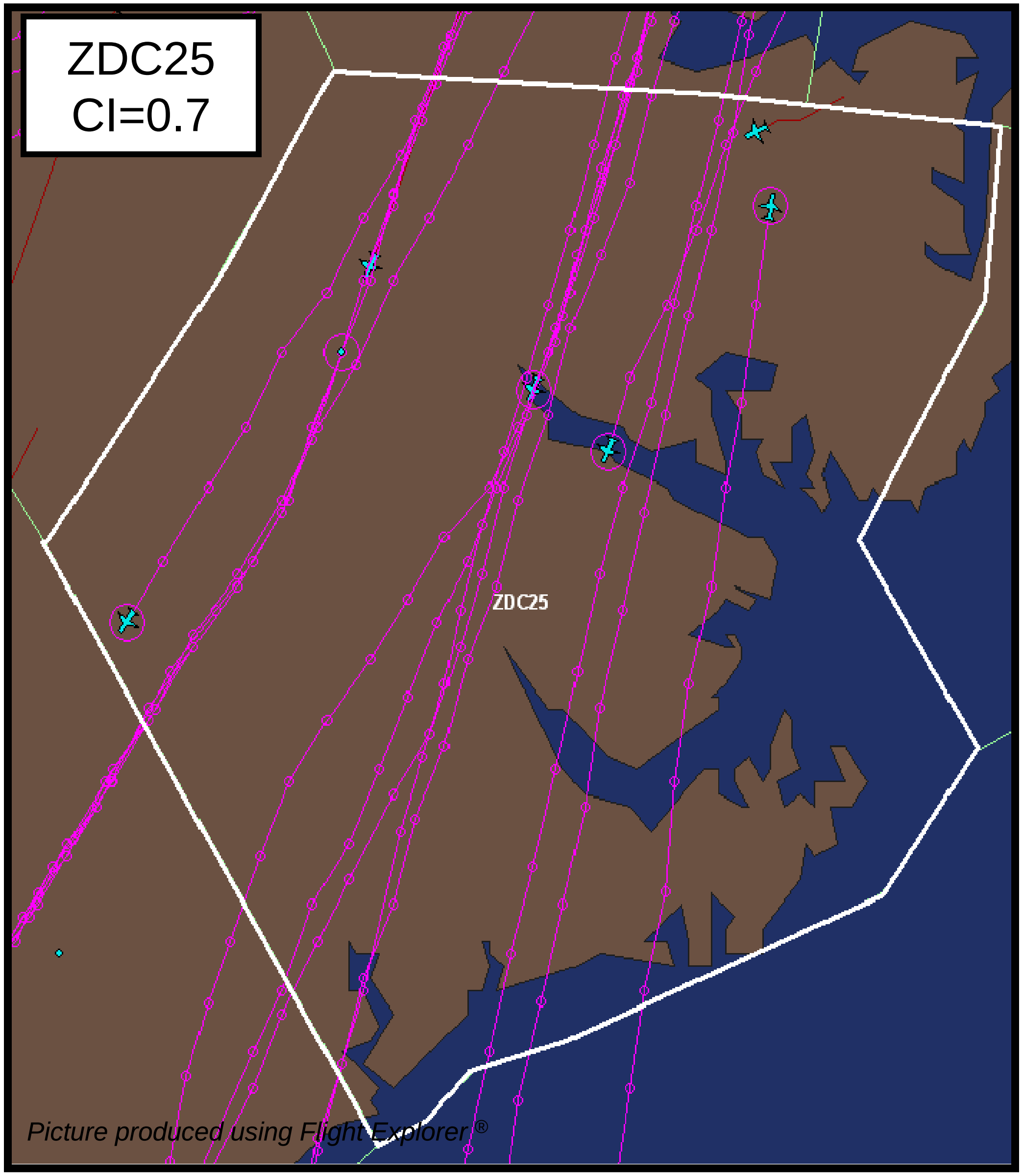
- Ultra high
- Structured traffic
- Low density
- Next to non-controlled airspace
- No SUA
- Inter-sector handoff points are concentrated



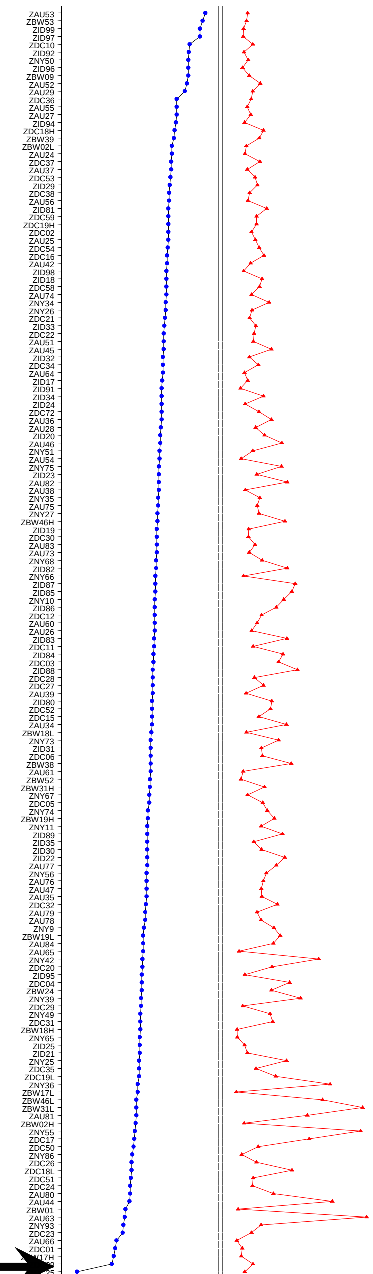
Complexity order: 161/162

Daily movement

CI: mean=1.86, max=2.61, min=0.7



- Low altitude
- Structured traffic
- Low density
- Next to non-controlled airspace
- No airport
- No SUA



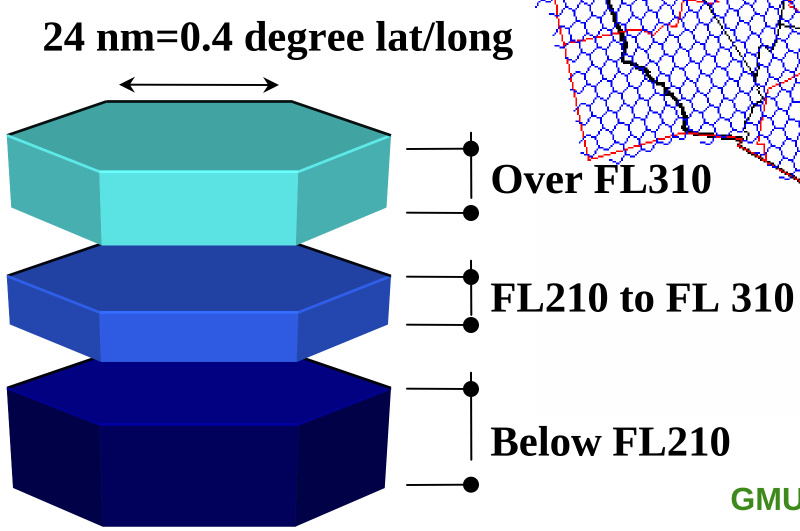
Complexity order: 162/162

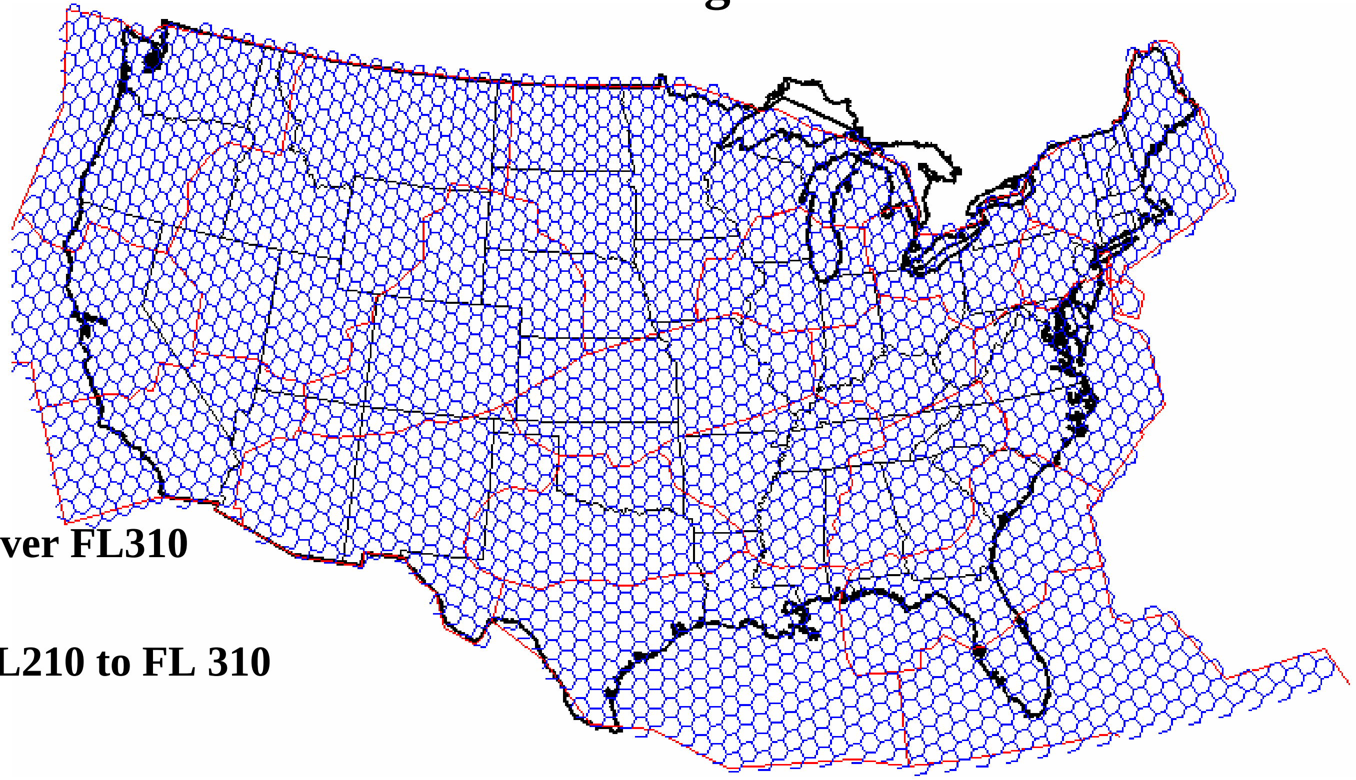
Apply CI Metric and Optimization Theory to New Concepts in Airspace Design

