Evaluation of University Team Concept: High Volume Ribbon Shaped Sectors with a Complexity Constraint

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University Team Concept

- **Concept Team Membership**
  - **NASA HQ**
  - **Volpe Research Center**
  - **Massachusetts Institute of Technology**
  - **San Jose State University**
  - **George Mason University**
- **Evaluation is being done by GMU alone**

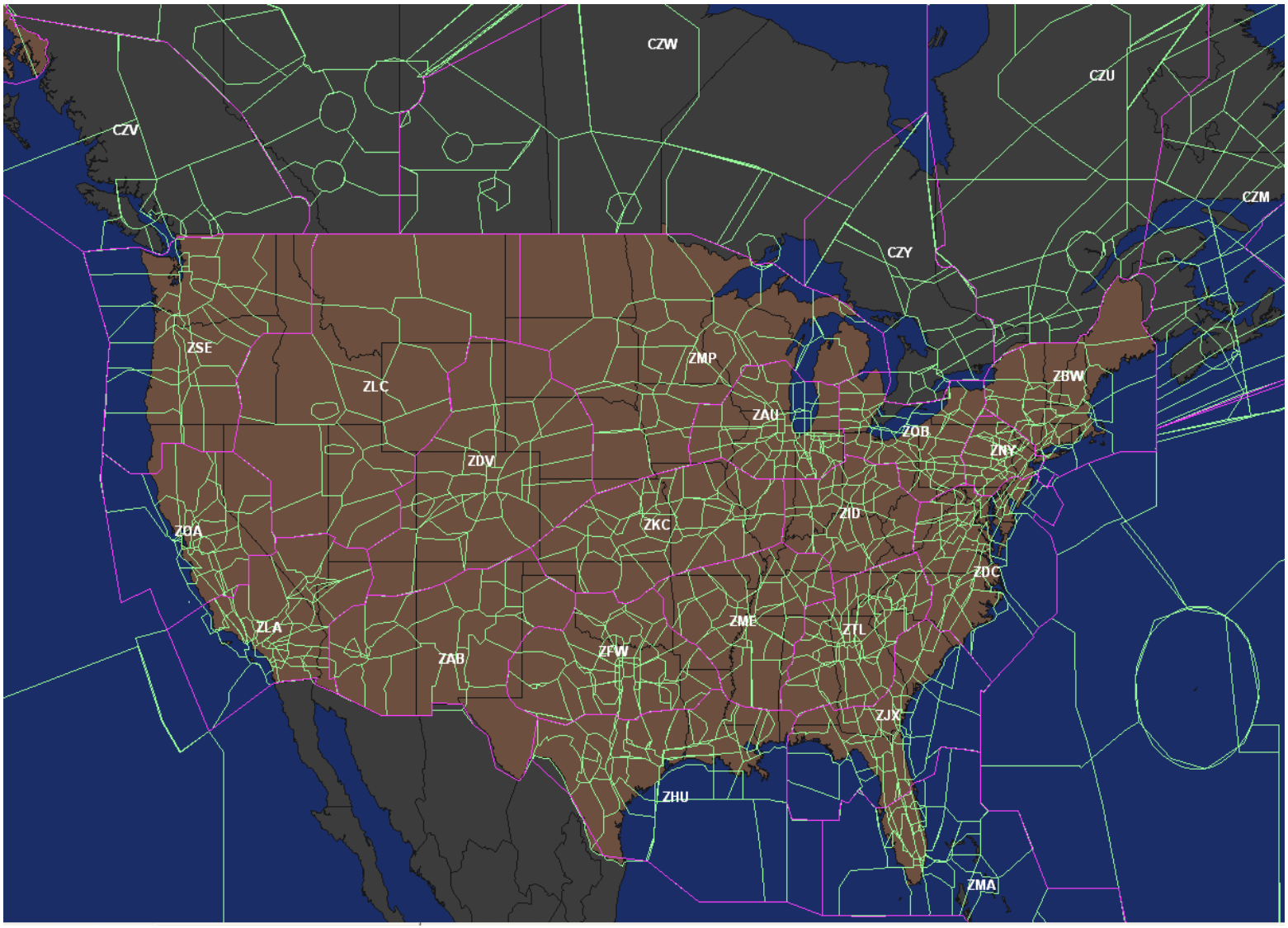
Outline

- **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 University Team Sector Design Concept using TAAM**
  - **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

- **Need for a Blending Framework of Important Advanced Concepts with a Transition Strategy**
  - **Aircraft based Separation (w/ Incentives to Equip)**
  - **Optimal Best-Wind Routes**
  - **Accommodate Dynamic Weather Re-Routing**
  - **Accommodate Both PTP and Structured Routes**
  - **Reduce Controller Workload under Increasing levels of Traffic**
  - **Enforce Stochastic Safety Constraints**
  - **Accommodate Potential future Demand Management Procedures**
- **~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.**

Current Sectorization has Historical – Not Analytic Origins



Sector Workload Design Issues

- **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.**
- **Any New ATC Paradigm MUST <u>Decrease</u> Controller WL**

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 Hypothesis:**
  - ***"There is 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

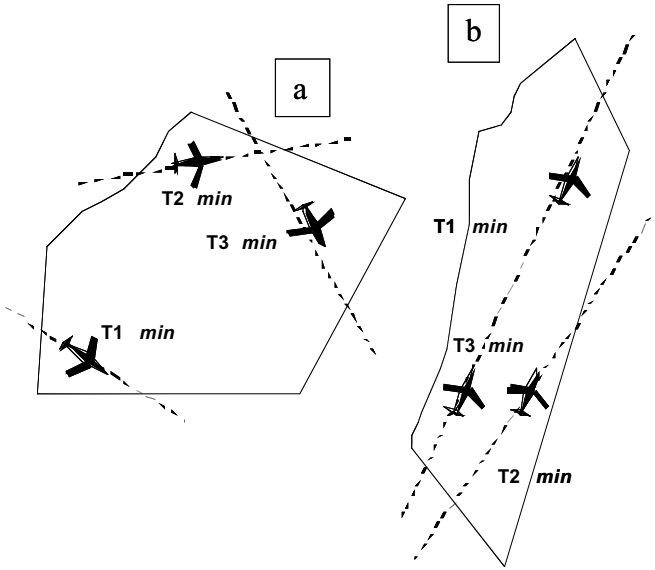
Total Transit time = $\sum_{i=1}^{n} T_i \Big/ Sector$ [minute/sector]

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]



$den_a = den_b = 3$

$Trans_a \neq Trans_b$

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

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

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.

$$WL_{HM} = F_{HM} \times (N_{HM} \times T) \qquad \text{where:}$$

F_{HM} = Adjustment factor for horizontal movement

N_{HM} = Number of aircraft passing through the sector

T = 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.

$$WL_{AC} = F_{AC} \times N_{AC} \qquad \text{where:}$$

F_{AC} = Altitude clearance factor

N_{AC} = 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

$$WL_C = F_C \times N_{CA}$$ where:

F_C = Cordination action factor

N_C = Number of aircraft with this coordination action

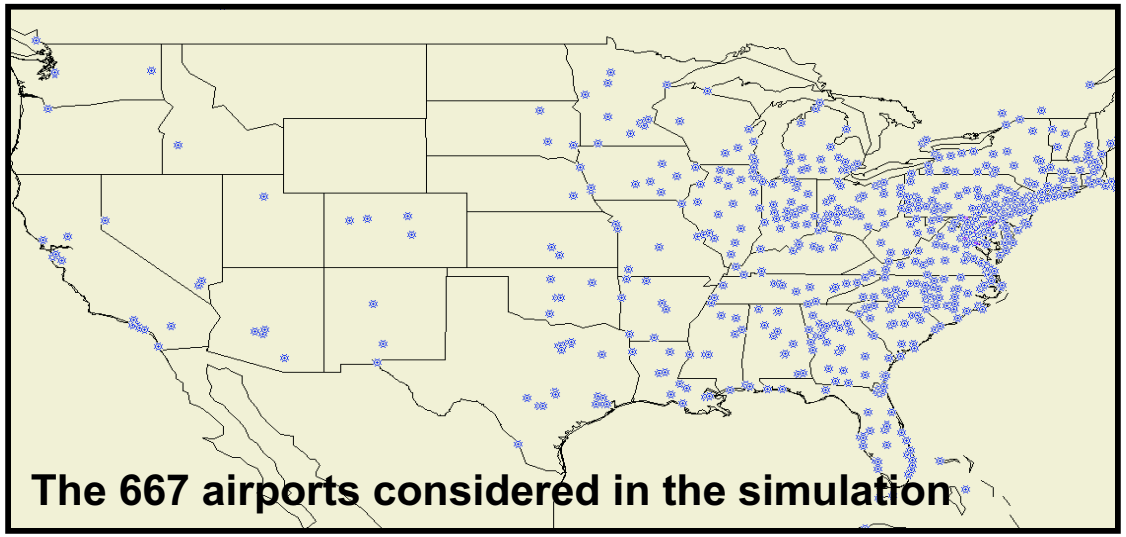
Airspace Complexity Quantification

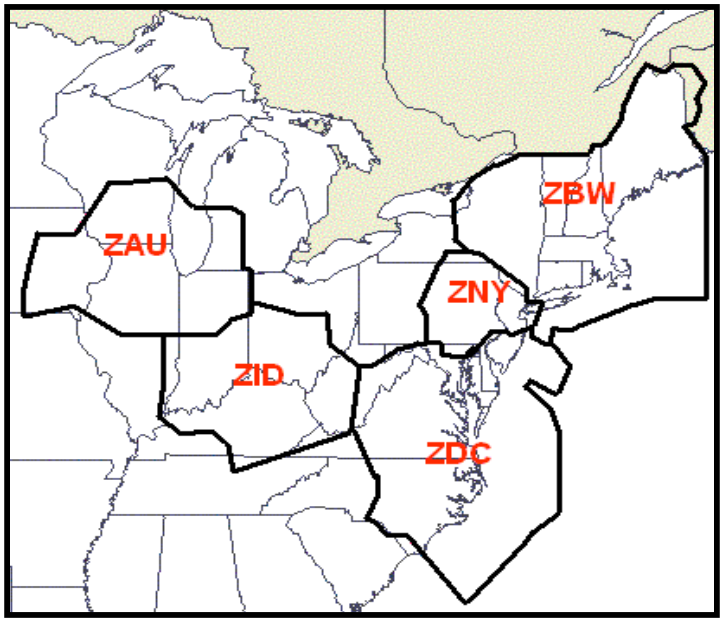
- **Aircraft in each sector, based on the sector complexity, create different workload levels.**
- **For each sector, *Complexity Index (CI)* is defined as the average workload per each aircraft.**
  - **For a given time epoch:**

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

- **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





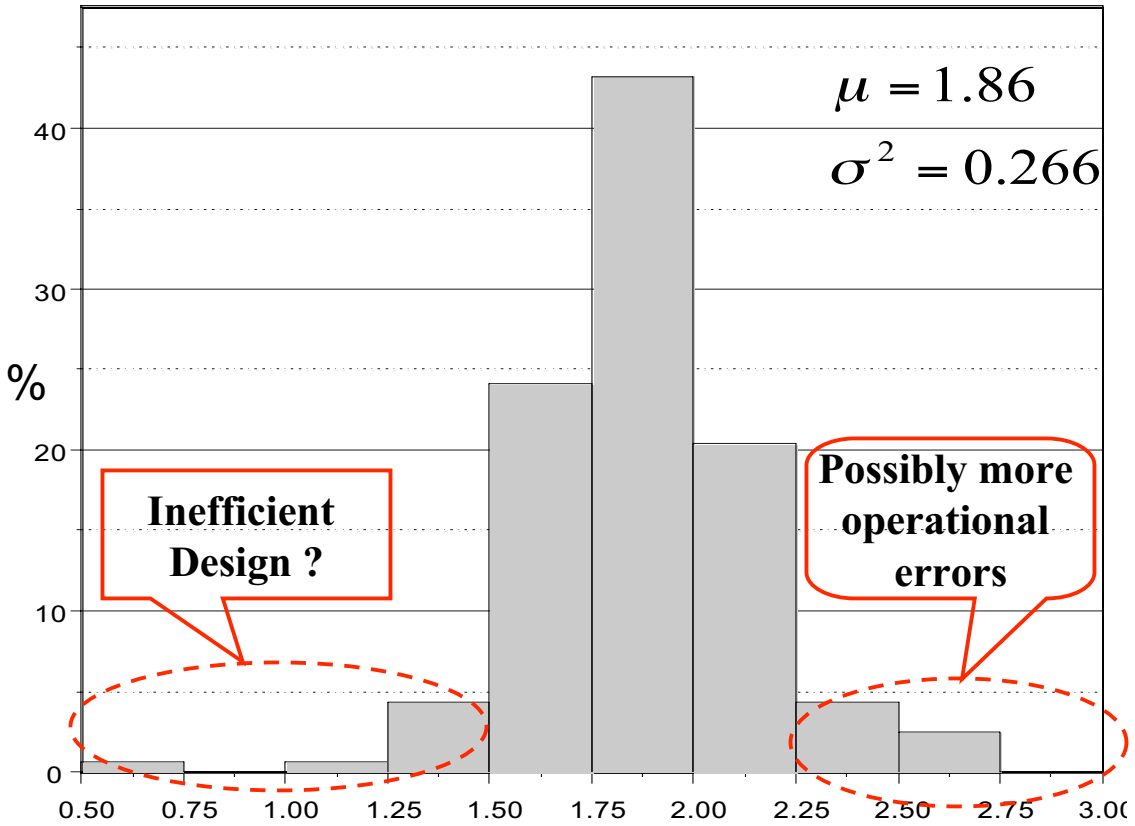
Market segment	Number of daily flights
- Non-GA including Commercial, GA and Cargo (IFR) extracted from the Flight Explorer	22764
- General Aviation traffic (IFR and VFR) generated using economic activities between OD	7051
Total	**29815**

NY25ZID34ZBW19ZAU41	

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

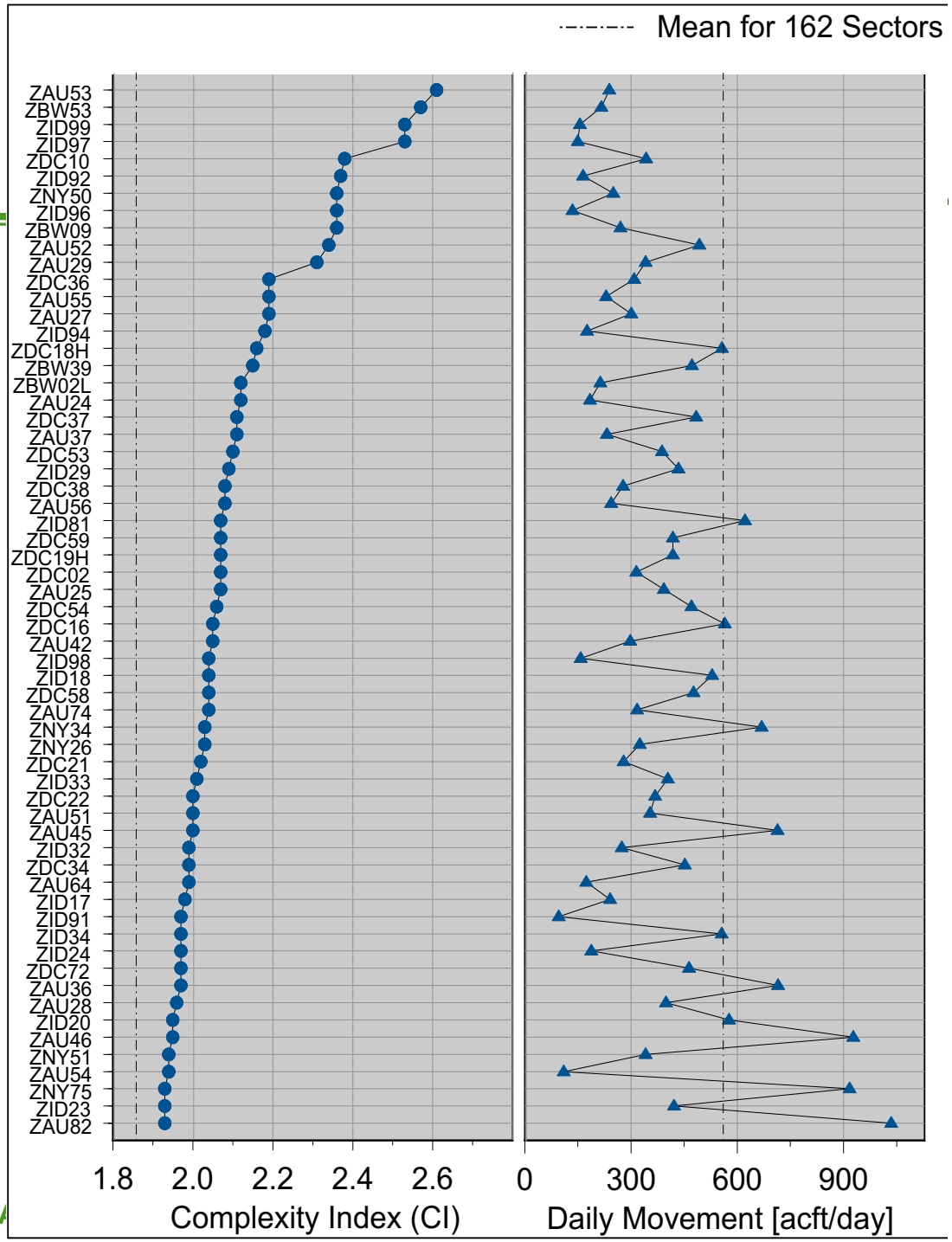


Complexity Index (CI) for 162 simulated sectors

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

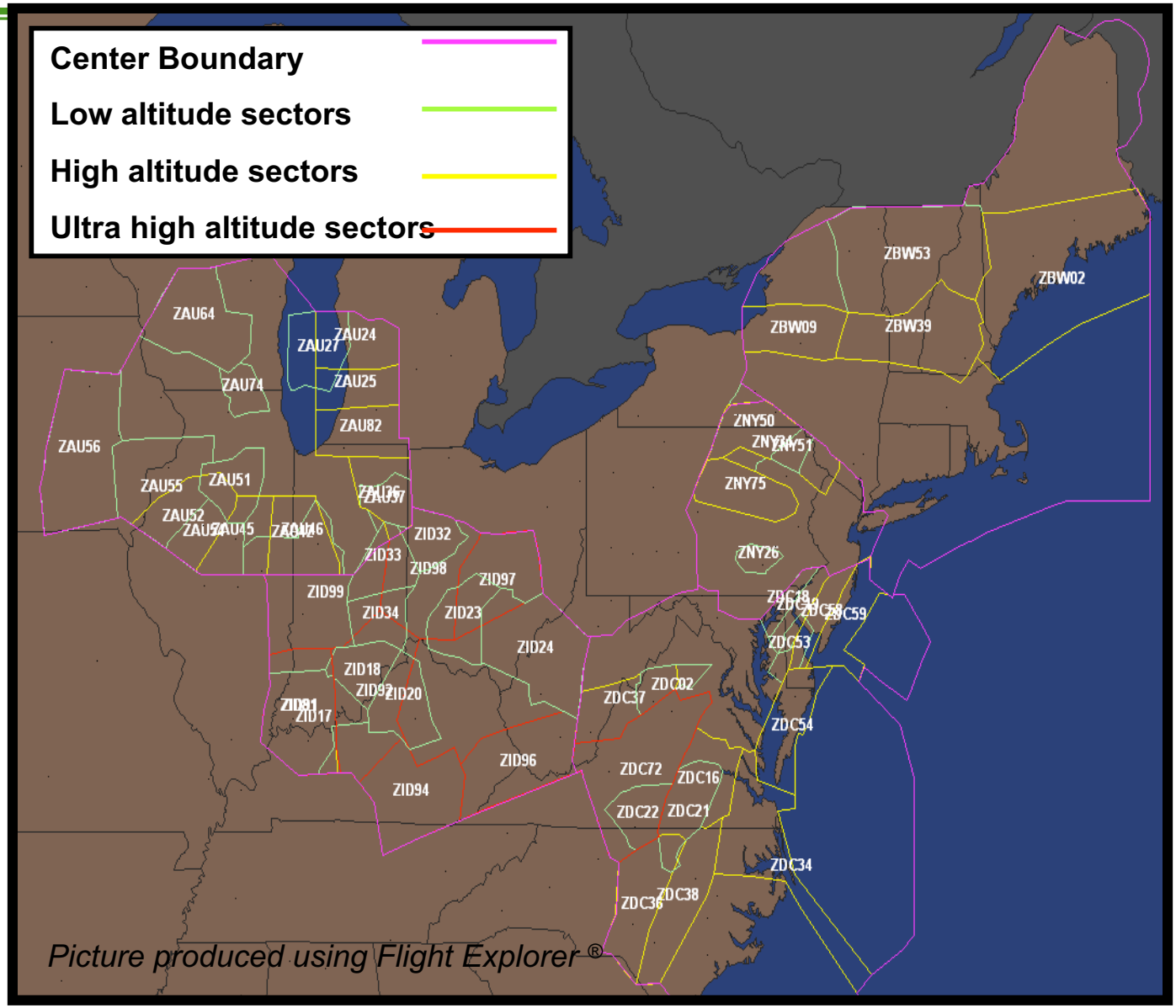
Result: Sector Rank by CI

- **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.

