HUMAN FACTORS IN AIR TRAFFIC CONTROL

Jonathan M. Histon

International Center for Air Transportation

Massachusetts Institute of Technology

September 2006

What is Human Factors?

- Understanding the interactions among humans and other elements of a system.
- Understanding how human capabilities and limitations affect system performance

To Radar Controllers….

Sources: www.faa.gov

To Traffic Managers and Coordinators

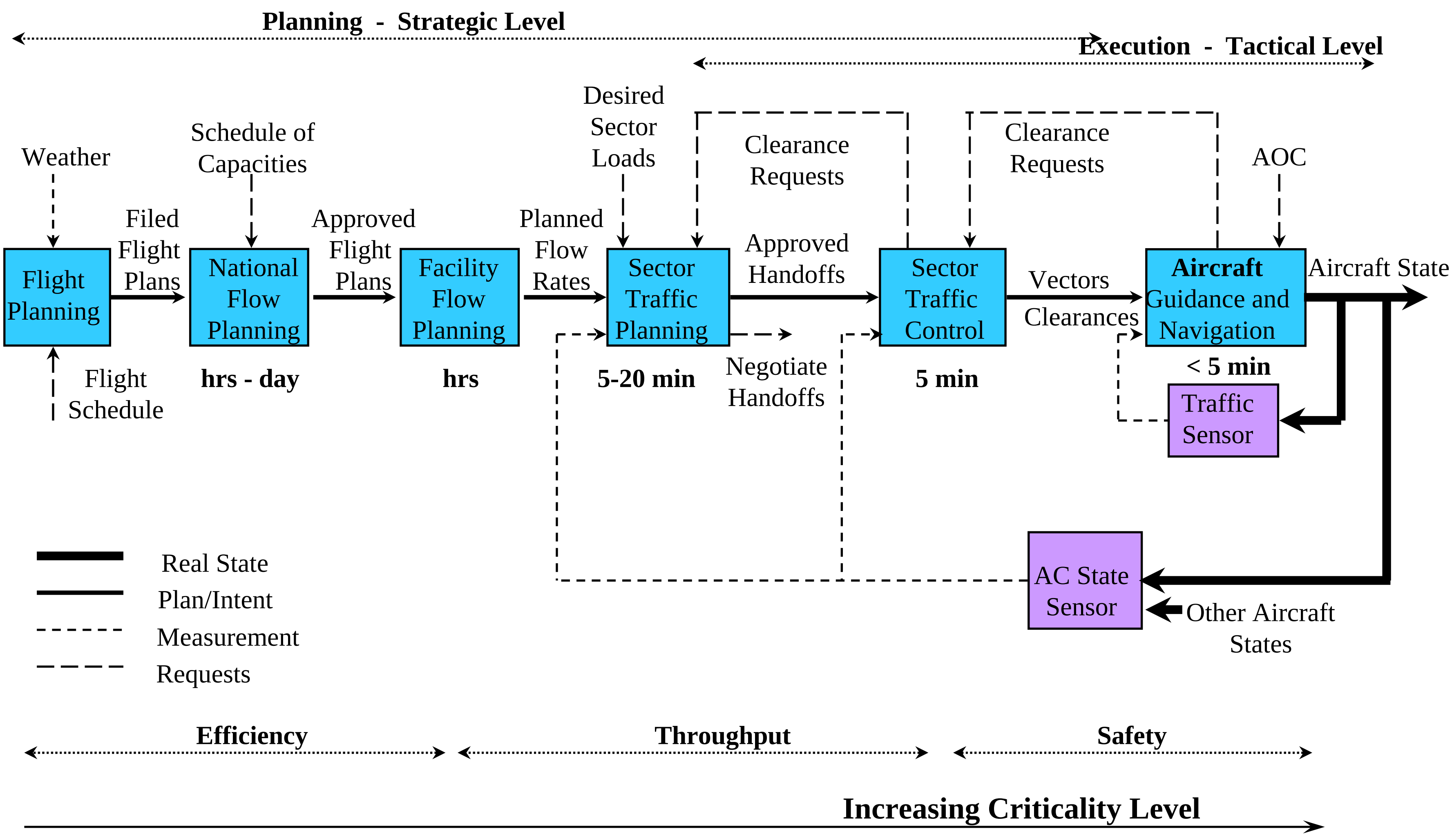
http://www.fly.faa.gov/Products/Information/Tour/tour.html

ATM System is a Human-Centered Contract Process

- **Contract process – "Clearance"**
  - Negotiate
  - Execute
  - Monitor
  - Re-negotiate/Amend
- **Limited resources**
  - Runways
  - Airspace
  - Airport surface
- **Agents**
  - Controllers (strategic & tactical)
  - Pilots
  - Airlines
  - Airports

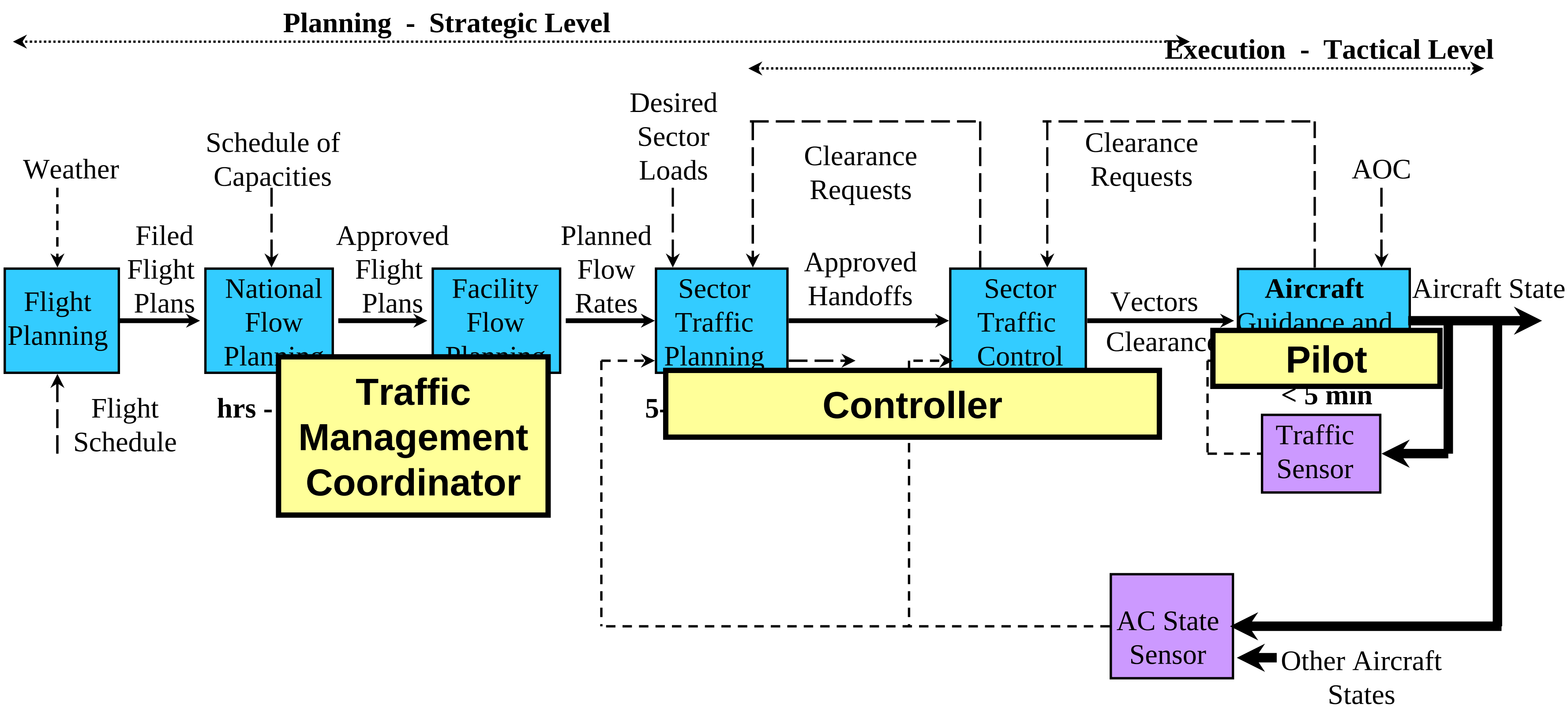
Adapted from Dr. R.J. Hansman, MIT

ATM System Current Functional Structure



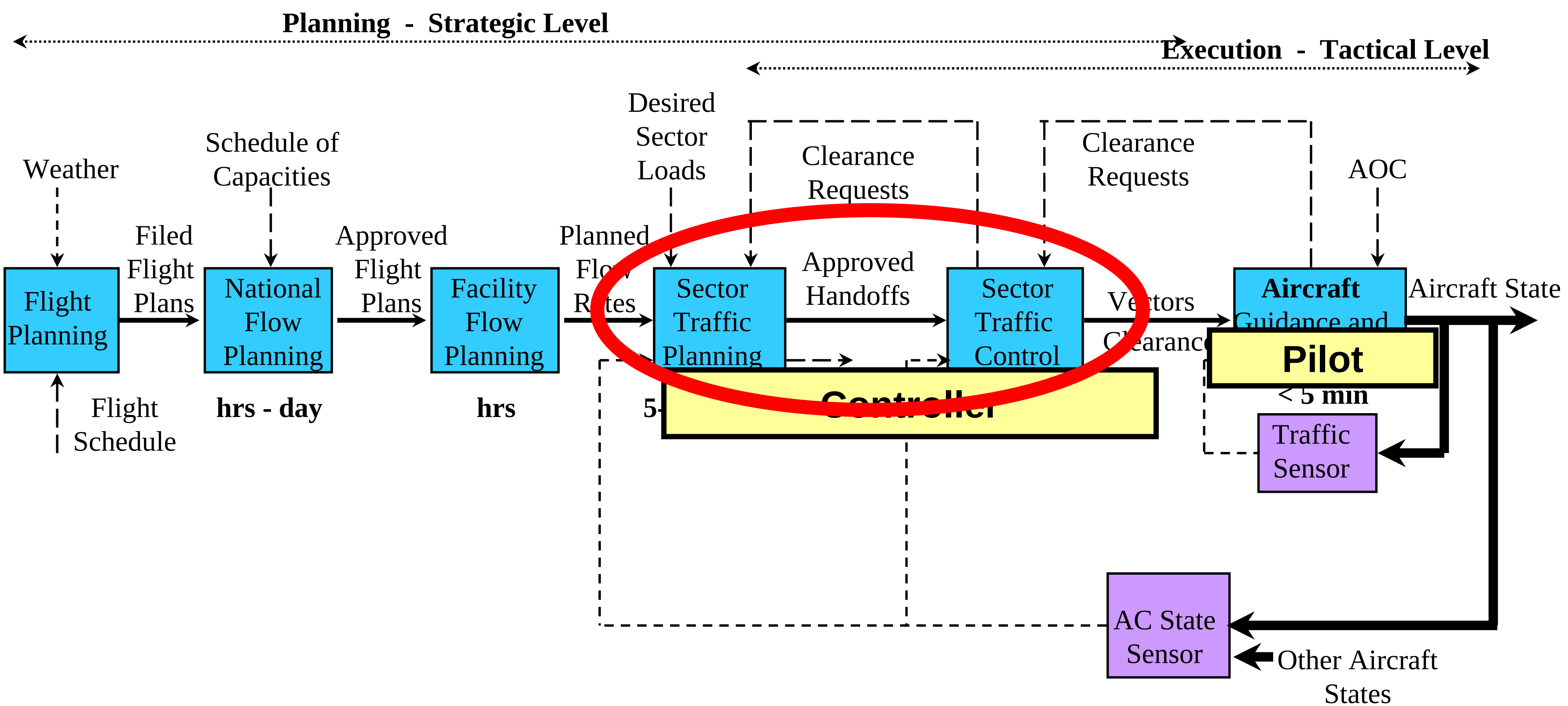
Source: A. Haraldsdottir Boeing

Human Agents Within Functional Structure



Source: A. Haraldsdottir Boeing

Controller's Task



Source: A. Haraldsdottir Boeing

Controller Goals & Tasks

- **Goals:**
  - ☐ Prevent a collision between aircraft operating in the system
  - ☐ Organize and expedite the flow of traffic
- **Tasks**
  - ☐ Ensure separation
  - ☐ Give control instructions
  - ☐ Monitor and operate interphones and radios
  - ☐ Accept and initiate handoffs
  - ☐ Enter instructions /clearances into computer
  - ☐ Coordinate with surrounding controllers, including pointouts
  - ☐ Request/receive and disseminate weather, NOTAMs, NAS status, traffic management and Special Use Airspace status messages.

Separation

- **Multiple separation standards**
  - ☐ Radar
  - ☐ Procedural
  - ☐ Visual
- **Separation standards can depend on**
  - ☐ Wake vortex
  - ☐ Aircraft size
  - ☐ Distance from radar site

Sectors

- **“High Altitude” Sectors Across United States**

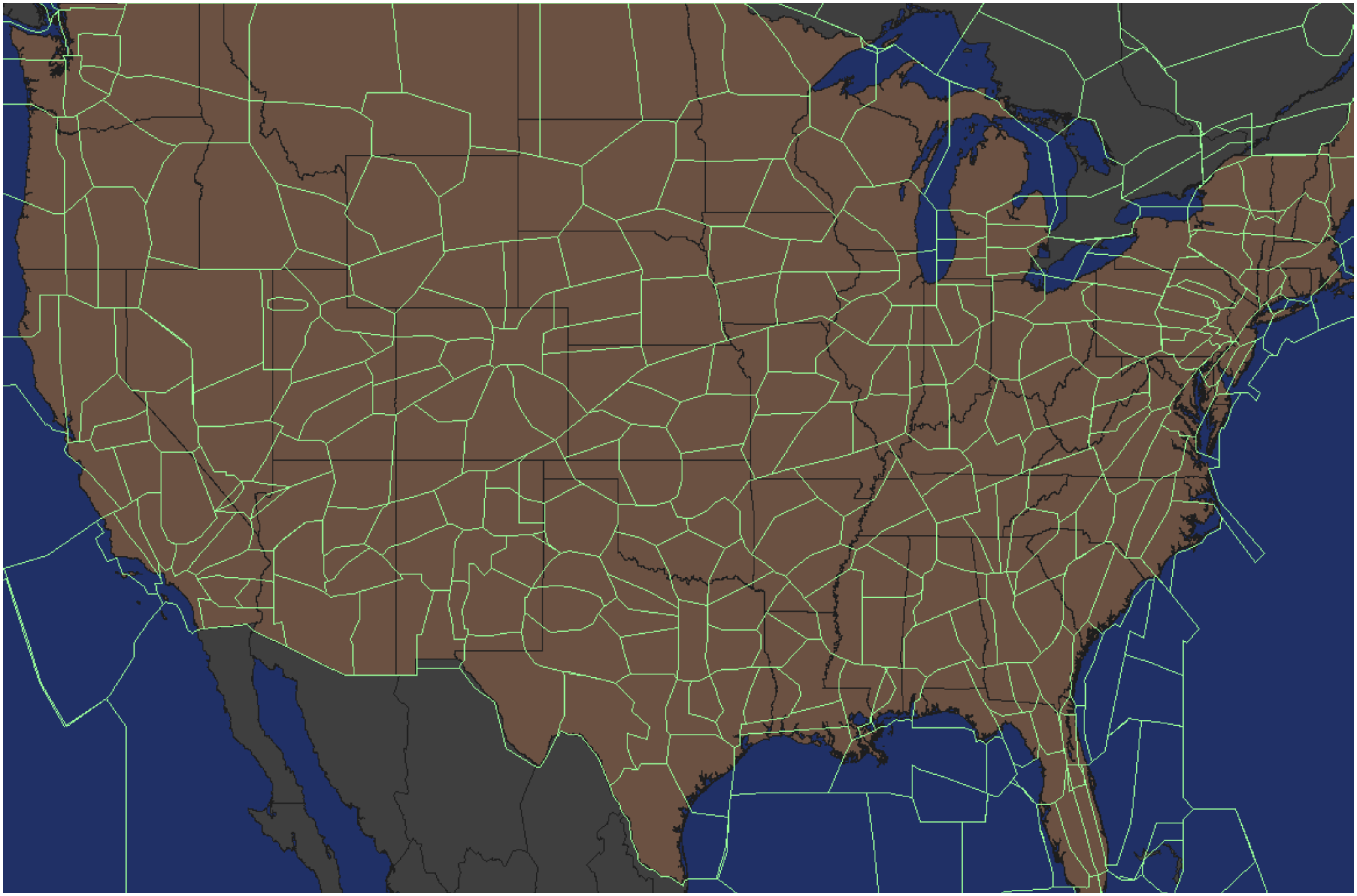
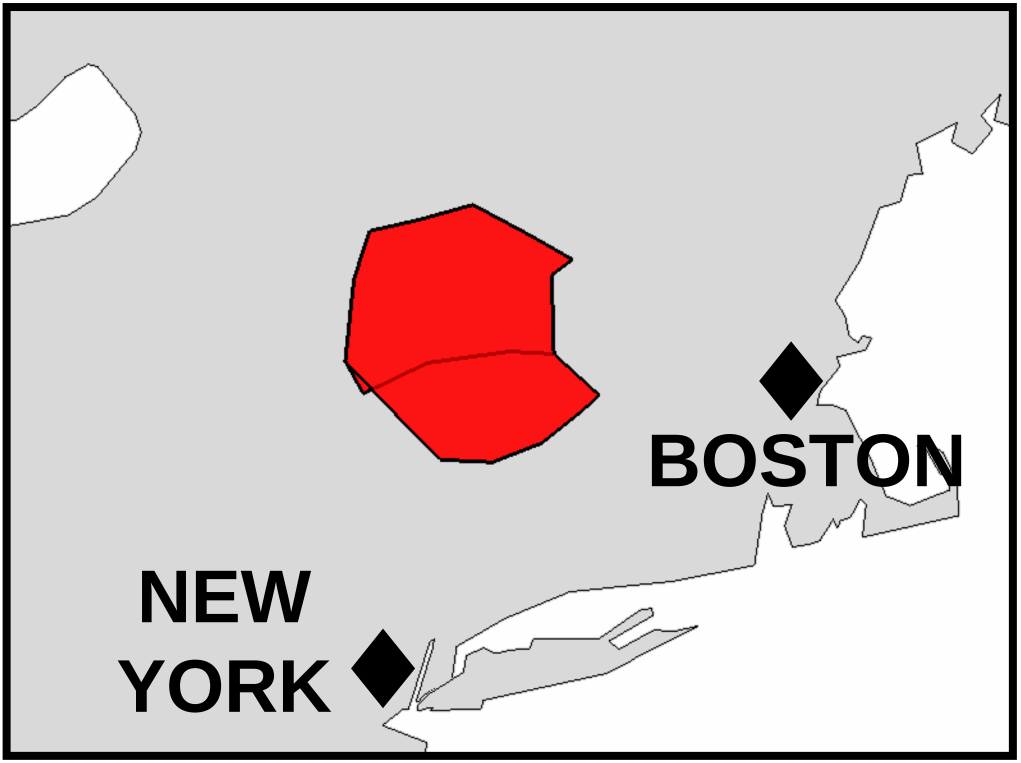
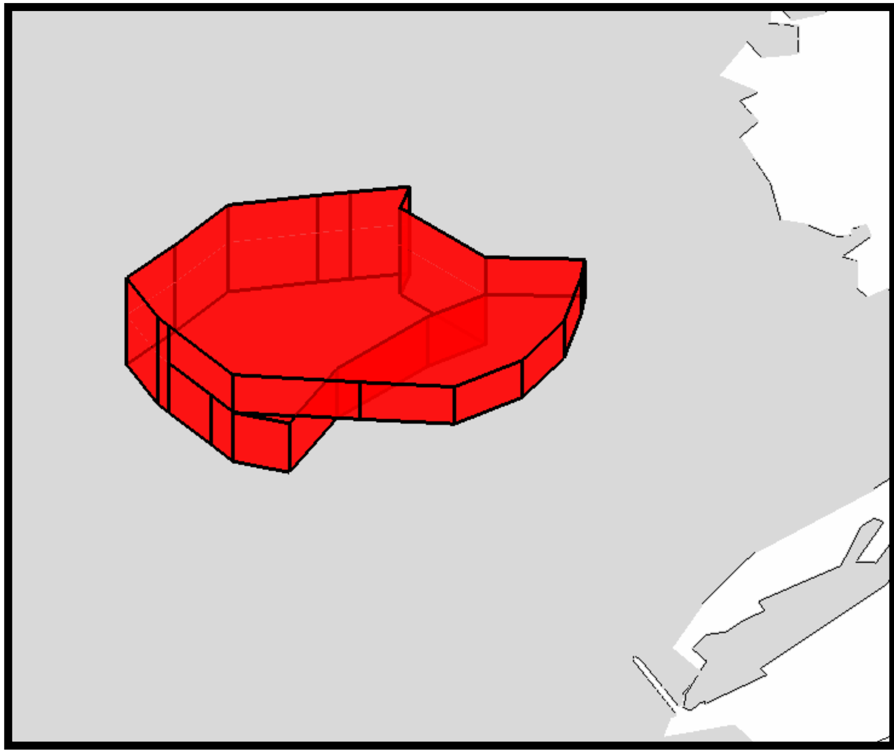