- **Two distinct concepts:**
  1. **Using complexity measures in designing the polygonal shape sectors**
     - **One of the objectives is minimizing the number of sectors while WL in each sector does not exceed a certain threshold**
     - **Avoid concave sectors**
  2. **High-Volume Tube-Shape Sectors (HTS)** ***(Initiated by university research concept team, Zellweger, et al, NASA unpublished report)***
     - **Like HOV lanes in the sky connecting congested airports**
     - **ADS-B usage**
     - **One or more ATCs are assigned to each HTS from origin to destination**
     - **Lower separation minimum**
     - **Eliminating ATCs distraction on trajectories.**
     - **Cost benefits by reducing flight distance**
     - **etc …**

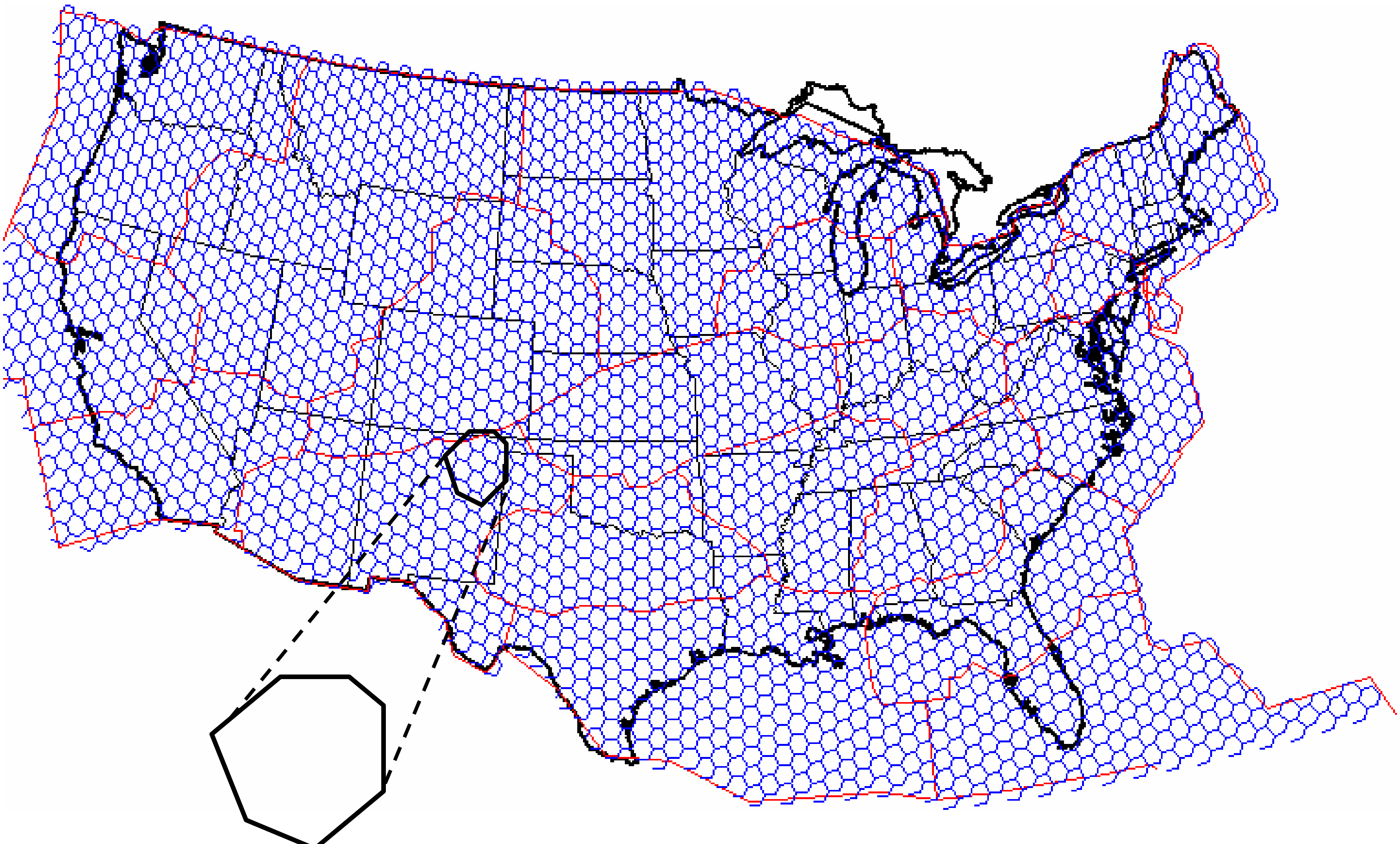
Hex-Cells Chosen as Airspace Building Block Elements

- The airspace of 20 CONUS ARTCCs is divided to three altitude layers with 2566 cells.
- Hex-Cells are airspace elements and it is possible to compute complexity and workload metrics for each cell based on historic flight data.





Clustering Hex-Cells to Construct Sectors



Flight Layers – University Team Concept

- **Based on OD tracks and number of daily operations in each OD pair, different layers of flights are identifiable:**

  A. **Scheduled Flights**

     I. **Non-congested routes: Between low traffic OD pairs (less than 10 operations per day). = ~ 2/3 of total scheduled flights**

     II. **Congested routes: Between congested OD pairs (more than 10 operations per day). ~1/3 of total scheduled flights**

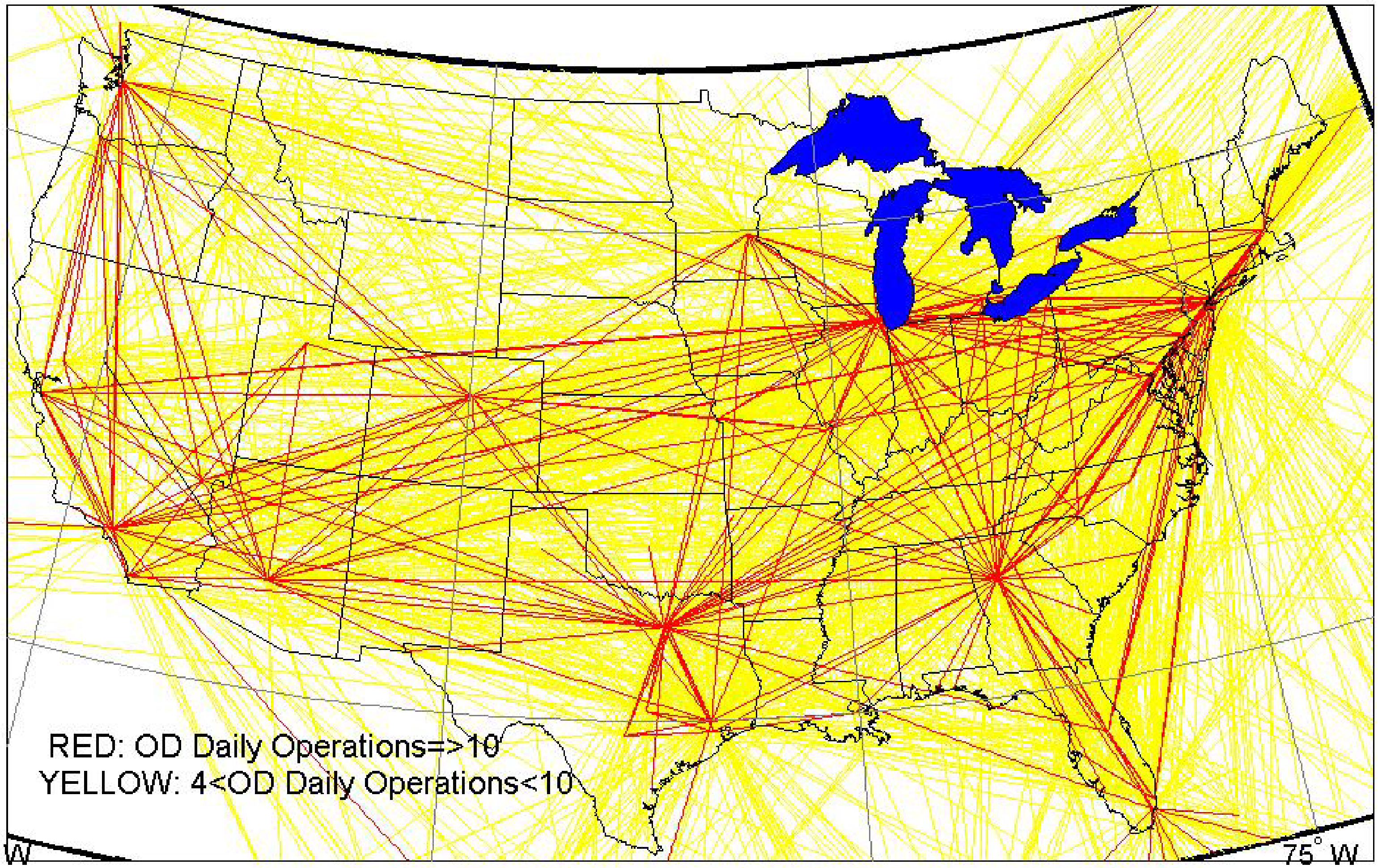
  B. **Non-Scheduled (~1/3 layer A)**

     I. **Short range GAs**

     II. **Long range GAs**

Layer A – Potential HOV Ribbons

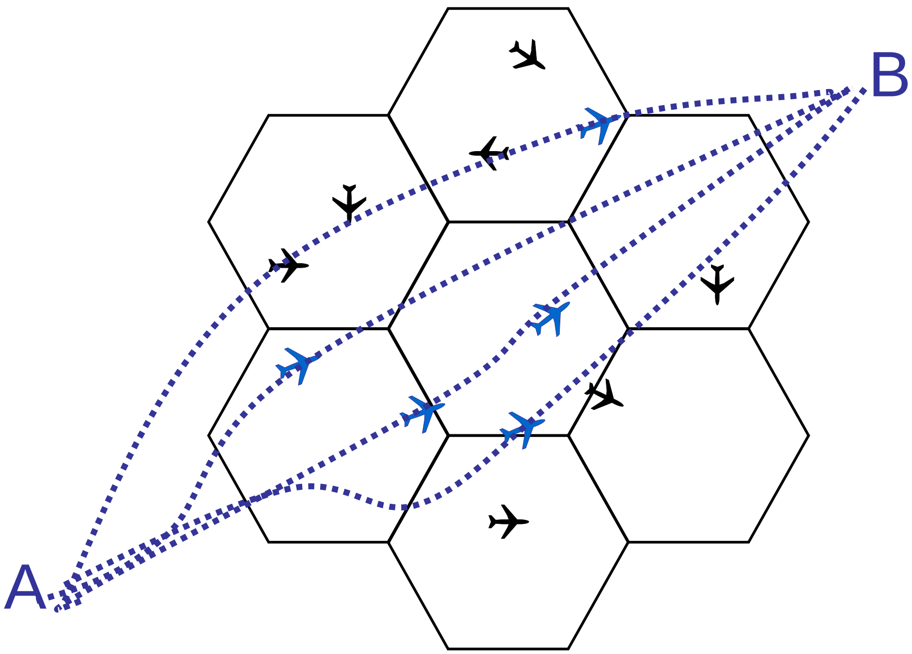
- **Yellow→ Layer AI,**
- **Red → Layer AII**