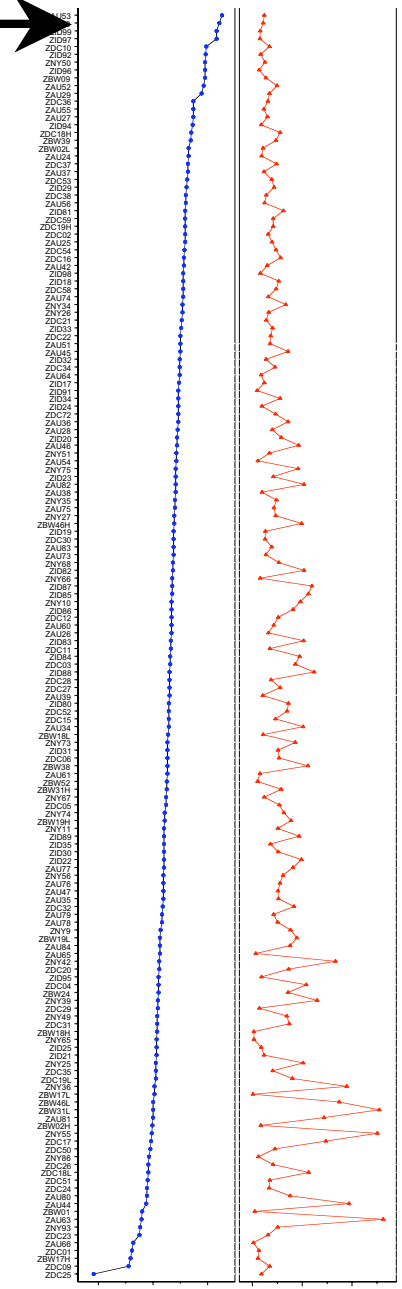


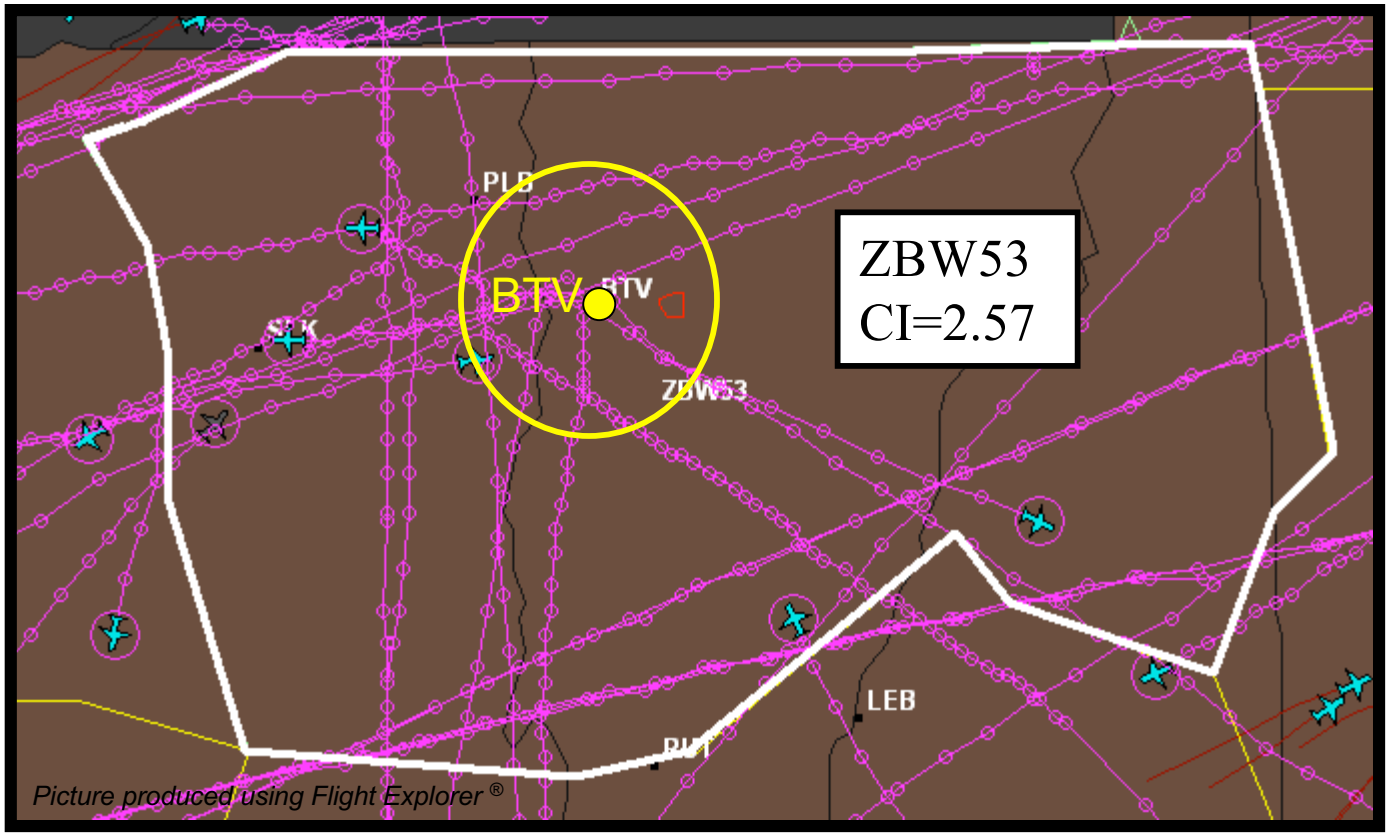
- Low altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Burlington INTL Airport
- Many level changes for flights operating out of BTV
- Short sector transit-times at the edges

Daily movement

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

Complexity order:
2/162



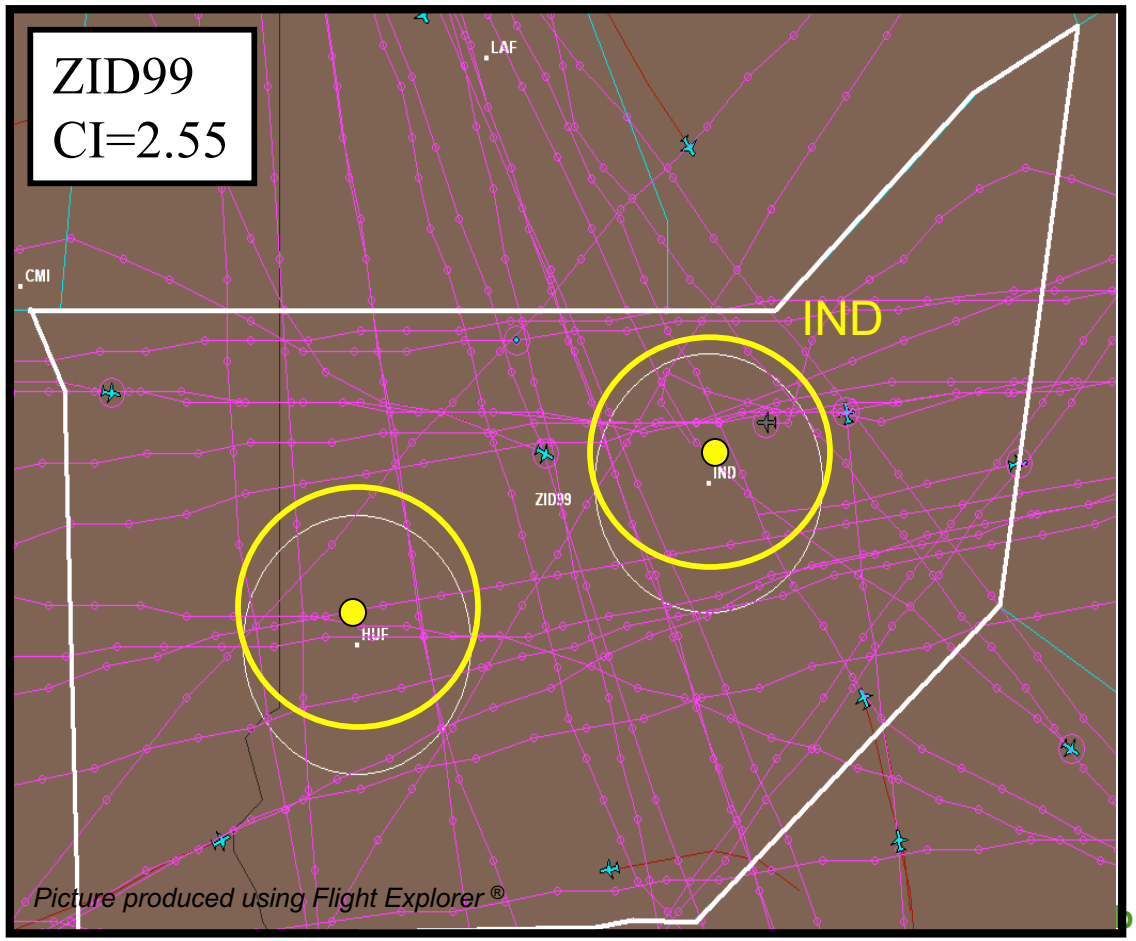


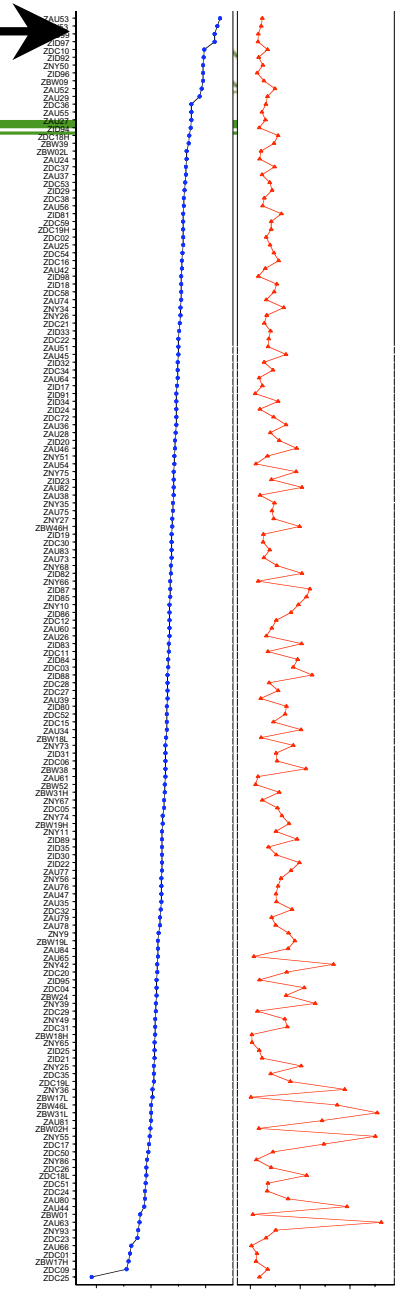
- High altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Indianapolis INTL & Terre Haute INTL Airports
- Many level changes for flights operating out of IND

Daily movement

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

Complexity order: 3/162

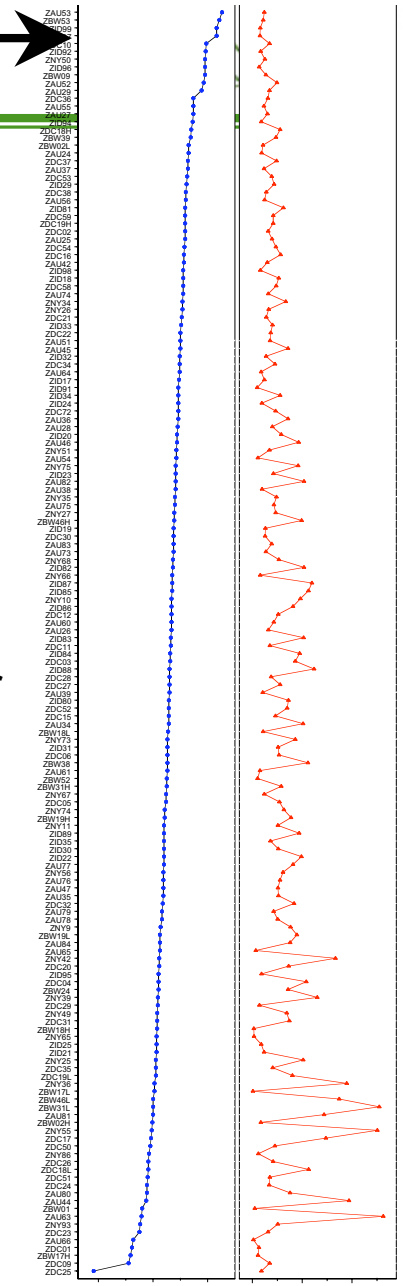


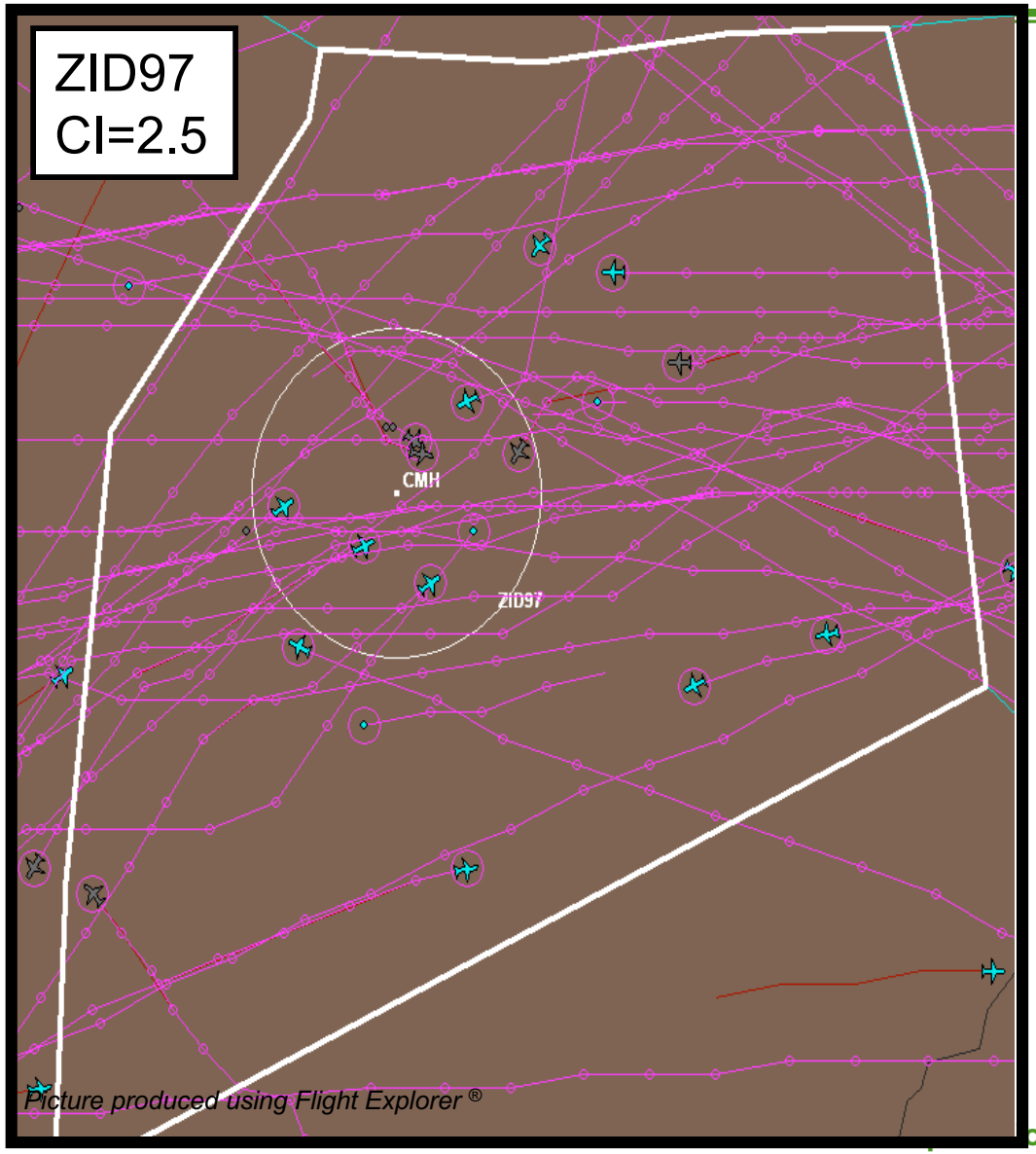


Daily movement

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

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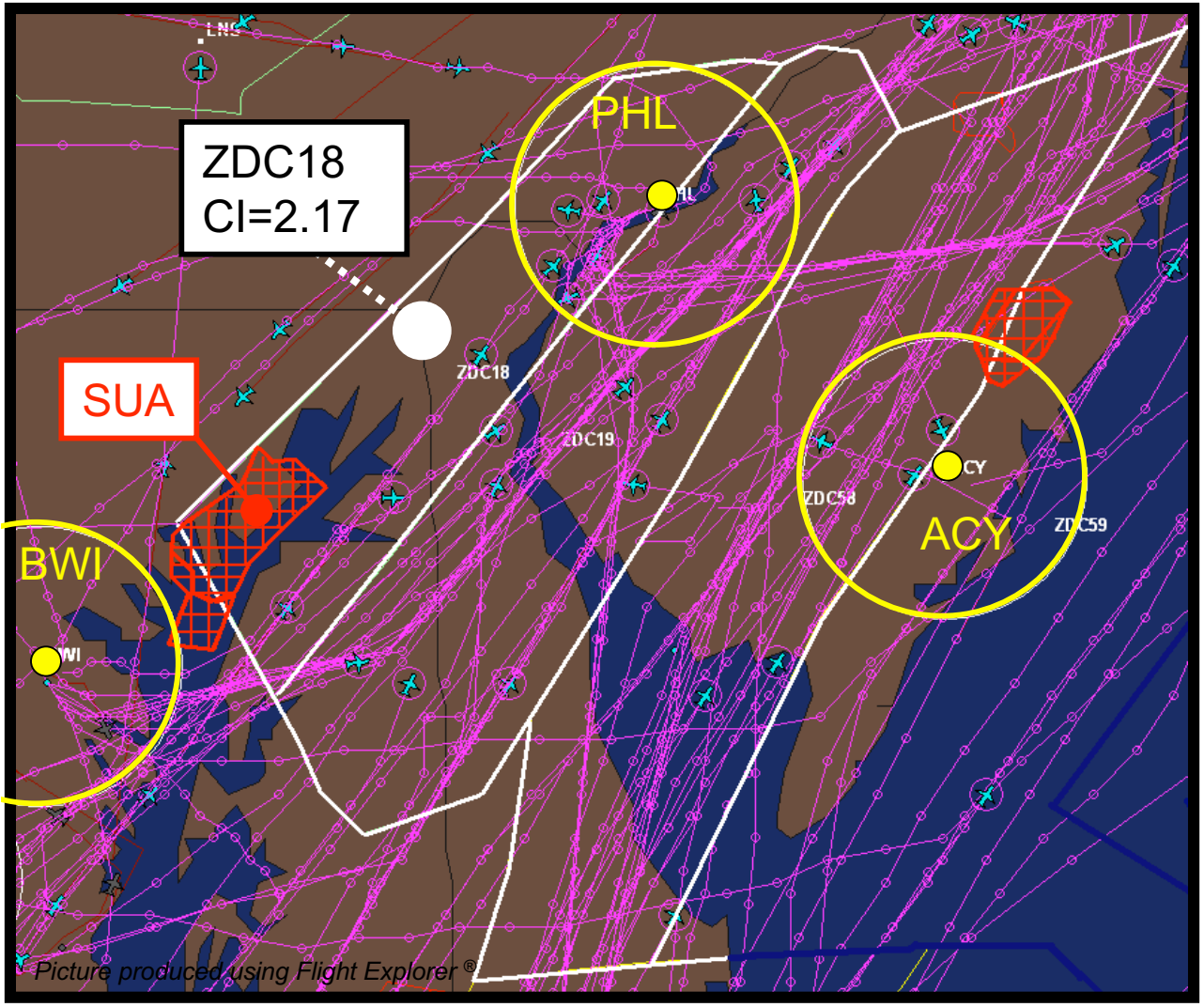
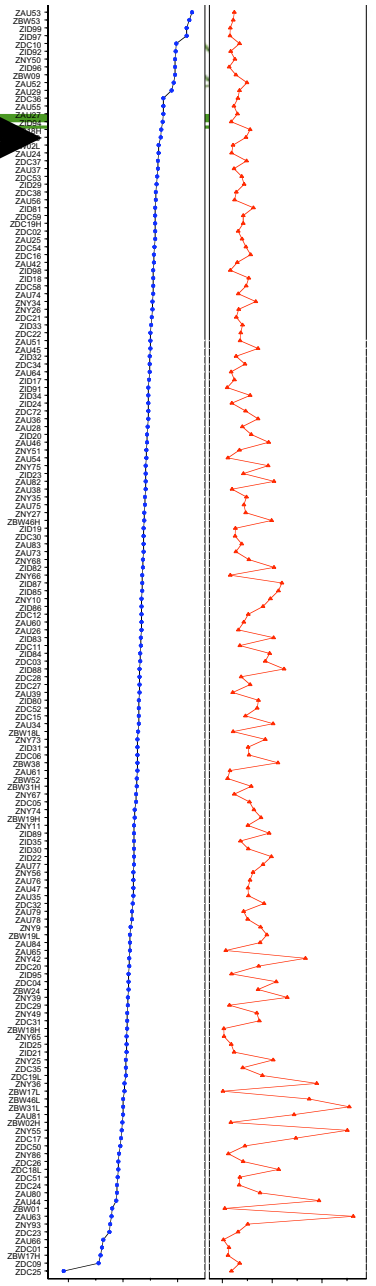
- Low altitude and small
- SUA blocks sector entrance
- Proximity of two large airports (BWI and PHL)
- Many altitude changes
- Almost structured but also many crossing traffic
- Short sector transit-times at the edges