Image generated from Flight Explorer software, www.flightexplorer.com

Example Sector: Albany

- **Sectors come in multiple shapes and sizes**



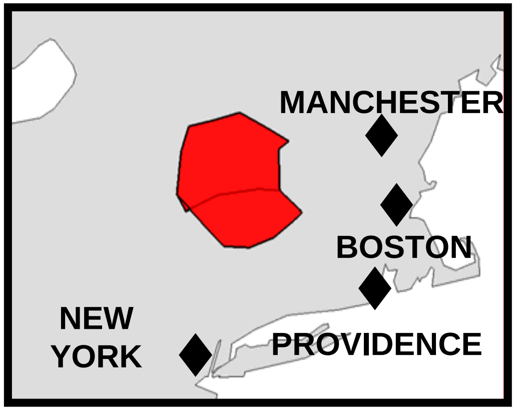


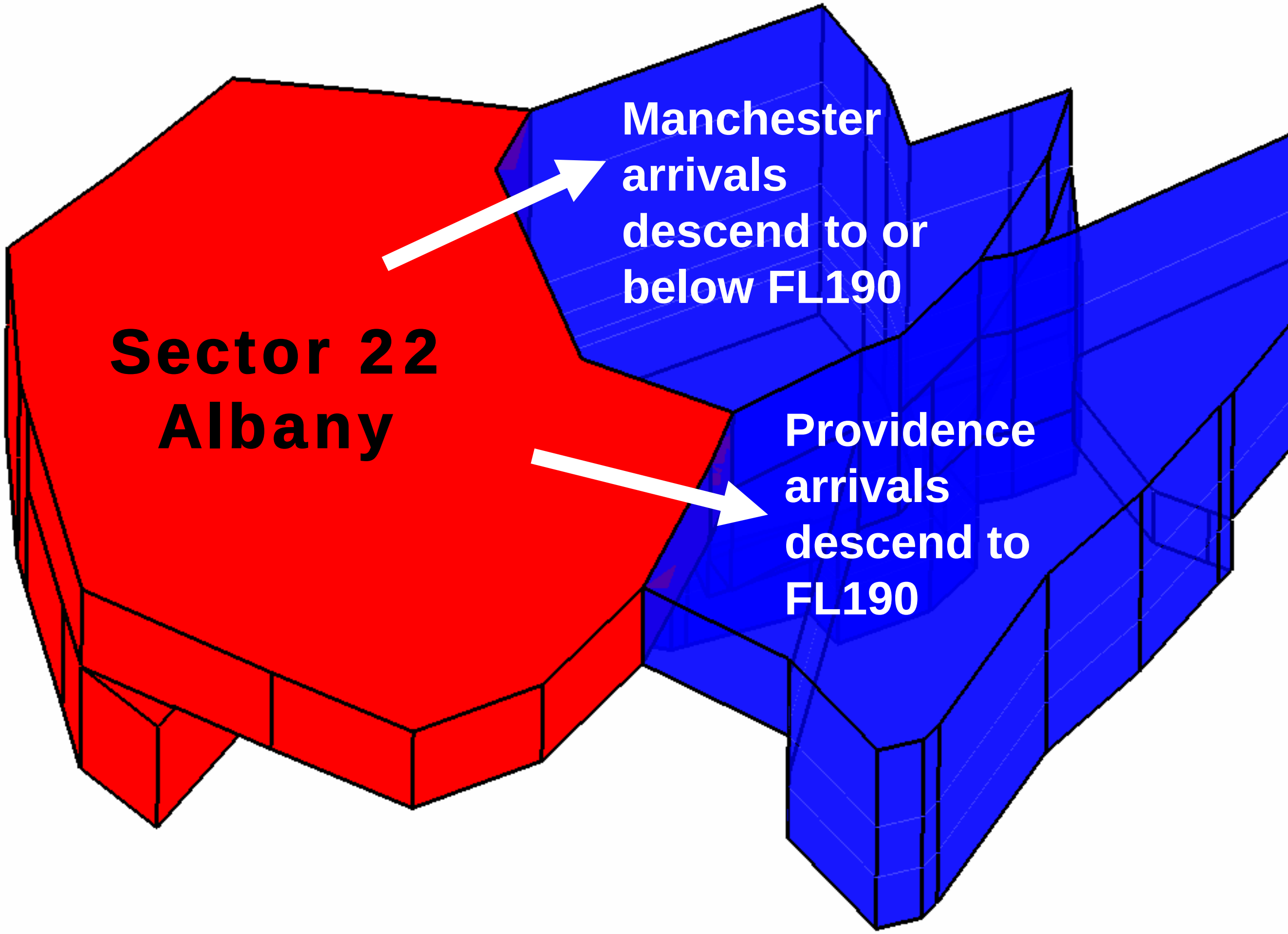
Example Procedures

- **Altitude for Direction**
  - IFR, Even Thousands Westbound, Odd Eastbound (0-179 Magnetic)
  - VFR +500
  - DRVSM above FL29
- **Radar Contact**
- **Transponders**
  - Codes
  - Mode C altitude verification
- **Hand Offs**
  - BOS, NY Transition LOAs
- **Lost Communication**
- **Holding Patterns**

From Dr. R. J. Hansman

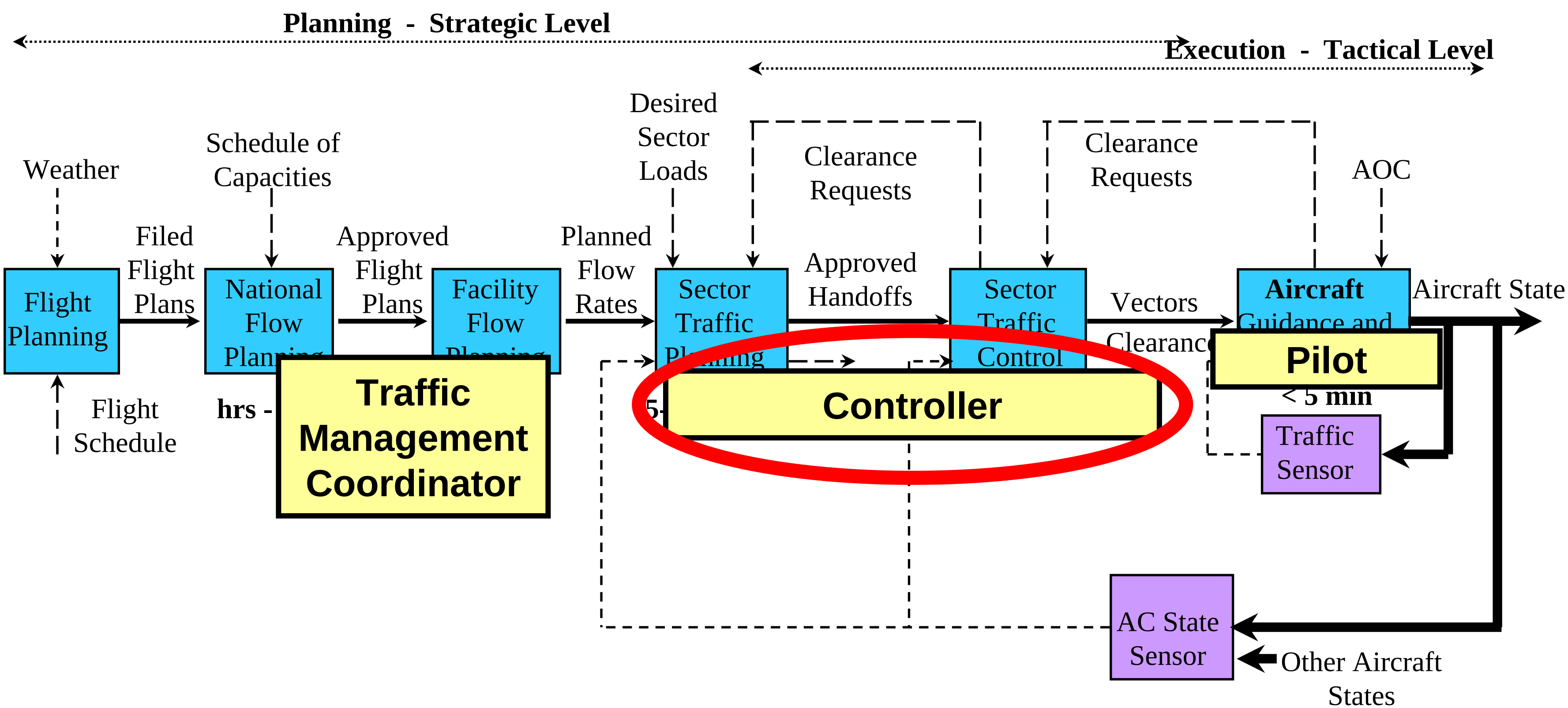
Procedures





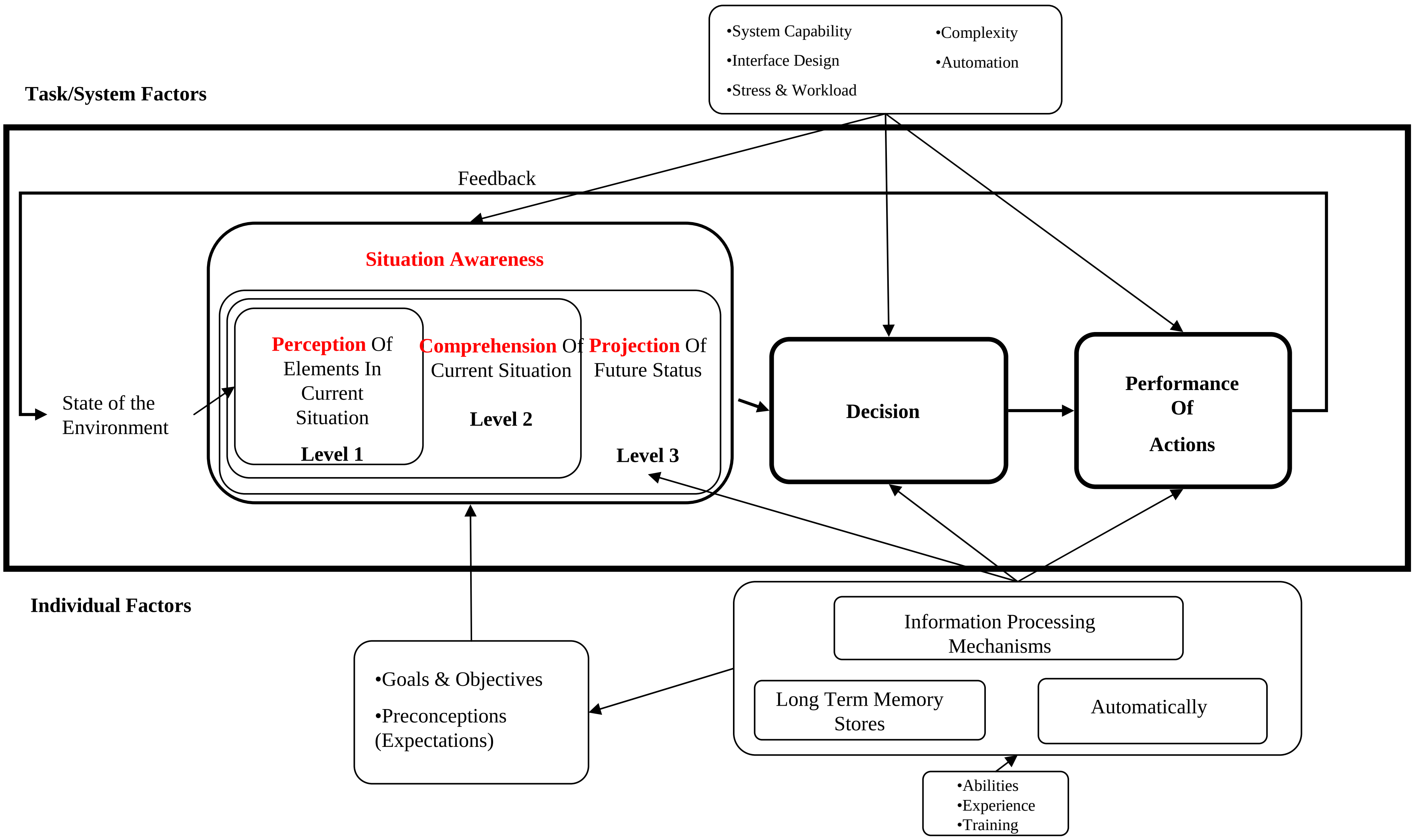
Source: ZBW 7110.33N, Boston ARTCC Standard Operating Procedures, Oct. 1999

Cognitive Capabilities and Limitations Affect Performance of the ATC Task

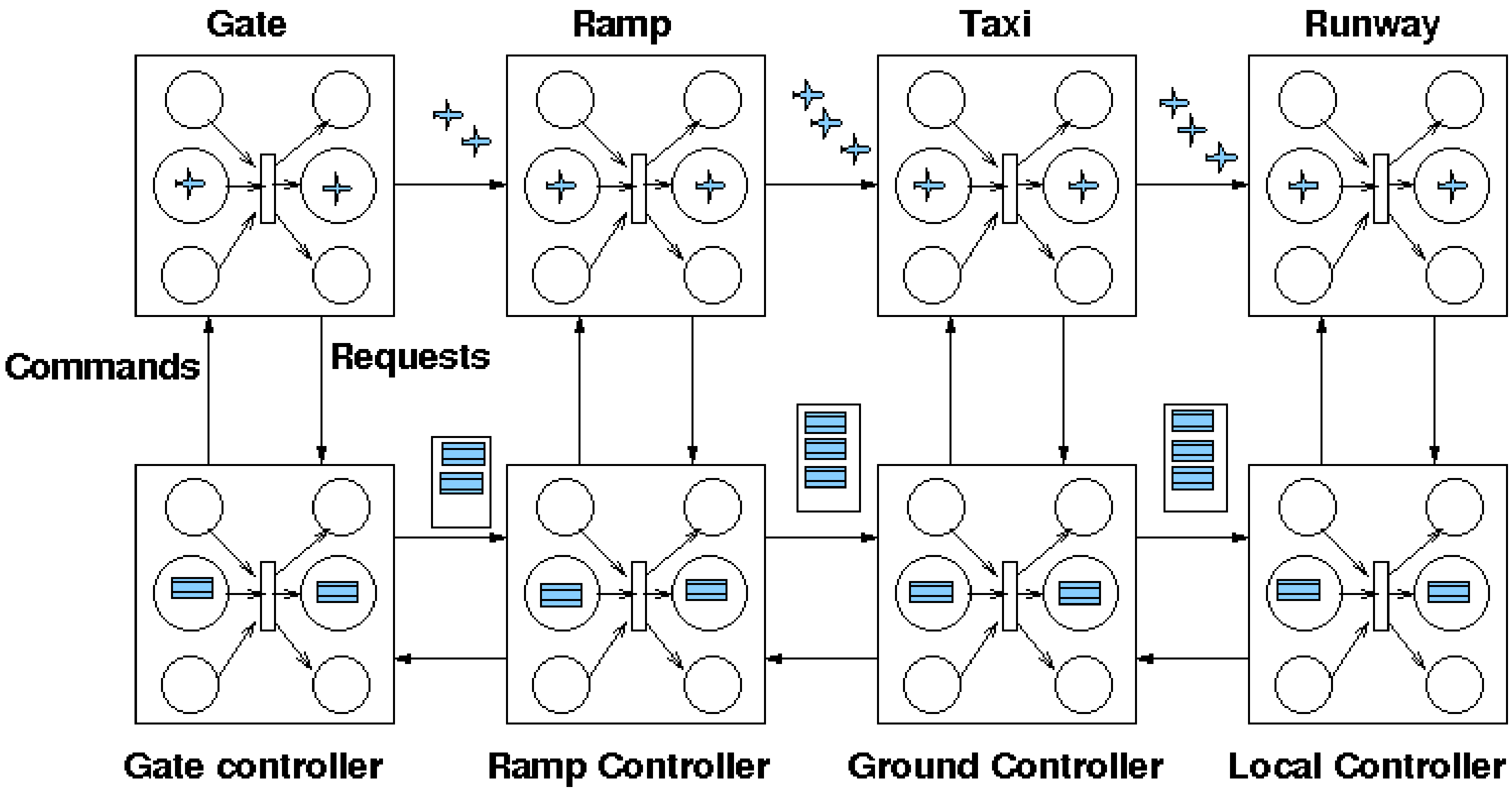


Source: A. Haraldsdottir Boeing

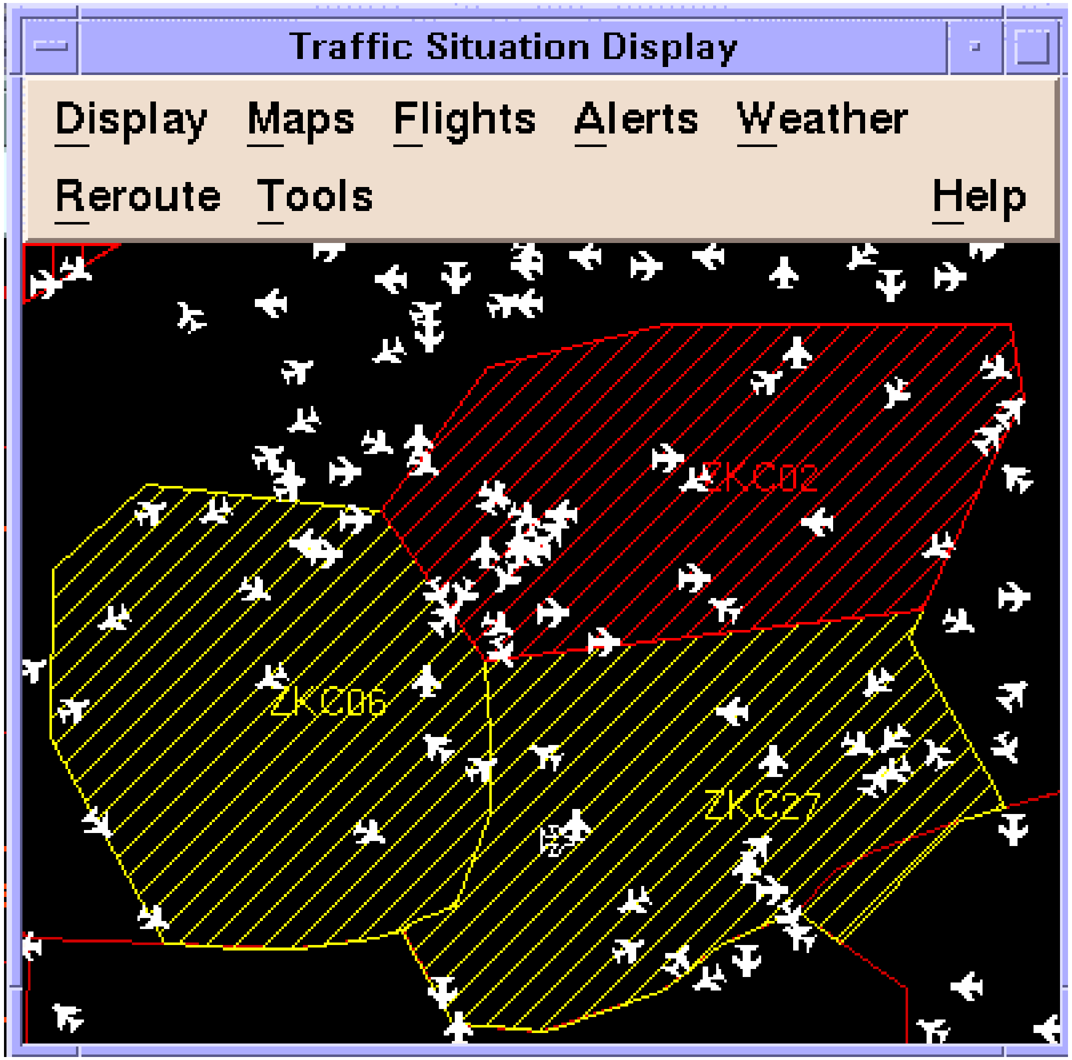
Endsley Situation Awareness Model



ATC Workload as a System Constraint



Traffic Situation Display (Sector Alert)



- **Monitor Alert Parameter (MAP)**
- **Intervention necessary to prevent controller from being cognitively overloaded**

From www.fly.faa.gov

Cognitive Complexity

- **Difficulty of controlling an air traffic situation**
- **Represents limiting factor in ATC operations:**
  - ☐ Determines acceptable level of traffic
  - ☐ Limits sector and system capacity
- **Sector Capacity Limits (10-20 AC)**