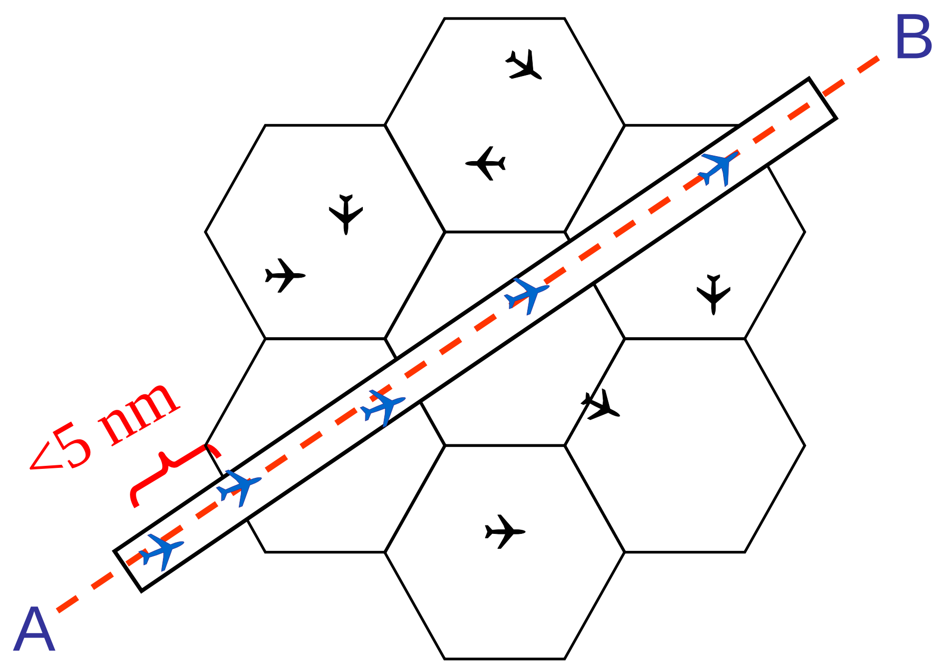
High-Volume Tube-Shape Sectors (HTS)

- Passenger share for flights in layer A is much larger than layer B
- Like interstate highways connecting large airports with higher number of operations
- In HTS's minimum separation standards are less than current values
- They can be mono or bi directional
- Aircraft with advanced CNS equipment are allowed to enter the tubes
- One or more controller assigned for entire HTS from origin to destination
- ADS-B usage

High-Volume Tube-Shape Sectors (HTS)

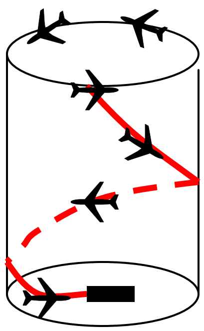


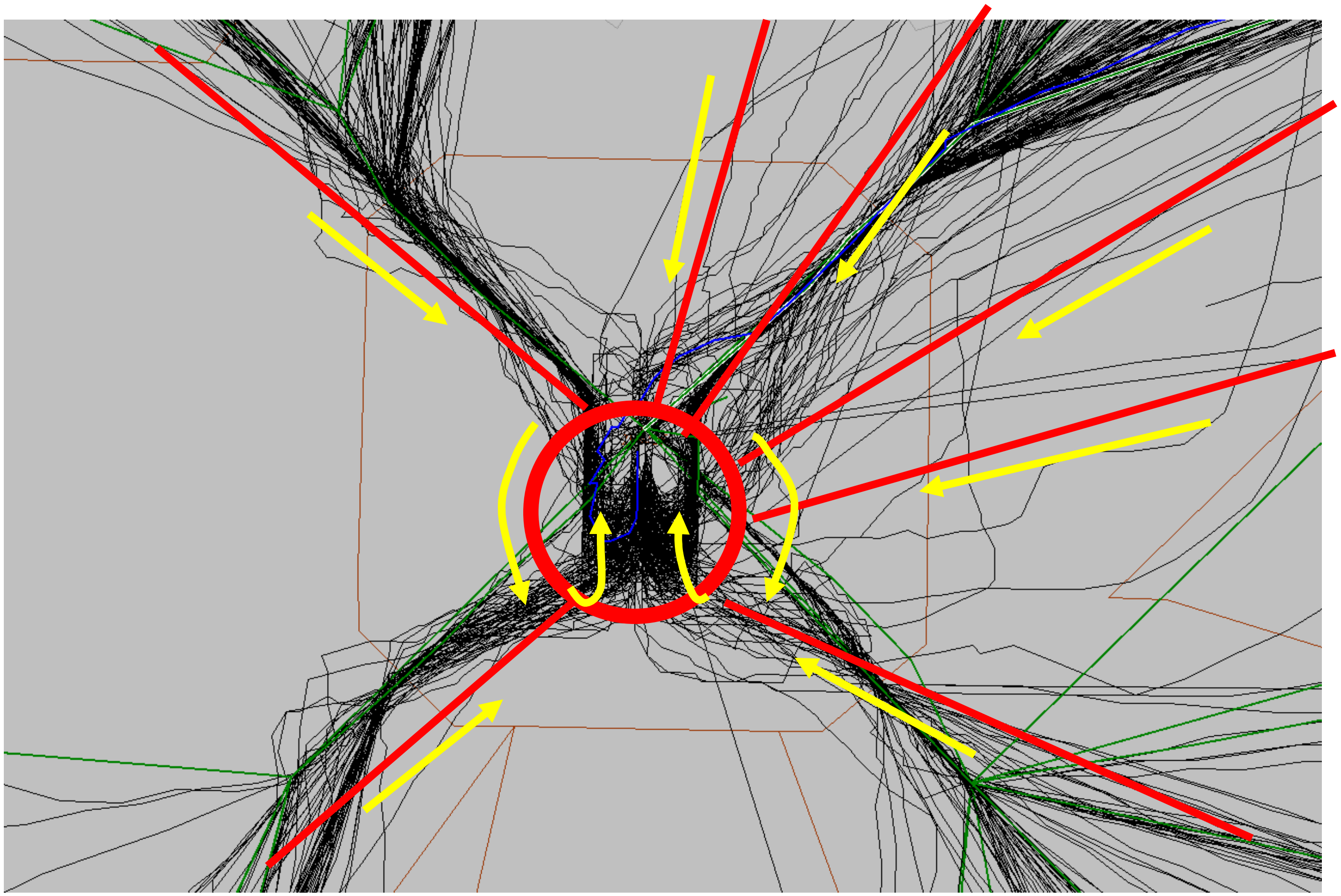
Weather Uncertainty will Dynamically Rubber-Band the HTS



Example of a High-Volume Tube-Shape Sector (HTS) Network Node

HTS intersections in terminal area



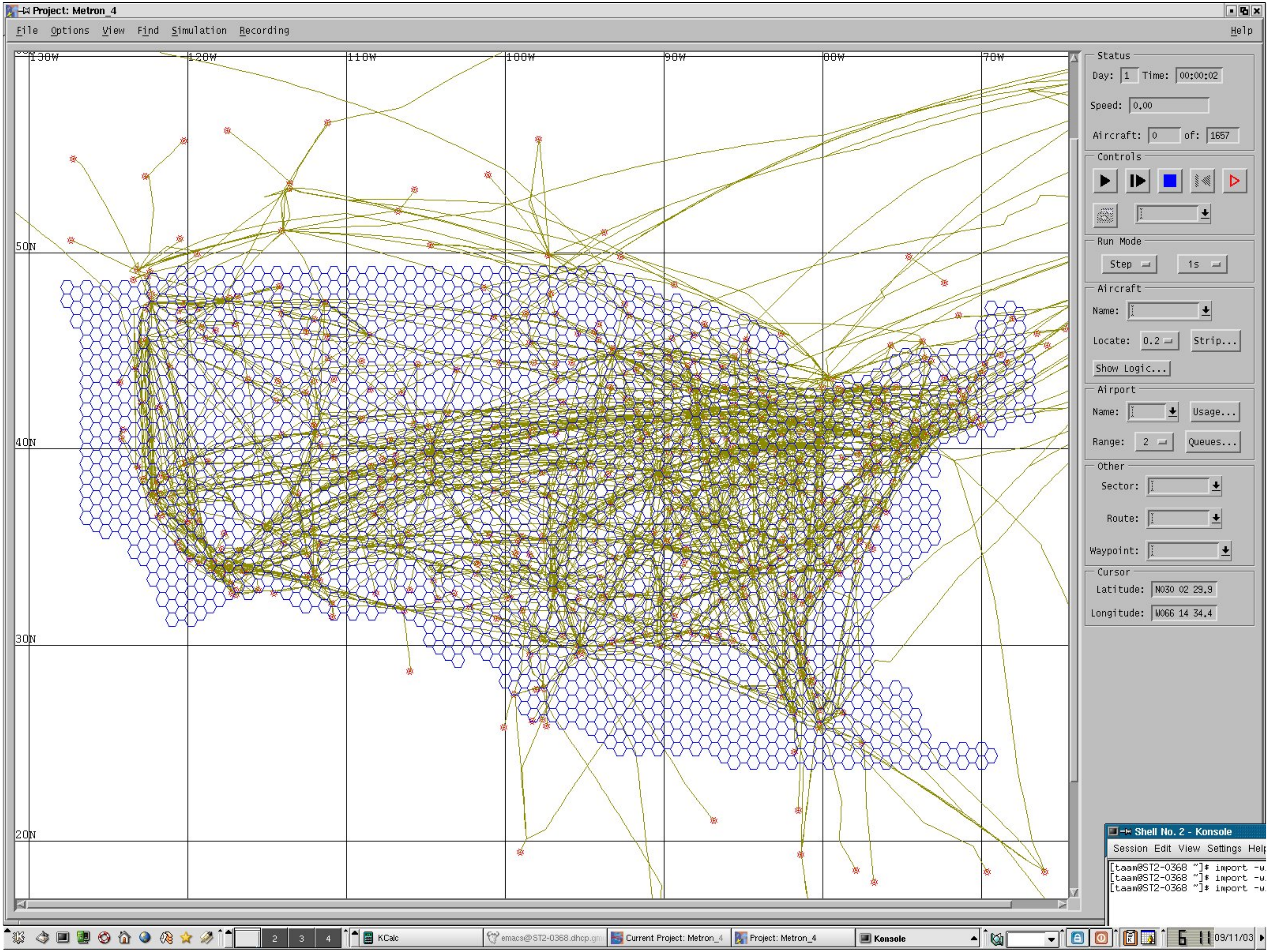


Select 45,000 ETMS Flight Plan Tracts and Compute Simulated HEX-Cell WL/CI using TAAM