Daily movement

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

Complexity order:
16/162



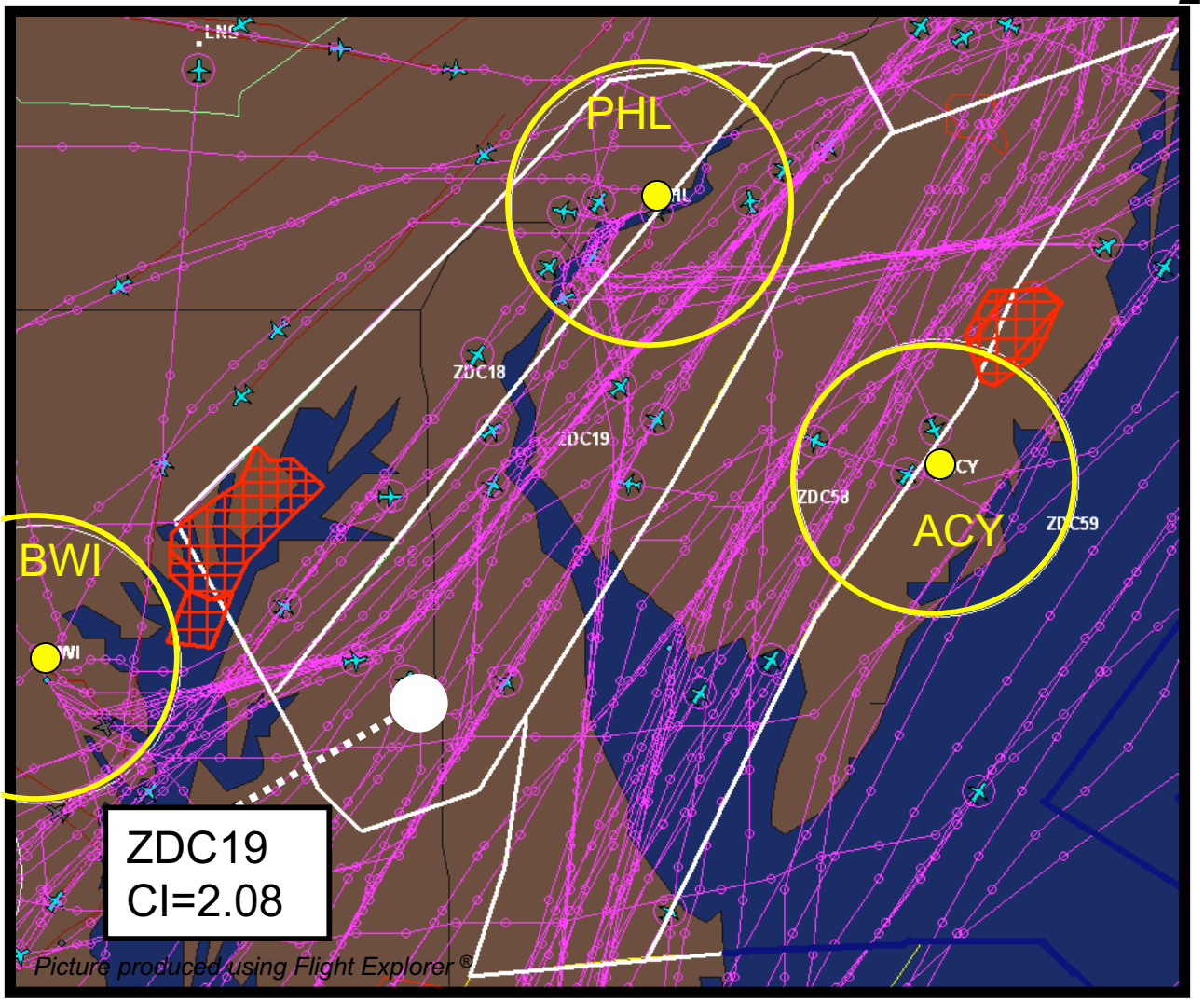


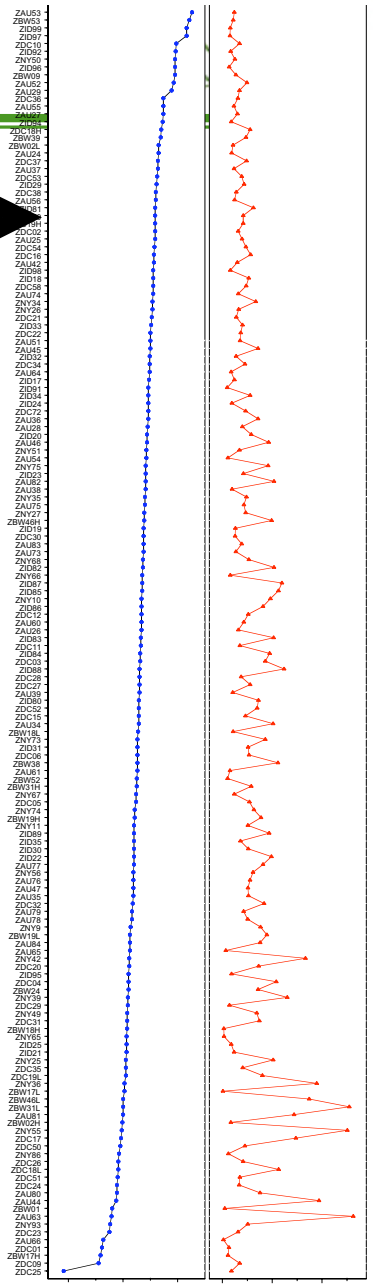
- Low altitude and small
- Structured but also many crossing traffic
- Proximity of three airports (BWI, PHL & ACY)
- Many altitude changes

Daily movement

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

Complexity order: 28/162



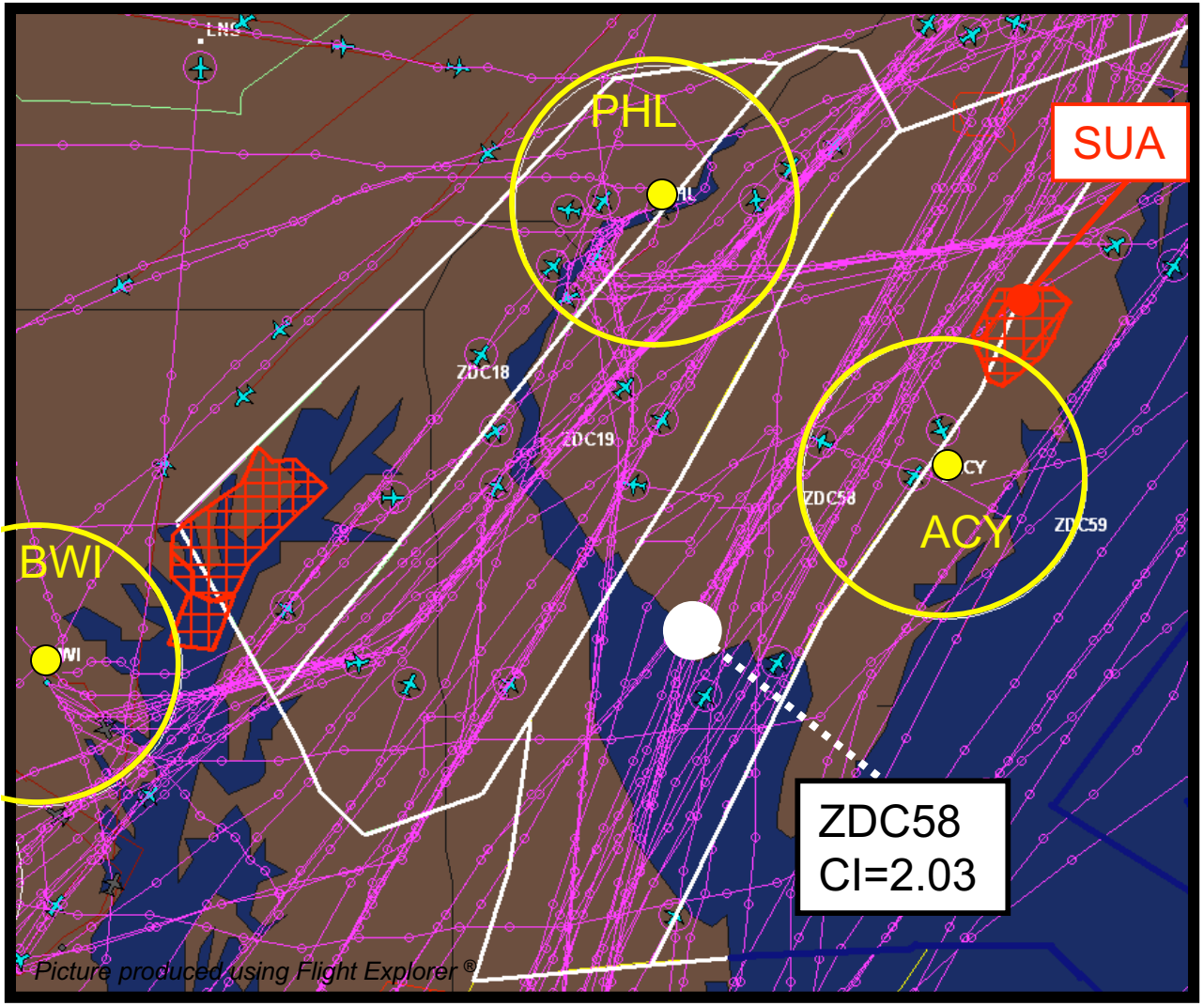


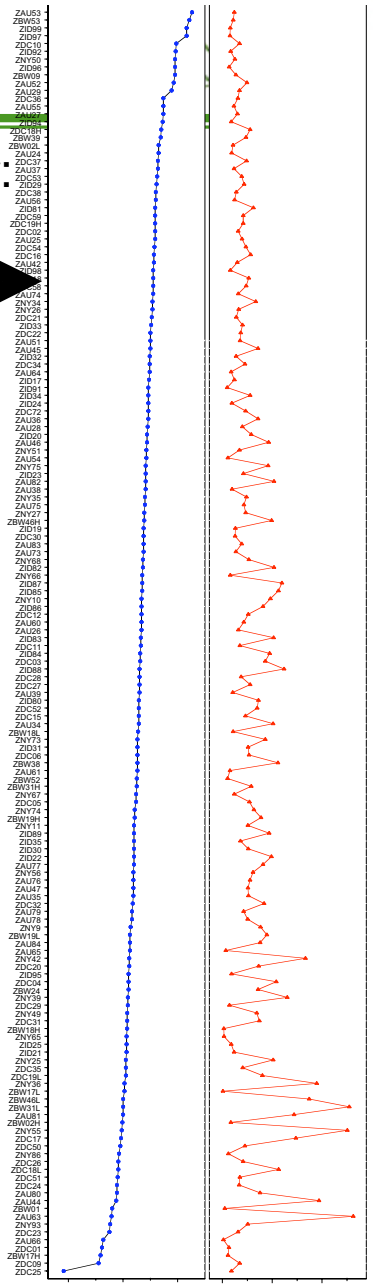
- High altitude
- Small volume
- Structured but also many crossing traffic
- ~~Proximity of two large airports (BWI and PHL)~~
- Proximity of SUA