MIT ICAT

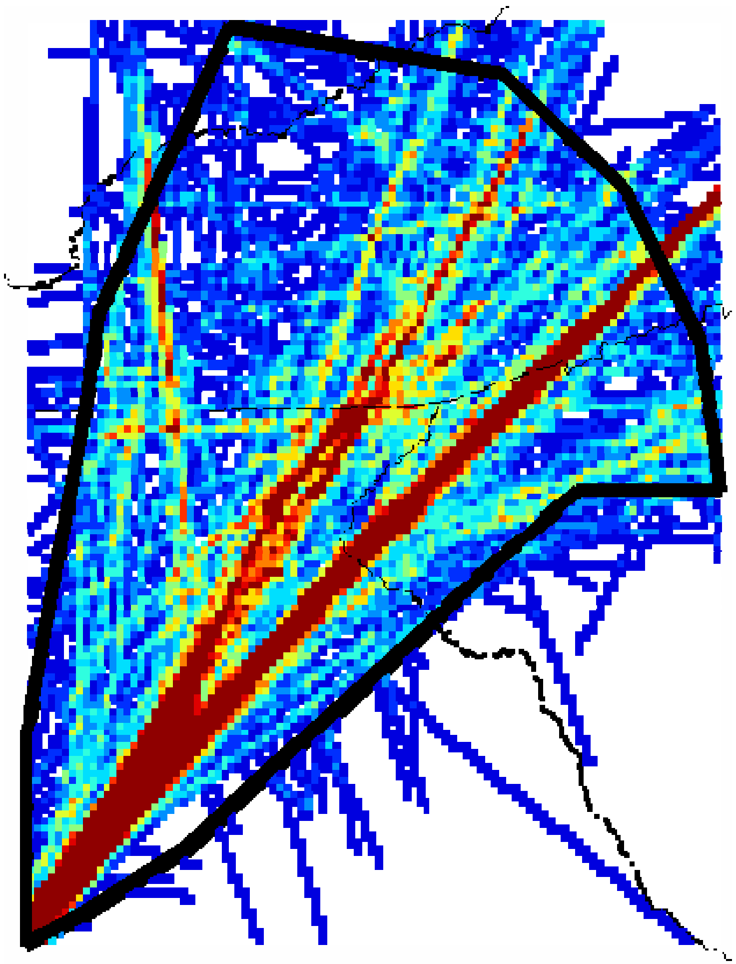
Structure in Operational Environment

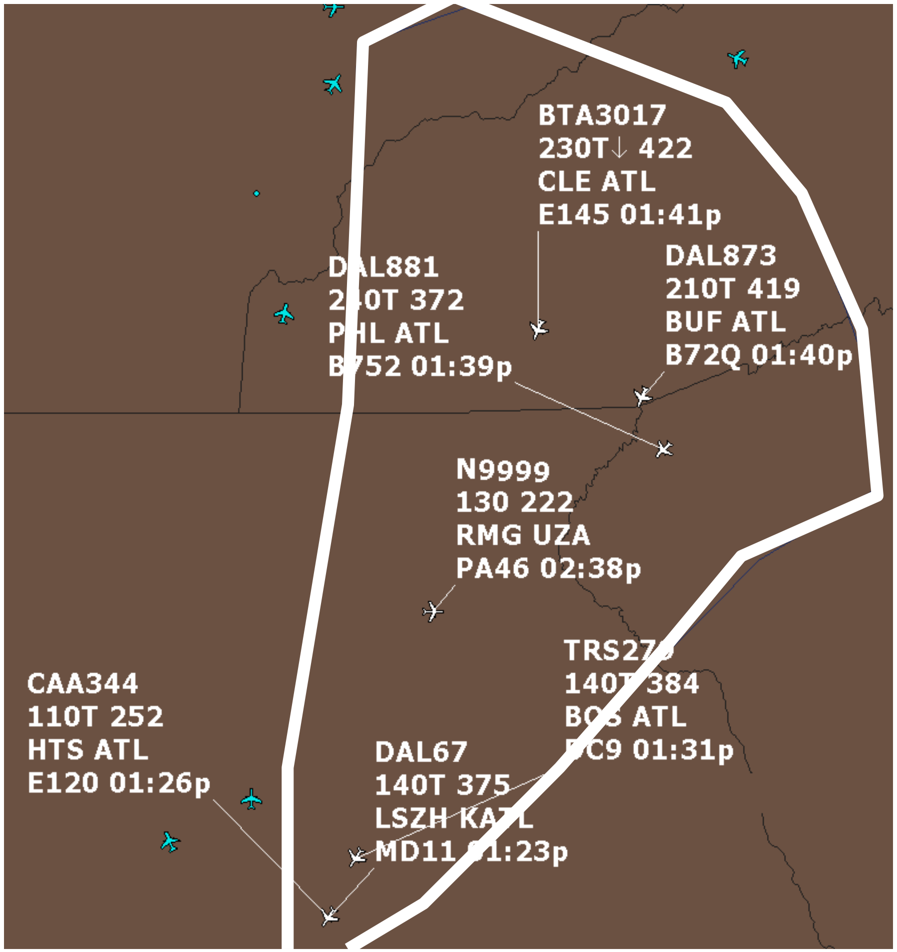
STRUCTURE

	Layer	Elements Within Layer	Specific Examples
	Patterns	Focus Areas	*ATL merge point*
		Flows	*“Final” / ATL flow*
		Aircraft Groups	*Flight Level groups*
Procedure Layers	ATC Procedures	Informal Operating Procedures	*“Trombone” Vector Sequences*
		Formal Operating Procedures	*Letters of Agreement / SOPs*
	Published Procedures	Communication Protocols	*Frequency Change Procedures*
		Trajectory Procedures	*STARS / SIDS*
		Regulations	*Separation Standards*
Framework Layers	Airspace Boundaries	ATC Boundaries	*Sector Boundaries*
		Externally Driven Boundaries	*Military Operating Area Boundaries*
	Reference Elements	Path Definitions	*Airway / Jet Route*
		Location Definitions	*Intersection / Fix / Waypoint*
	Physical Elements	CNS Elements	*Radio / VORs / Radar Antennas*
		Core Elements	*Airports / Aircraft / Terrain*

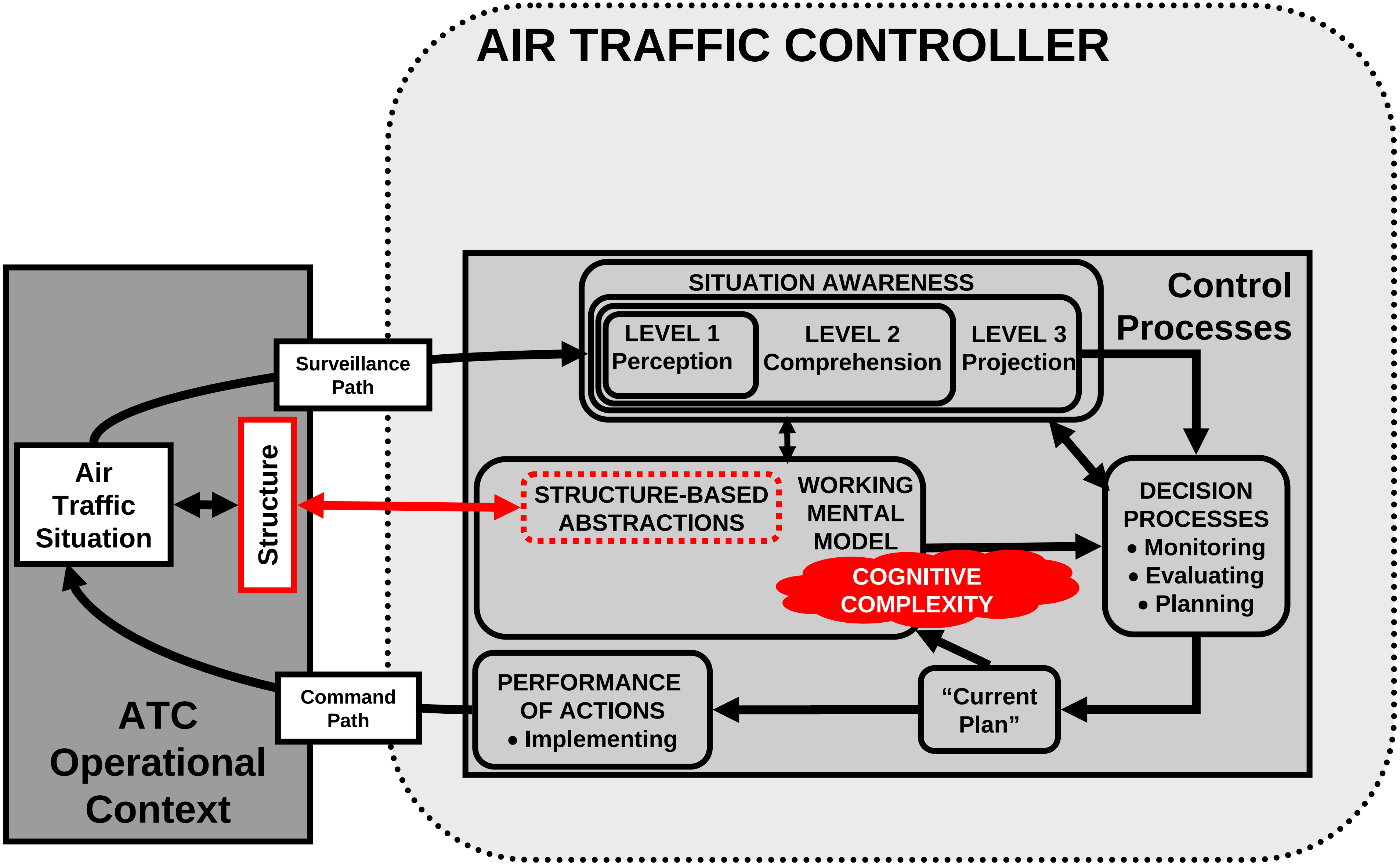
Example of Underlying Structure

ZTL, Logan Low Altitude Sector (110 – FL230), October 19, 2001





Structure-Based Abstractions and Controller Process Model



Examples of Structure-Based Abstractions

- **Standard Flows**
  - ☐ Aircraft classified into standard and non-standard classes based on relationship to established flow patterns.
- **Groupings**
  - ☐ Common, shared property, property can define non-interacting groups of aircraft
    - o E.g. non-interacting flight levels
- **Critical Points**
  - ☐ E.g. merge point
  - ☐ Reduce problem from 4D to 1D "time-of-arrival".
- **Responsibility**
  - ☐ E.g. discounting non-relevant parts of situation
  - ☐ E.g. delegating separation responsibility ("maintain visual separation")

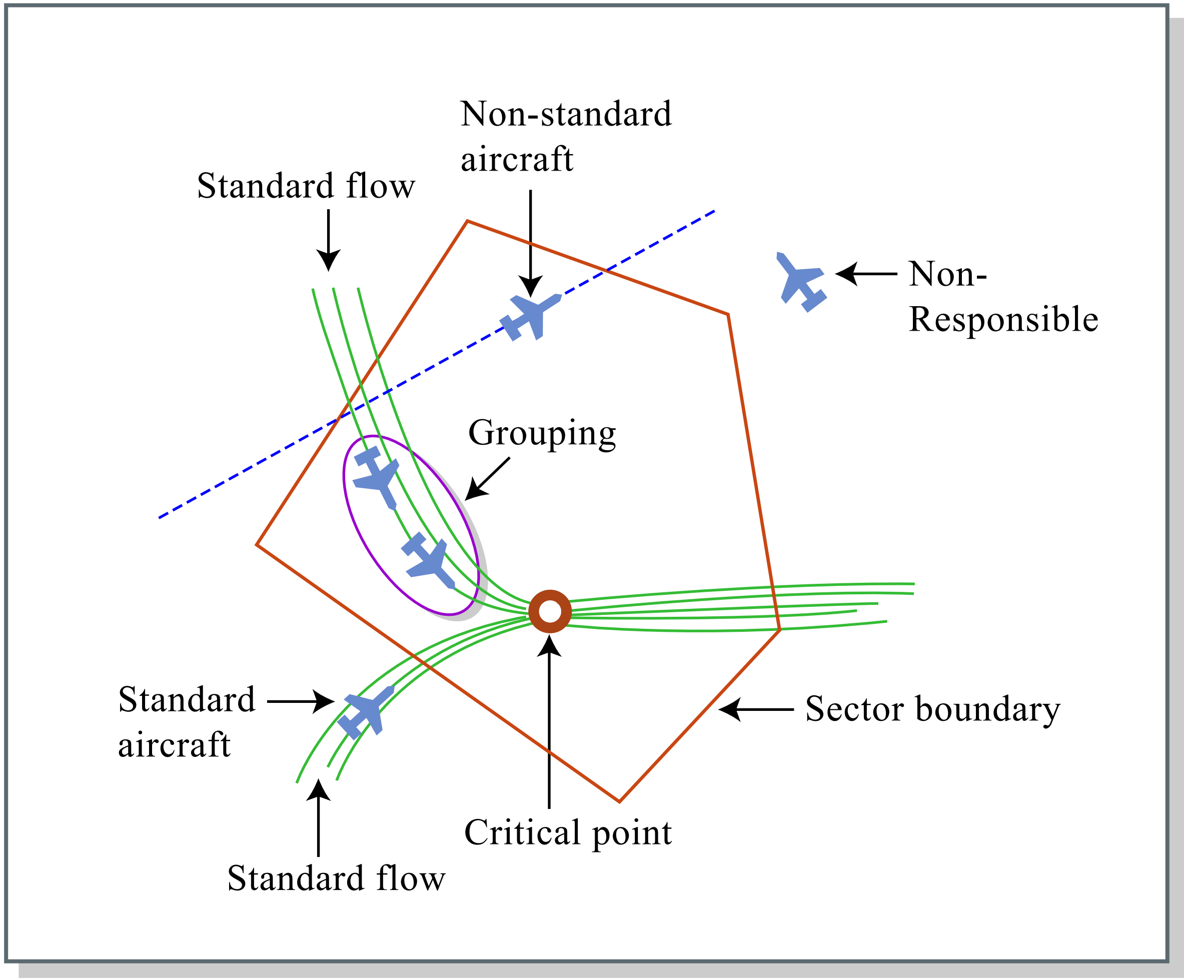
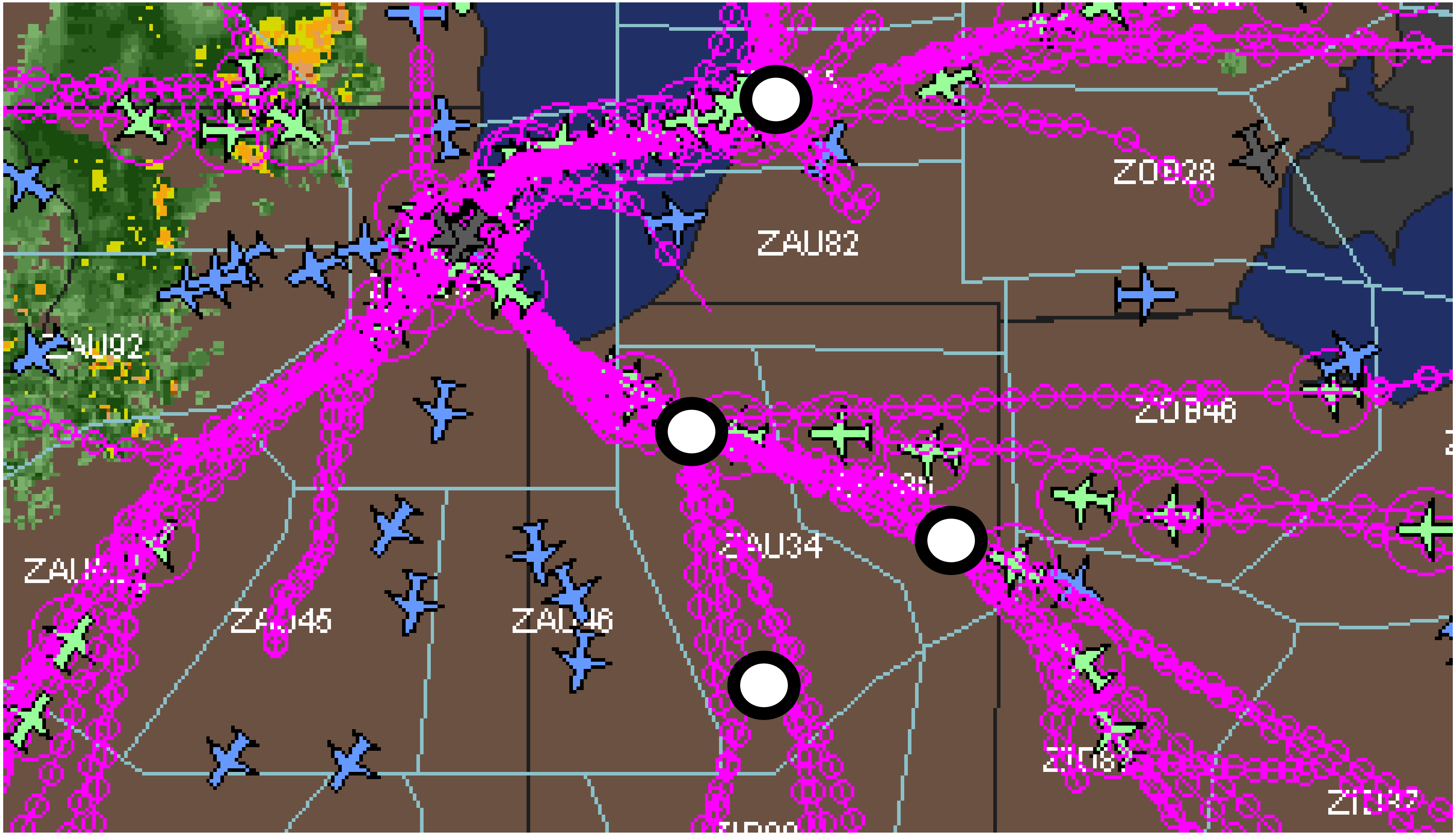


Figure by MIT OCW.

Critical Points Example

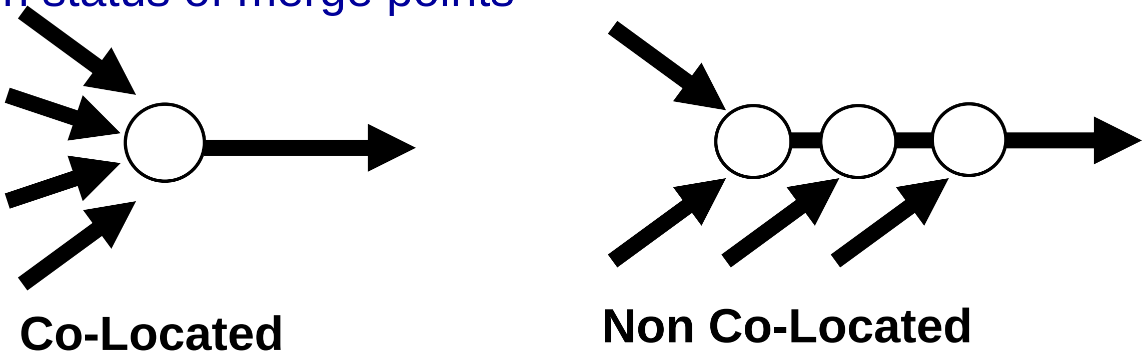
Chicago Arrival Sectors



Chicago Arrivals, May 3, 2002. 8:59 p.m.

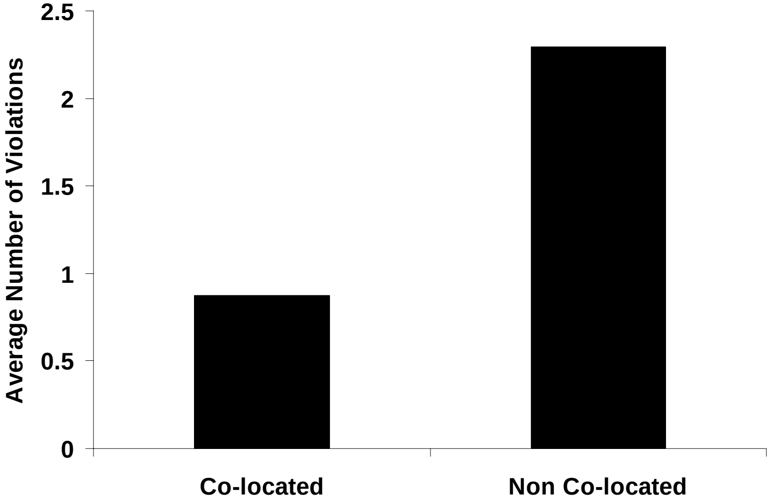
Preliminary Experimental Study of "Critical Point Abstraction"

- **Based on the results obtained from observation channels, can develop and test hypothesis about effects of structure.**
- **Preliminary Experiment:**
  - ☐ Vary specific structural factors in merging task:
    - o Number of incoming flight paths
    - o Co-location status of merge points

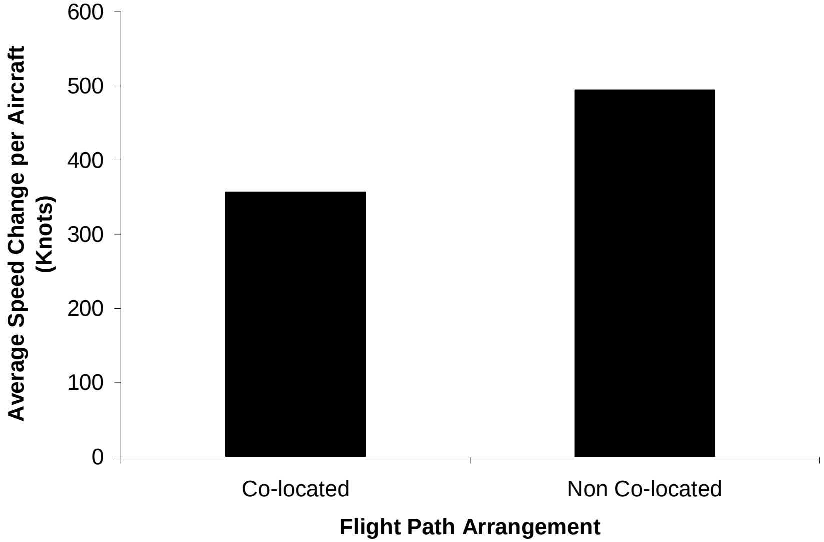


- **Critical Point Abstraction Hypotheses**
  - ☐ Scenarios with non-co-located merge points will be more complex
  - ☐ Scenarios with a larger number of incoming flight paths will be more complex

Co-located Merge Point Scenarios Showed Fewer Violations, Less Commands, and Better Perceived Controllability

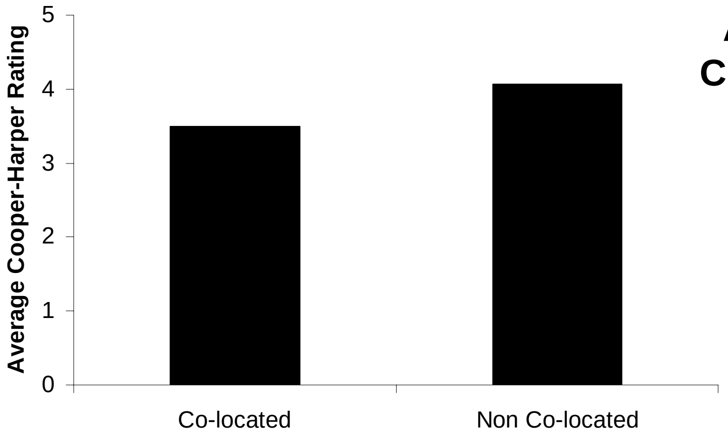


SEPARATION VIOLATIONS



WORKLOAD

AVERAGE SPEED CHANGE COMMANDED PER AIRCRAFT

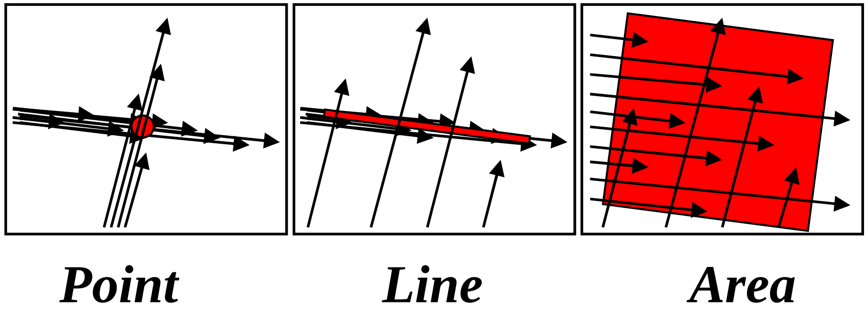


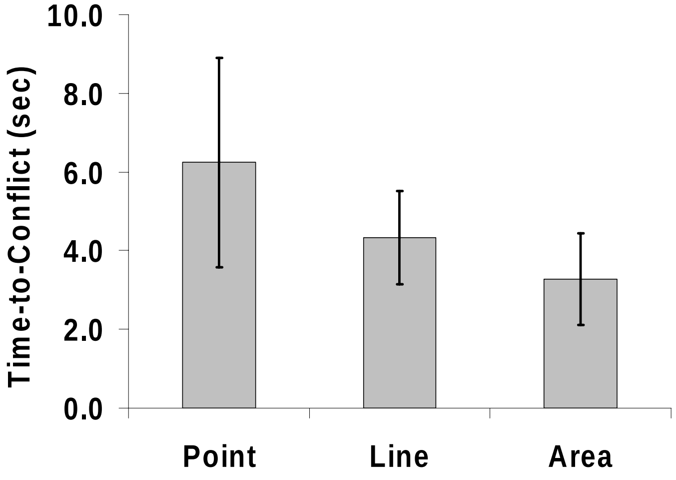
SUBJECTIVE CONTROLLABILITY

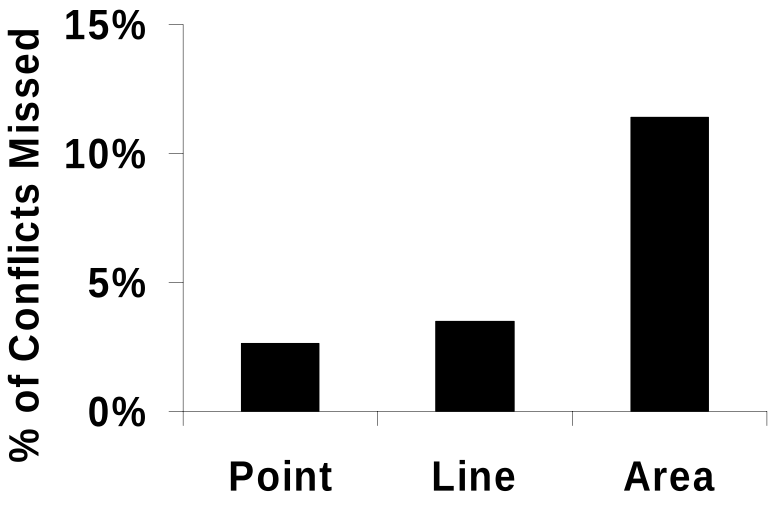
COOPER-HARPER RATINGS

Experimental Support for Structure-Based Abstractions

- Probed conflict anticipation time for 3 structural configurations of traffic (Point / Line / Area)
- Configurations with a reduced order, or dimensionality of problem, showed earlier anticipation and fewer errors