- **For each flight ID in ETMS database there are few flight plans reported by airlines**
  1. ***Filed flight plan :*** **Before the ETD of each flight, airlines update the flight plan to avoid adverse weather or congested areas or ….**
  2. ***Advisories:*** **FAA issues flight plans as late as few minutes before the flight to relieve congestion or avoid adverse weather. Airlines are free to follow or decline them.**
  3. ***Amended:*** **Issued by FAA and airlines have to follow them.**
  4. ***Flown:*** **Actual flight track that aircraft have flown.**
- **The latest filed flight plan has been parsed to TAAM.**
- **Missing attributes**
- **~ 45k flights on Tuesday July 02 02**

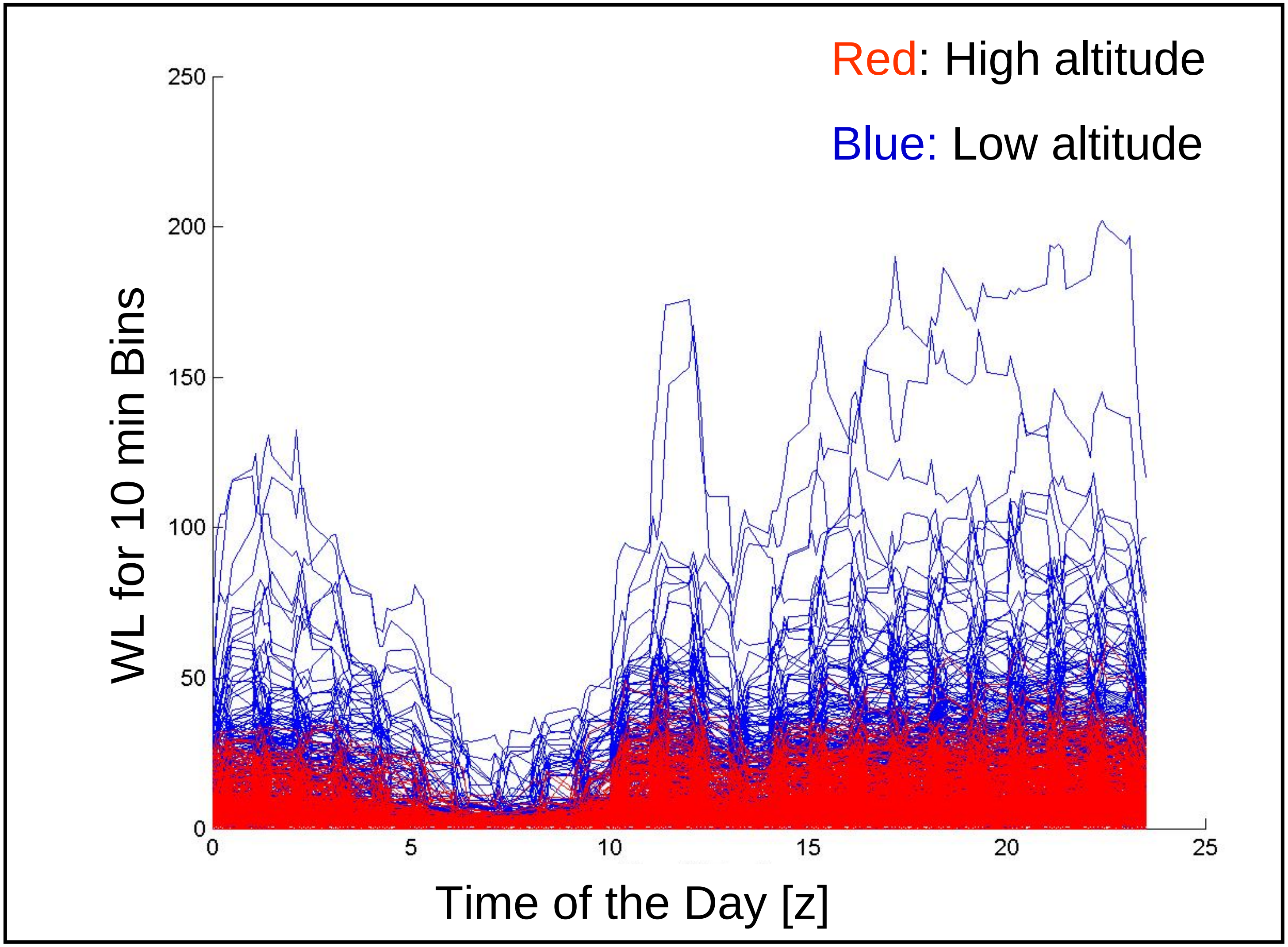
```
AAL2998 B752 1 KSTL_KTPA_2 ? 01,00:00 01,01:53 1 0 S
@A KSTL
@LL N38 45 0.0 W90 22 0.0
@LL N38 51 0.0 W90 29 0.0
@LL N38 33 0.0 W89 58 0.0
@LL N37 49 0.0 W88 58 0.0
@LL N37 37 0.0 W88 42 0.0
@LL N37 32 0.0 W88 32 0.0
@LL N35 7 0.0 W86 57 0.0
@LL N31 32 0.0 W84 57 0.0
@A KTPA
```

Sample Flight track

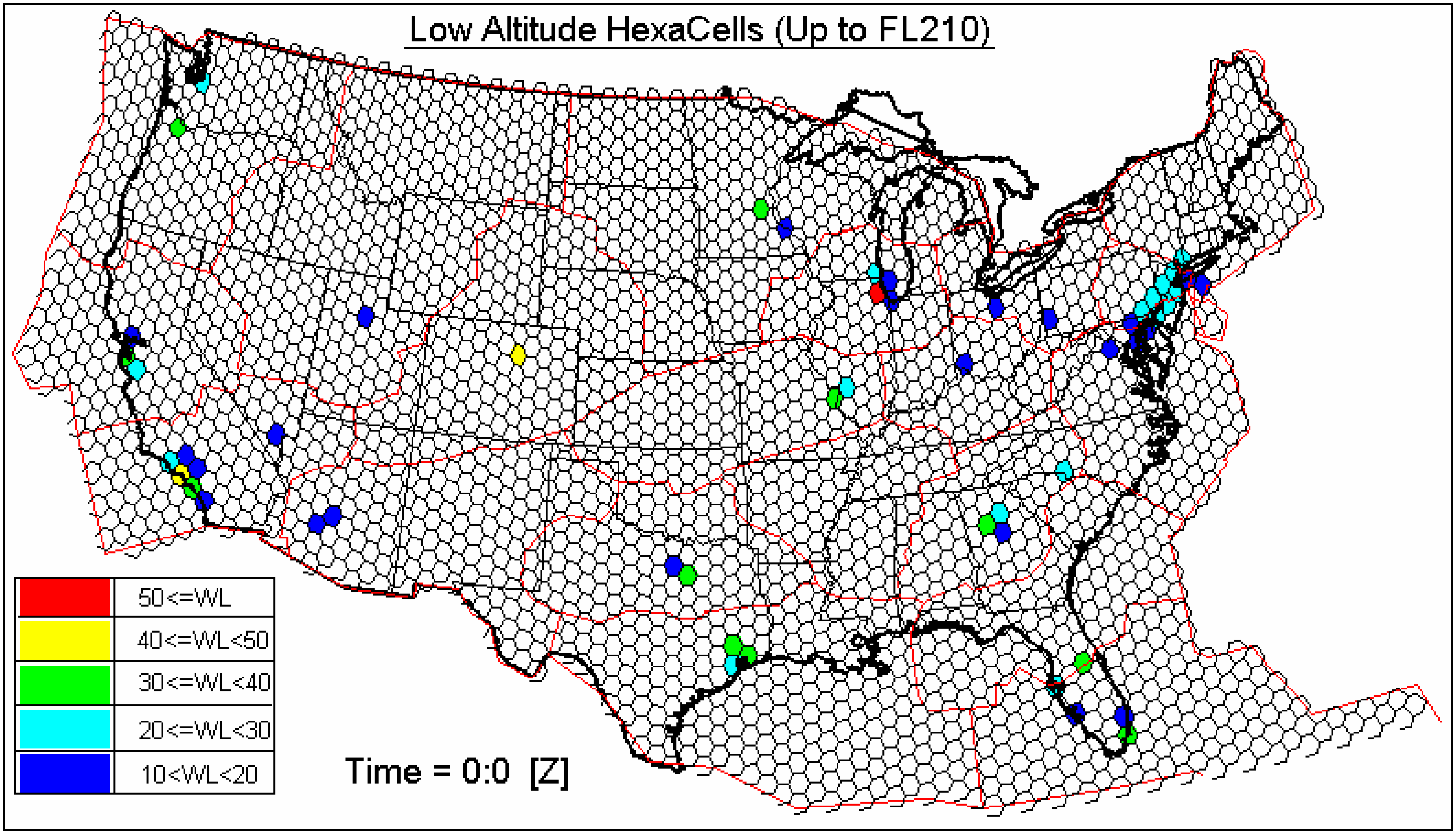


Project: Metron_4
File Options View Find Simulation Recording Help
130W
120W
110W
100W
90W
80W
70W
50N
40N
30N
20N
Status
Day: 1 Time: 00:00:02
Speed: 0.00
Aircraft: 0 of: 1657
Controls
Run Mode
Step
1s
Aircraft
Name:
Locate: 0.2
Strip...
Show Logic...
Airport
Name:
Usage...
Range: 2
Queues...
Other
Sector:
Route:
Waypoint:
Cursor
Latitude: N030 02 29.9
Longitude: W066 14 34.4
Shell No. 2 - Konsole
Session Edit View Settings Help
[taam@ST2-0368 ~]$ import -w.
[taam@ST2-0368 ~]$ import -w.
[taam@ST2-0368 ~]$ import -w.
KCalc
Current Project: Metron_4
Project: Metron_4
Konsole
09/11/03