Daily movement

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

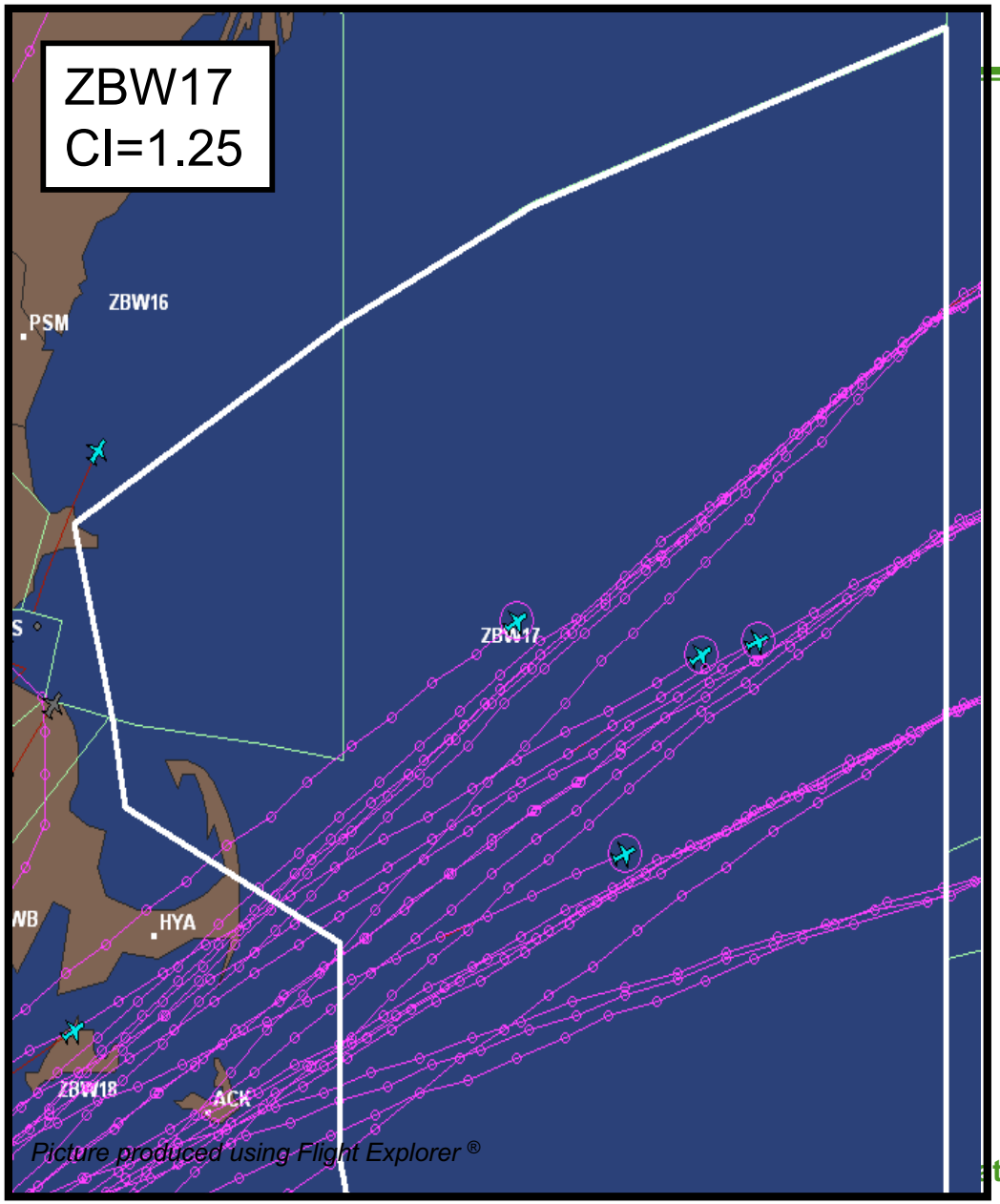
Complexity order: 36/162



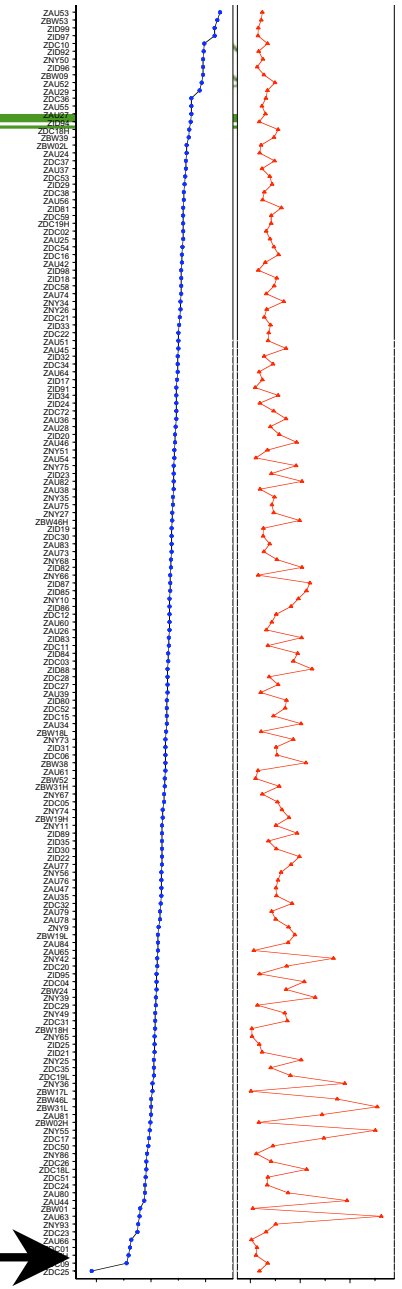


Daily movement

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



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



Complexity order: 160/162

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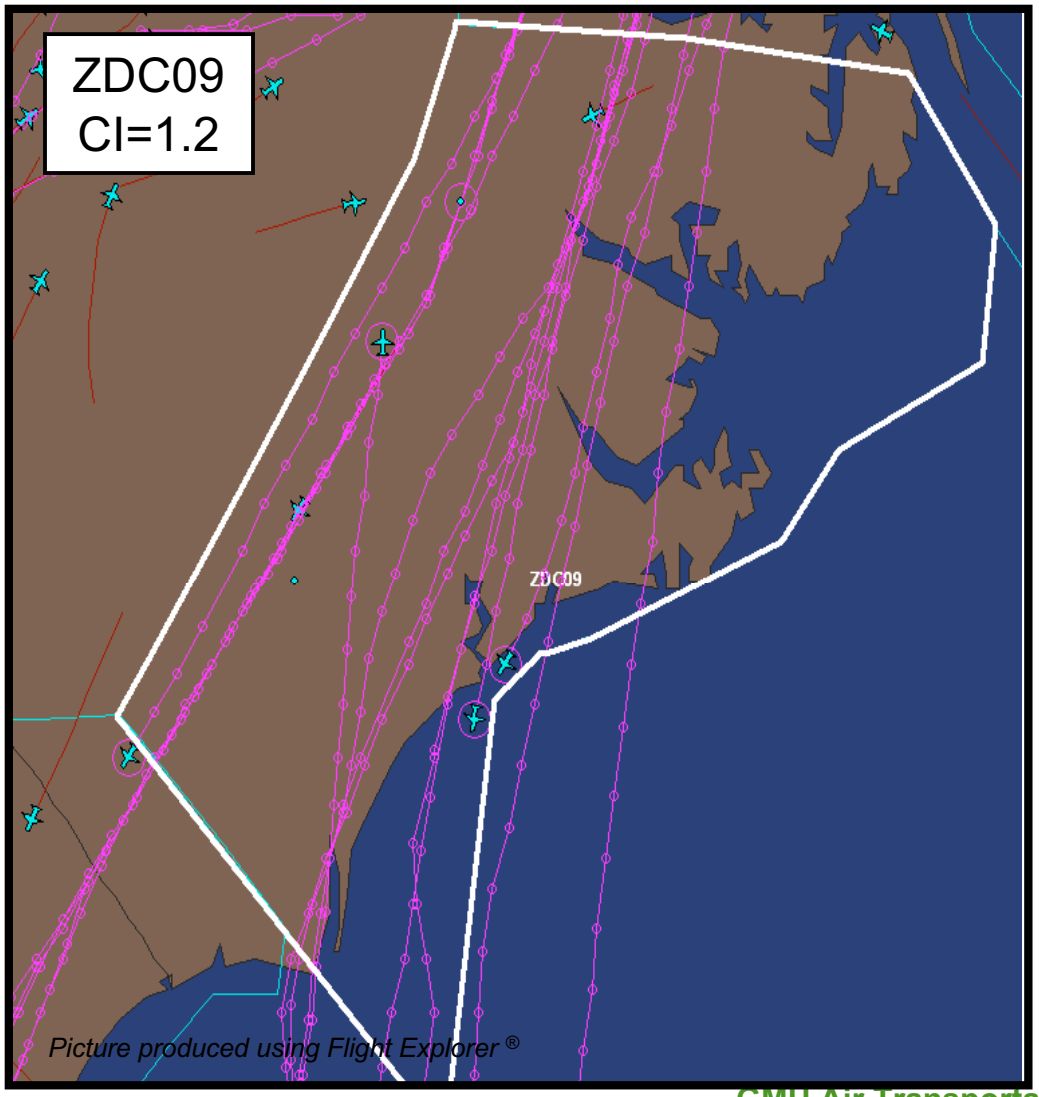
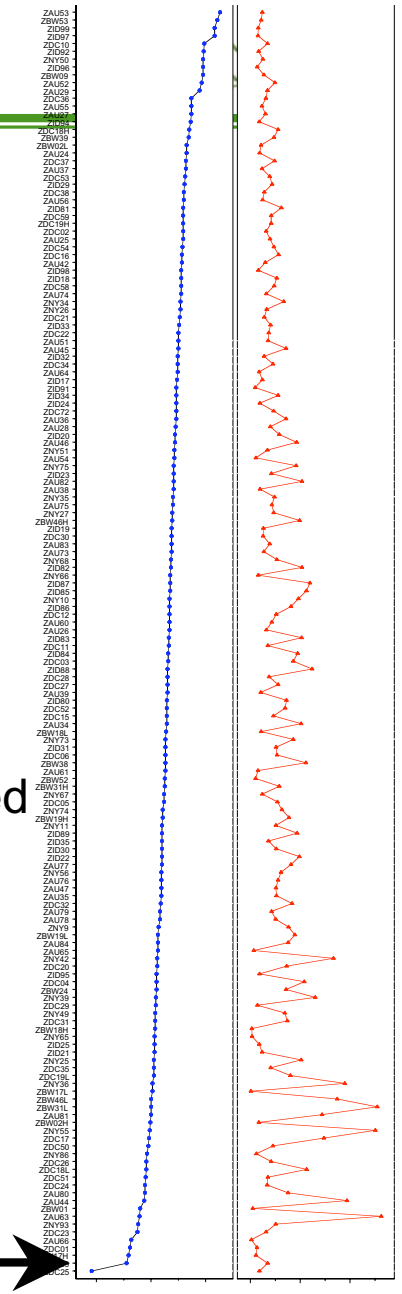
Daily movement

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



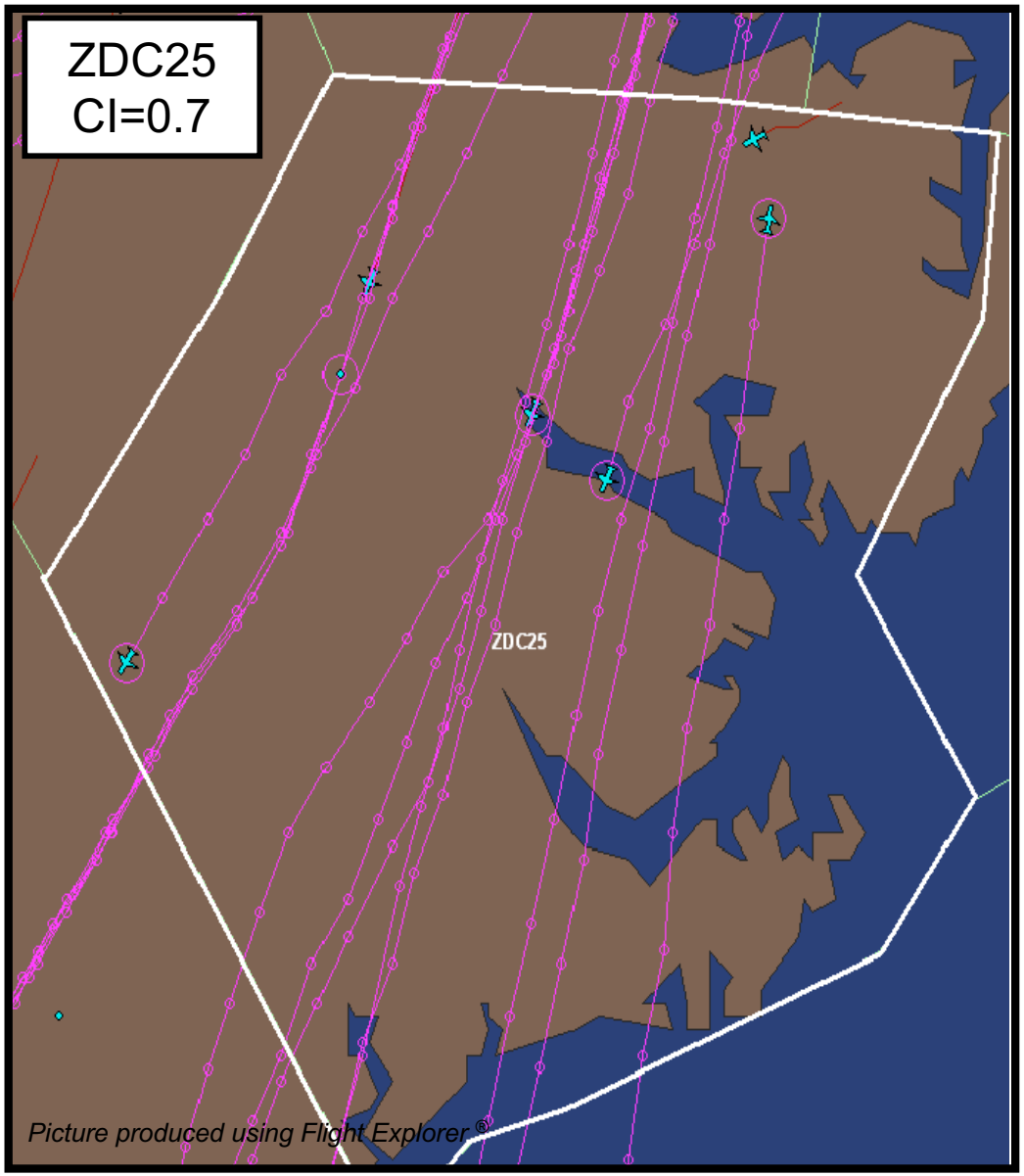
- Ultra high
- Structured traffic
- Low density
- Next to non-controlled airspace
- No SUA
- Inter-sector handoff points are concentrated



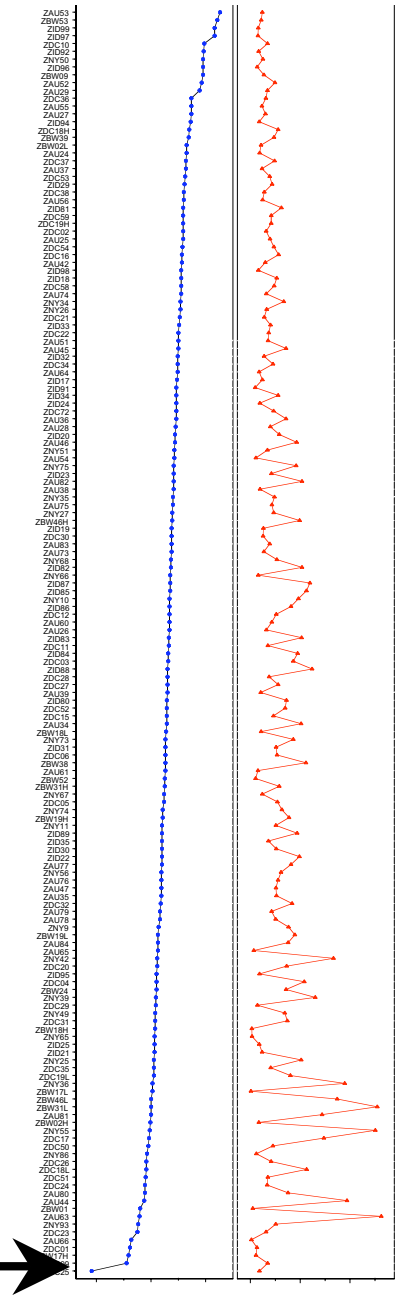
Complexity order: 161/162

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



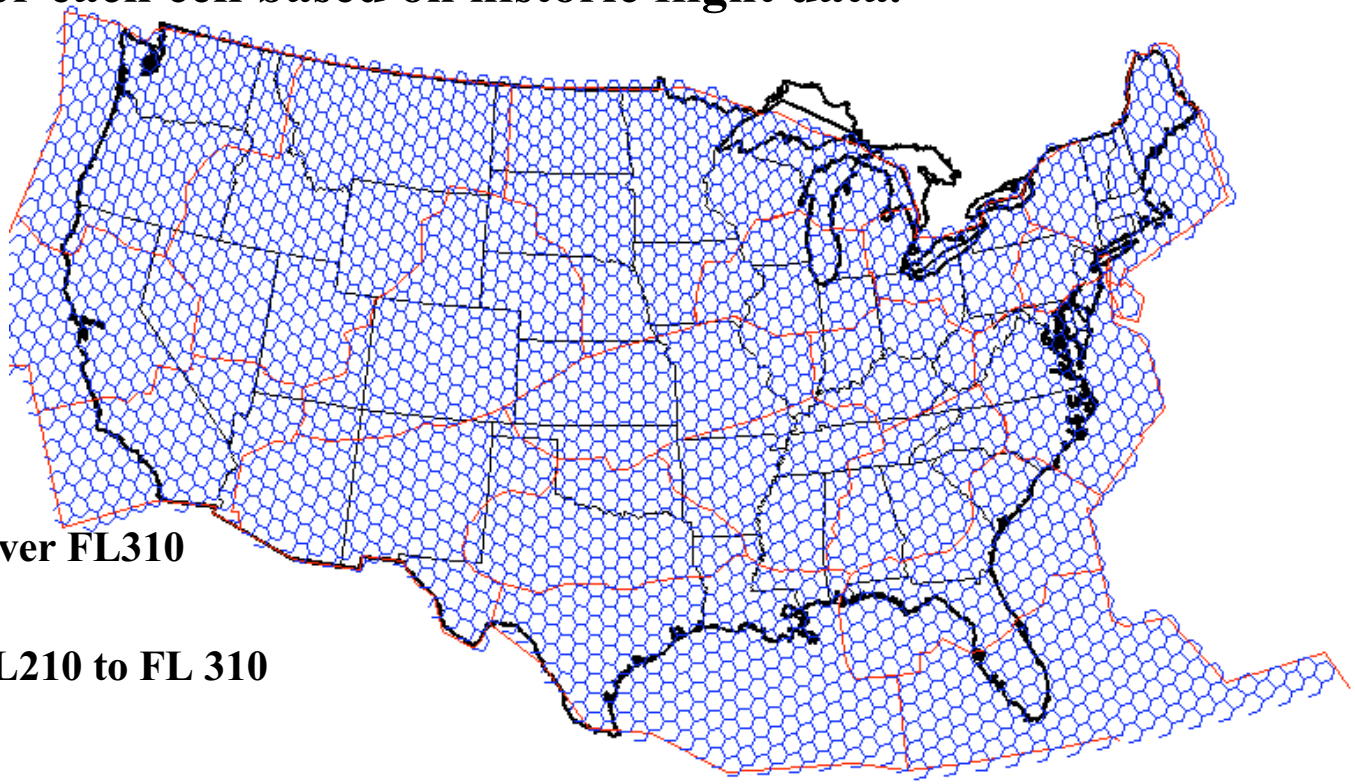
Complexity order:
162/162

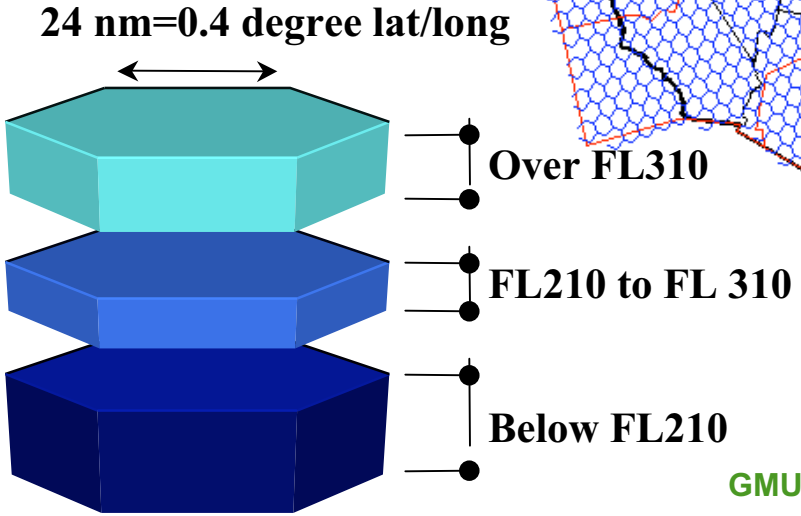
Apply CI Metric and Optimization Theory to New Concepts in Airspace Design

- **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 …**

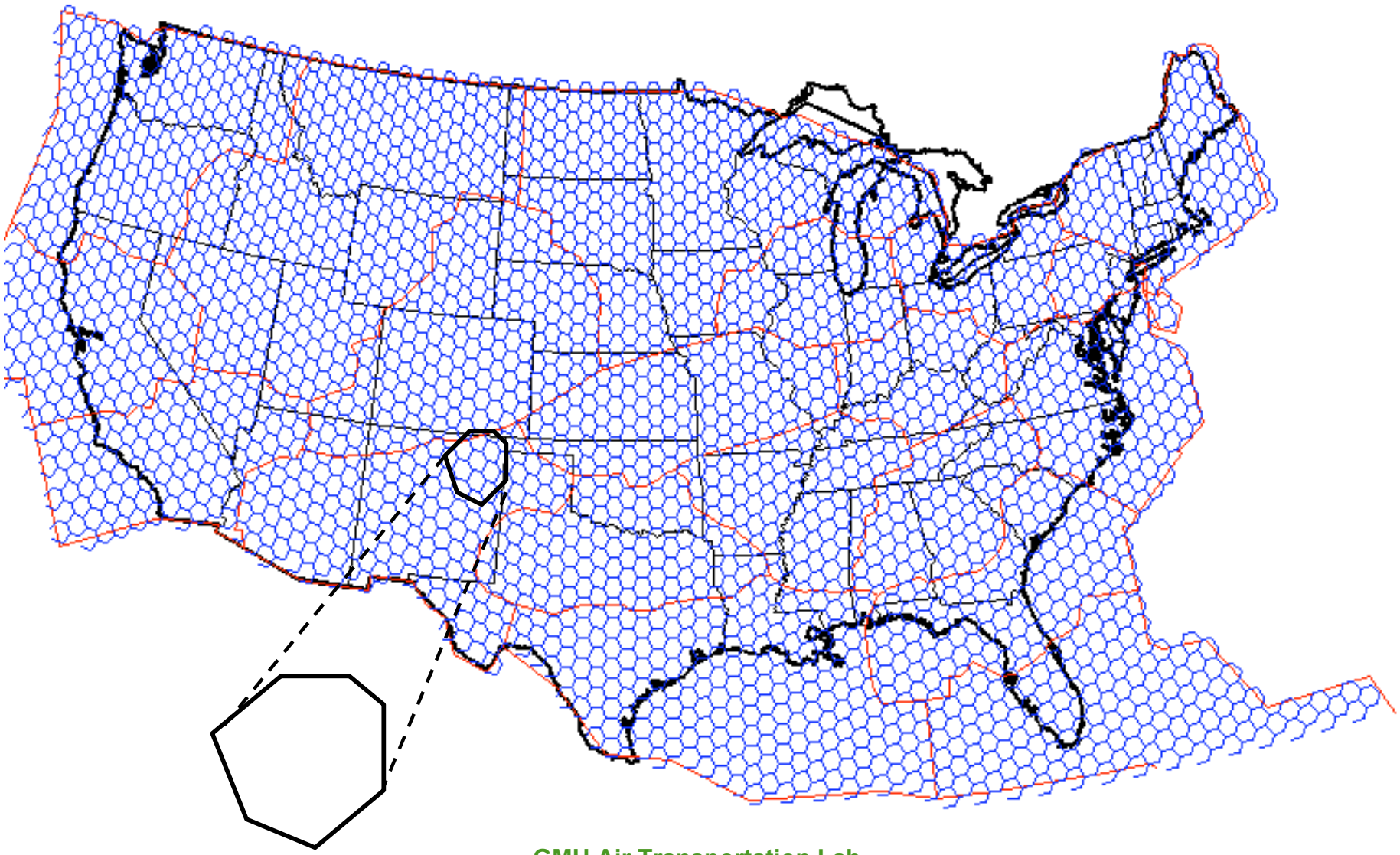
Hex-Cells Chosen as Airspace Building Block Elements