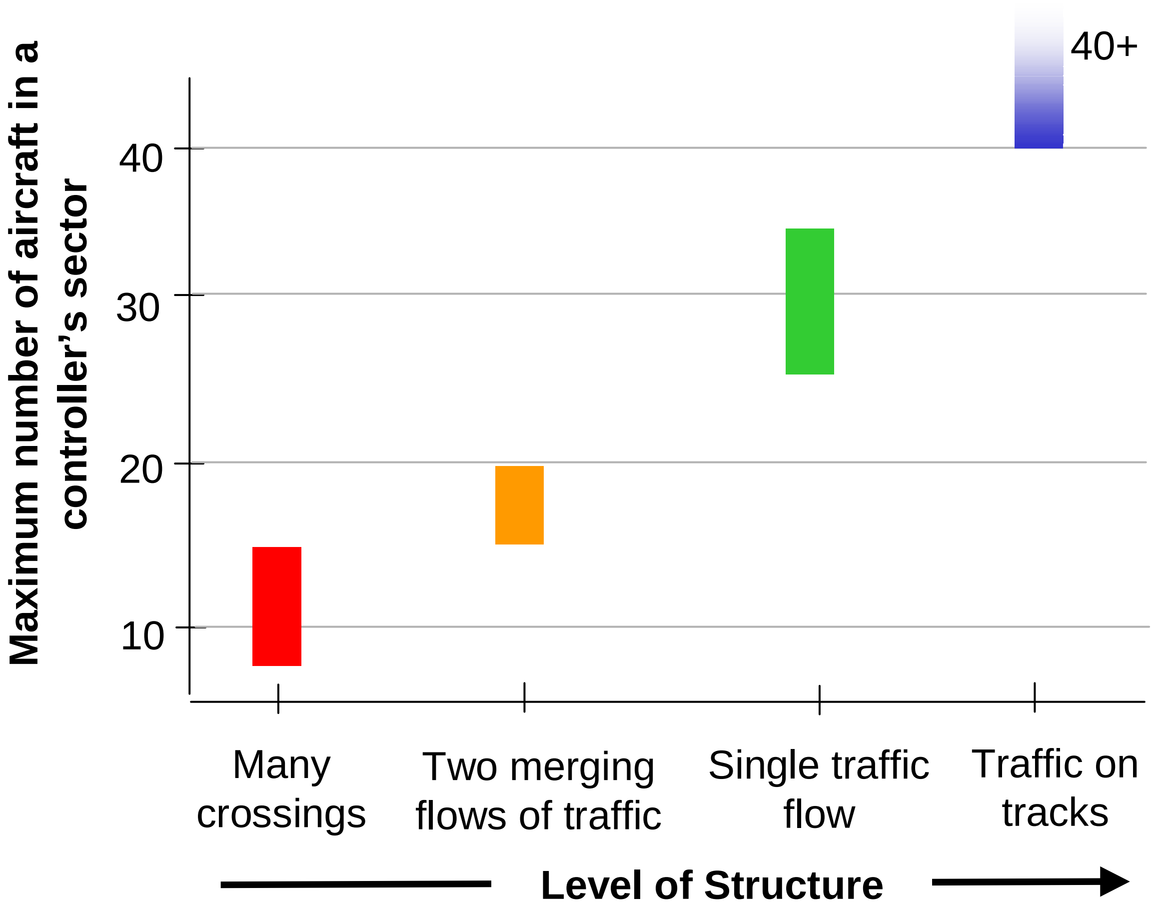






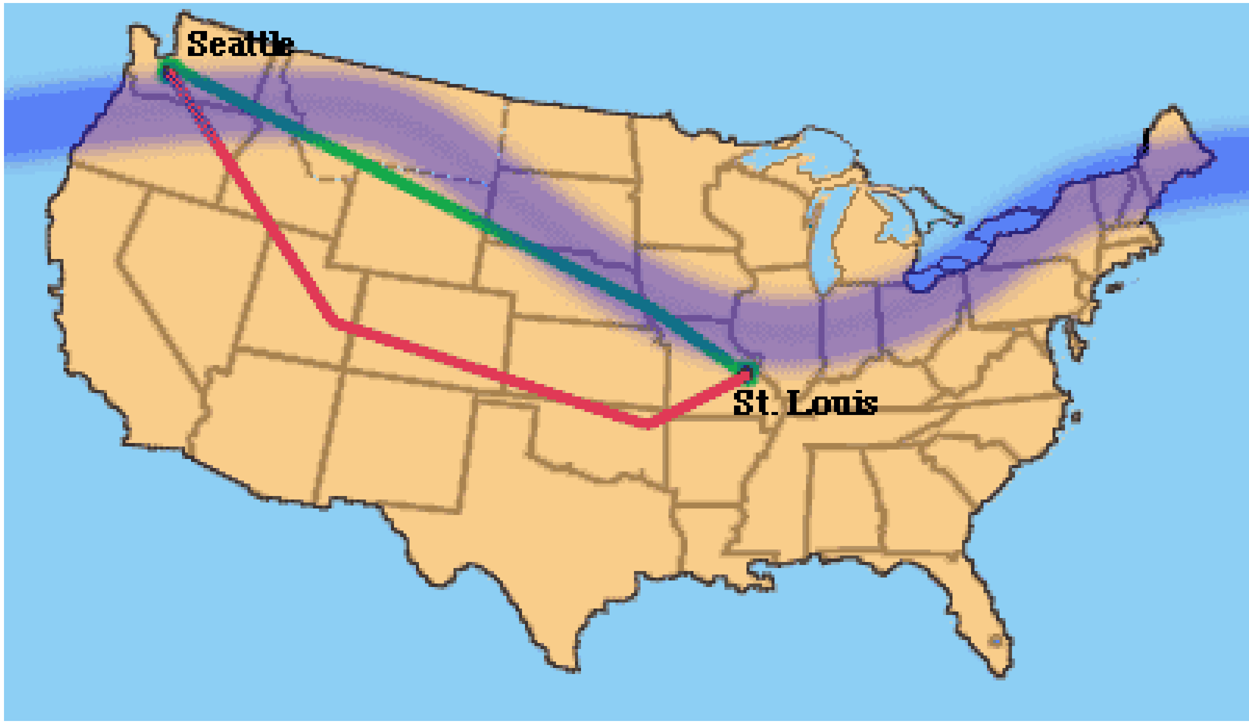
Power of Structure-Based Abstractions

- **Handle more traffic as structure increases**



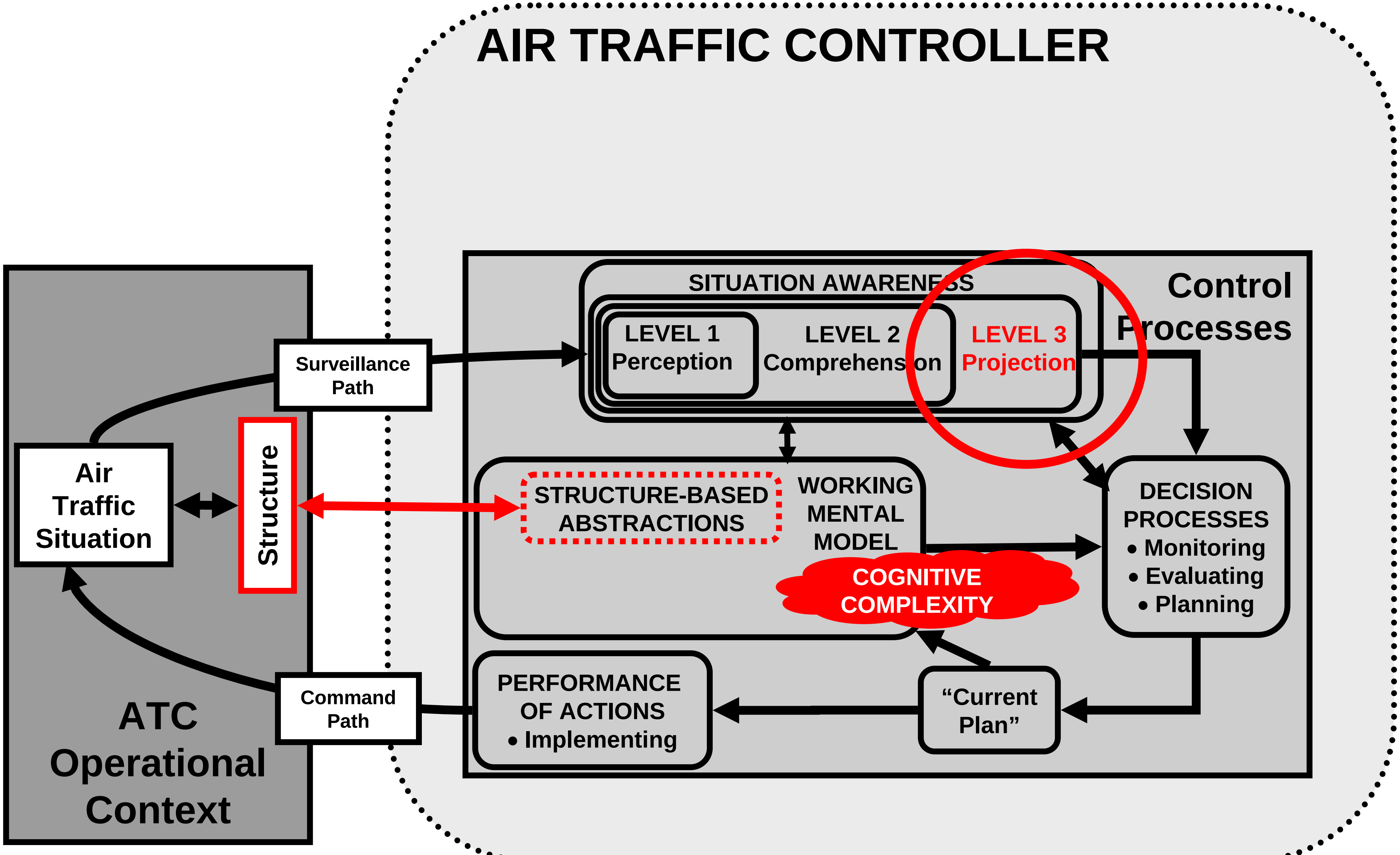
Free Flight

- **Operators have the freedom to select their path and speed in real time**
  - ☐ User-preferred routes chosen for operating efficiency rather than compatibility with air traffic management (ATM) structures
- **Undermines structural basis for Structure-Based Abstractions**
  - ☐ Important to understand and consider users' abstractions and mental models



Source: http://virtualskies.arc.nasa.gov/research/tutorial/tutorial3.html

Projection is a Key Element of Maintaining Situation Awareness

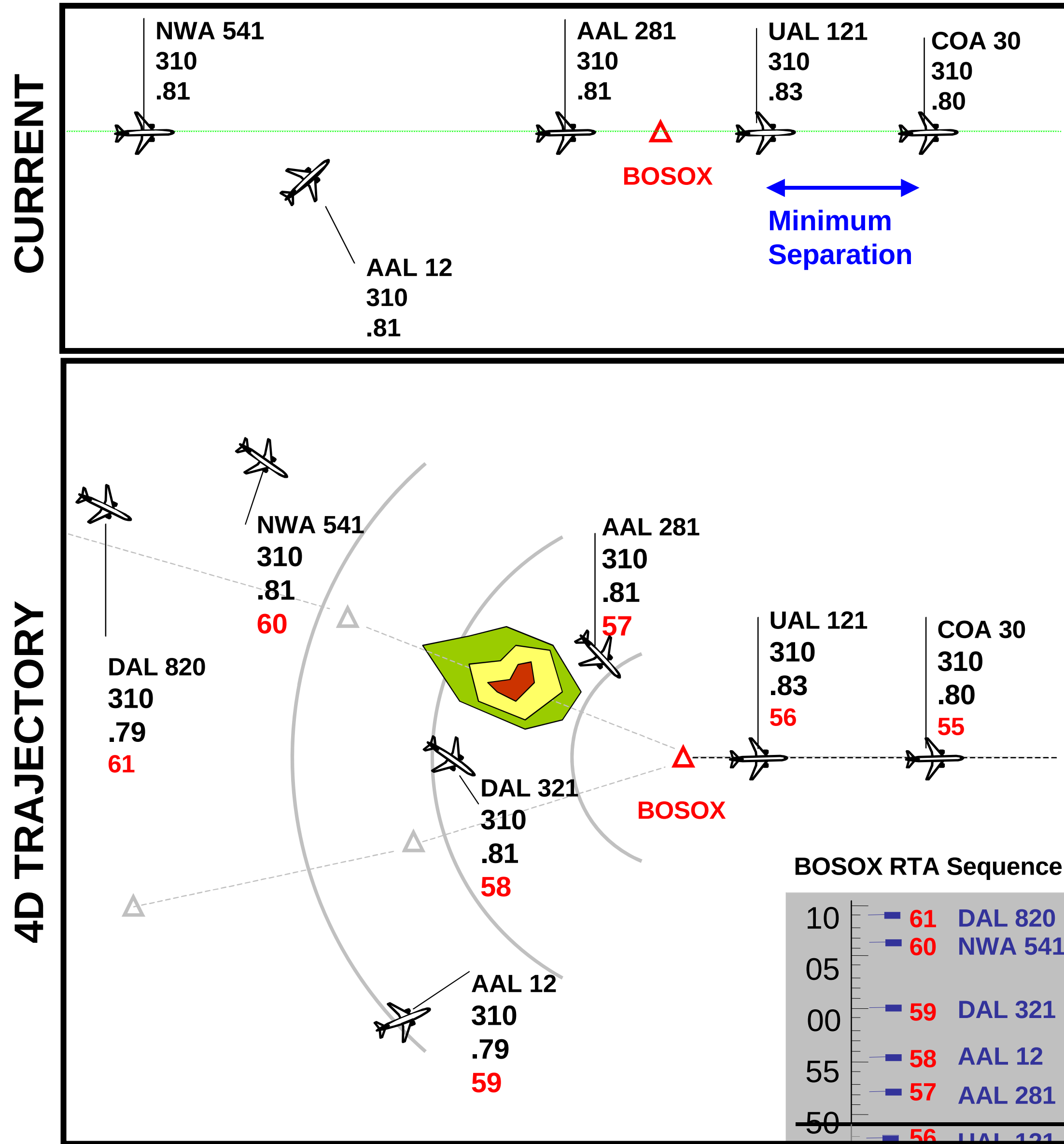


Temporal/Spatial Projection

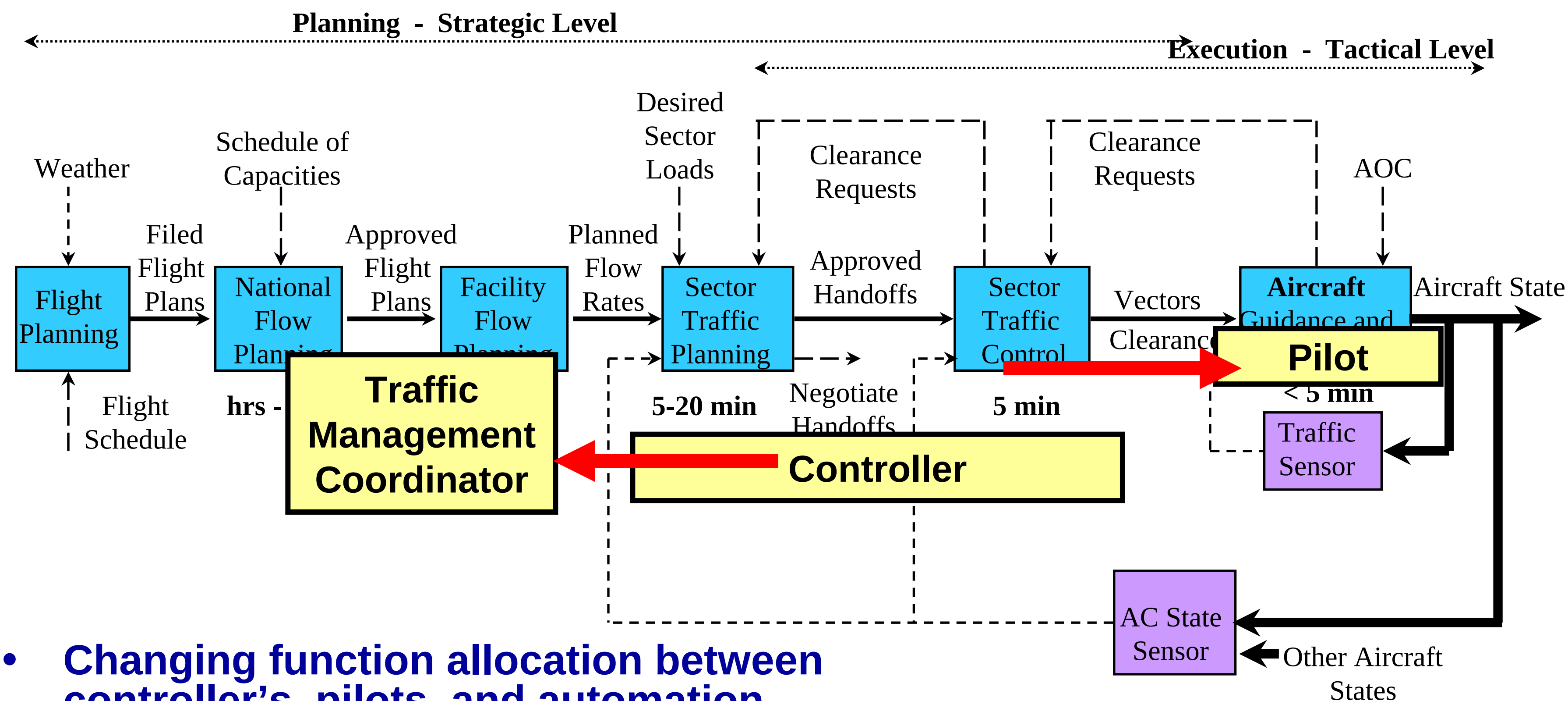
- **Task, mental model and available abstractions strongly affect ability to maintain situation awareness of projected future states of the situation.**
- **Projection has been observed in field studies to be significantly different in various ATC environments:**
  - TRACON- spatial projection
  - En Route Center- mixed spatial/temporal projection
  - Oceanic environments- procedural temporal projection (no cognitive projection required)

Future Operations: 4D Trajectories Will Require New Abstractions & Procedures

- **Projecting additional states**
  - New temporal abstractions
- **New Structural elements:**
  - Procedures for meeting Required-Time-of-Arrival