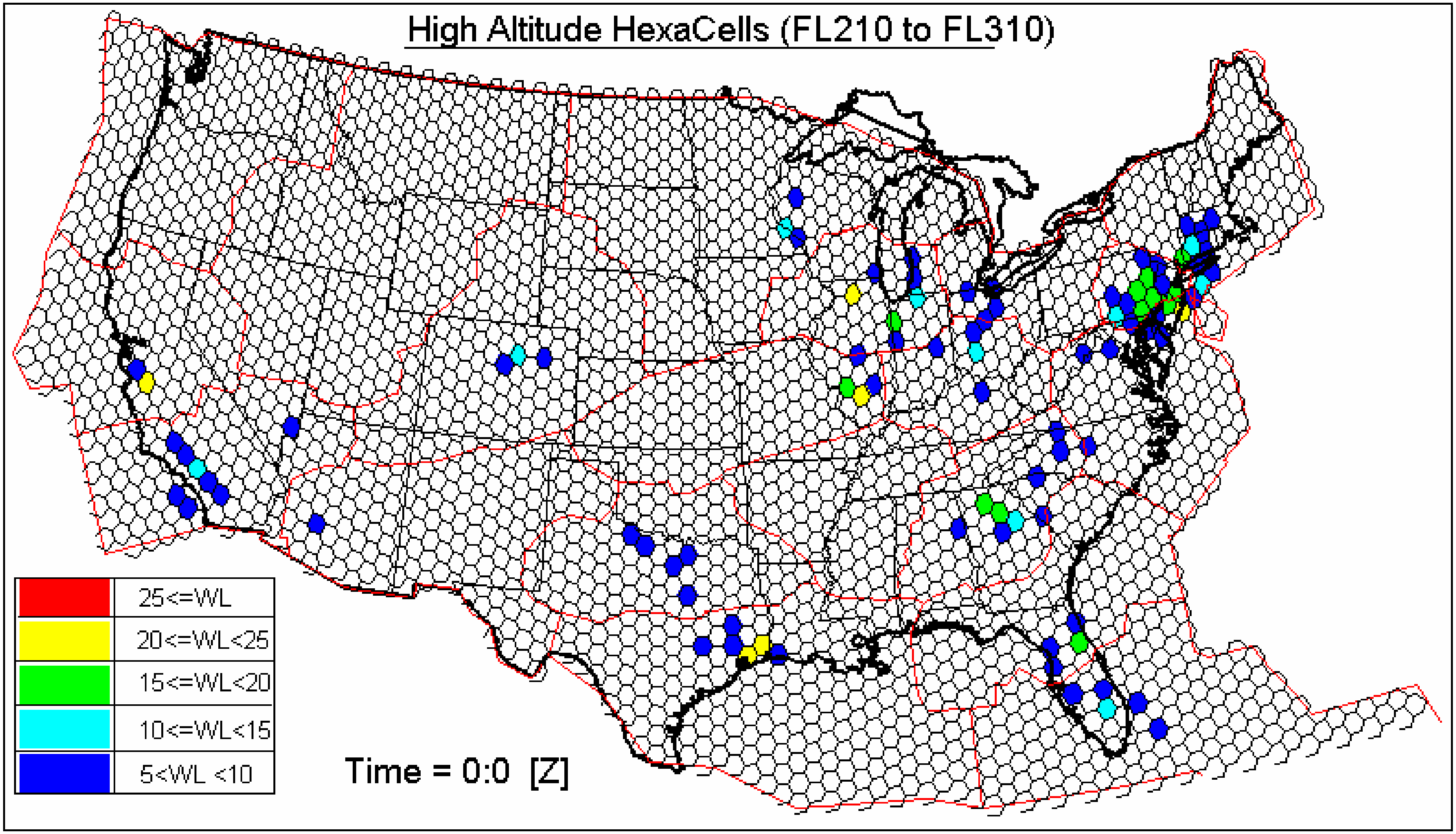
WL Trend in Each Hex-Cell Throughout the Day



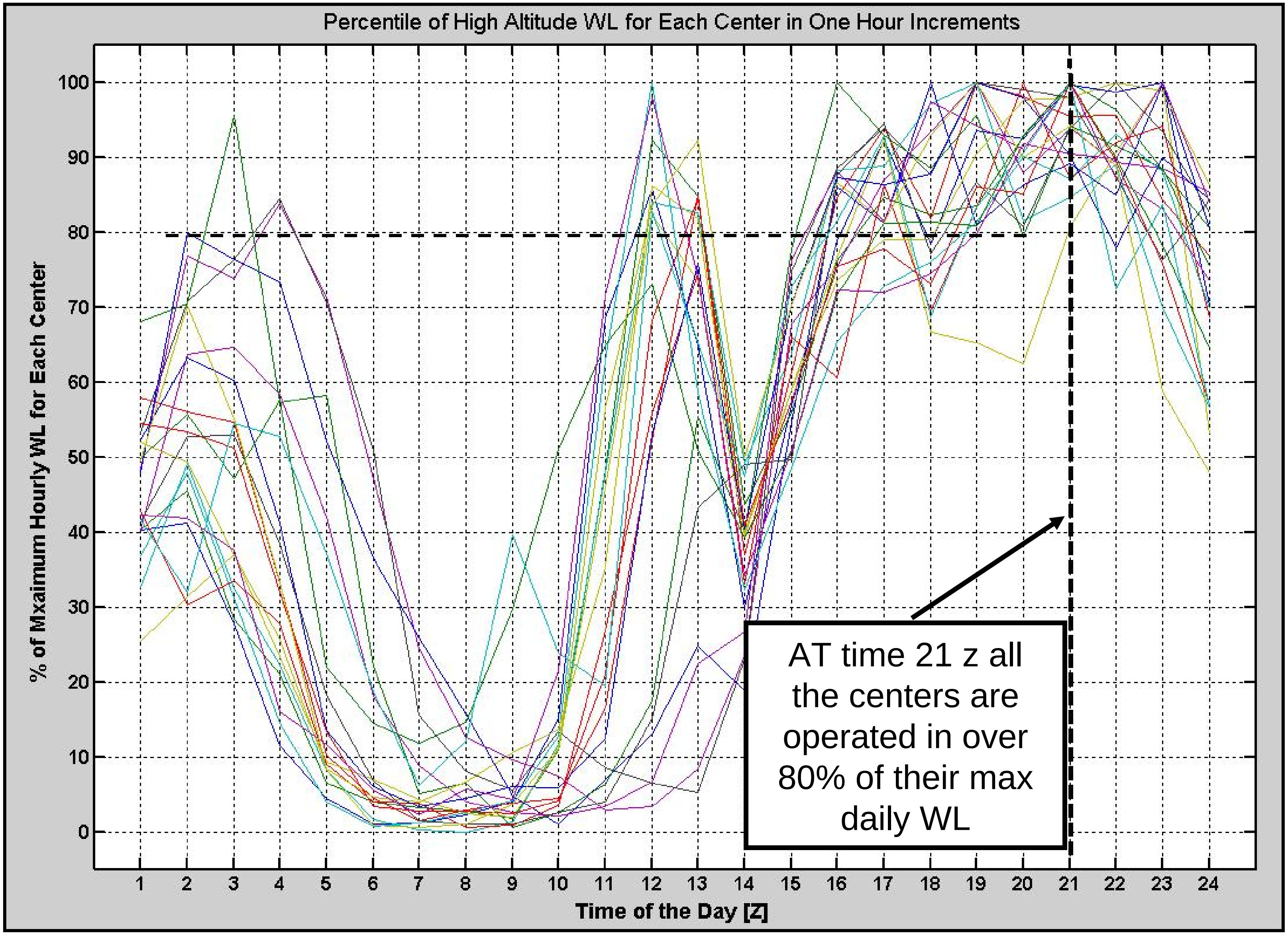
Airspace Complexity Visualization (Low)



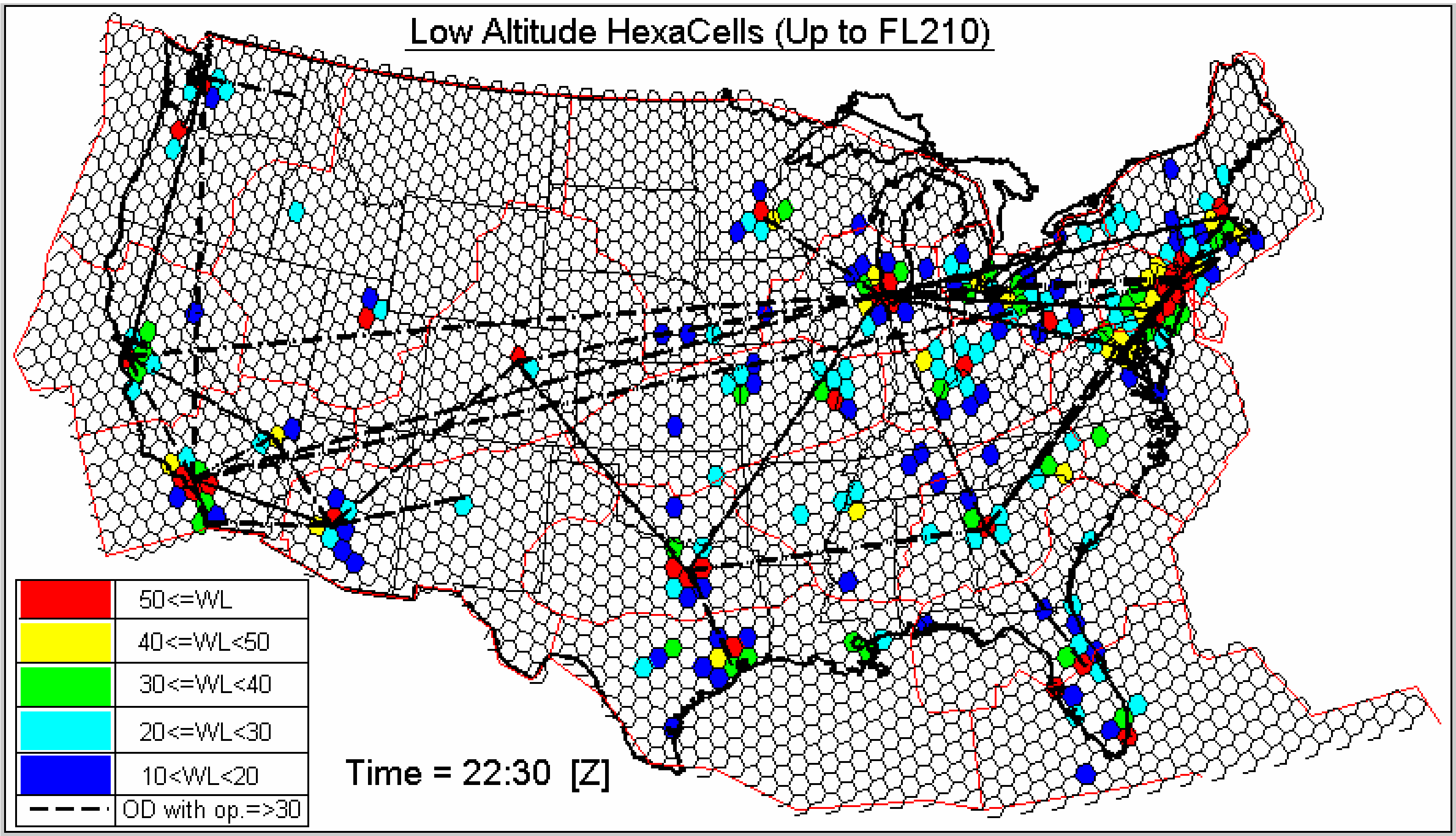
Airspace Complexity Visualization (High)