- 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

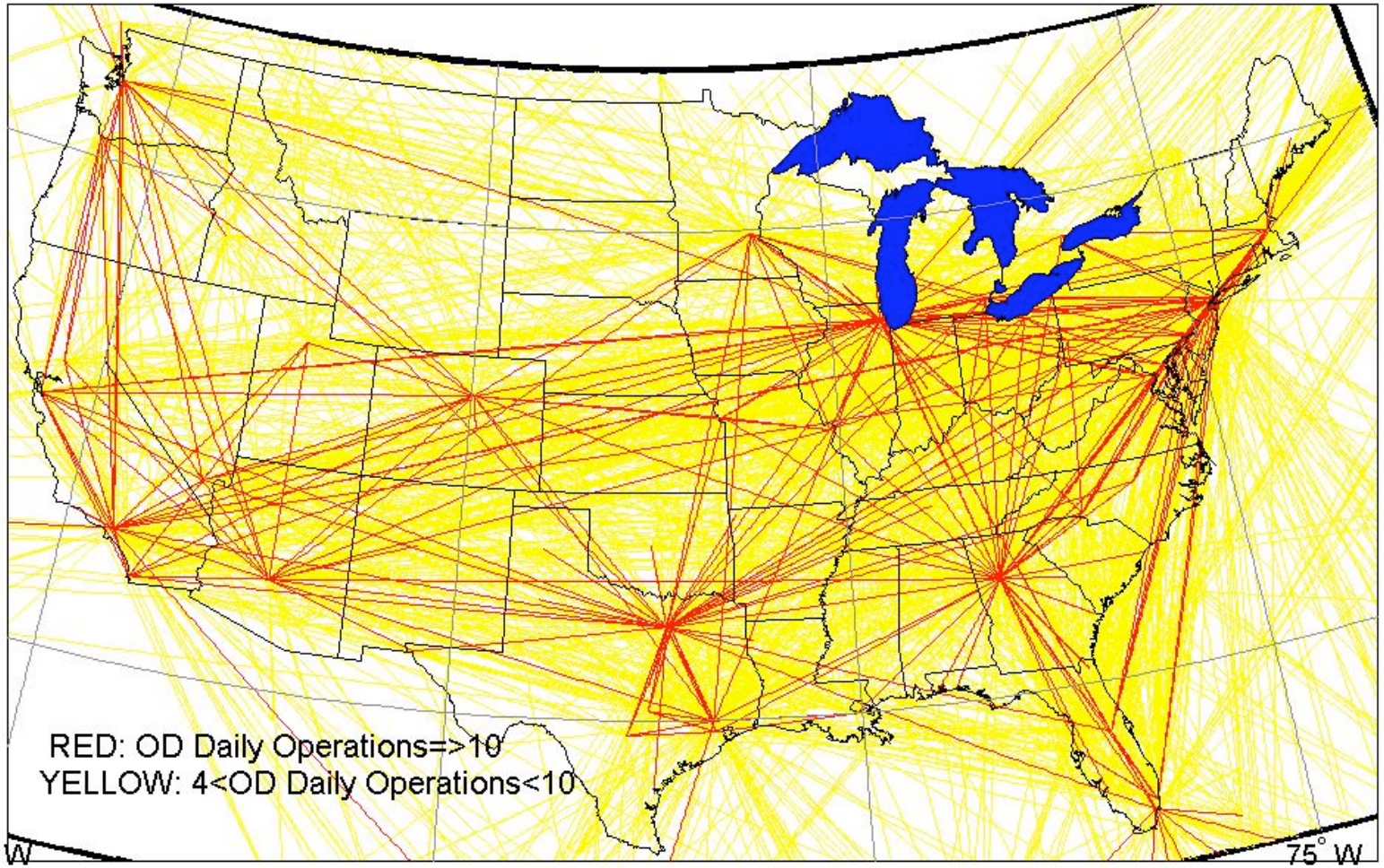
B. Non-Scheduled (~1/3 layer A)

I. Short range GAs

II. Long range GAs

Layer A – Potential HOV Ribbons

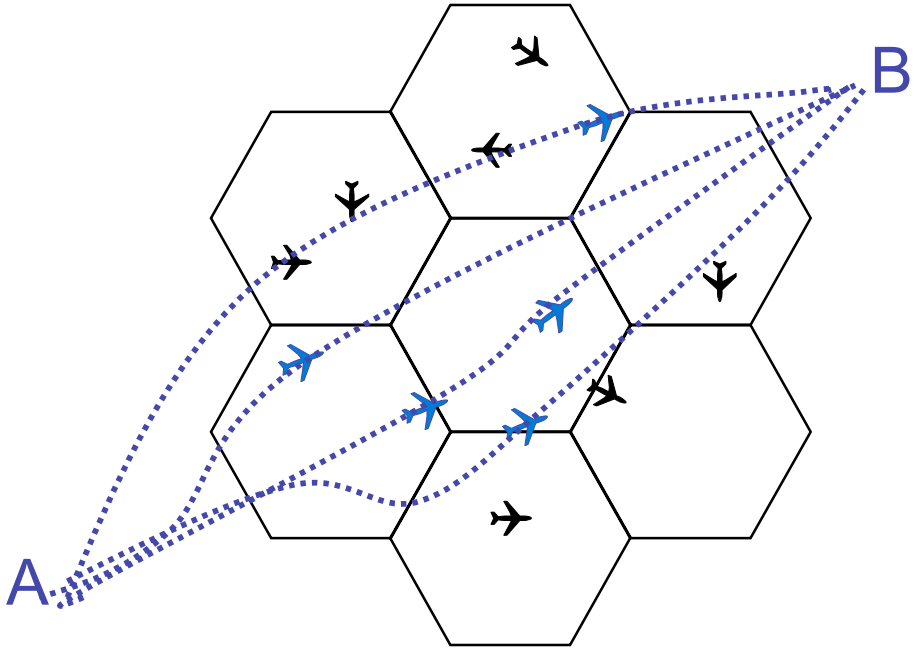
- Yellow→ Layer AI,
- Red → Layer AII



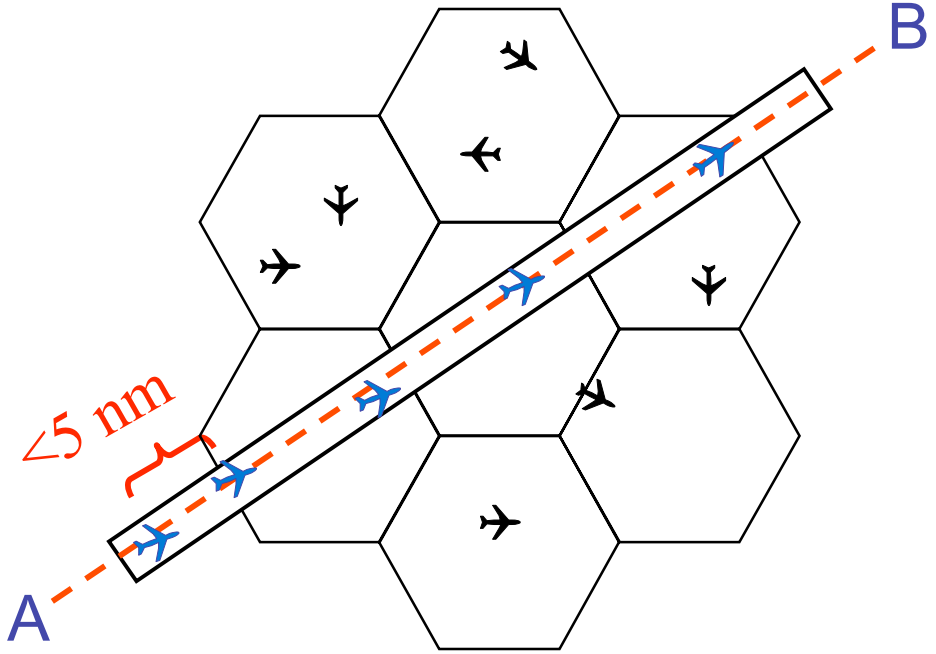
High-Volume Tube-Shape Sectors (HTS)

- 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

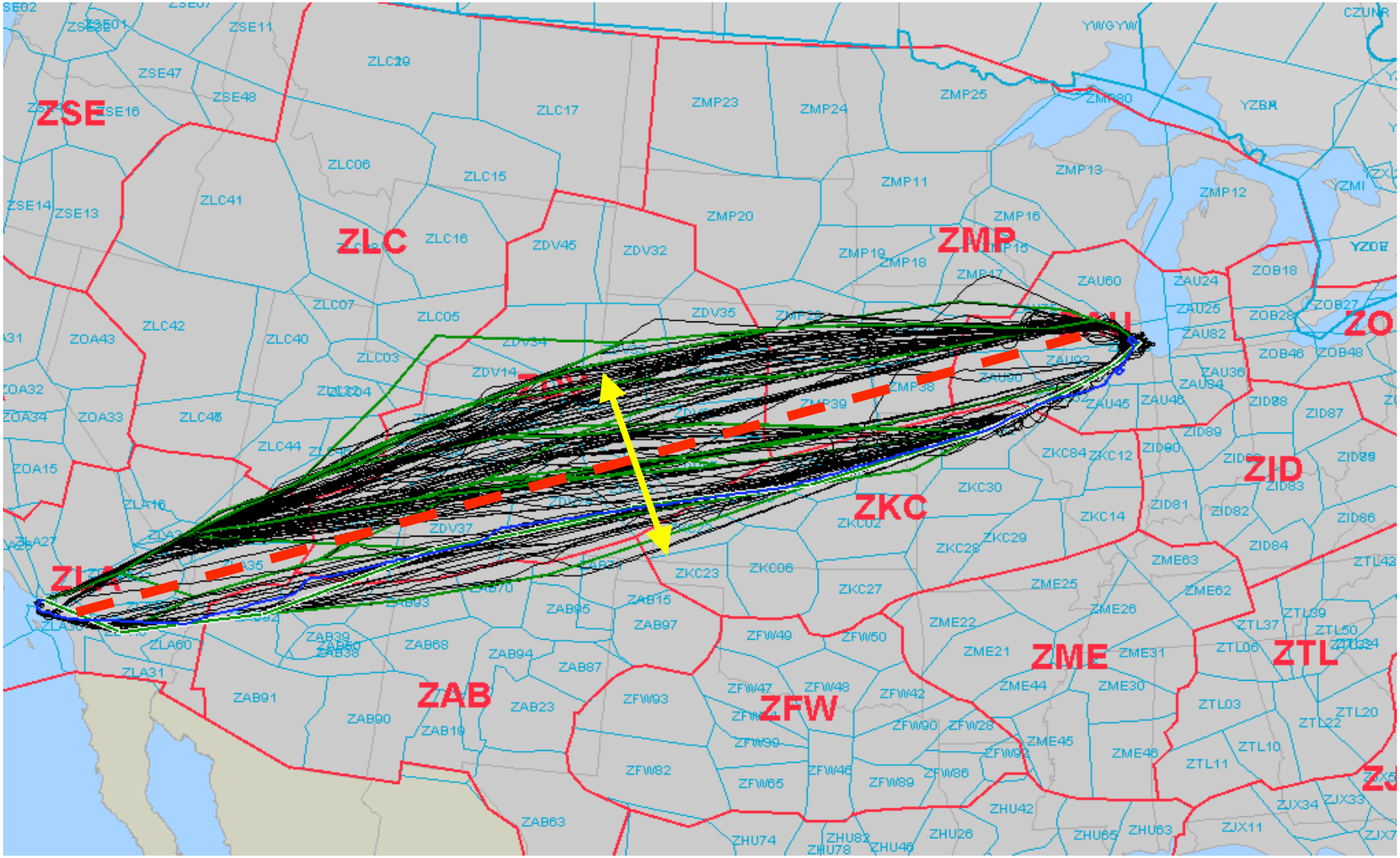
High-Volume Tube-Shape Sectors (HTS)



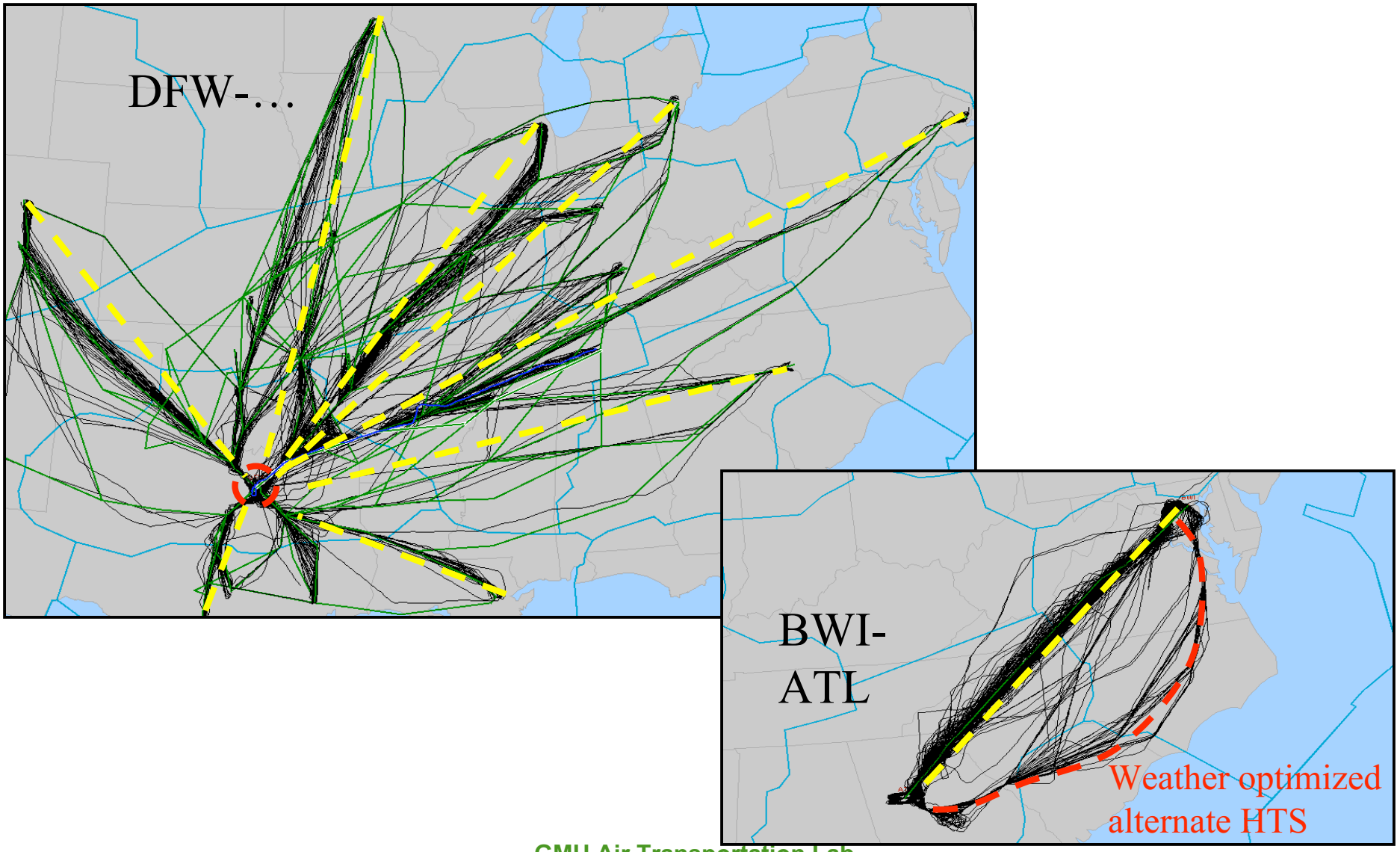
Weather Uncertainty will Dynamically Rubber-Band the HTS



ORD-LAX HTS

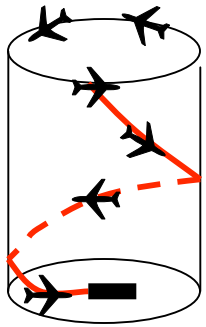


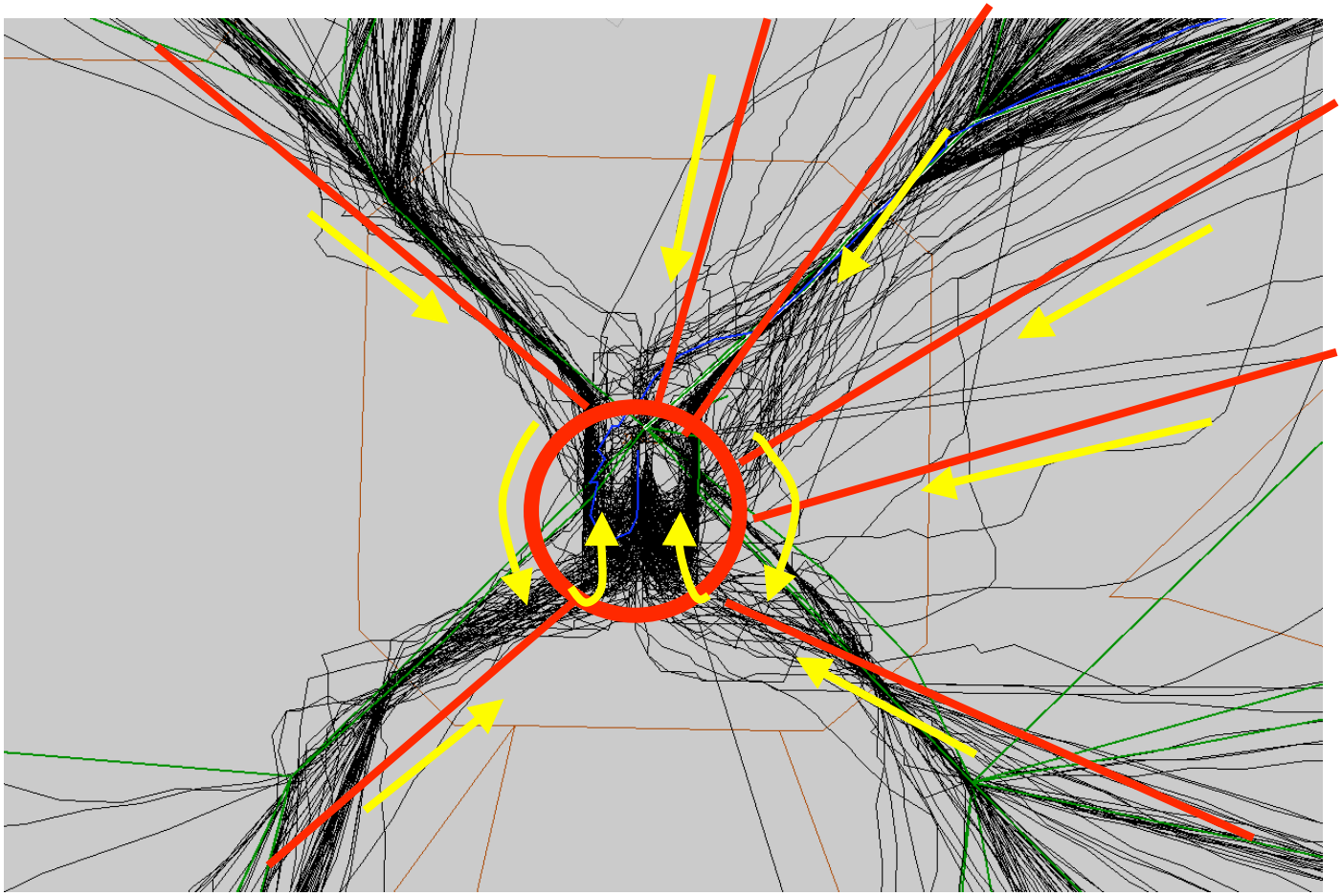
High-Volume Tube-Shape Sectors (HTS)