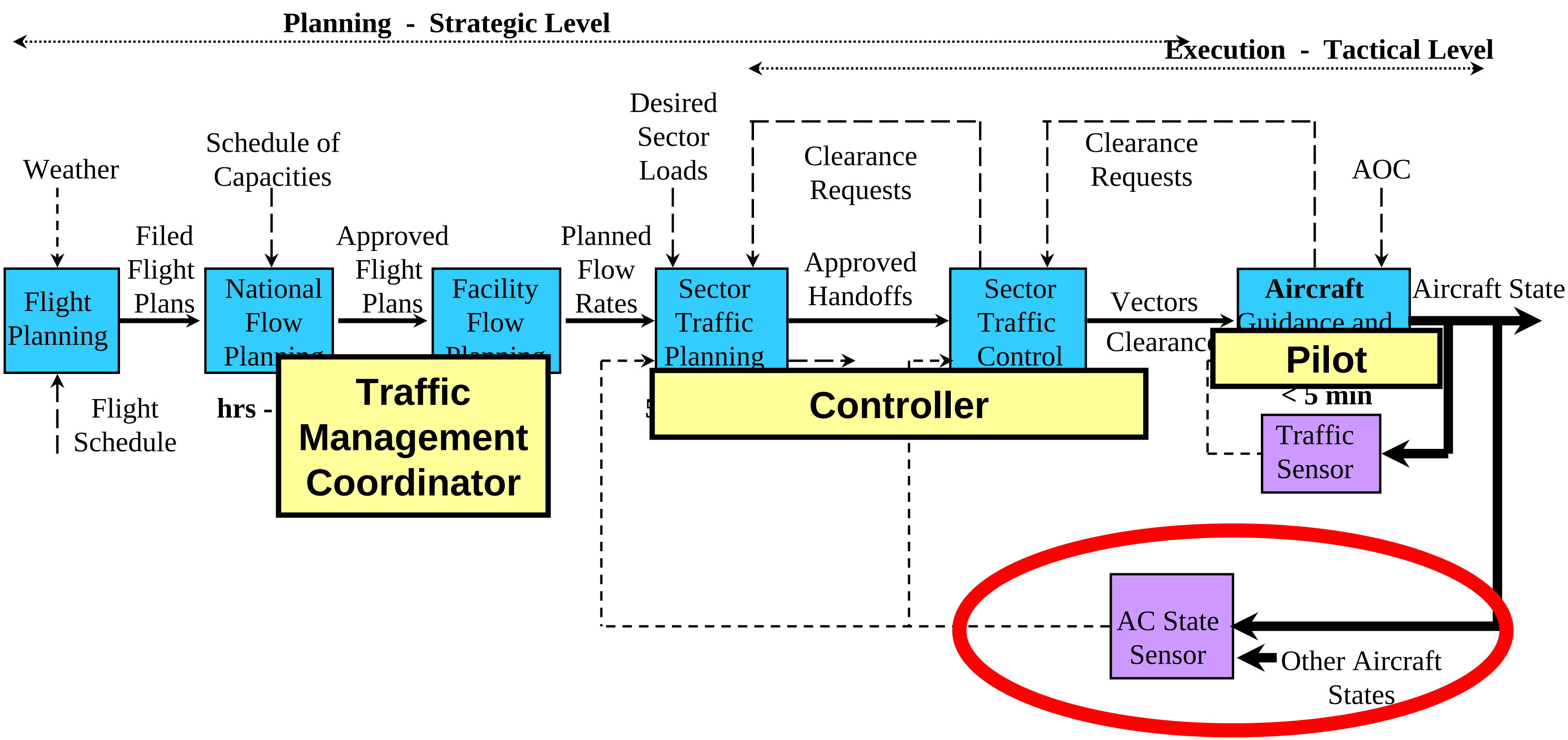
Future Concepts May Transform Roles of Controllers



- **Changing function allocation between controller's, pilots, and automation**
  - ☐ Delegating separation function to pilot / automation
  - ☐ Controller as system manager, supervising automation
- **Challenges**
  - ☐ Responsibility
  - ☐ Humans as monitors
  - ☐ Fail-safe modes and intervention

Source: A. Haraldsdottir Boeing

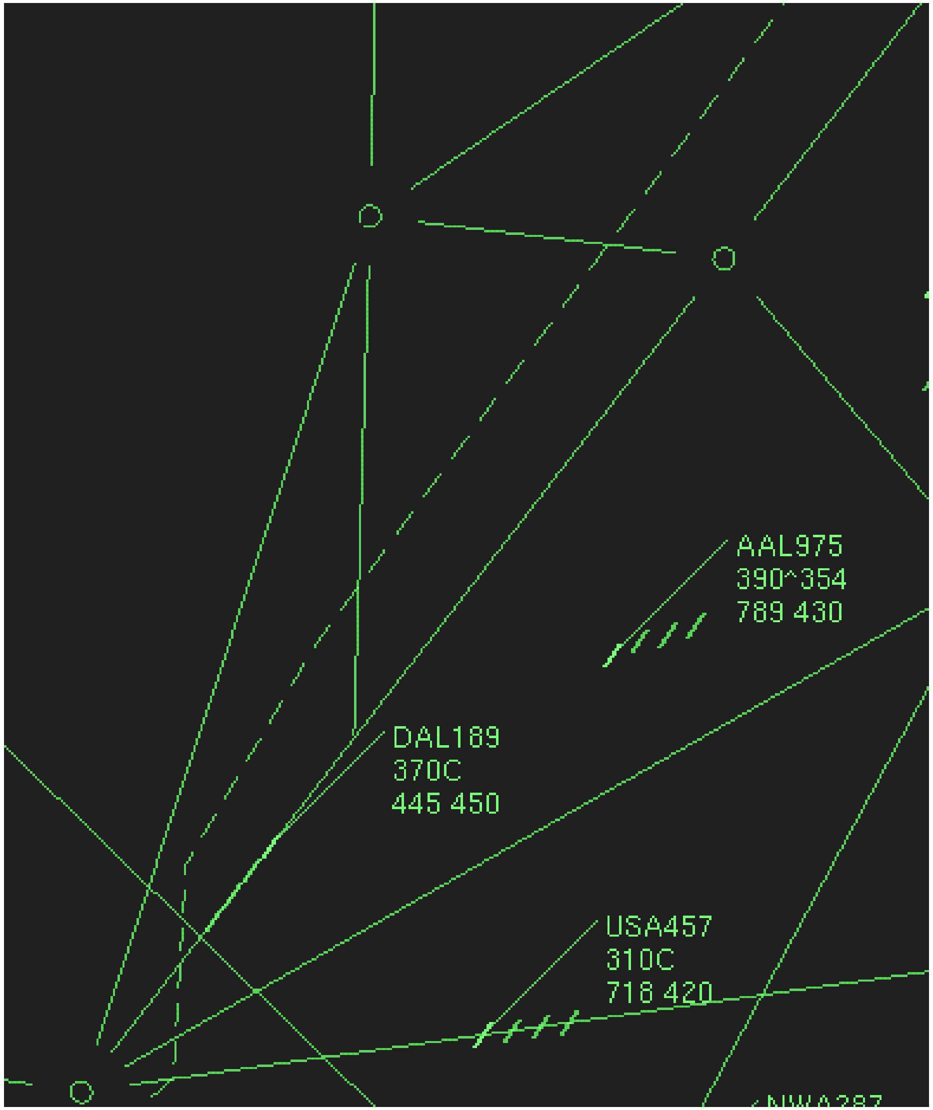
Surveillance of the Operational Environment



Source: A. Haraldsdottir Boeing

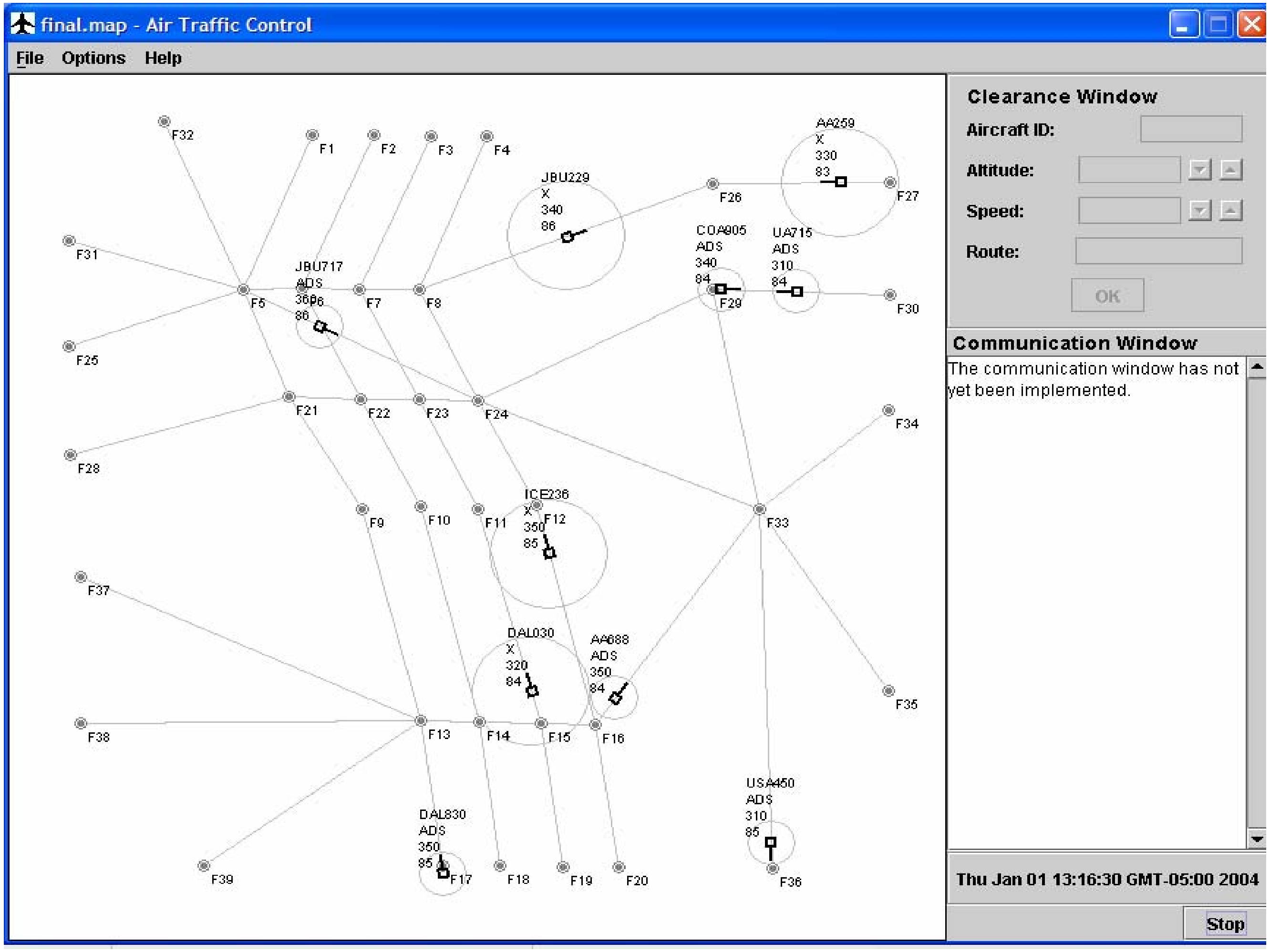
Key Surveillance Properties

- **Update Rates**
  - ☐ Radar
    - o Enroute – 12 seconds
    - o Terminal – 4.2 seconds
  - ☐ Procedural / Oceanic
    - o Reporting points – 10 degrees of longitude
- **Data quality**



Human Factors Challenge: Mixed Equipage Environment

- **Experiment, using part-task simulator, to identify cognitive implications of mixed equipage environment**



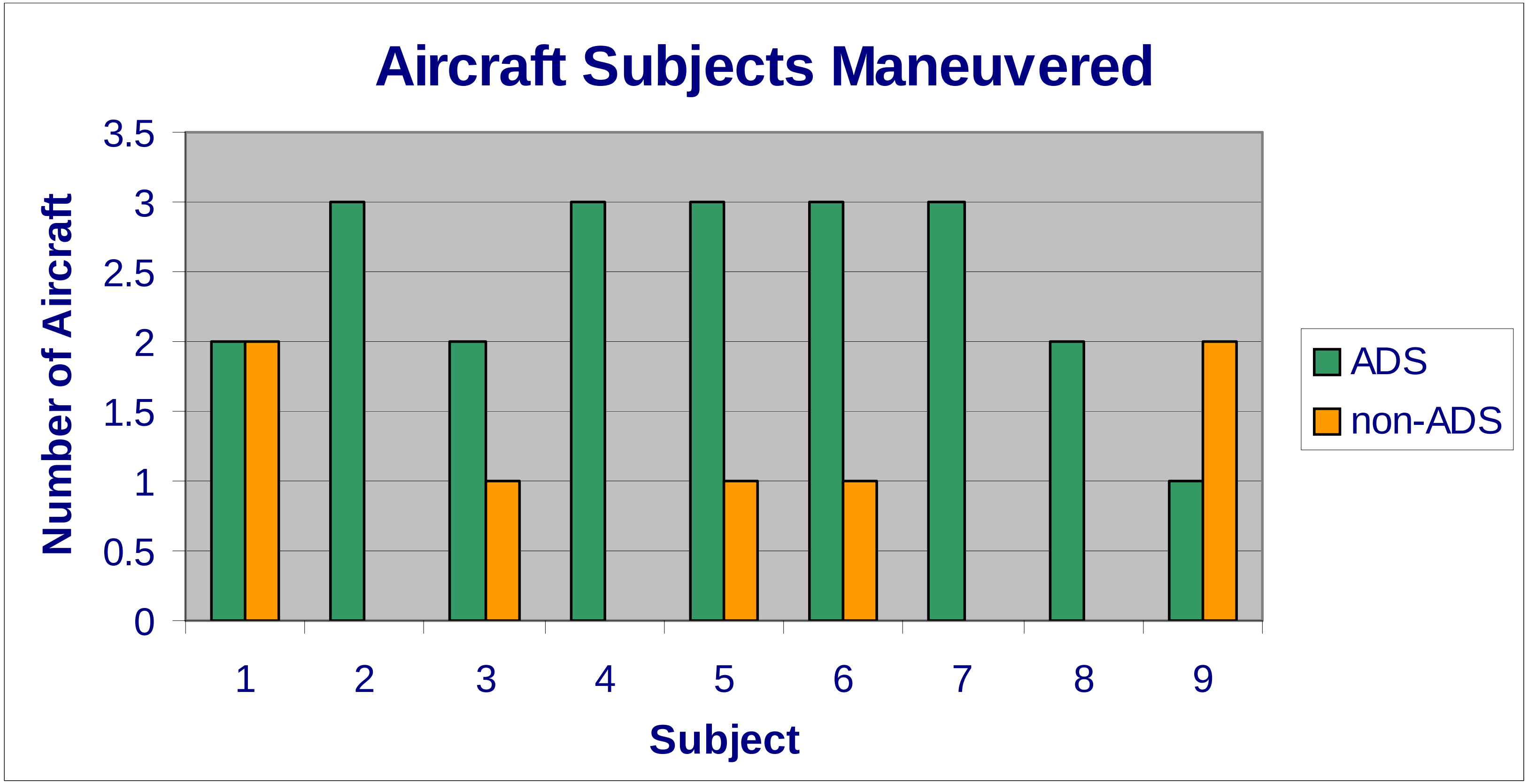
3 Scenarios:

- **ADS equipped aircraft** (high frequency surveillance) – 20 nm separation minima
- **non-ADS equipped aircraft** (low frequency surveillance) – 50 nm separation minima
- **Mixed aircraft**

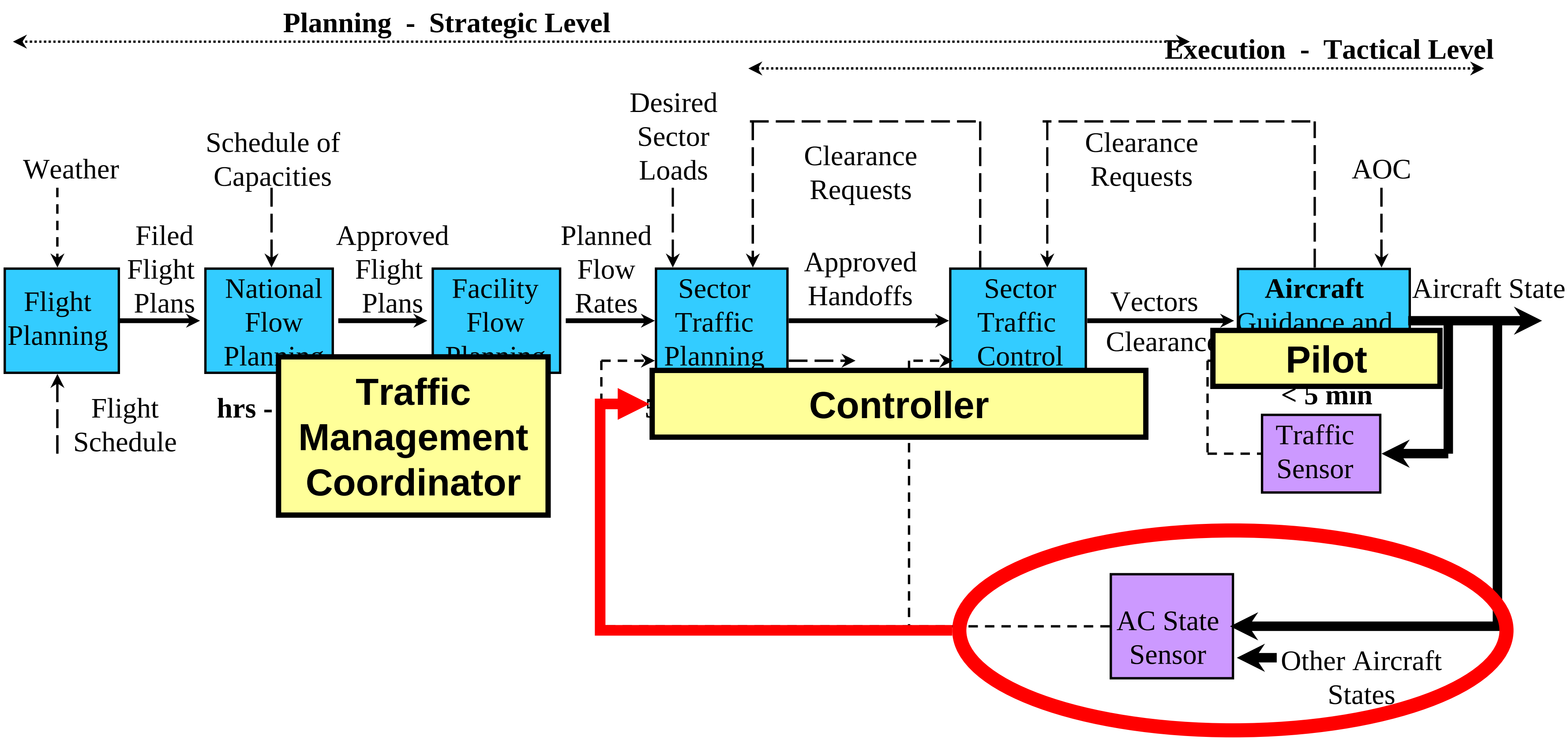
Aircraft Subjects Maneuvered

"Which aircraft were you more likely to maneuver to resolve the conflict?"

All responded: Aircraft equipped with High Frequency Surveillance



Displays

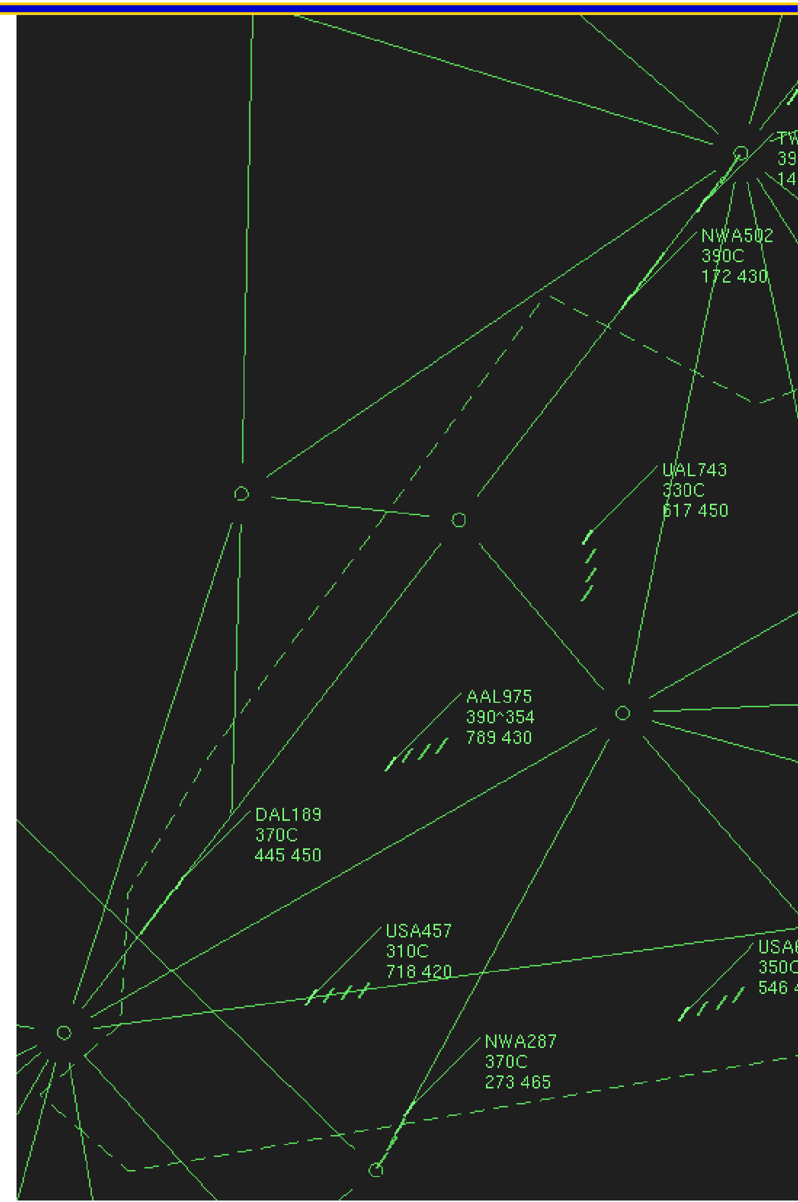


Source: A. Haraldsdottir Boeing

Data Blocks

- **Datablock information:**
  - Altitude
  - Aircraft Type
  - Ground speed
- **Challenges**
  - Information saturation
    - o Route / Intent
    - o Equipage
  - Legibility
  - Overlap