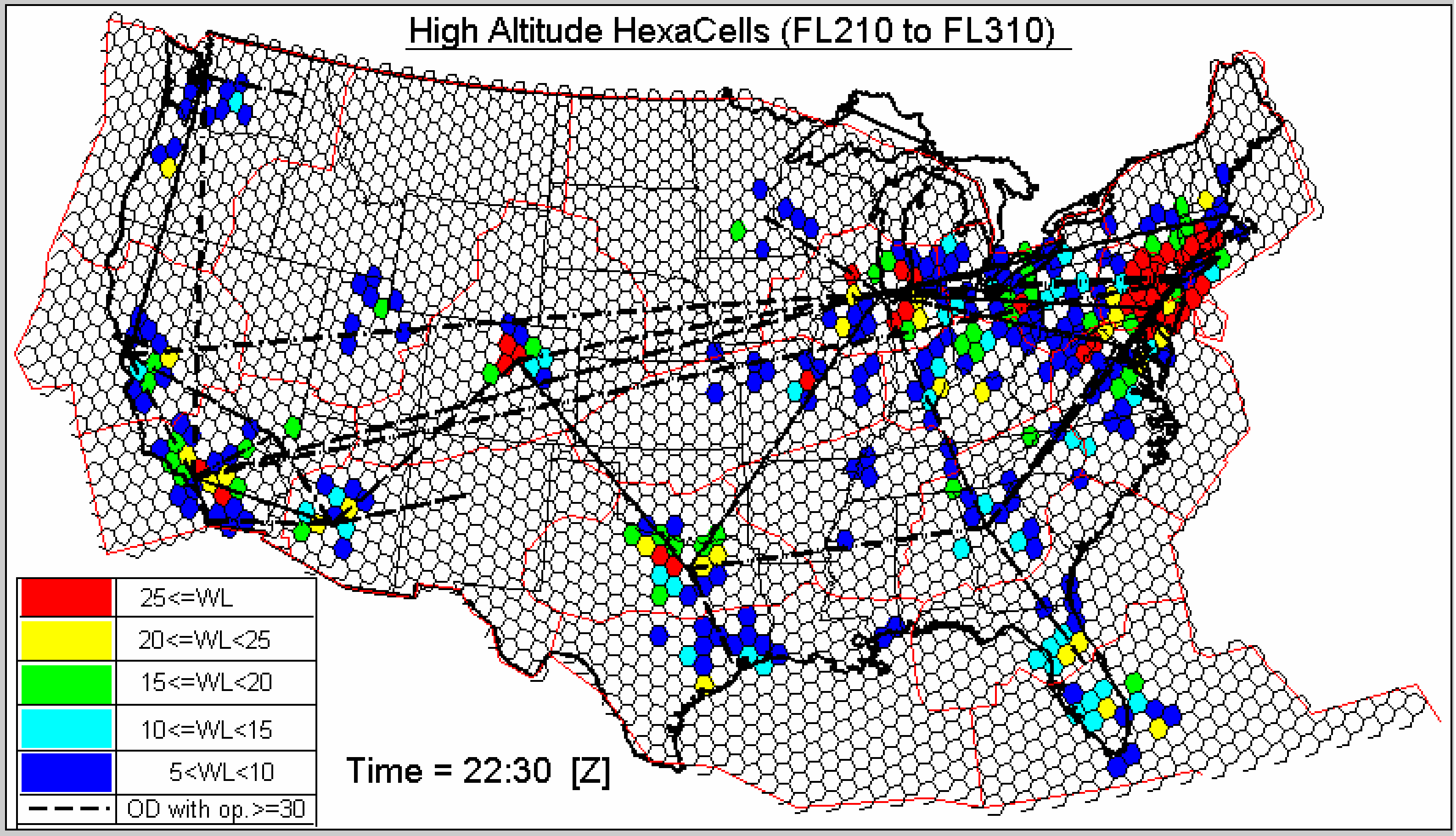
WL Variation Within Centers *(cnt.)*



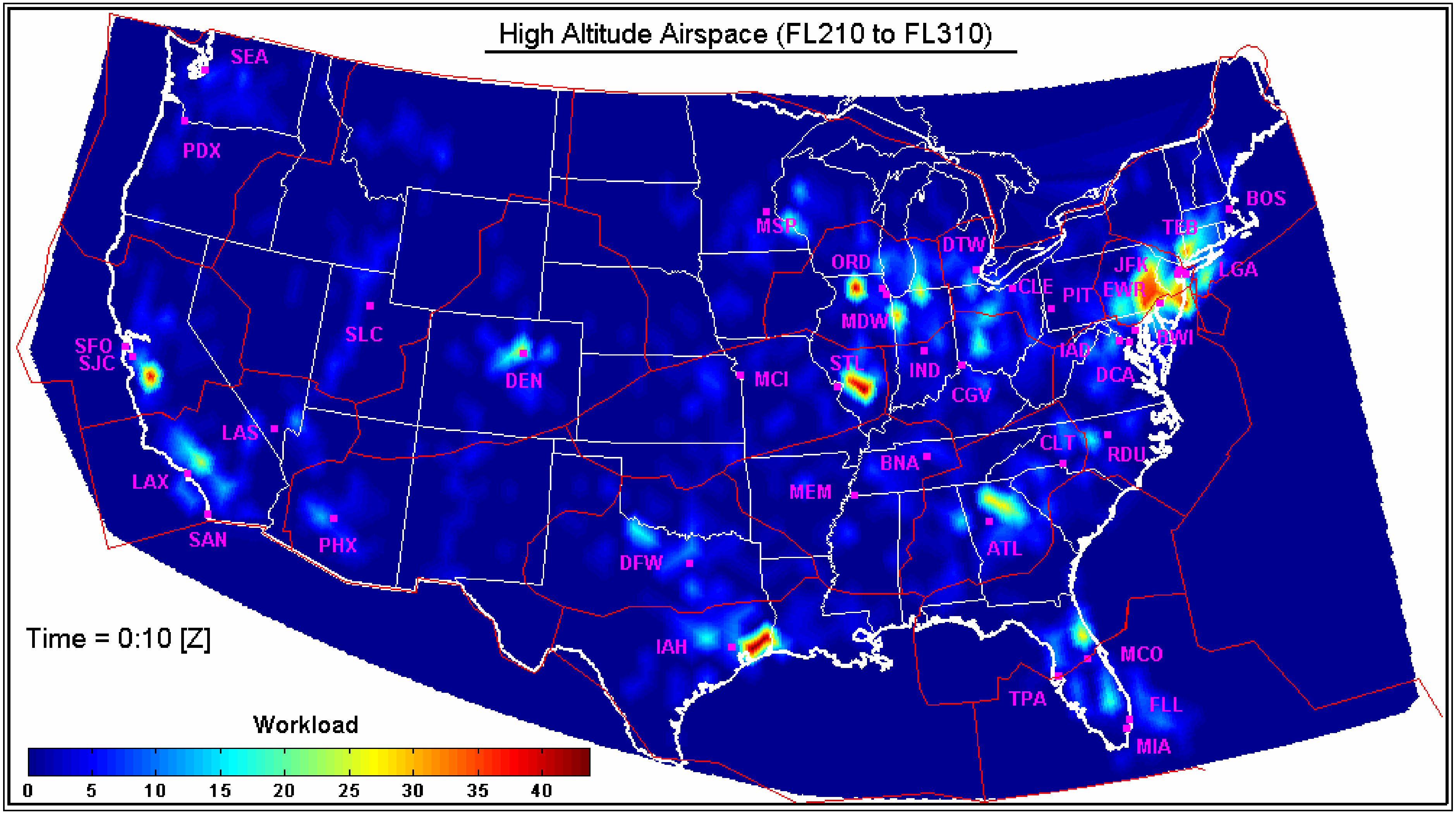
Role of HTS in Reducing Complexity



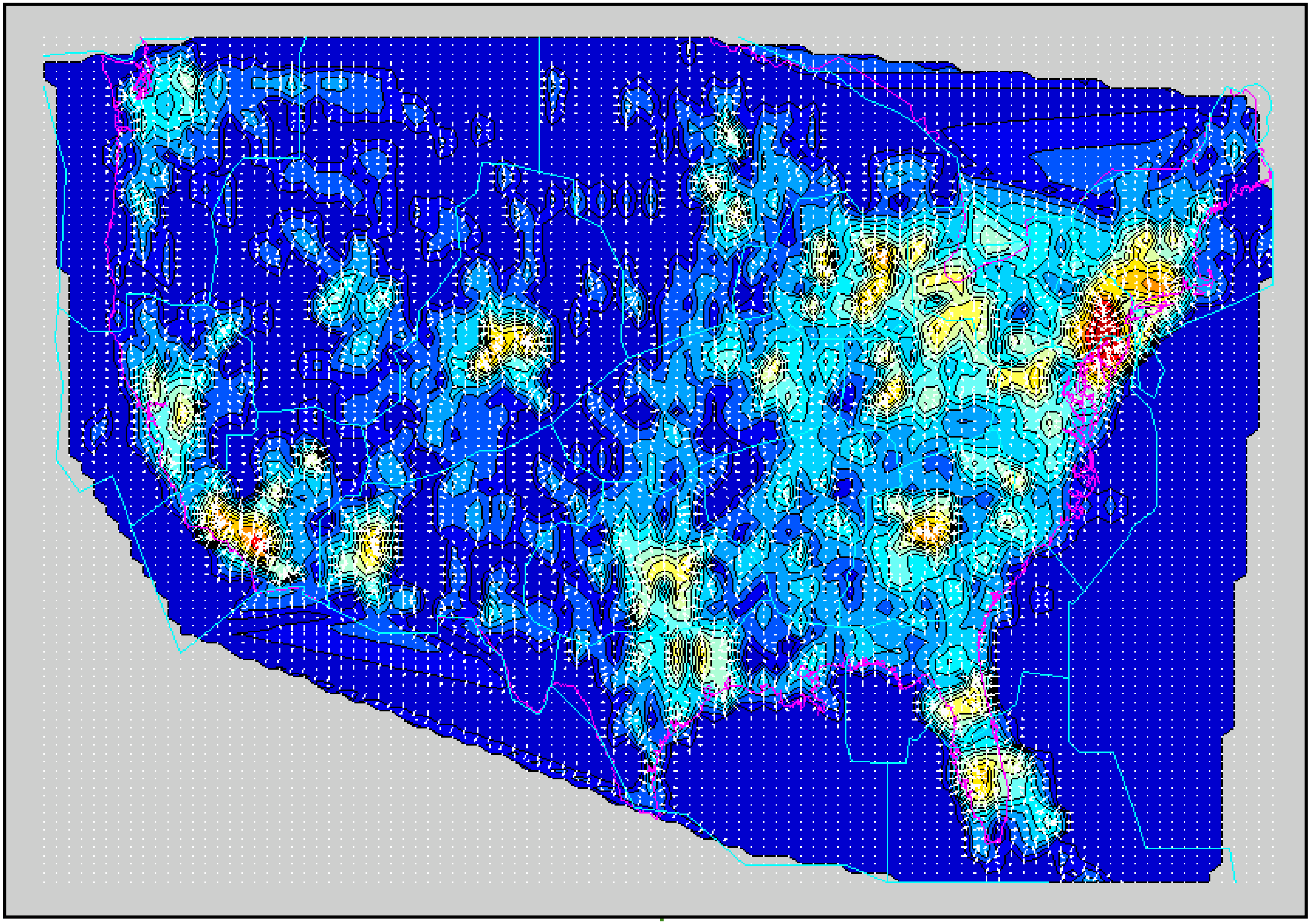
Role of HTS in Reducing Complexity



WL as a Continues Function of *lat*, *long* and *t*



WL Vector Fields



Observations to Date

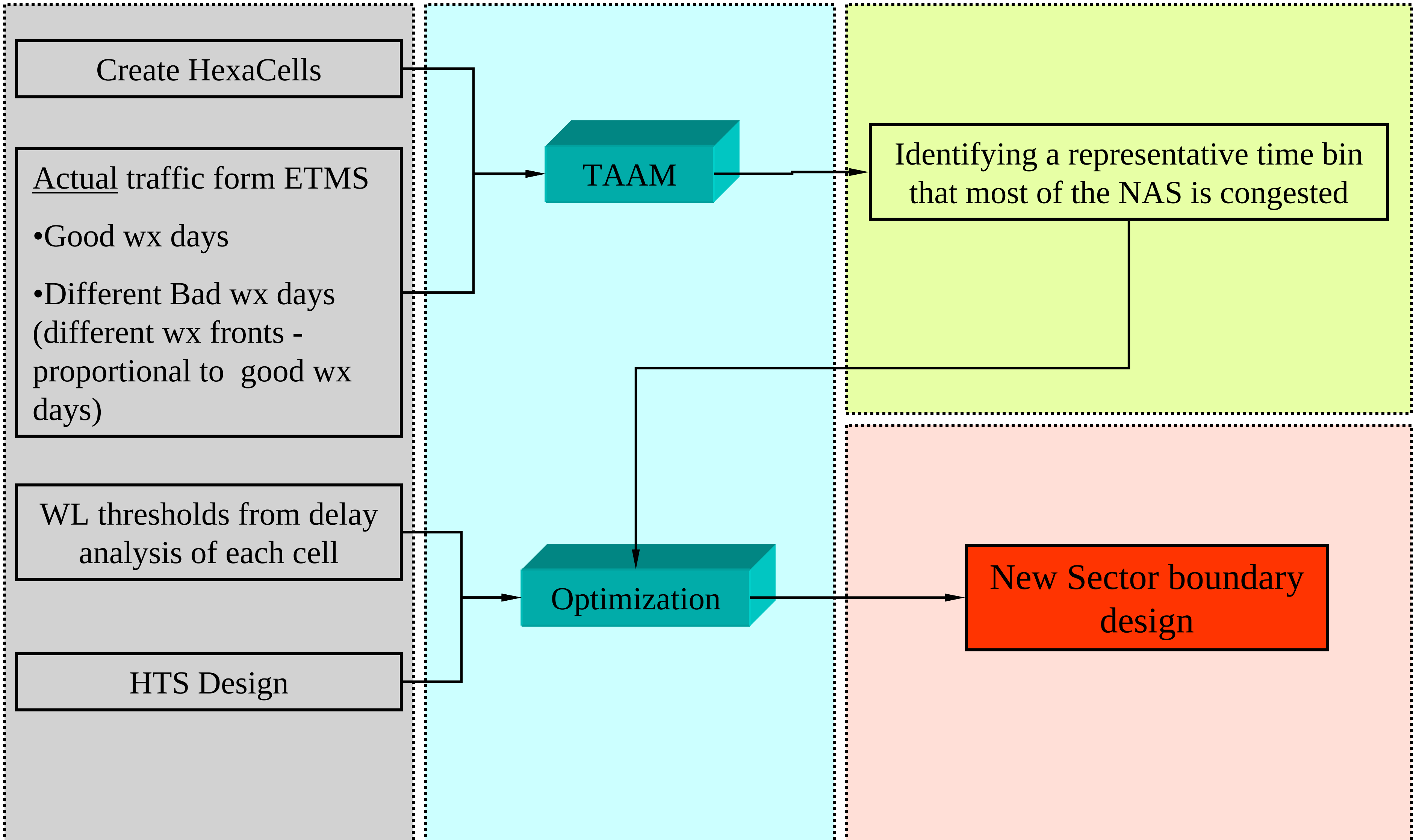
- TAAM WL/CI Metric seems to properly Identify High and Low Workload Sectors
- High Fidelity Simulation Models may be useful in Evaluating Innovative new sector Design Paradigms