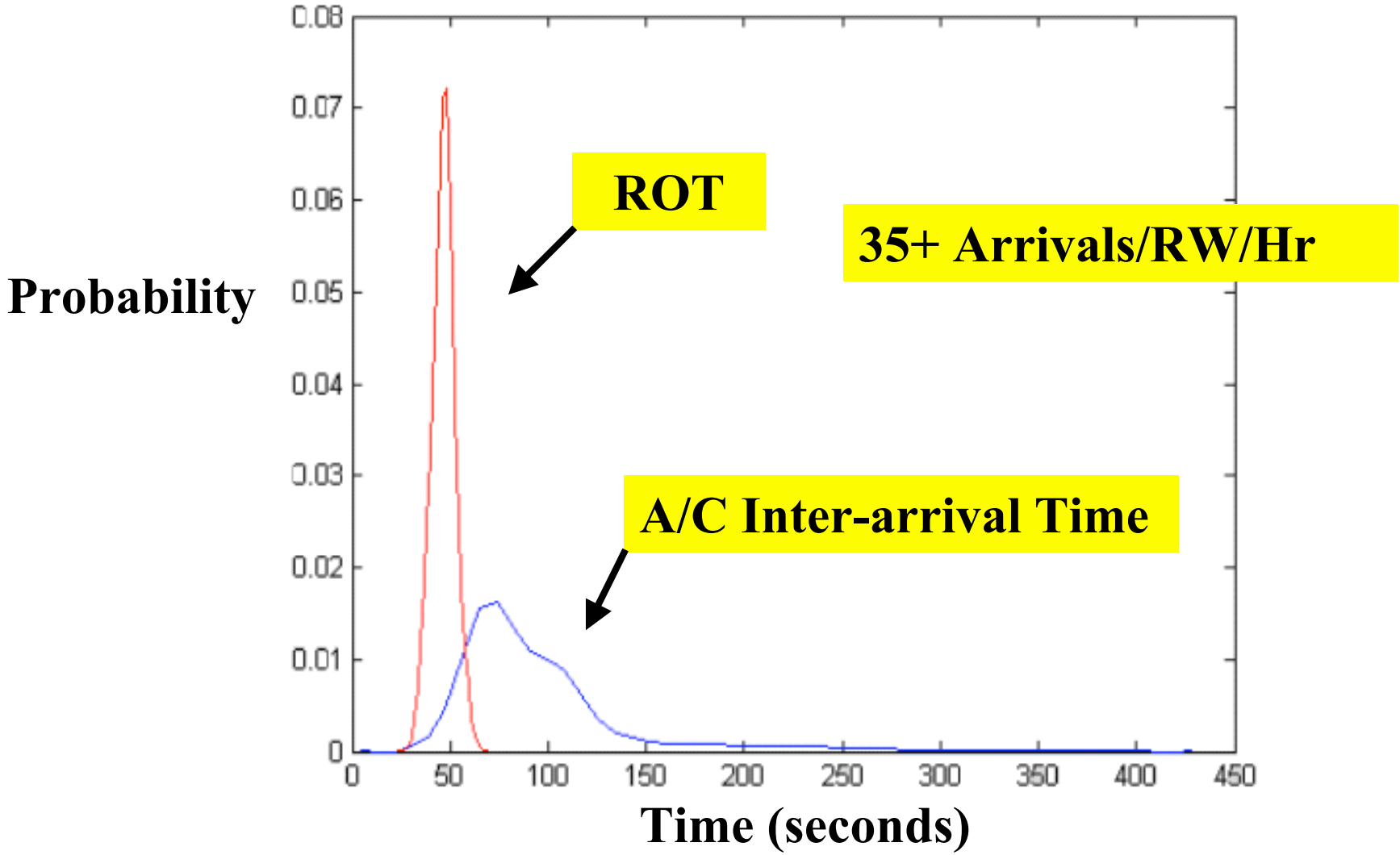
Example of a High-Volume Tube-Shape Sector (HTS) Network Node

HTS intersections in terminal area





Time Separation PDF's Contribute Strongly to the SAFETY Limitations

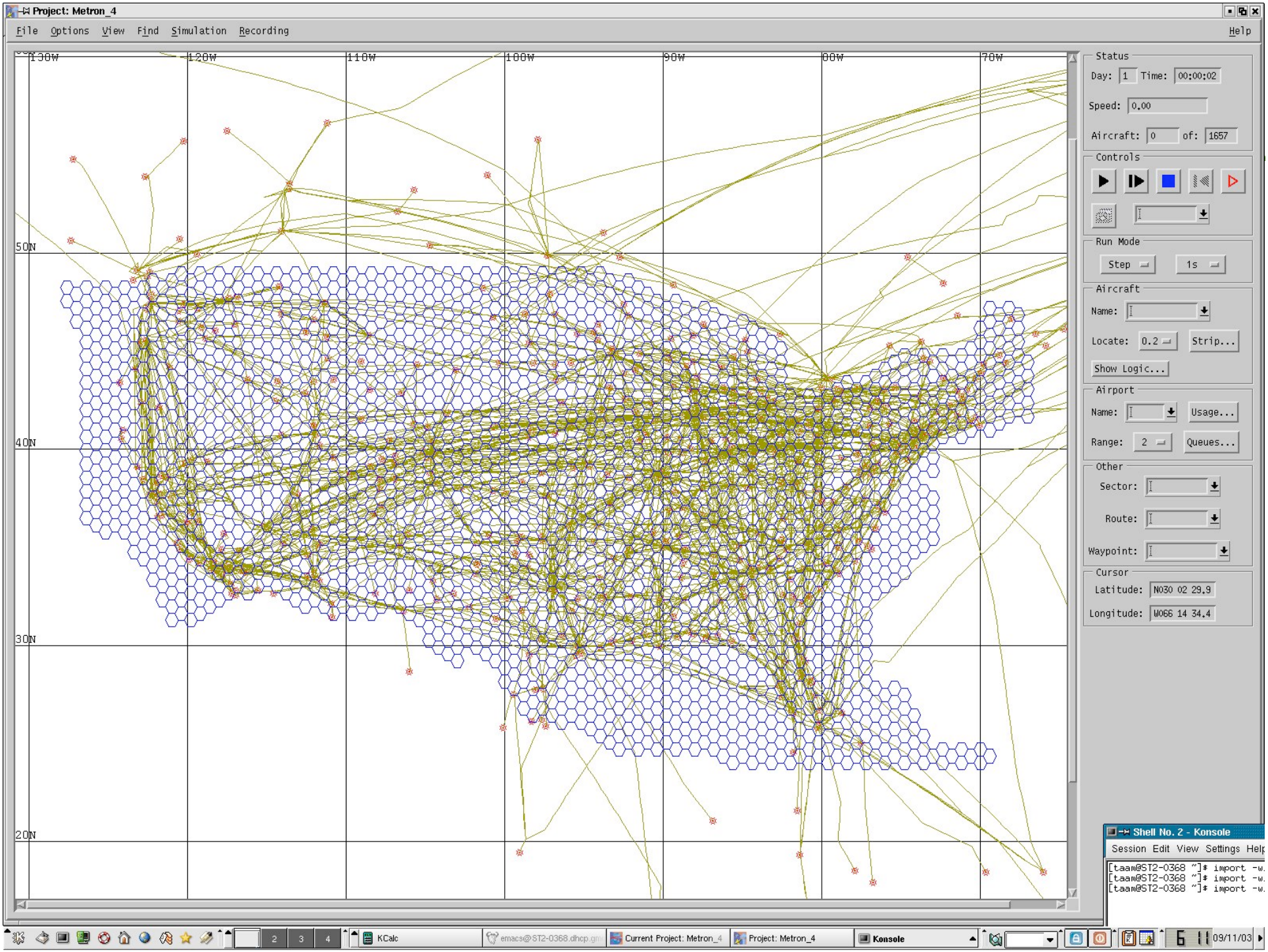


Select 45,000 ETMS Flight Plan Tracts and Compute Simulated HEX-Cell WL/CI using TAAM