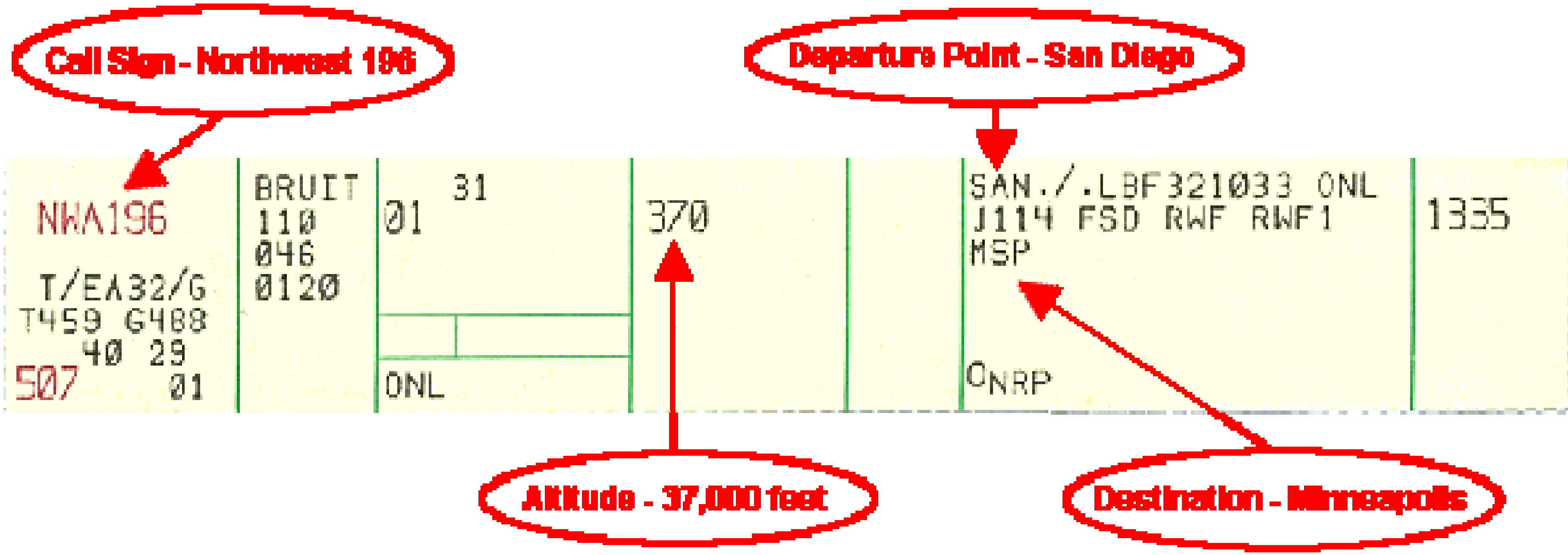
CO 123
350C
B757 310



Increased Computing Power Creates New Human Factors Challenges

- **Increased information availability**
  - ☐ Weather displays
- **Avoiding overwhelming user**
  - ☐ Clutter
  - ☐ Overlapping windows
- **Increased use of color**
  - ☐ Color blindness / deficiencies
  - ☐ “Christmas Tree” effect
  - ☐ Standardized / cultural meanings

Flight Progress Strips



- **Intent communicated through description of route of flight**

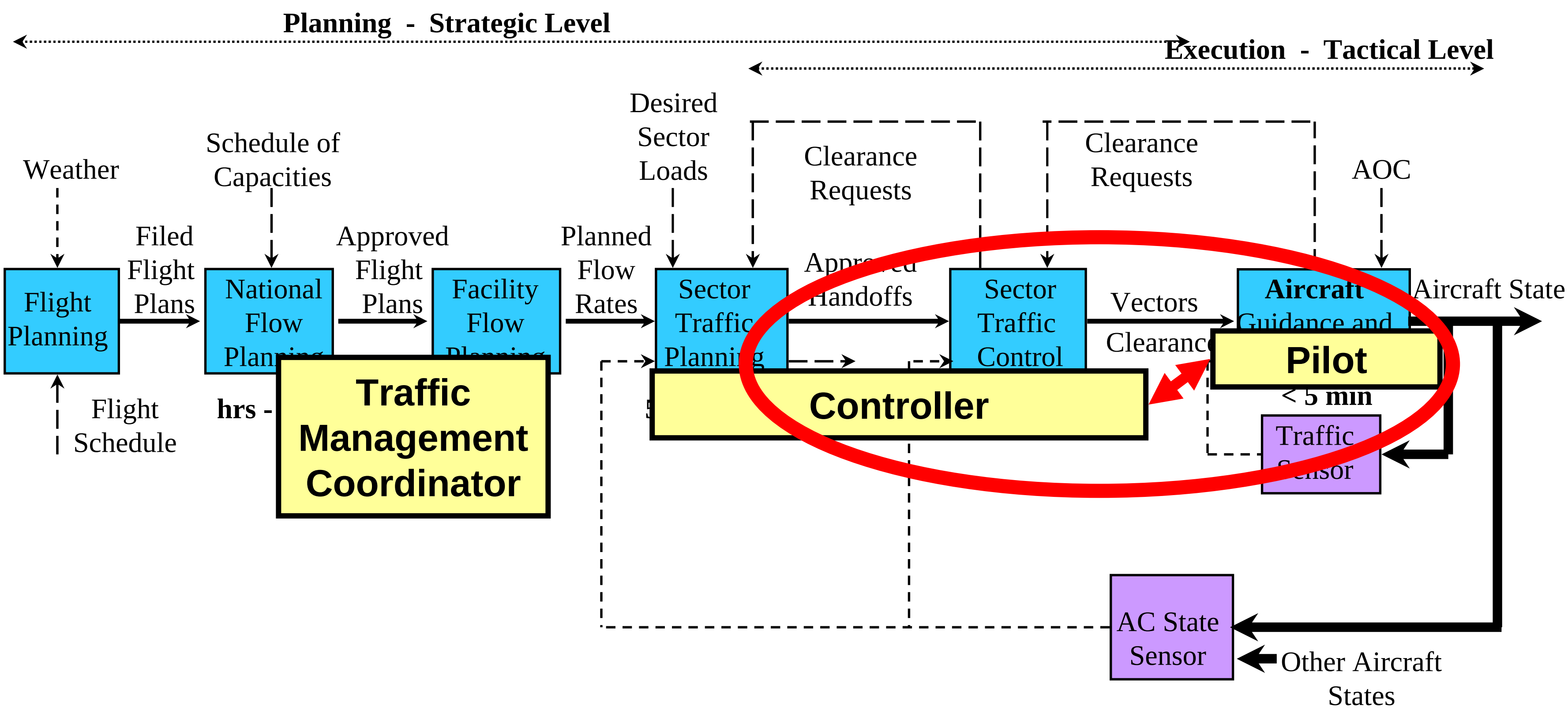
Future: Electronic Flight Strips

- **Capture and present flight data information in a digital form**
- **Expands set of available information**
  - Improves data flow & coordination
- **Are there consequences of losing tangible physical object?**

Digistrips (CENA)

- Enroute control
- Touch screen replaces strip rack
- Character recognition and pop-up menus

Controller – Pilot Communications



Source: A. Haraldsdottir Boeing

Human Interaction Within ATM Based on Assumed Set of:

- **Common Rules**
  - ☐ Federal Aviation Regulations
  - ☐ ICAO standards
- **Common Information (static)**
  - ☐ Published charts
  - ☐ NAVAID and airport data
  - ☐ NOTAMS
  - ☐ Airways, intersections
- **Common Procedures**
  - ☐ Instrument Approach Process (IAP)
  - ☐ Standard Terminal Arrival Routes (STARs)
- **Common Language**
  - ☐ English, ICAO standard procedures
- **Common Background and Culture**
  - ☐ Safety Critical Culture
  - ☐ Professionalism, Shared Respect
  - ☐ Apprentice training

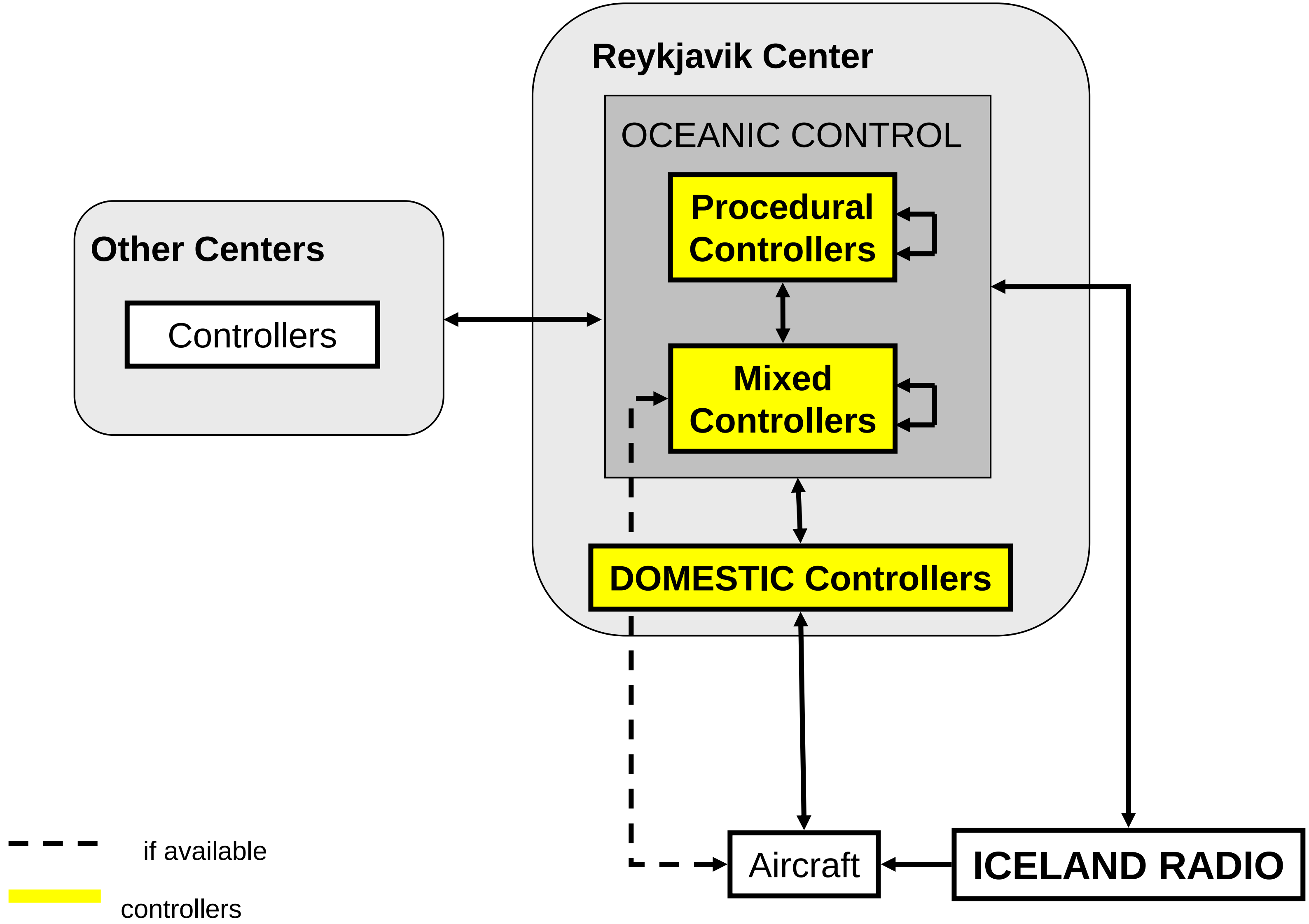
Communication: Controller Pilot Interaction

- **Primary interaction element is the clearance**
  - Contractual agreement for resources
    - Airspace
    - Runway
    - Airport surface
- **Interaction increases with amendments due to…**
  - Weather
  - Traffic
  - Airspace/NAVAID
  - Fuel state

Current Communication Paths

- **HF - High Frequency**
- **VHF - Very High Frequency**
- **Delegated / indirect communications**

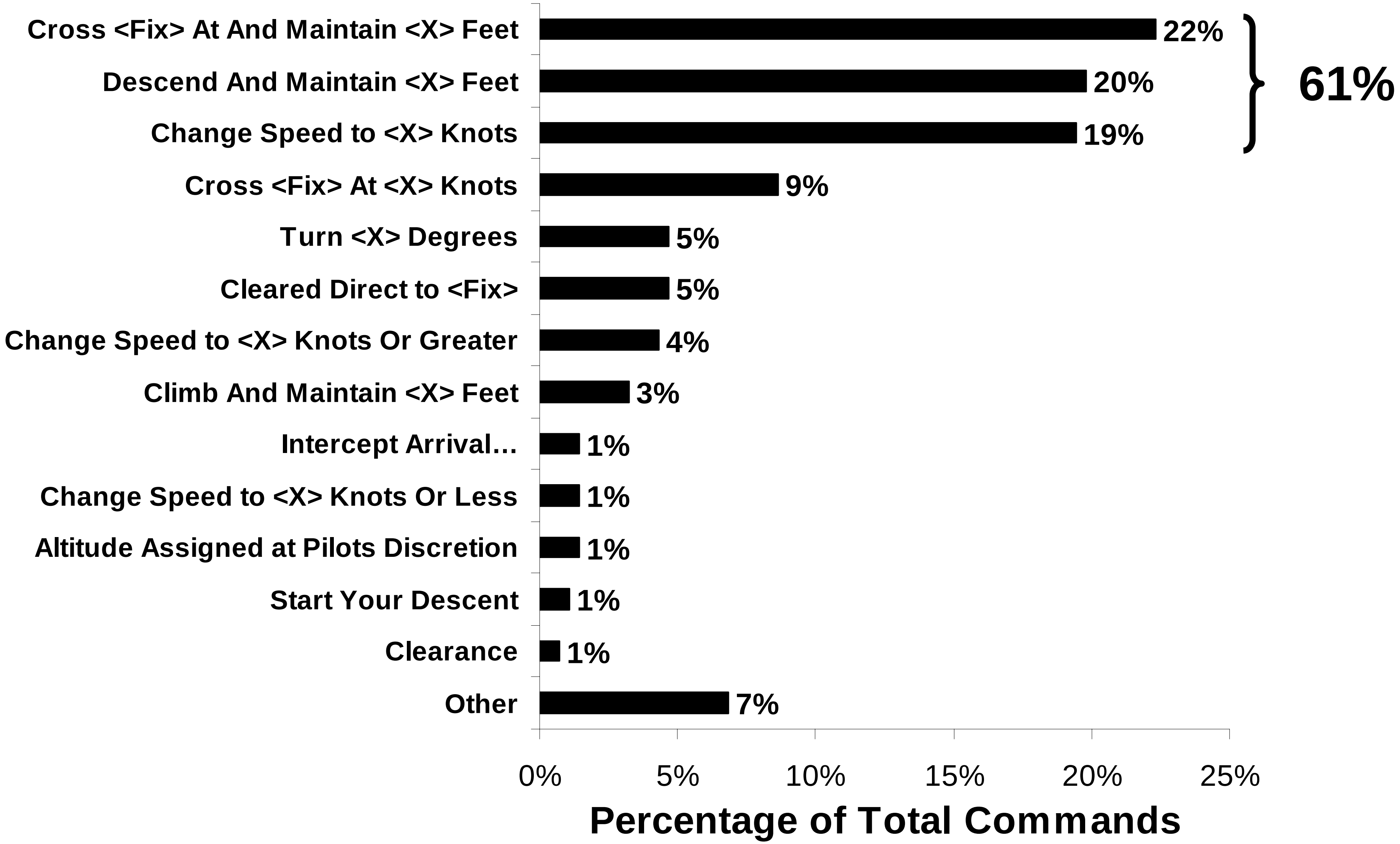
Indirect Communication
Oceanic Voice Relay



Controller-Pilot Communication Limitations

- **Language**
- **Foreign/local accents**
- **Speech rate**
- **Technology limitations**
  - Frequency congestion
    - "Blocked"
  - HF limitations – Oceanic airspace
- **Responses:**
  - English common language
    - Local adaptations / policies
  - Redundancy & readbacks
  - Standardized phraseology

Standardized Phraseology



Introducing New Technologies: CPDLC

- **CPDLC – Controller/Pilot Datalink Communications**
  - ☐ "Email" for controllers

First CPDLC message sent from ground to aircraft

image source: http://www.faa.gov/programs/oep/v6/Smart%20Sheets/ER/ER-3%20V6.htm

(Some) CPDLC Human Factors Issues

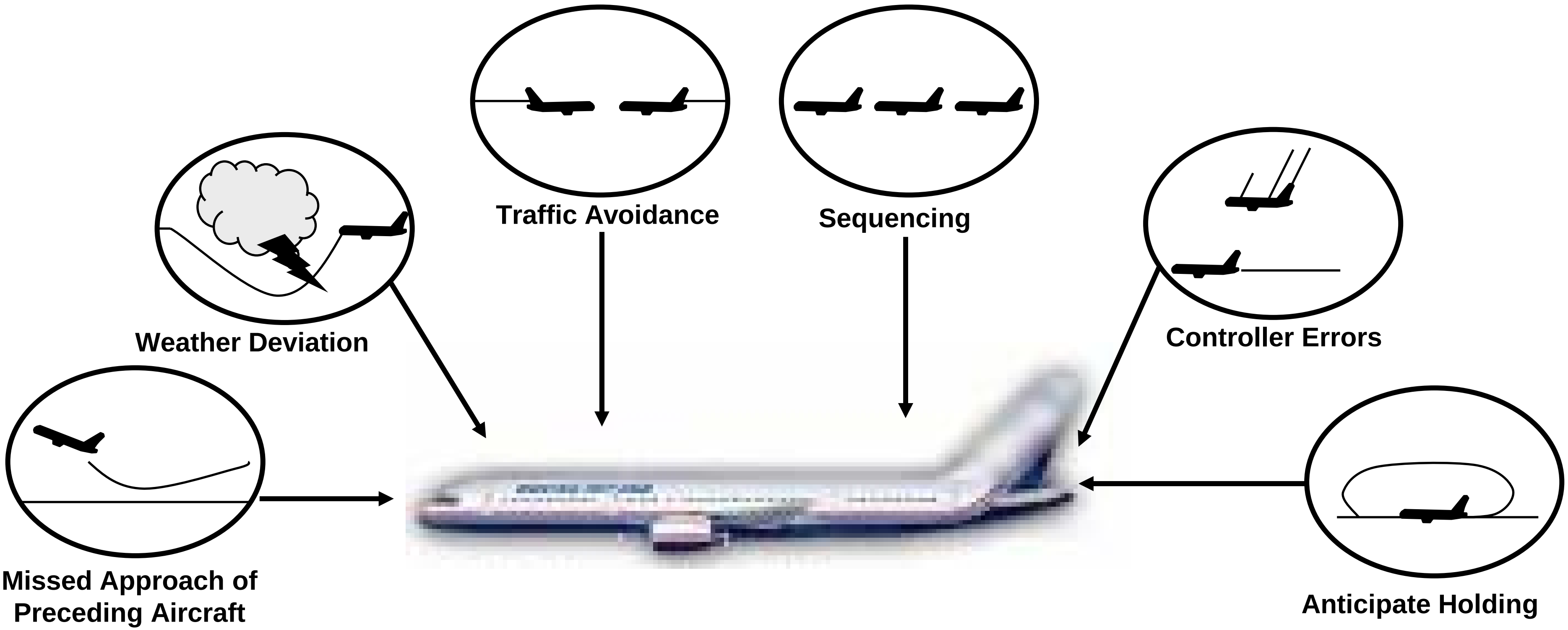
- **Reaction / response times**
- **Synchronization**
  - ☐ Complex instructions
- **Security**
  - ☐ Verifiability?
- **Social?**
- **Situation awareness**

Affective States Accessible Over Radio

- **Affective states**
  - Emotional states
  - Workload
  - Urgency
  - Stress
  - Capability
  - Attenuation
- **Voice communications**
  - Speed of response
- **Controller assesses**
  - Competency
  - Attentiveness
  - Reliability
- **Pilots assess**
  - Workload
  - Urgency
- **Possible loss of this affective state information with datalink systems**

From Dr. R.J. Hansman, MIT

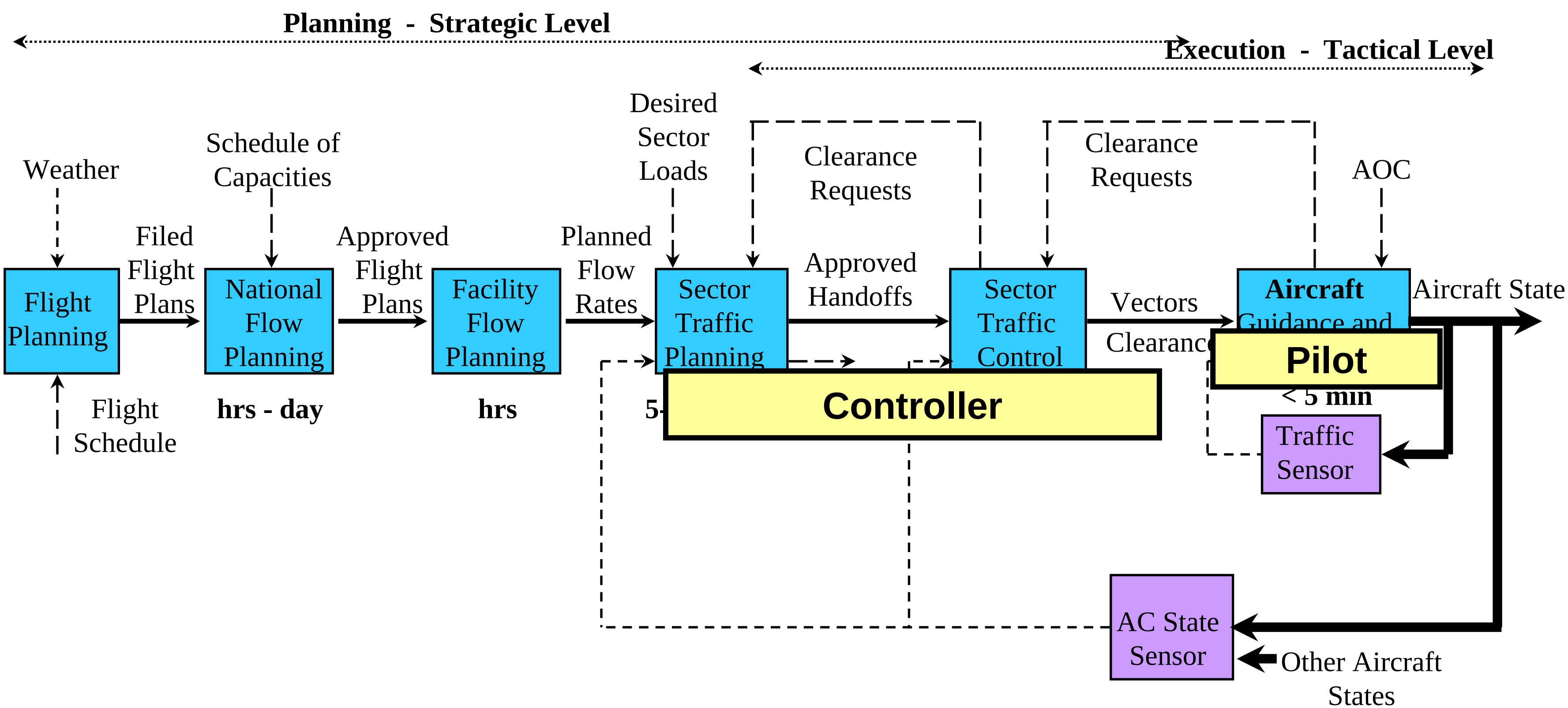
"Party Line" Information



- "Party Line" Information was found to be an important, but unreliable source of information in surveys, analyses & simulator studies
- Future datalink systems should integrate the important PLI elements during the design of Controller/Pilot Datalink Communications (CPDLC)