- Metric Flow Visualization Techniques may be used in Conjunction with Optimization Theory to Minimize High WL/CI "Hot Spots" in the ATC network that require extensive experience to deal with
  - Future Concerns for En-Route Capacity Restrictions
  - Future Concern for increases in Loss-of-Separation Violations

BACKUP SLIDES

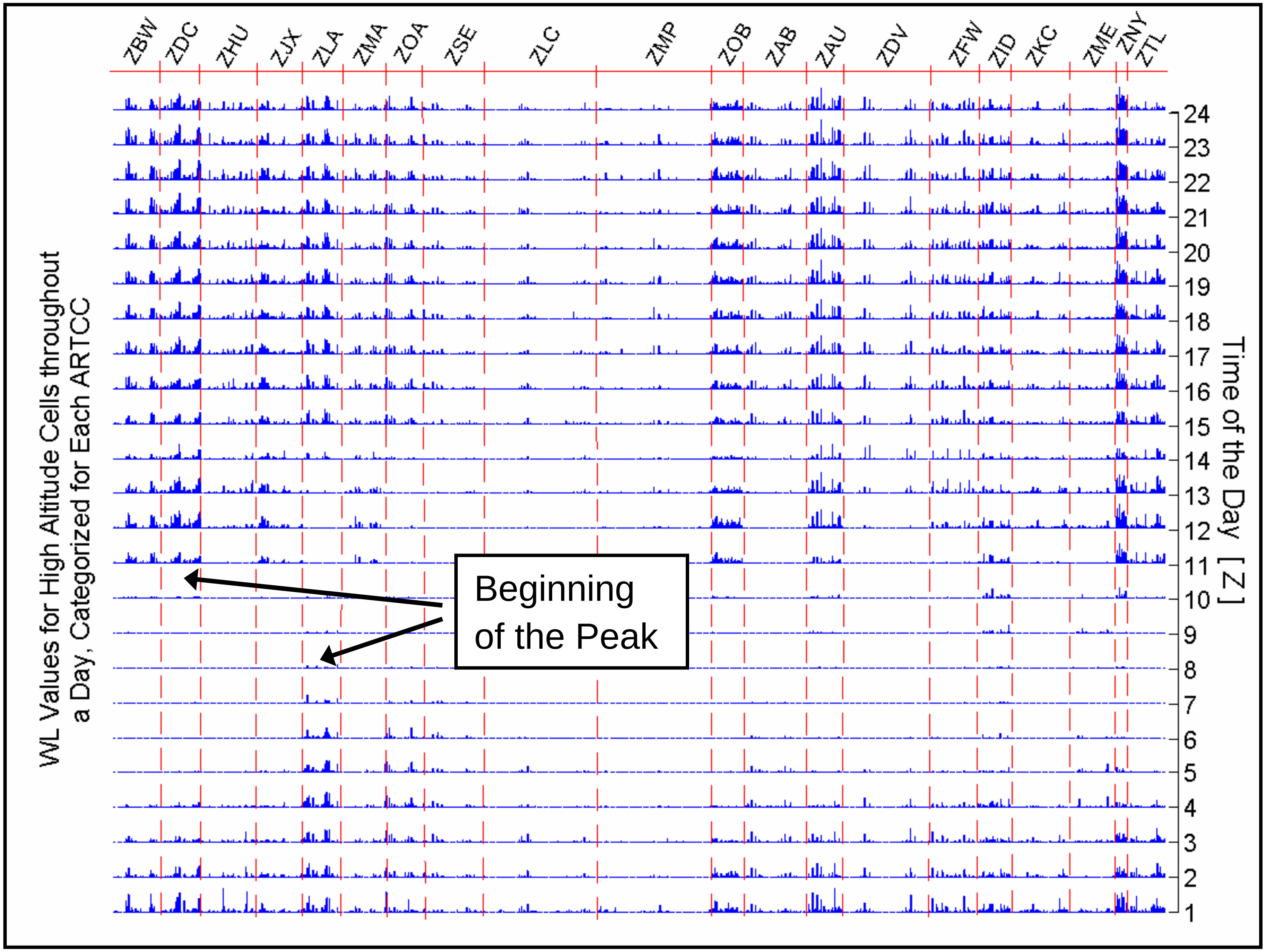
Details of TAAM Simulation

- Total daily flights = ~45k
- Number of sectors in each run= 2566
- Aircraft characteristics file is updated for all aircraft in ETMS
- CD&R is ON
- Graphic is OFF
- Sim. time in a P4 processor with 2GB RAM &1G rpm HD= ~8 hours
- Reporter run time= ~2 hours