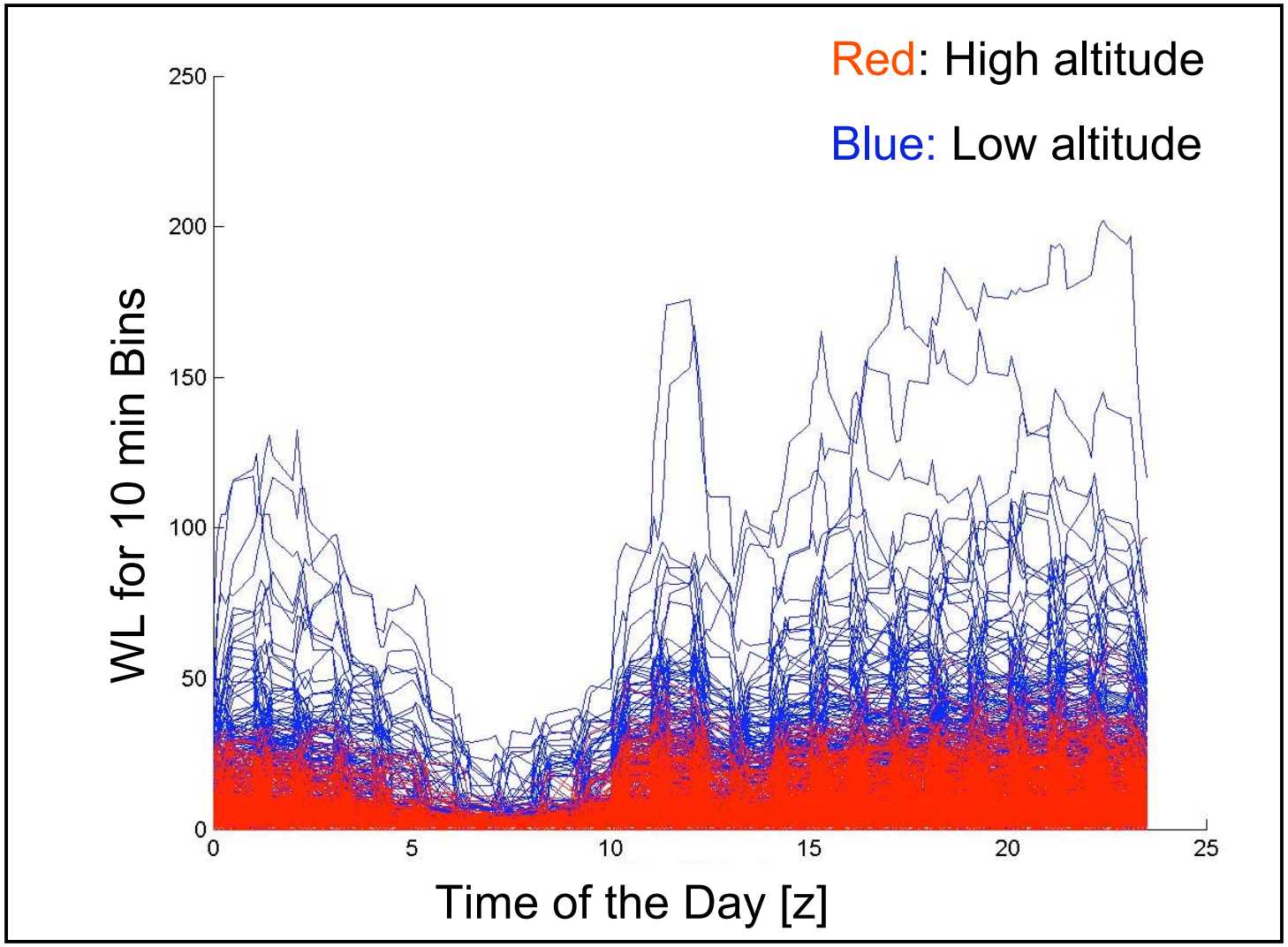
- For each flight ID in ETMS database there are few flight plans reported by airlines
  1. ***Filed flight plan :*** Before the ETD of each flight, airlines update the flight plan to avoid adverse weather or congested areas or ….
  2. ***Advisories:*** FAA issues flight plans as late as few minutes before 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
```

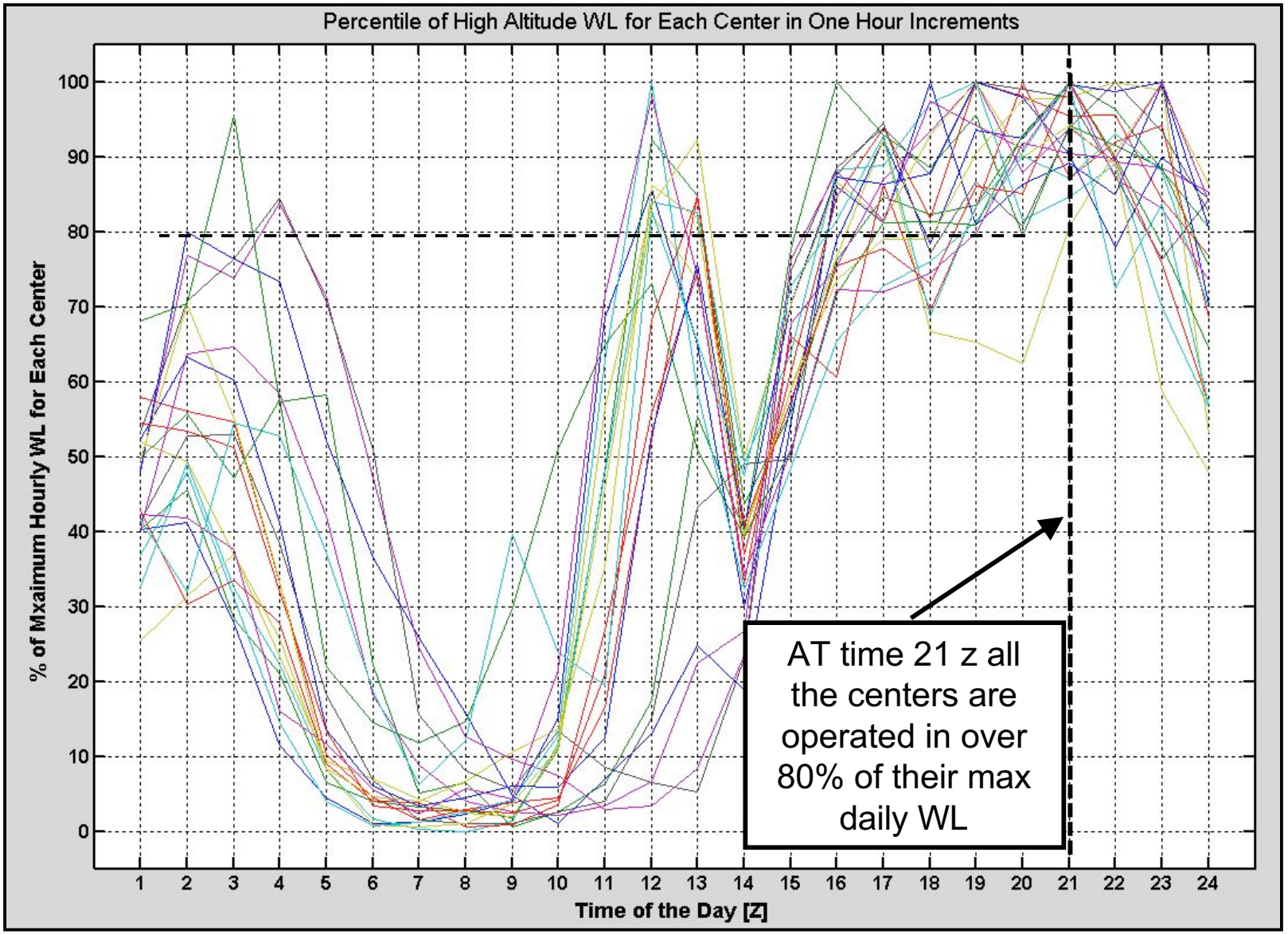
Sample Flight track


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

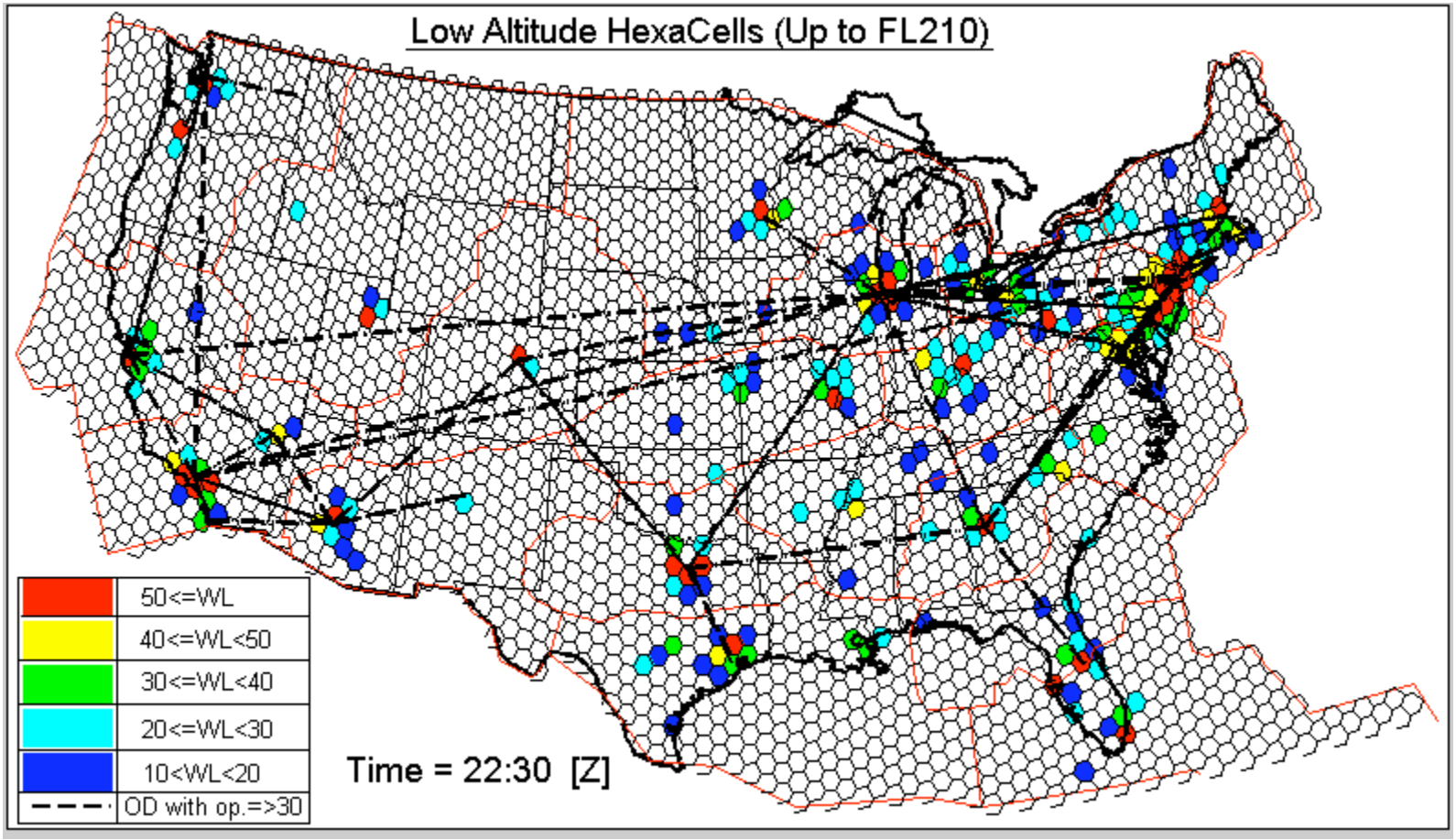
WL Trend in Each Hex-Cell Throughout the Day



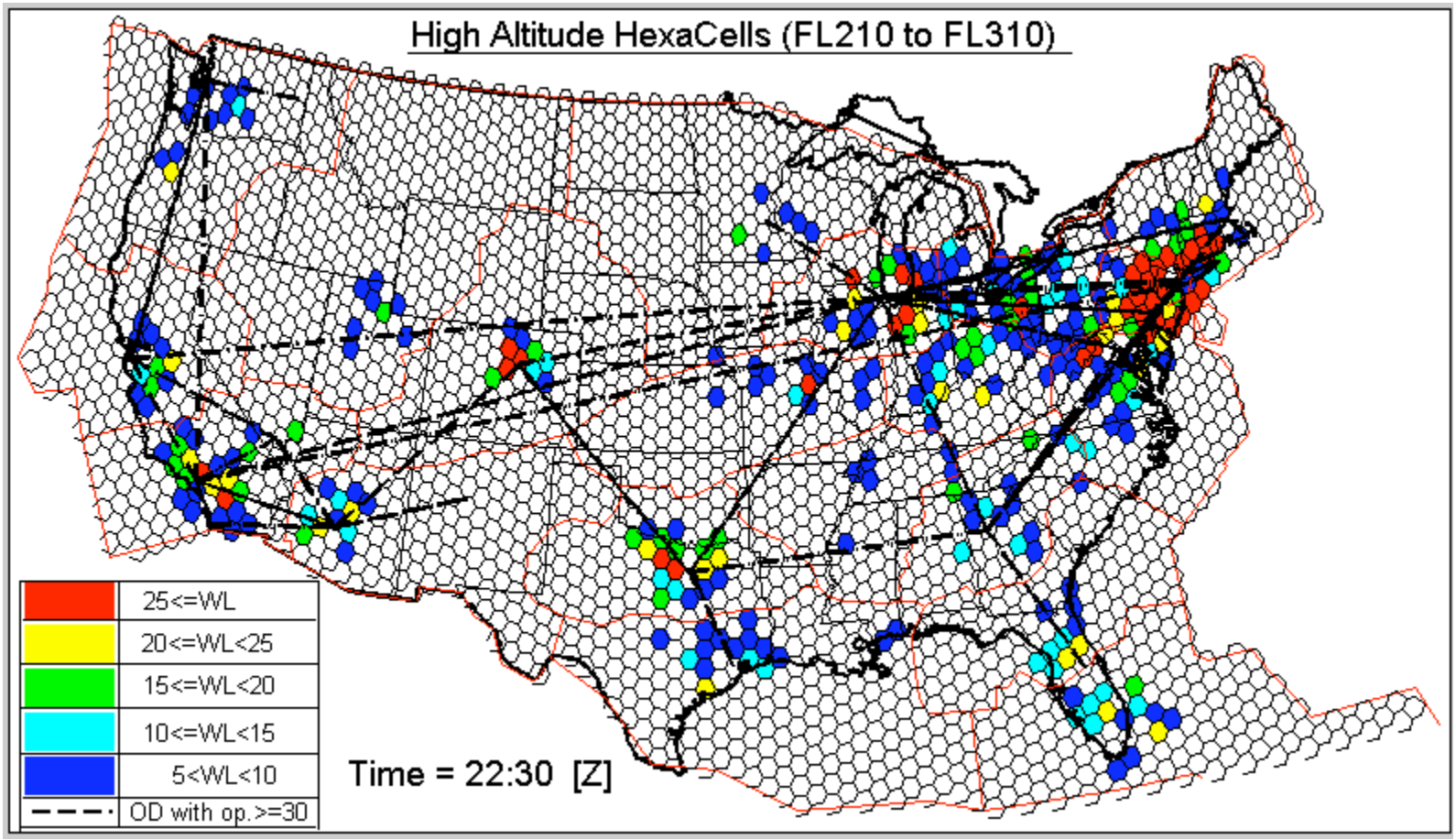
WL Variation Within Centers *(cnt.)*



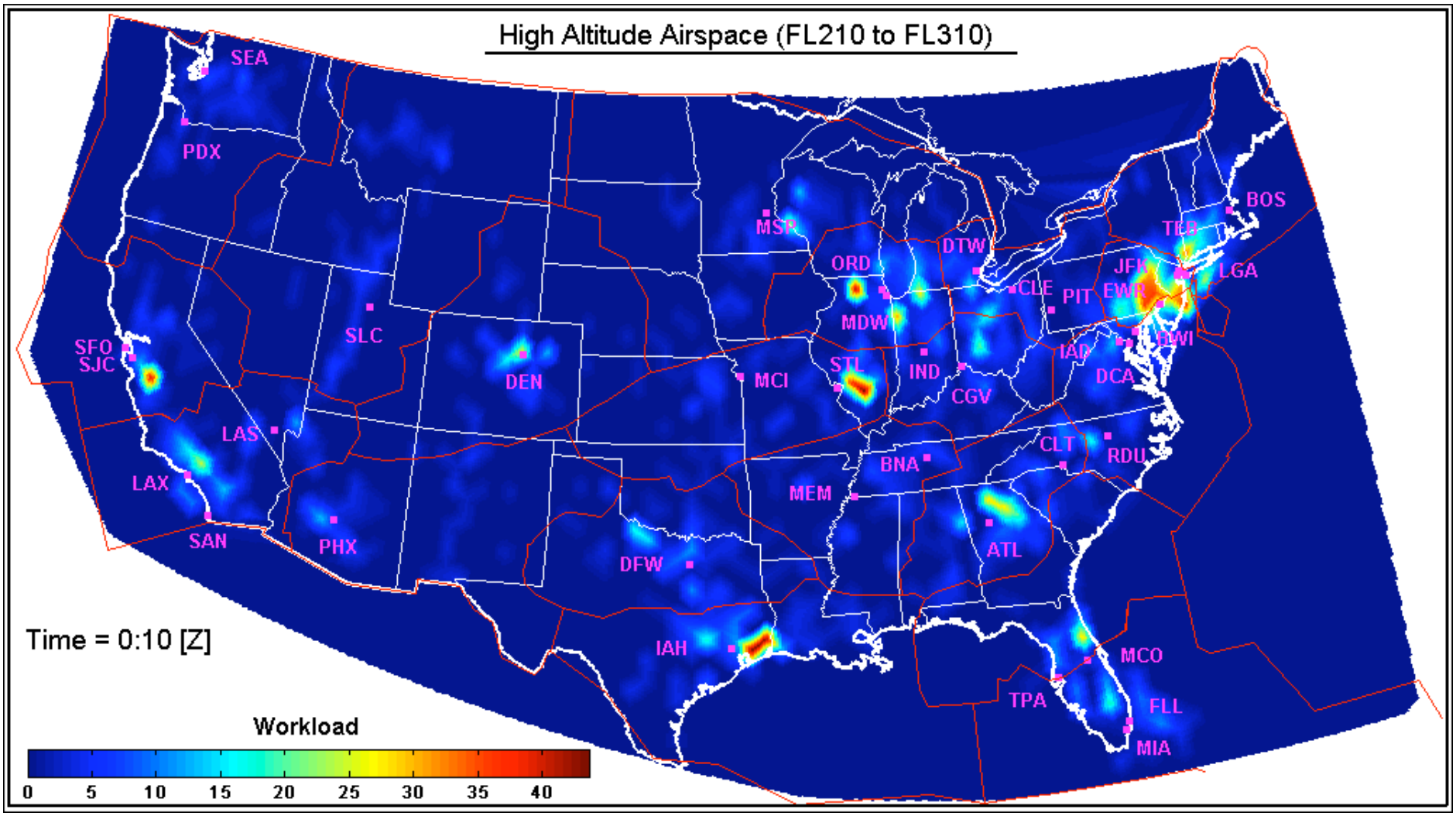
Role of HTS in Reducing Complexity



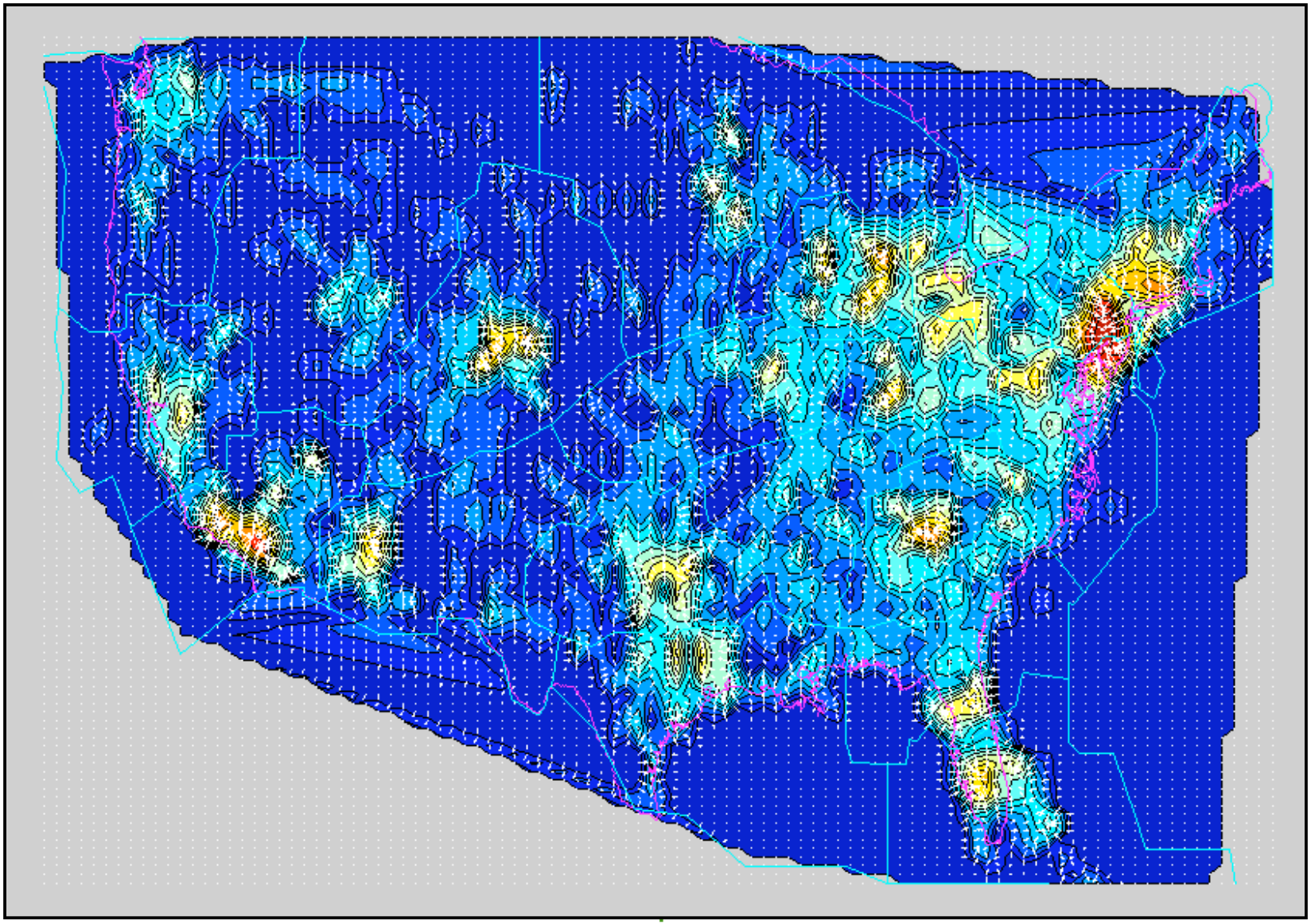
Role of HTS in Reducing Complexity



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



WL Vector Fields



Simulation and Operational Metrics Should be the SAME

- **Potential Non-Dimensional Scaling Metrics for Consideration**
  - **Quality of Service Vector Statistics:**
    - **(Delay, Cancellation, Variability) OD Correlation Matrix**
  - **Transportation:**
    - **Enplanement to Max Enplanement Ratio**
    - **HHI Competition Index**
  - **Safety: Estimated Hull Loss per Operation**
  - **Efficiency:**
    - **Airport Demand to Capacity Ratio @ 7 min. delay**
    - **Aircraft Block Time to Schedule Block Time Ratio**
    - **# Aircraft to # Controller Ratio**
  - **Cost: $/Aircraft Movement**
  - **Human Factors: Sector Complexity Index**

Observations to Date

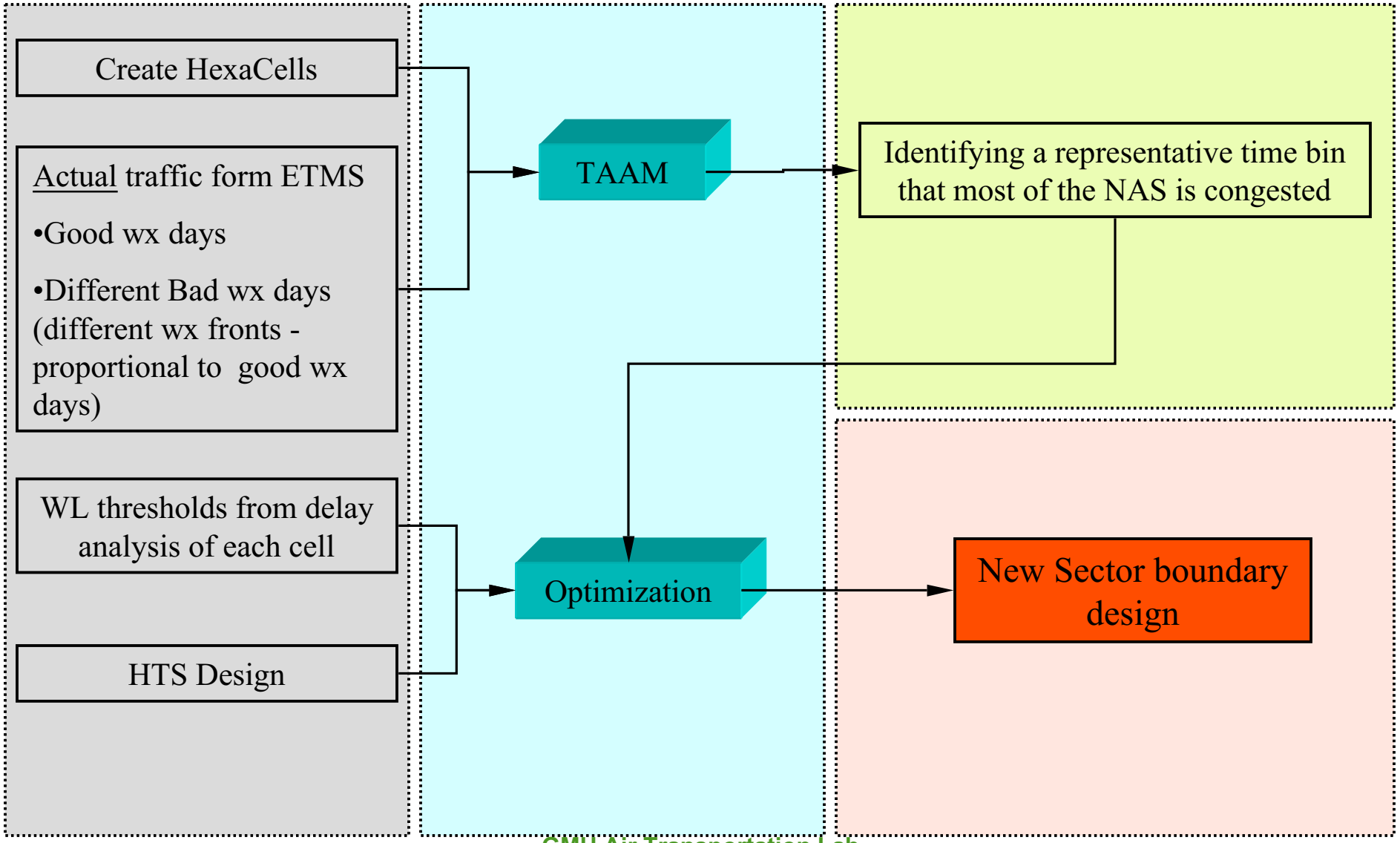
- **TAAM WL/CI Metric seems to properly Identify High and Low Workload Sectors**
- **High Fidelity Simulation Models such as ACES will be required to Evaluate Innovative new sector Design Paradigms**
- **Critical Non-Dimensional Flow Characterization Metrics Must be Defined (e.g. Reynolds Number, Space-Time Corr., etc. Equivalents)**
- **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**
- **Metron Adaptive Weather Concept Important to Dynamic Ribbon and Terminal Routing**