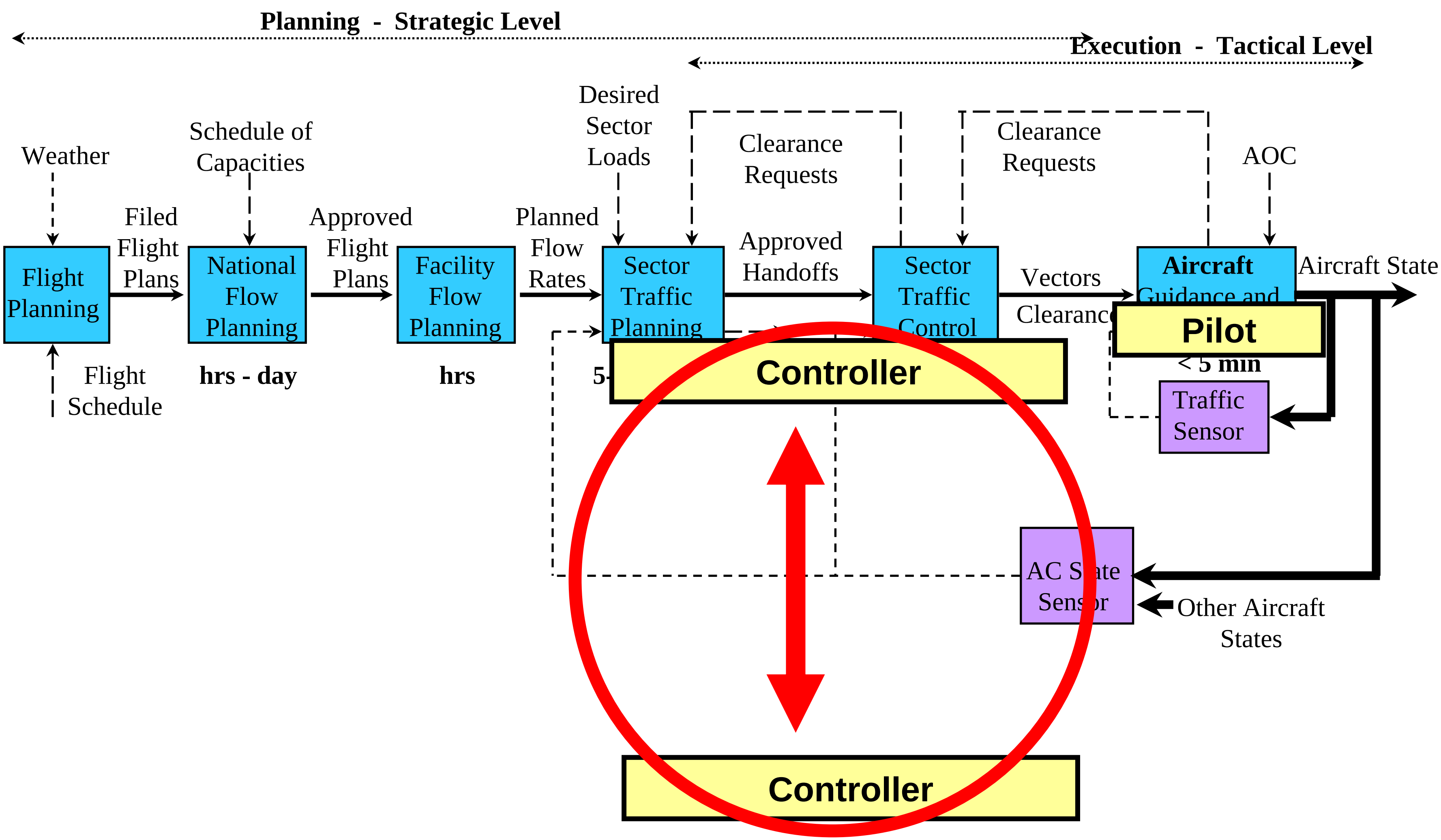
From Dr. R.J. Hansman, MIT

Controller – Controller Interactions



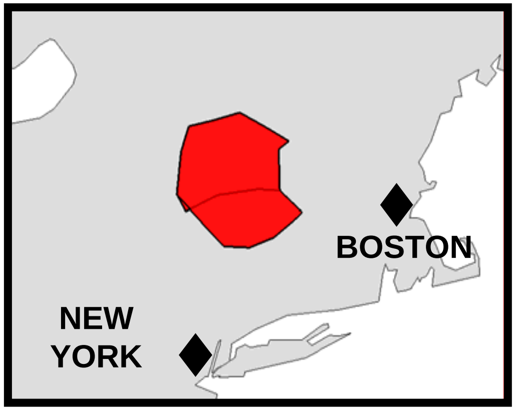
Source: A. Haraldsdottir Boeing

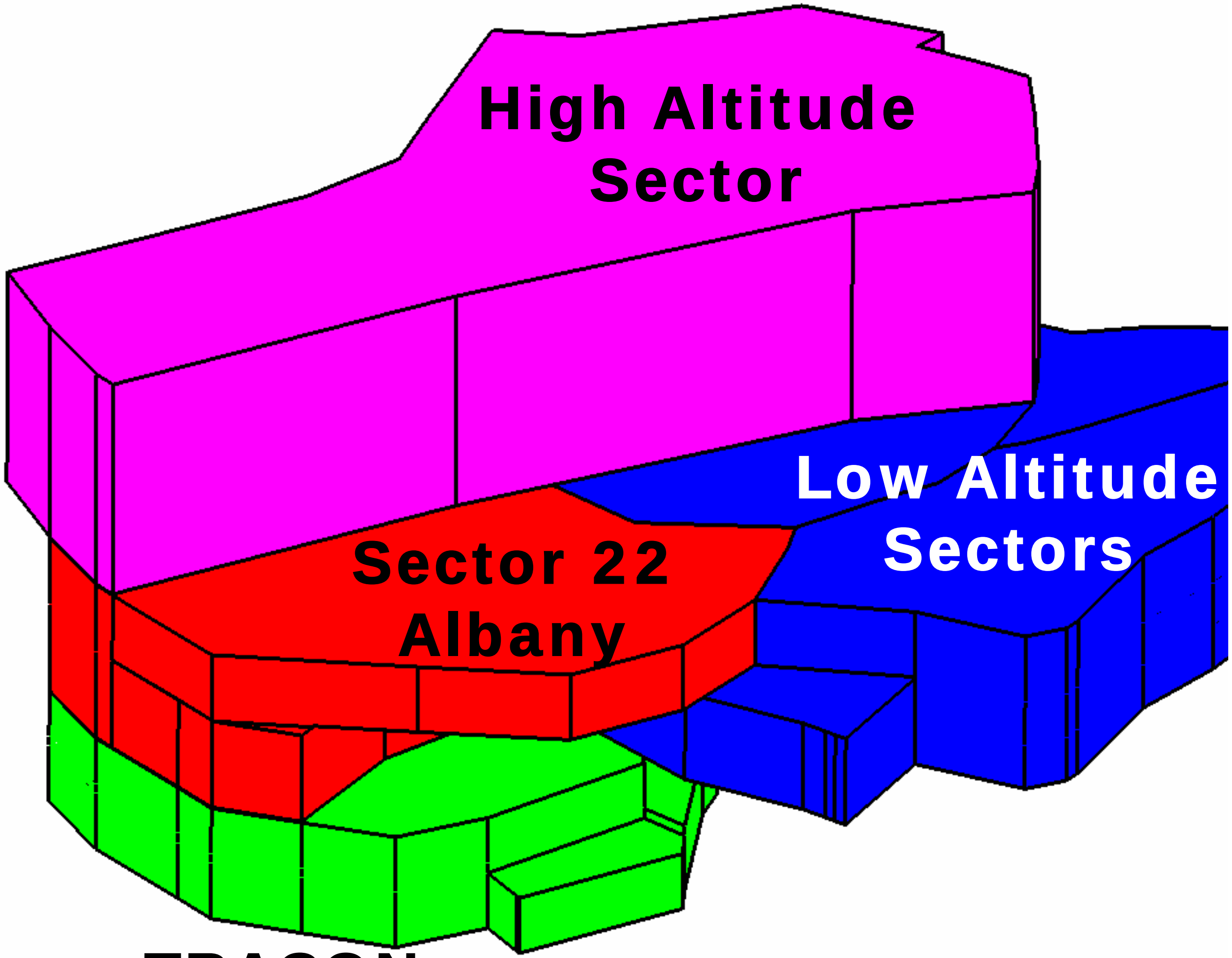
Controller – Controller Interactions



Source: A. Haraldsdottir Boeing

Airspace Structure Dictates Coordination and Information Sharing Needs





Albany TRACON

Controller-Controller Interactions

- **Controller/Controller coordination**
  - Individual flights
    - Coordination, Handoff
    - Special handling / Emergencies
  - Flow coordination
  - Resource status

- **Interaction mechanisms**
  - Supervisor
  - Flight progress strips
    - Annotation
    - Positioning (e.g., strip rack)
    - Accumulation (workload)
  - Affective
    - Posture
    - Gesture

Area of Responsibility / Control / Regard

- **Complexity of controller-controller interactions reflected in 3 key "areas" of controller activity and attention**

- **Area of responsibility:**
  - ☐ Formal sector boundaries

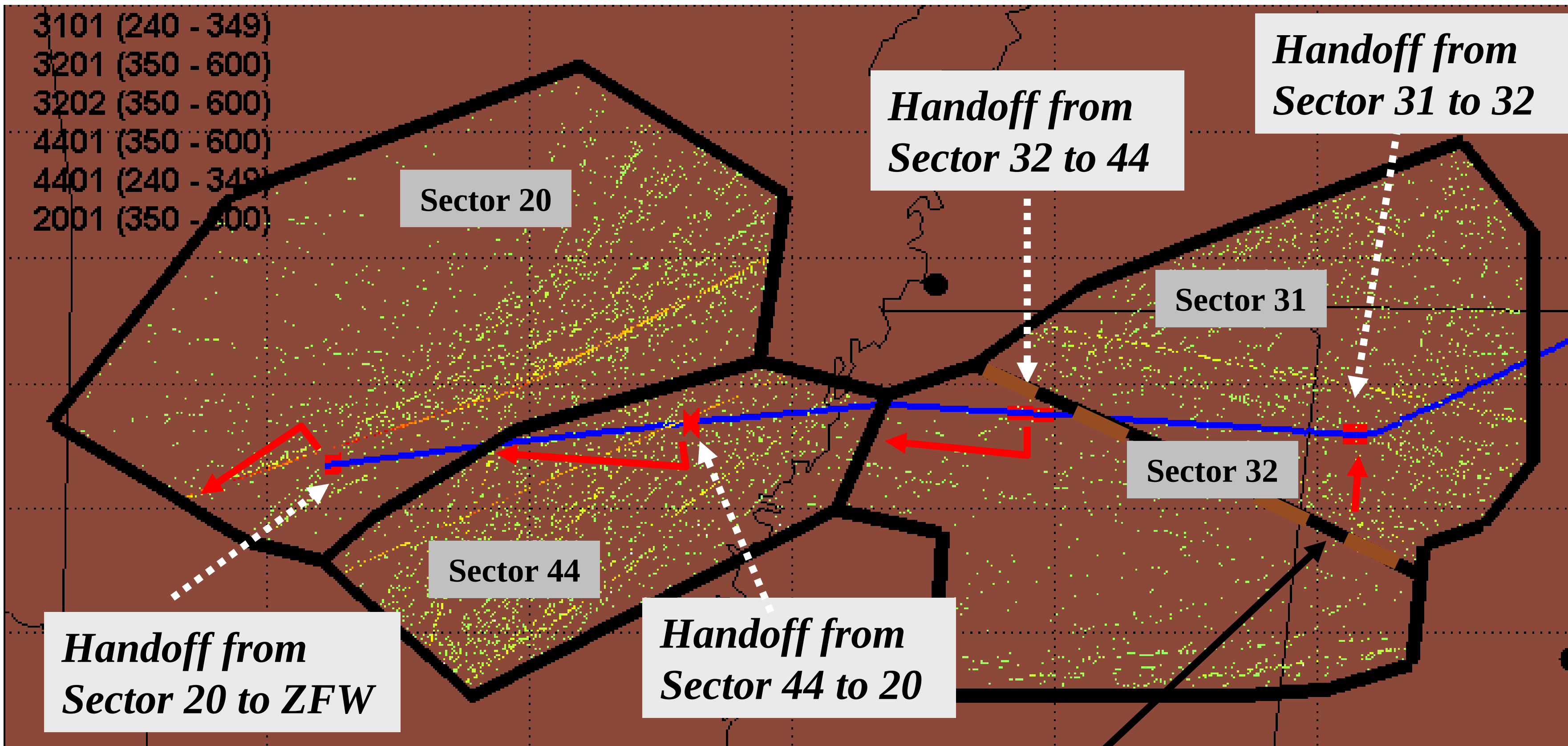
- **Area of control:**
  - ☐ Region where commands are issued
  - ☐ Typically encompasses "upstream" of sector boundaries
  - ☐ Typically does not include all of own sector
    - o Aircraft are "shipped" as soon as possible

- **Area of regard:**
  - ☐ Region controller devotes attention to
  - ☐ Anticipating aircraft upstream

- **Consequences:**
  - ☐ Understanding complexity requires consideration of broader area than formal sector boundaries.
  - ☐ Areas likely expand / contract in response to complexity / task load

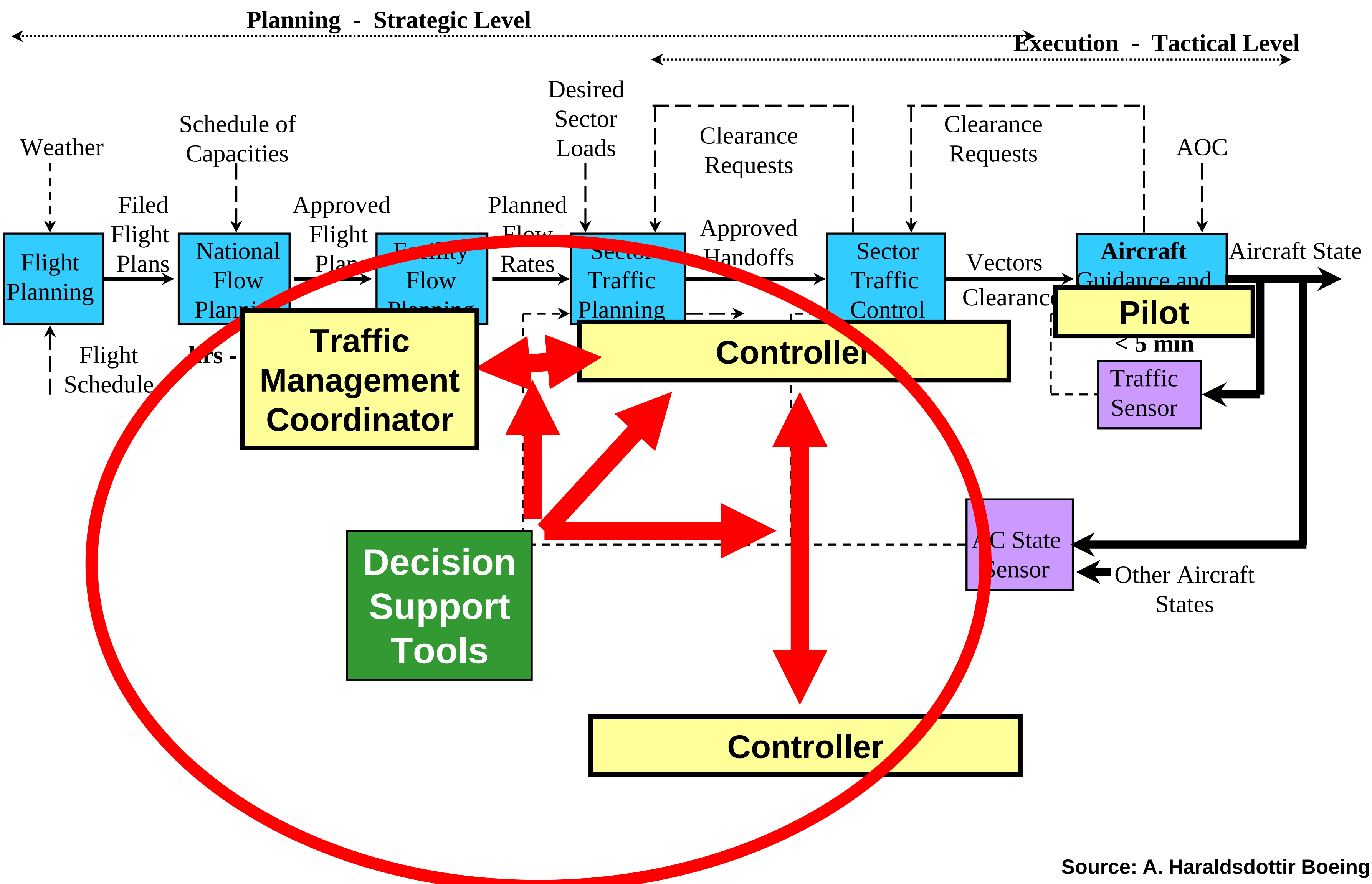
Handoffs Occur Upstream of Area of Responsibility Boundary

- Blue = Aircraft Trajectory
- Black Border = Sectors
- Red = Electronic Handoff Times (arrow points to relevant sector boundary)



Multi-altitude boundary (Sector 31 is only top right, Sector 32, sitting on top of Sector 31, is both pieces)

Decision-Support Tools Support Controller and Multiple Interactions

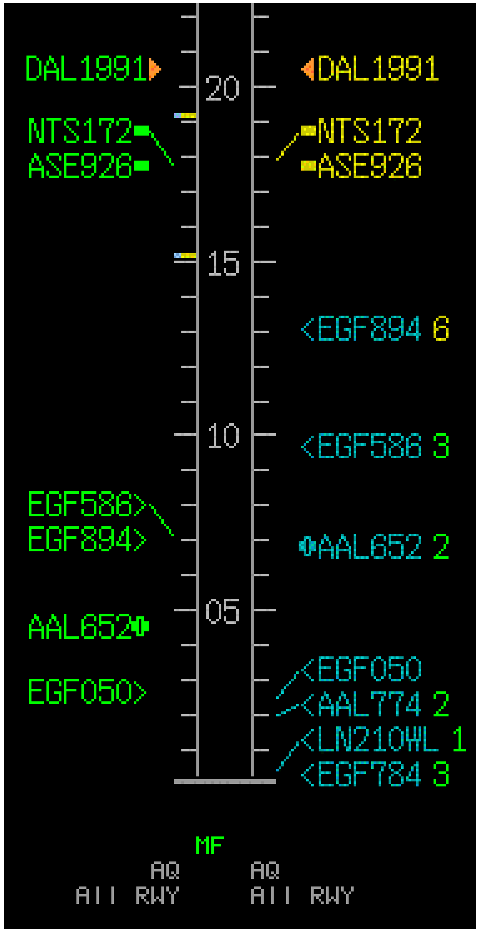


Source: A. Haraldsdottir Boeing

Supporting Controller - Controller Interactions

- **Information sharing technologies**
  - ☐ ETMS/ASD
    - ◆ Airborne traffic
    - ◆ Projected traffic flow
  - ☐ CTAS
    - ◆ TMA arrival coordination
  - ☐ URET
  - ☐ Electronic flight strips
    - ◆ Richer data potential
    - ◆ Input workload
    - ◆ Loss of physical artifact
    - ◆ Head down time (tower)

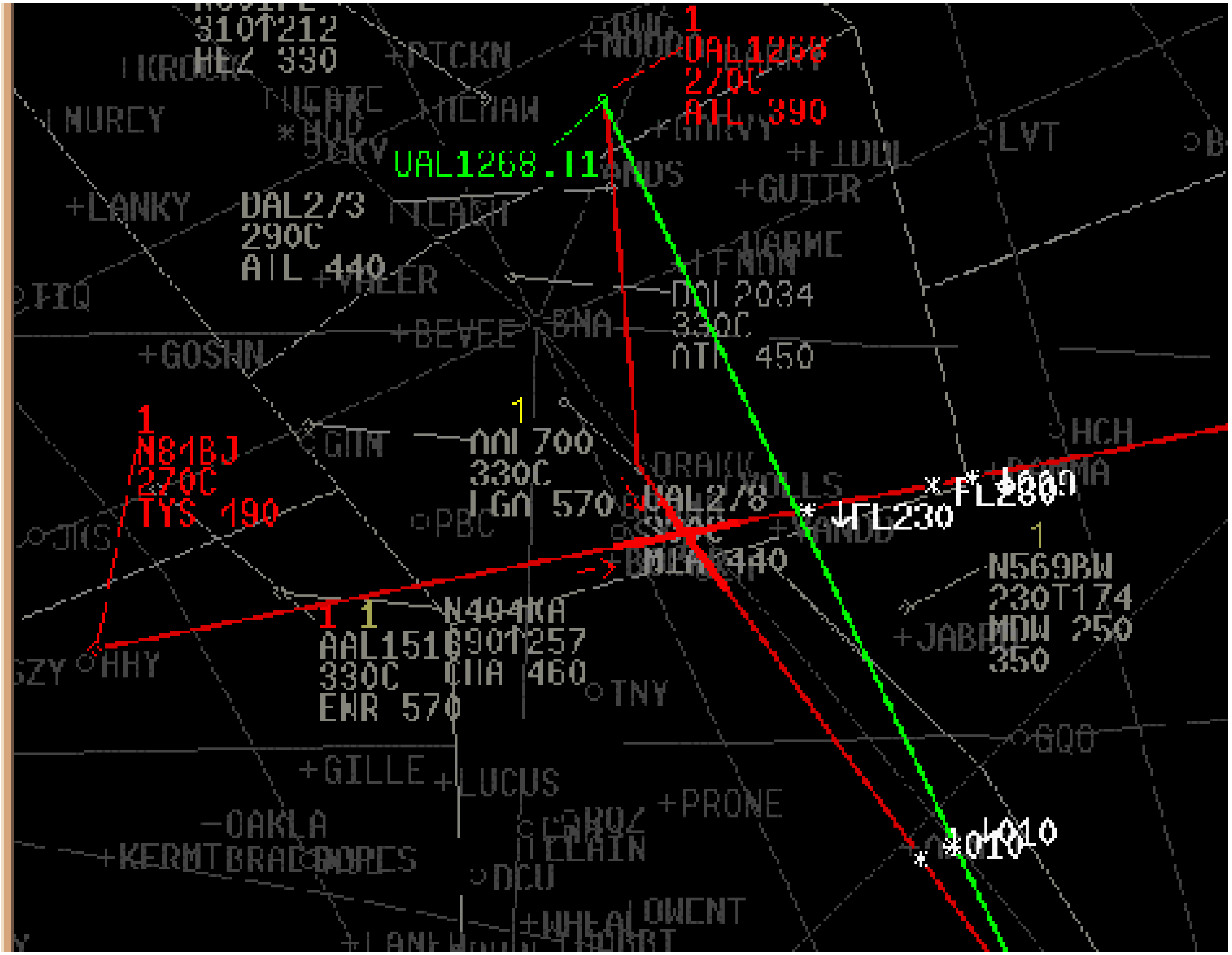
Traffic Management Advisor



ETA **STA**

URET: User Request Evaluation Tool

- **“What if” medium term conflict evaluation**



CRDA:
Converging Runway Display Aid

- Spacing for approaches to intersecting runways
- “Ghosts” simplify cognitive projection task
- Supports enhanced collaboration between terminal and tower controllers
- Decision aiding tool, not decision making tool