Proposed Network Sector Design Process

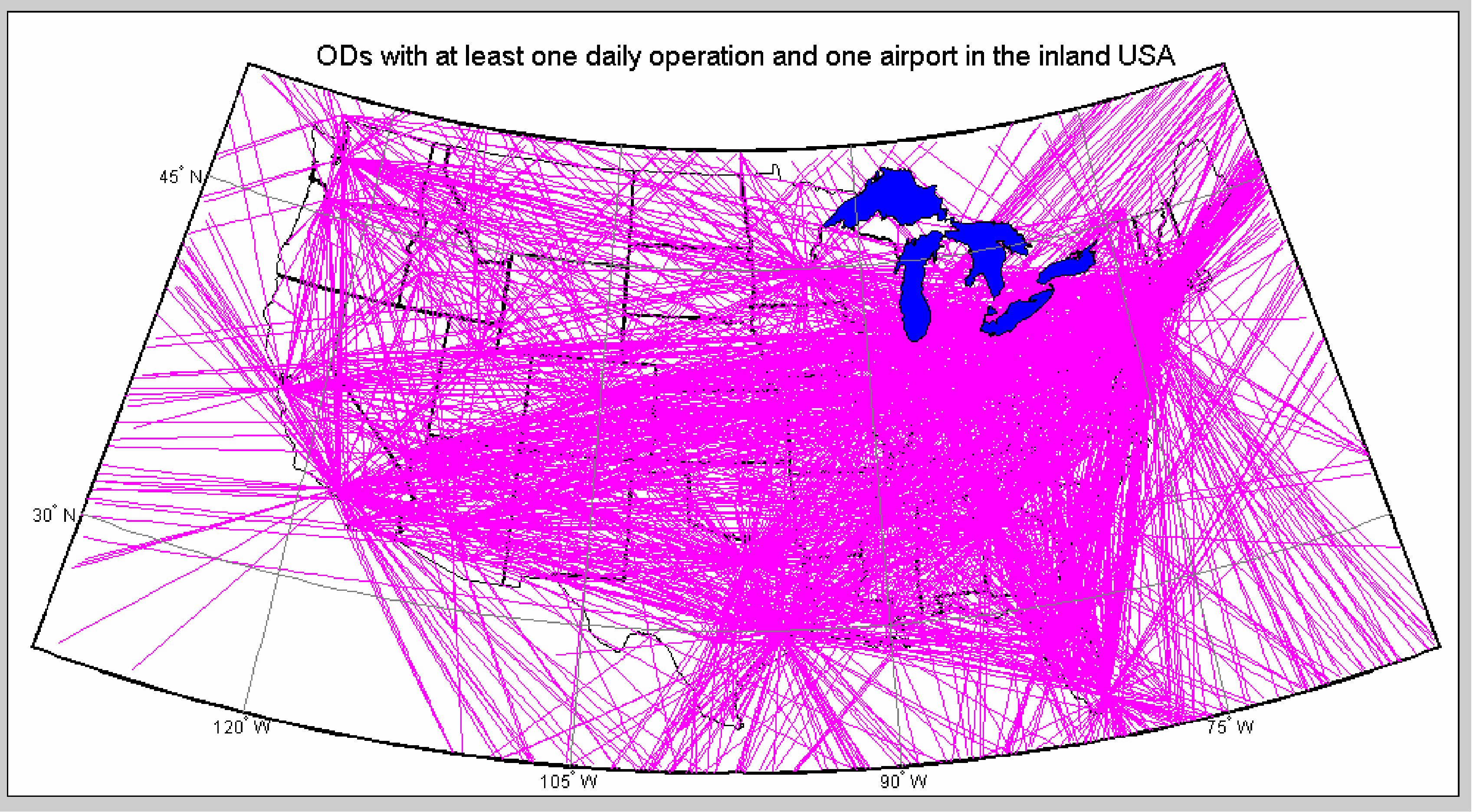


WL Variation Within Centers

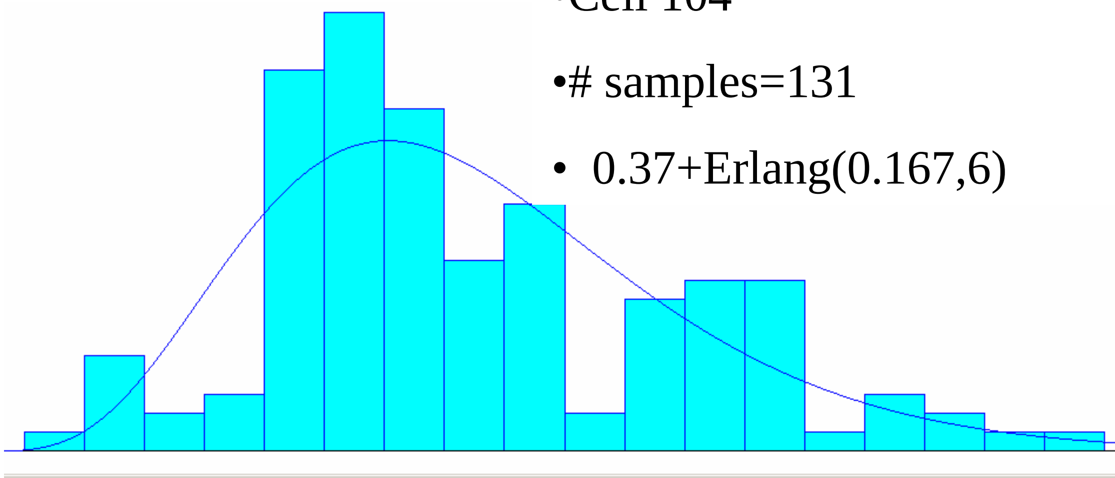


All Operational OD Pairs

- At least one leg in continental US and one daily operation
- Over 2000 tracks



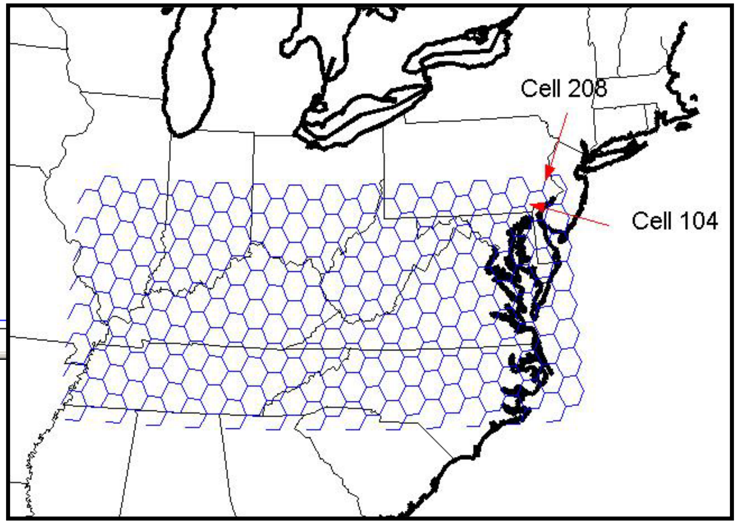
CI pdf for HexaCells 104 & 208

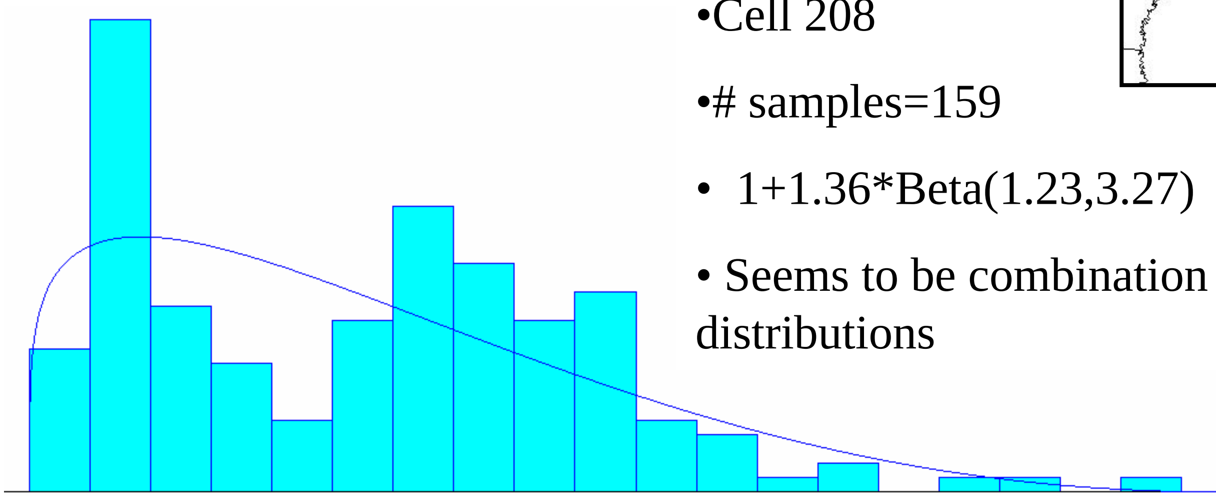


•Cell 104

•# samples=131

• 0.37+Erlang(0.167,6)





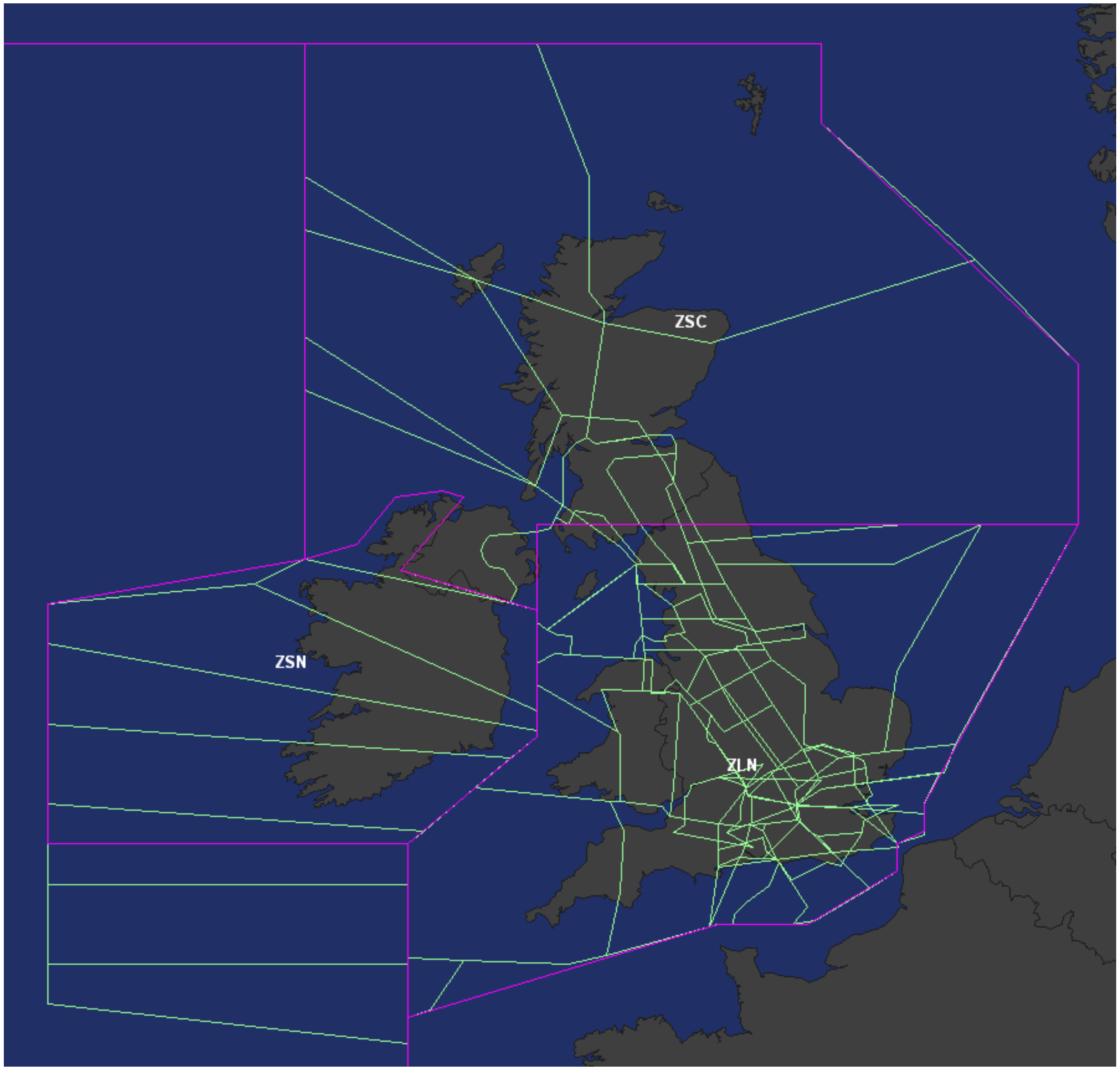
•Cell 208

•# samples=159

• 1+1.36*Beta(1.23,3.27)

• Seems to be combination of two normal distributions

European Sovereign Boundaries Produces a Similar Result



GMU Air Transportation Lab