- **AVOS or Raytheon Wake Vortex Closely Spaced Approach and Airport Runway and TERPS design Criteria are Important Elements of any Future High Capacity System with a Safety Constraint**

Future Research Directions

- **Continuation of Development of Non-Dimensional Metrics and Data Mining Filters for Airspace Design and Evaluation using ACES and/or TAAM**
- **Compare these Metrics for both TAAM and ACES simulations of standard Scenarios**
- **Continue Development and Evaluation of Optimal Sector Design using ACES or TAAM simulation**
  - **University Team Concept of Airspace segregation based upon Inherent Structure**
  - **High Volume Dynamic Ribbons as a function of Weather Scenarios and Normal Sector WL Reduction**
  - **Terminal Airspace Design considering WV and ROT Safety Constraints**
  - **PTP dedicated airspace design evaluation**

BACKUP SLIDES

Proposed Network Sector Design Process



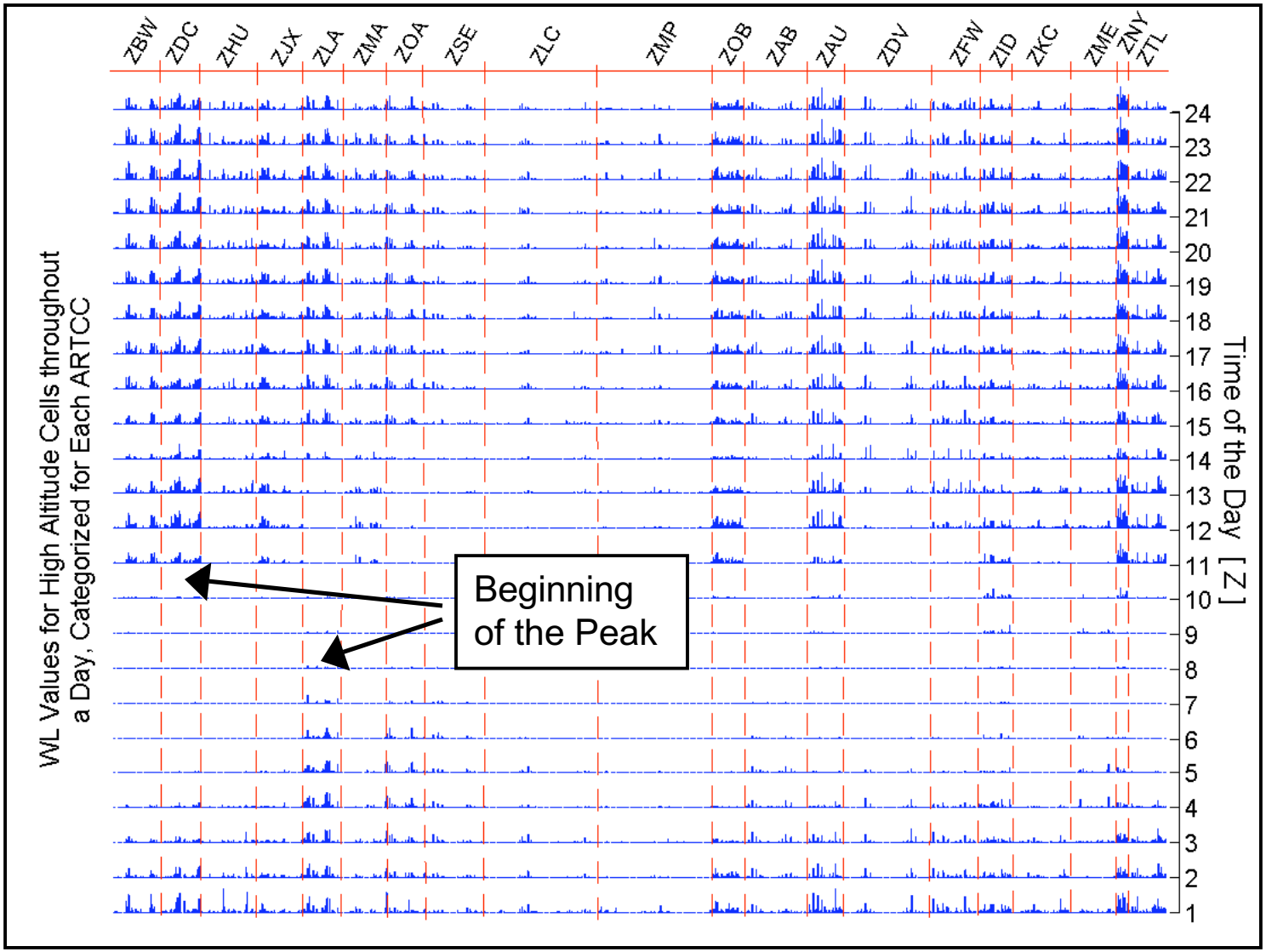
Recent Related WL Research

- **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 ...**

Details of TAAM Simulation

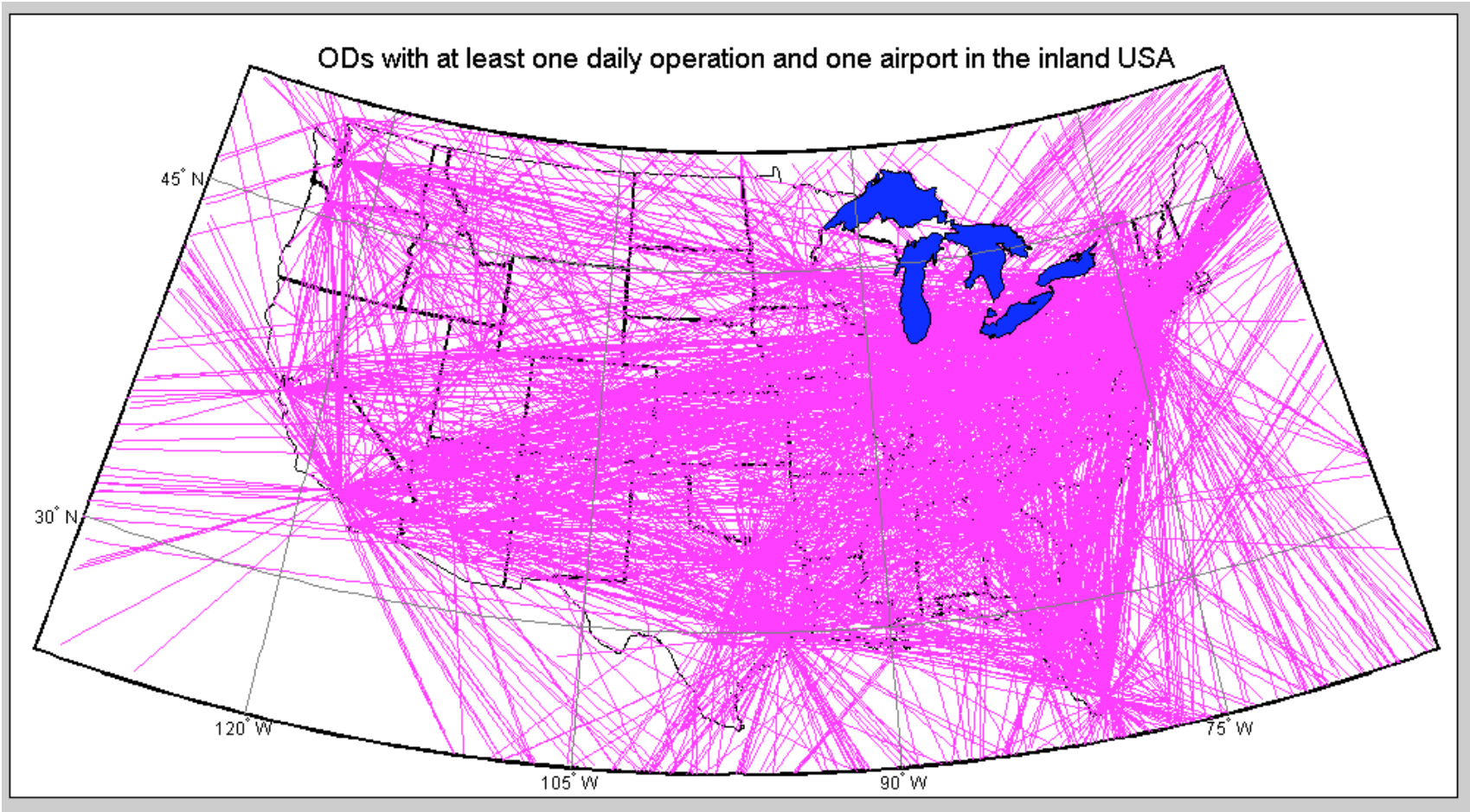
- Total daily flights = ~45k
- Number of sectors in each run= 2566
- Aircraft characteristics file is updated for all aircraft in ETMS
- CD&R is ON
- Graphic is OFF
- Sim. time in a P4 processor with 2GB RAM &1G rpm HD= ~8 hours
- Reporter run time= ~2 hours

WL Variation Within Centers

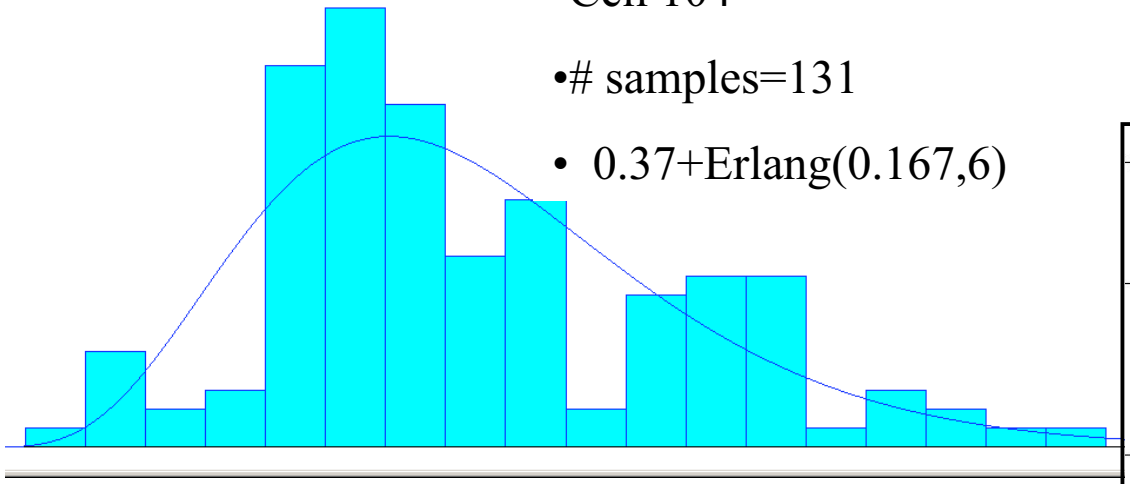


All Operational OD Pairs

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



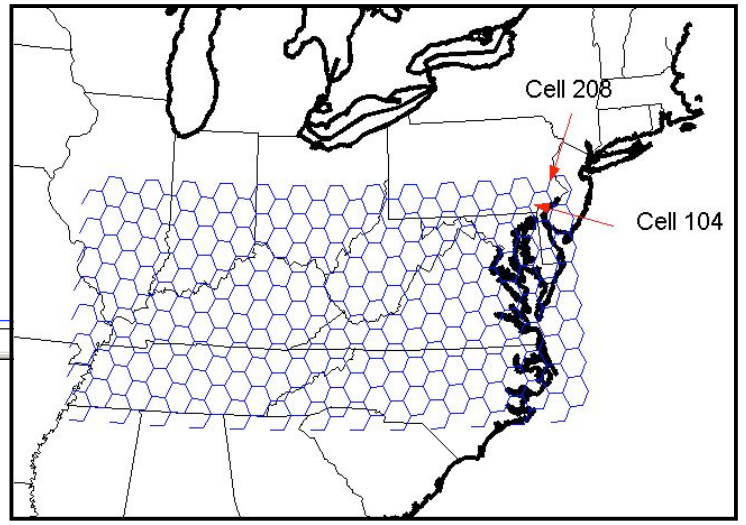
CI pdf for HexaCells 104 & 208

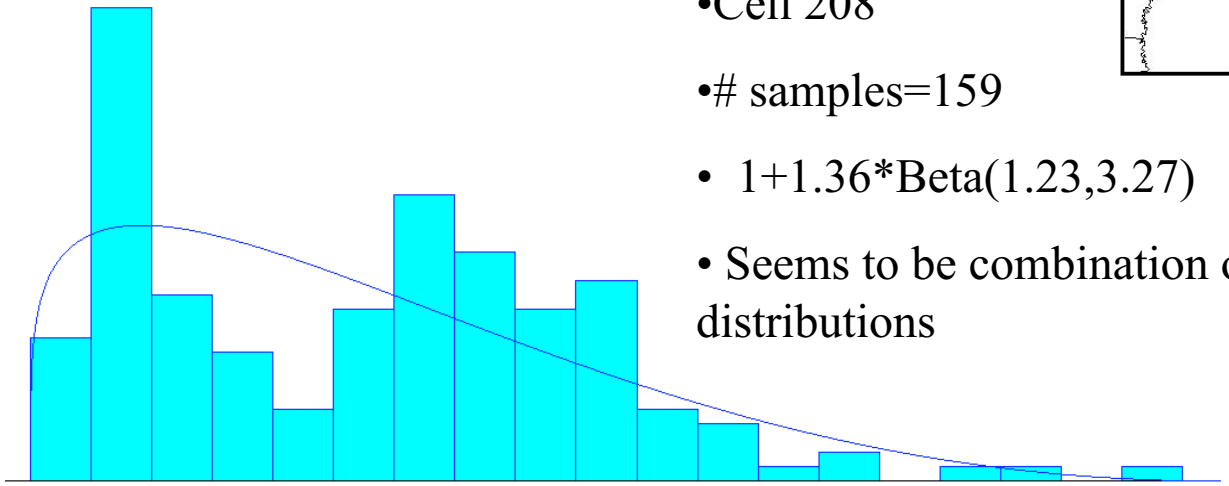


•Cell 104

•# samples=131

• 0.37+Erlang(0.167,6)





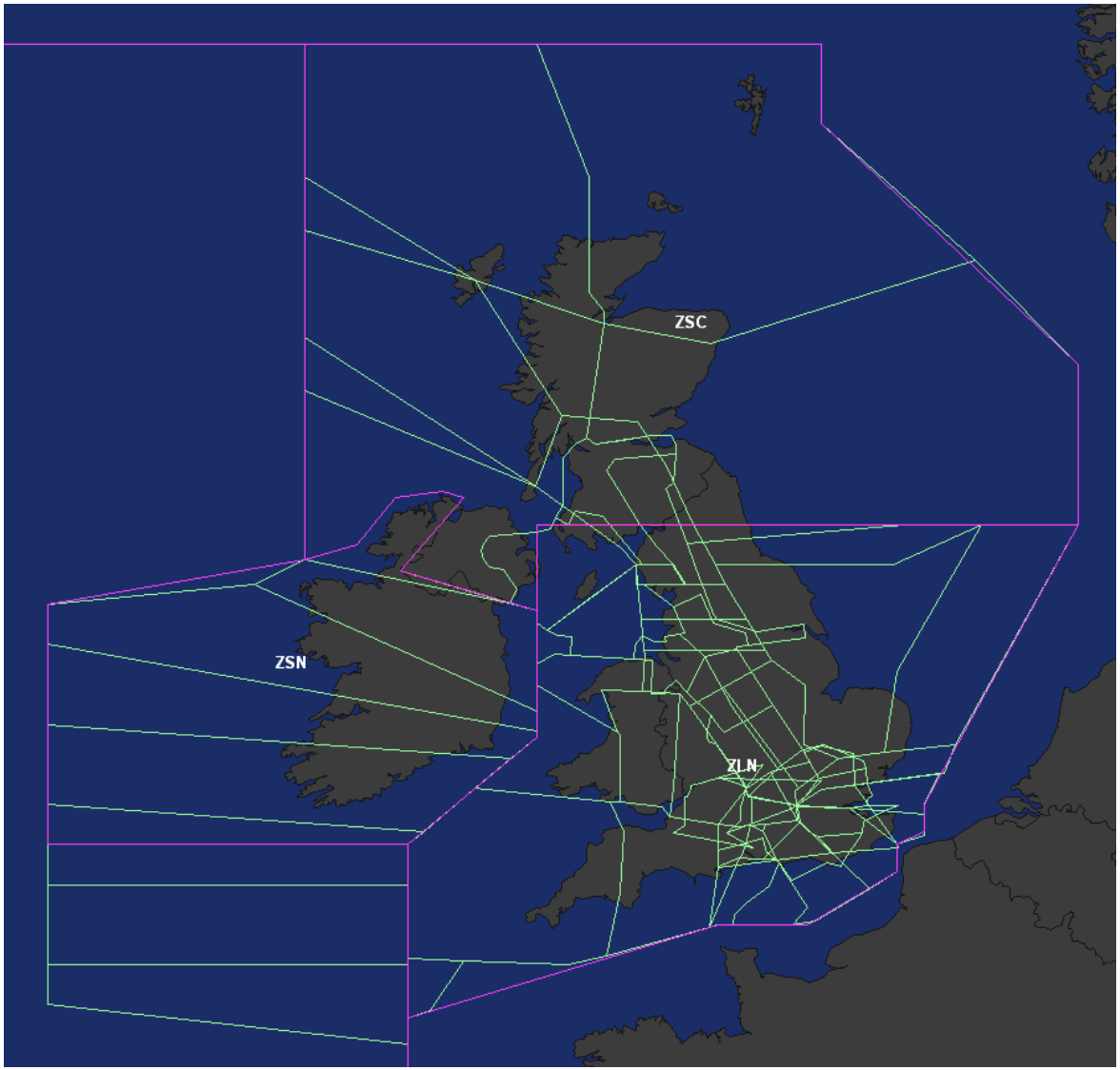
•Cell 208

•# samples=159

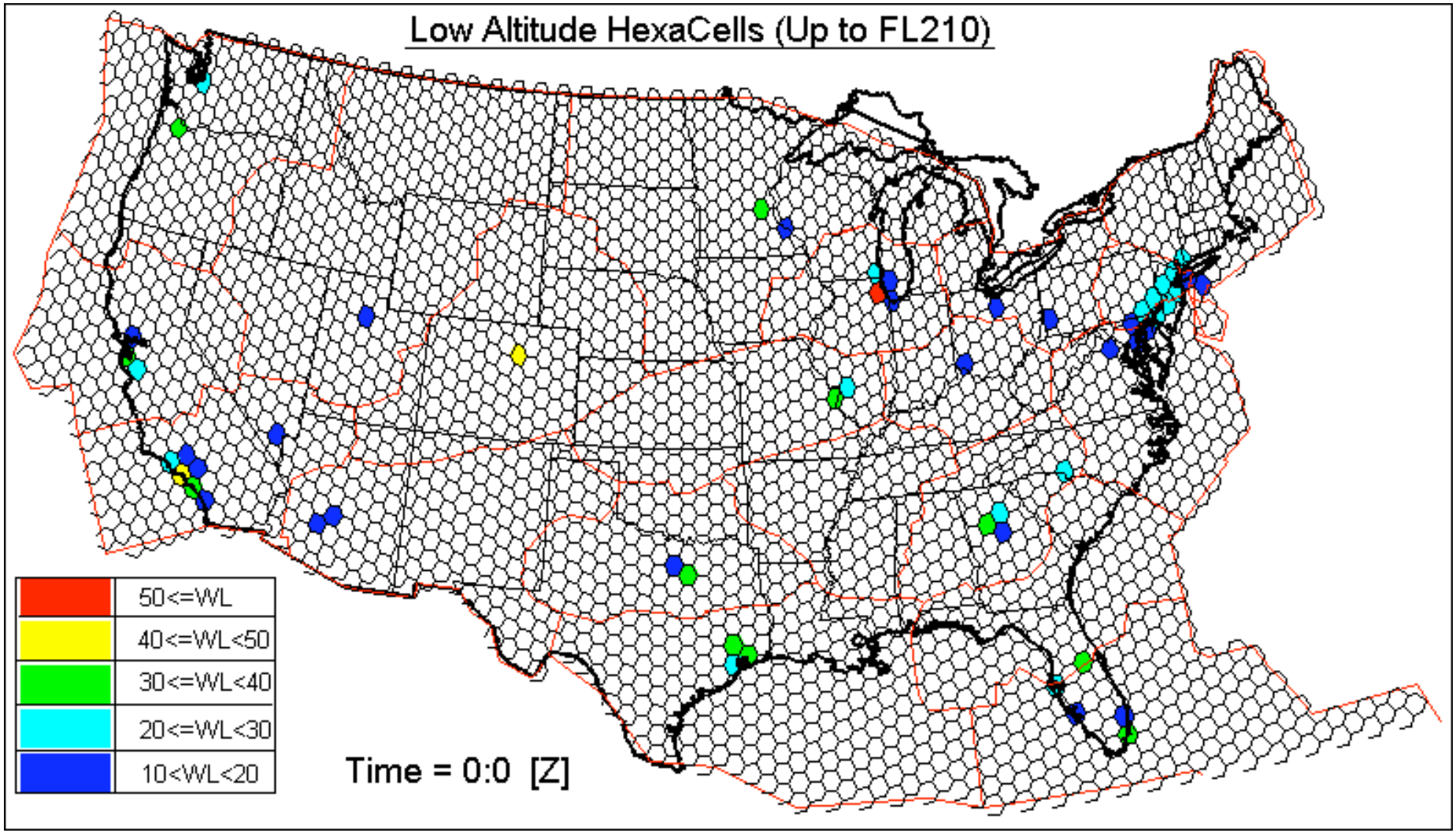
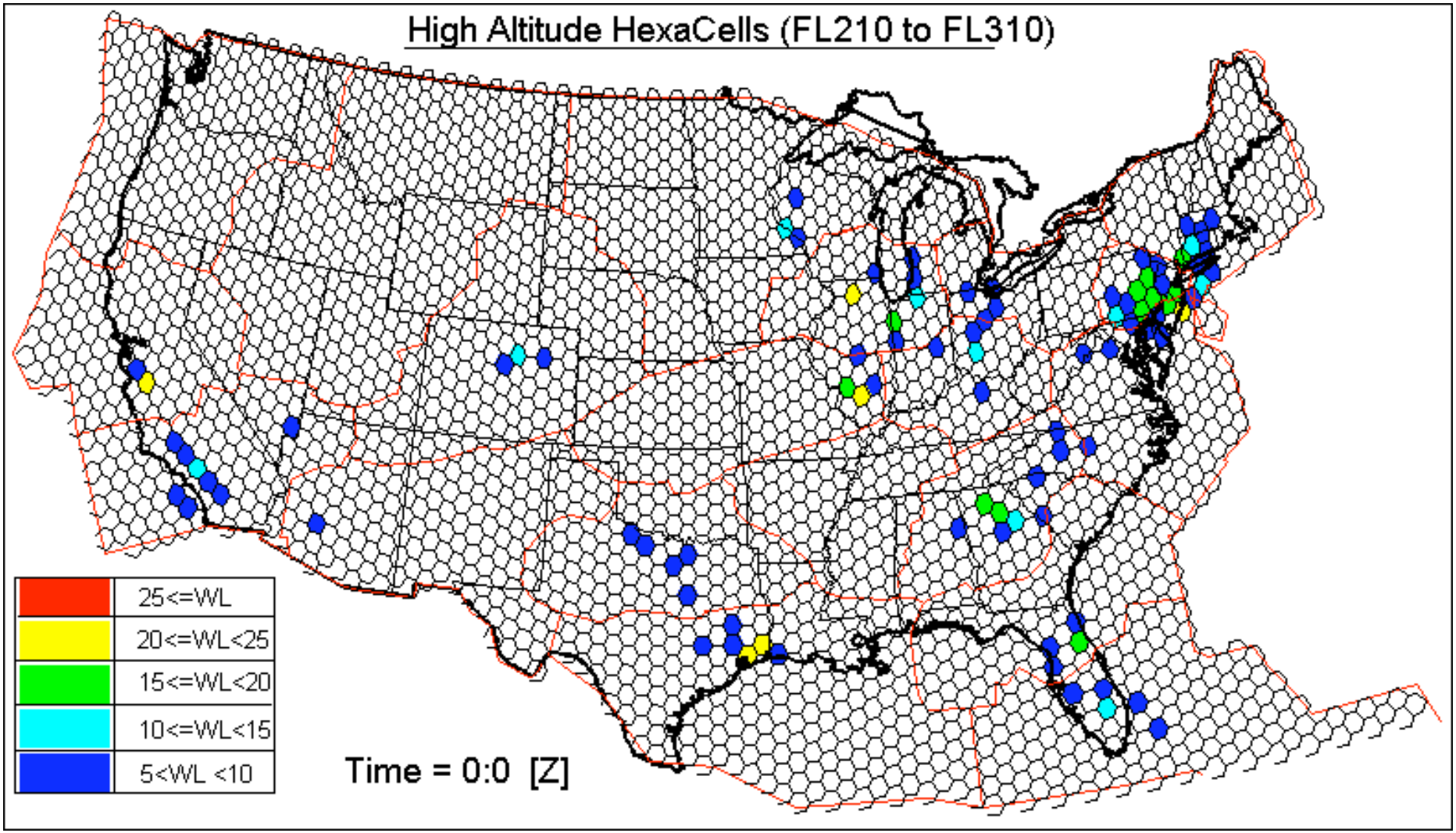
• 1+1.36*Beta(1.23,3.27)

• Seems to be combination of two normal distributions

European Sovereign Boundaries Produces a Similar Result



Airspace Complexity Visualization (Low)



Airspace Complexity Visualization (High)