Active FAST (aFAST)

- **Provides strategic and tactical advisories**
  - ☐ runway assignments and landing sequences
  - ☐ heading, airspeed and altitude commands
  - ☐ FMS approach clearances
- **Predicted to reduce excess in-trail separation**

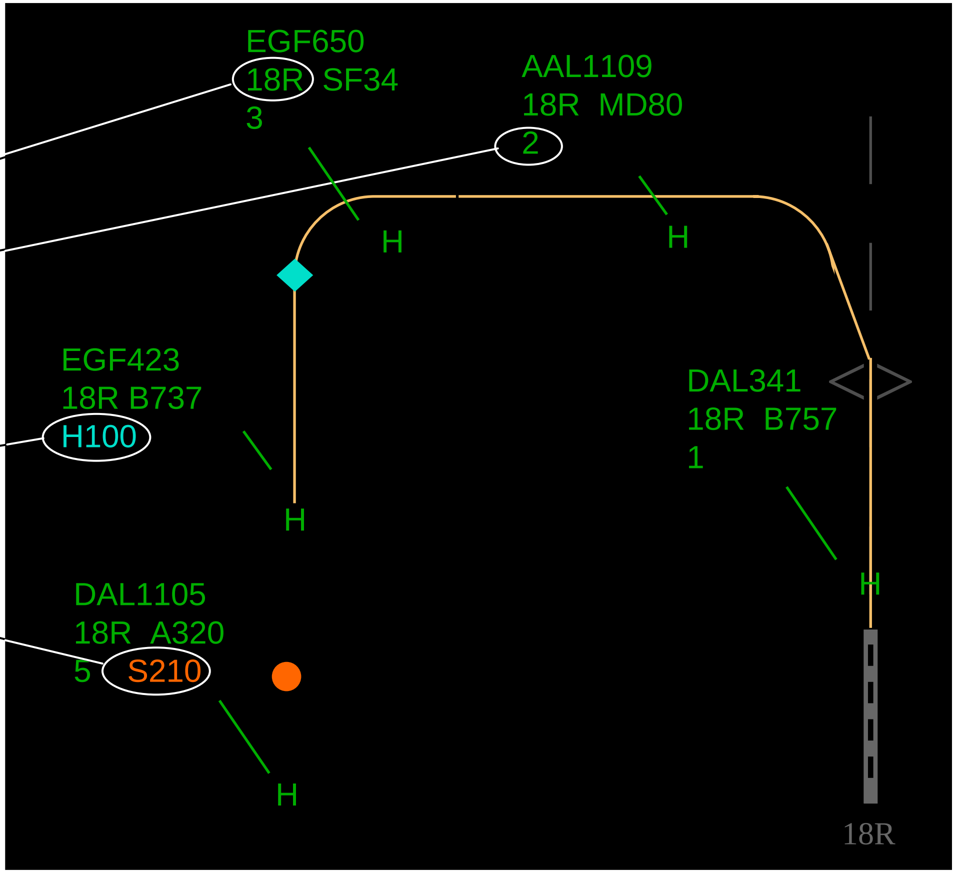
aFAST: Active Final Approach Spacing Tool

- **aFAST provides terminal area arrival controllers with**

<u>Passive Functionality</u>
- runway assignments
- landing sequences

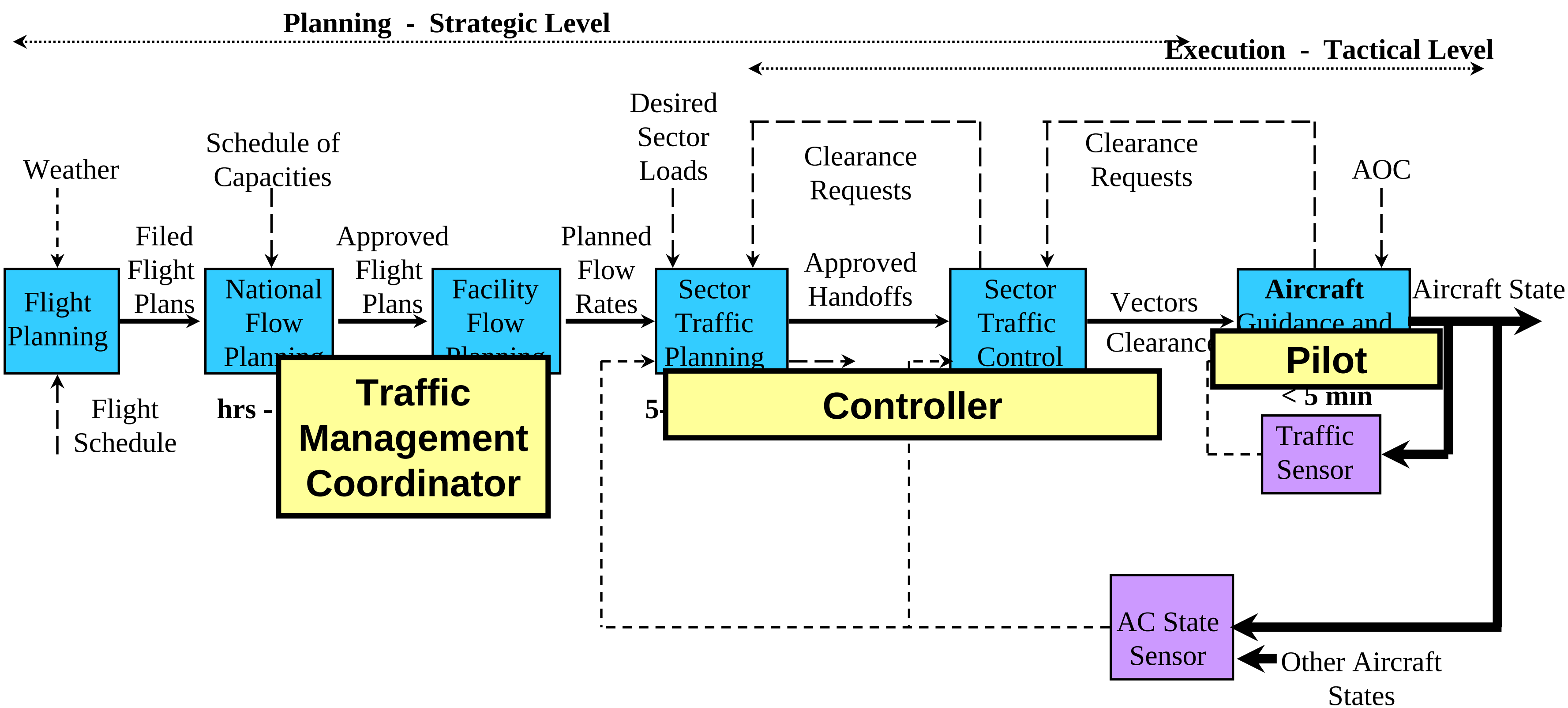
<u>Active Functionality</u>
- heading advisories
- speed advisories
- trajectory preview

<u>Future Functionality</u>
- altitude advisories
- FMS clearances



From Dr. R.J. Hansman, MIT

Controller – Automation Interactions



Source: A. Haraldsdottir Boeing

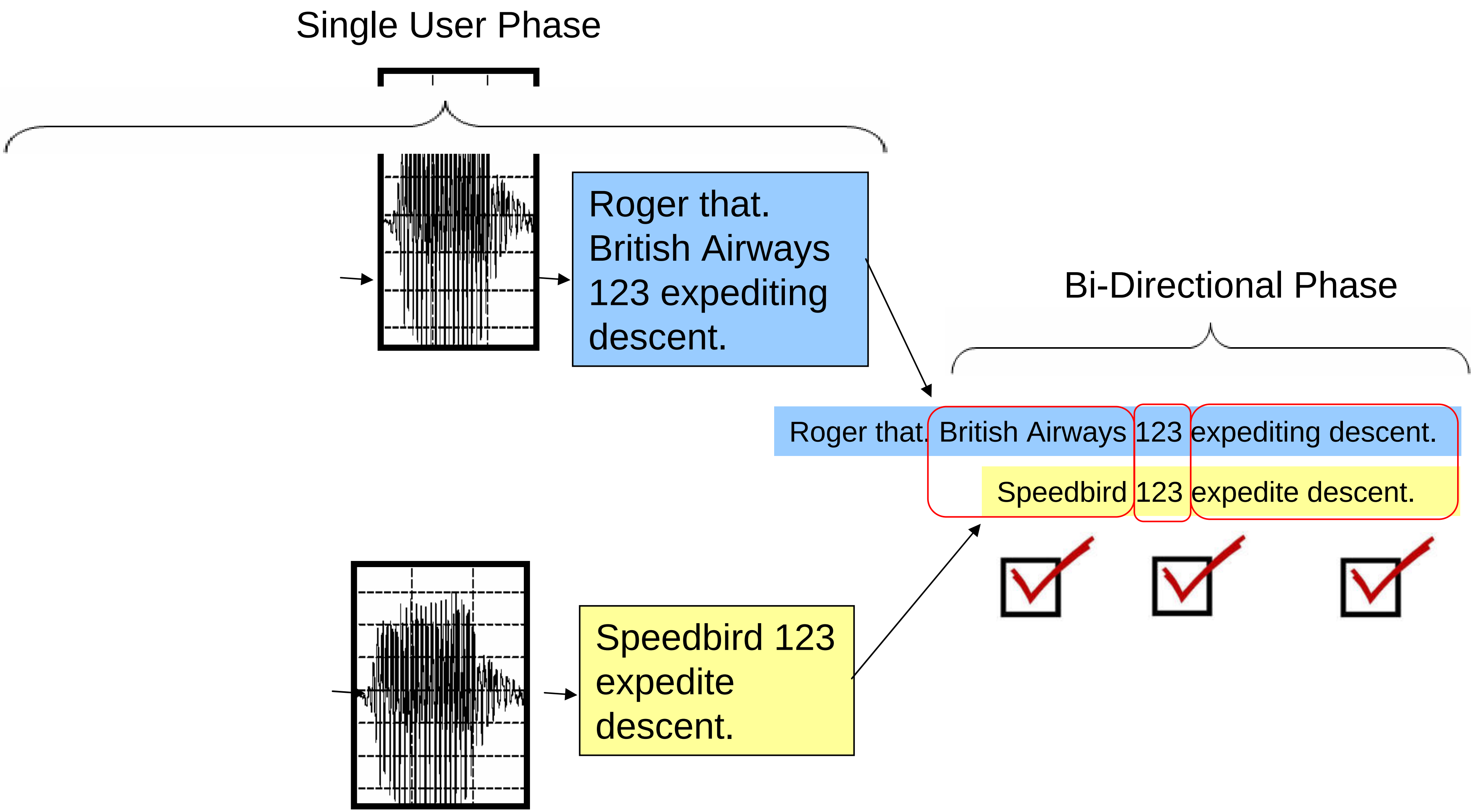
Automation / DST Interfaces

- **Controller – Automation communication critical**
- **Trackballs**
- **Customized keyboard**
- **Automation dependent on up-to-date understanding of intent**

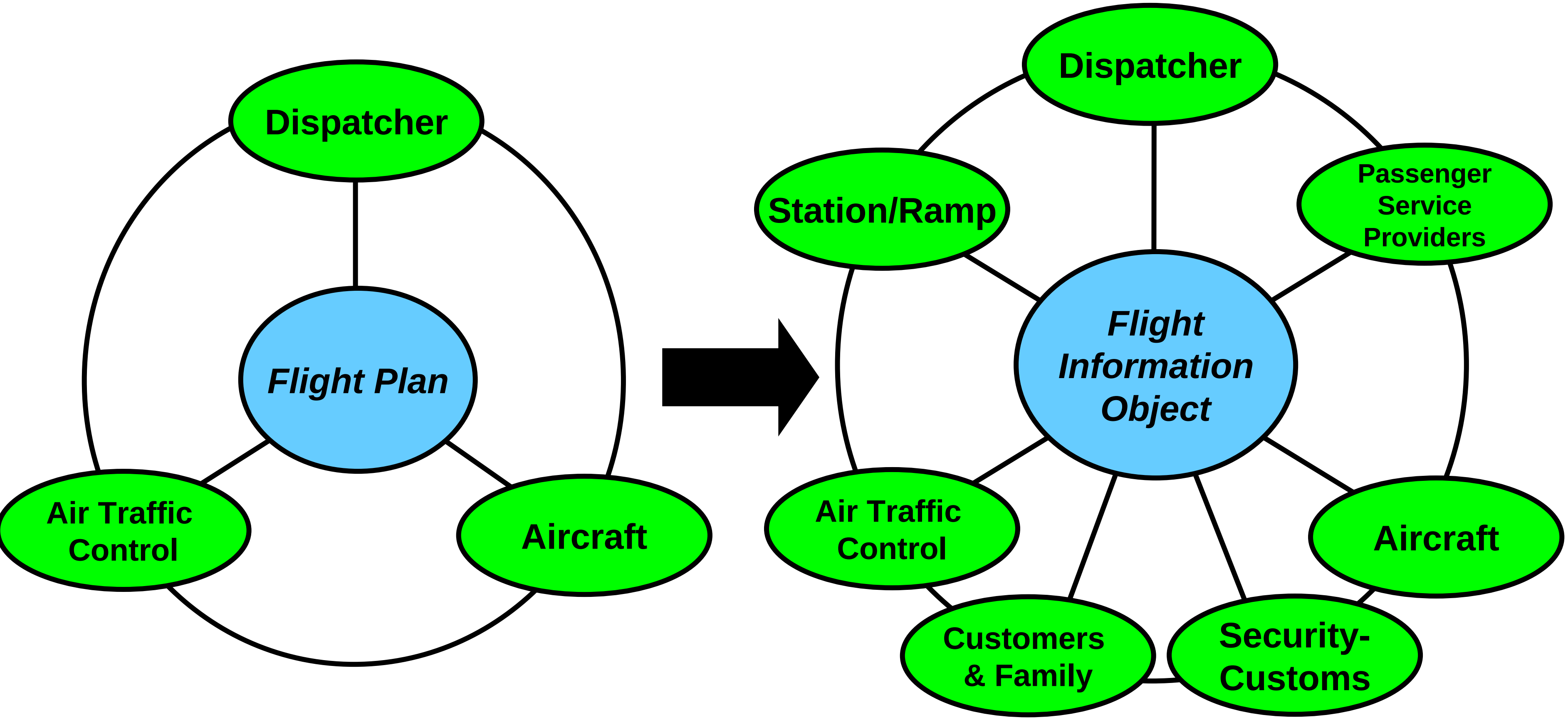
Unique Opportunities to Improve Voice Recognition

- Integrating domain specific features: e.g. Air Traffic Control
- Limited vocabulary
- Standardized speech patterns
- Bi-directional “recognition” opportunities

Improving Voice Recognition Using Bi-Directional Features



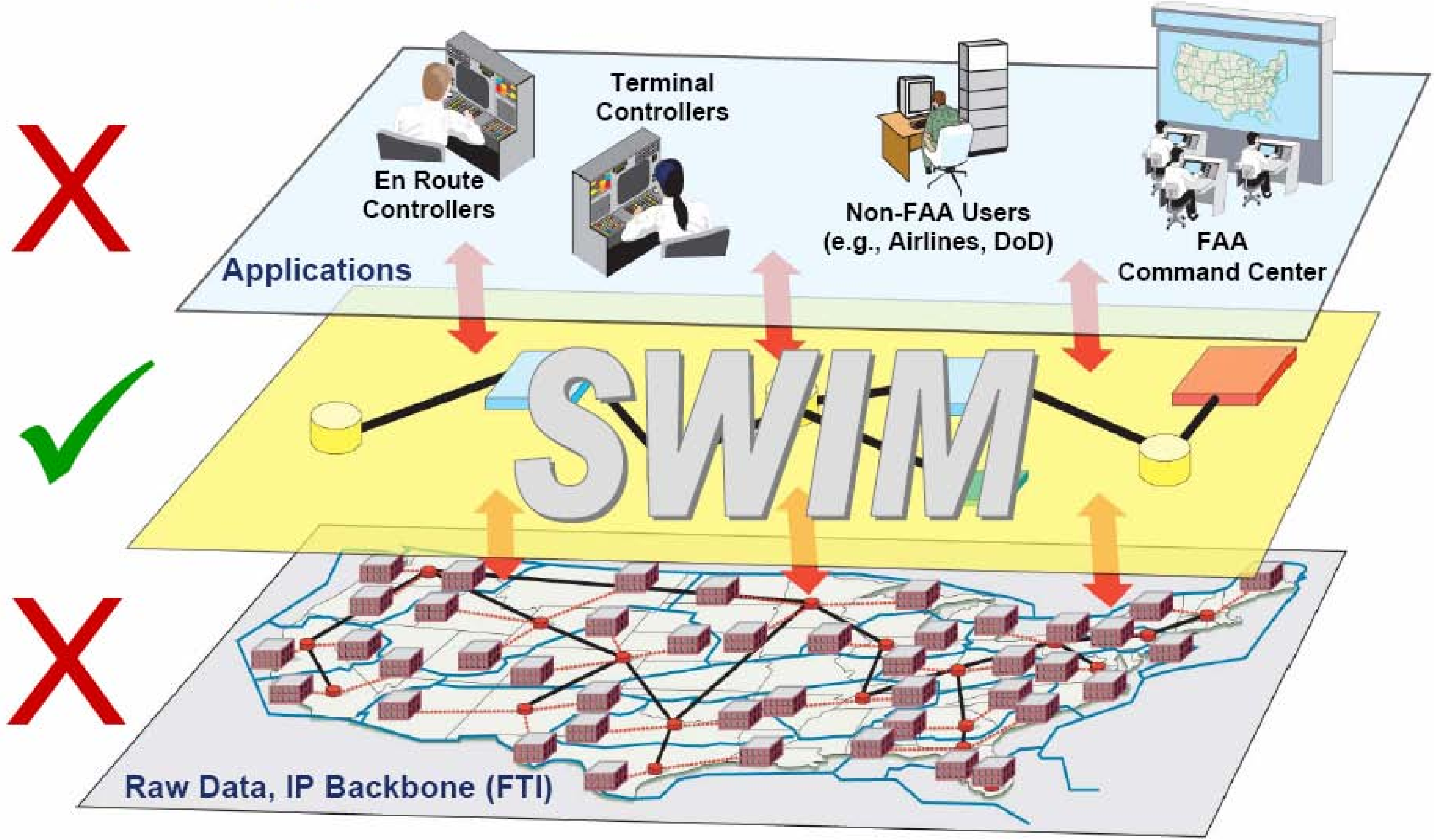
Future of Information Sharing



What is System Wide Information Management?

- **NAS-wide information grid**
  - Integrates NAS legacy systems and networks with NAS-wide management functions
  - Integrates NAS grid with external agency grids
- **Management of community information exchange**
  - Surveillance, weather, flight data, aeronautical and NAS status information
  - Defines data for all system users
  - Creates roadmap telling them how to find it
- **Potential Core Services**
  - Directory/Registry Service
  - Interface Service
  - Brokering Service
  - Infrastructure Management Service
  - Enterprise Security Service

Program Definition (Cont.)
What is System Wide Information Management?



Multi-Agent Semistructured Process

- **Agents typically have complex goal sets**
  - Pilots- aircraft-centric
  - Controllers- system-centric
  - Dispatchers- airline-centric
- **Shared goals**
  - e.g., Safety
- **Different goals**
  - e.g., Workload vs. Efficiency
- **Ambiguity of goal priority**
- **Negotiation vs. Hierarchy**
  - Shared information may increase negotiation
  - Need for clear Hierarchy in time constrained environments?

Other Issues

- **Training**
- **Multiple decision support systems / automation tools**
  - ☐ Warnings and alarms
  - ☐ Workspace design
- **Fatigue**

Summary: Human Factors Challenges

- **Situation awareness**
  - ☐ Required for informed control decisions
  - ☐ Effect of structure/procedure
  - ☐ Effect of complexity
  - ☐ Controller/Pilot shared SA
- **Attention limitations**
  - ☐ Humans poor monitors
  - ☐ Out of loop SA
- **Information and task overload**
  - ☐ Signal vs. noise (clutter)
  - ☐ Saturation

Adapted From Dr. R.J. Hansman, MIT

Summary: Human Factors Challenges (2)

- **Understanding of automation/optimization criteria**
  - Controller mental models
  - Complexity issues
- **Human acceptance of automation**
  - “Trust
  - Labor Issues, Job Security
  - Reliability
  - Change
- **Human reliance on automation**
  - Loss of base skills
  - Unexpected situations
  - Failure/degraded mode operation

Adapted from Dr. R.J. Hansman, MIT