Evaluating Transformations of the Air Transportation System Through Agent-Based Modeling and Simulation

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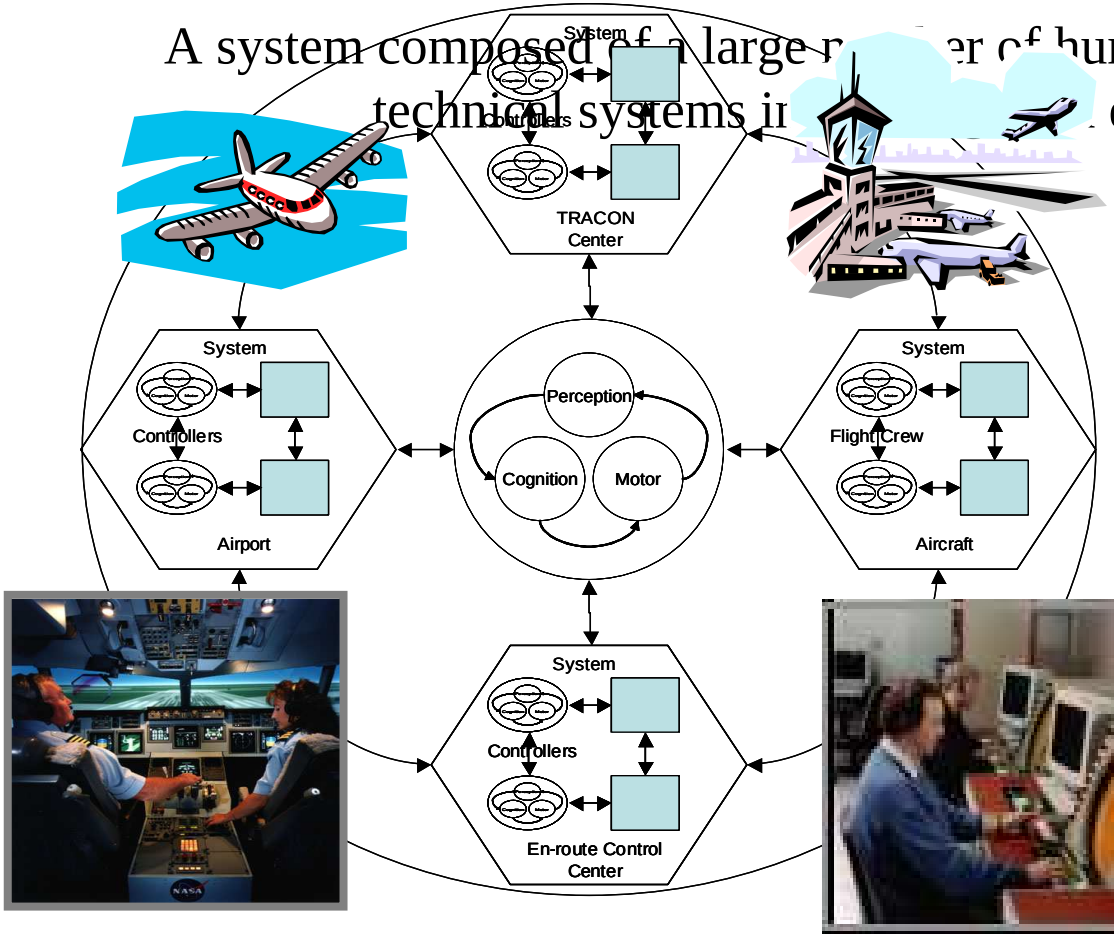
Socio-Technical System

A system composed of a large number of humans, machines and technical systems interacting with each other



- Characteristics
  - Dynamic
  - Interactive
  - Emergent behavior

Viewing Air Traffic System Behavior as Emergent

- "Emergent Behavior" – a behavior at one level of abstraction that can not be predicted from another level of abstraction
  - Needs simulation to predict!
- In this case, we view our agents as the individual humans and technologies in the air traffic system (a 'low', detailed level of abstraction)
- Out of their individually conducted (and motivated) actions emerge the higher-level system behaviors

Thought Experiments During Design

- Have we sufficiently determined what every one in an operational concept (con ops) is expected to do?
- If everyone in con ops does what they are supposed to, how well would the system work?
- If known, predictable aspects of human performance are ‘brought in’, how does that affect system performance?
- If the system runs as it ought, what will the humans be asked to do? Is this feasible? (Answer would provide early insight to the human factors community)

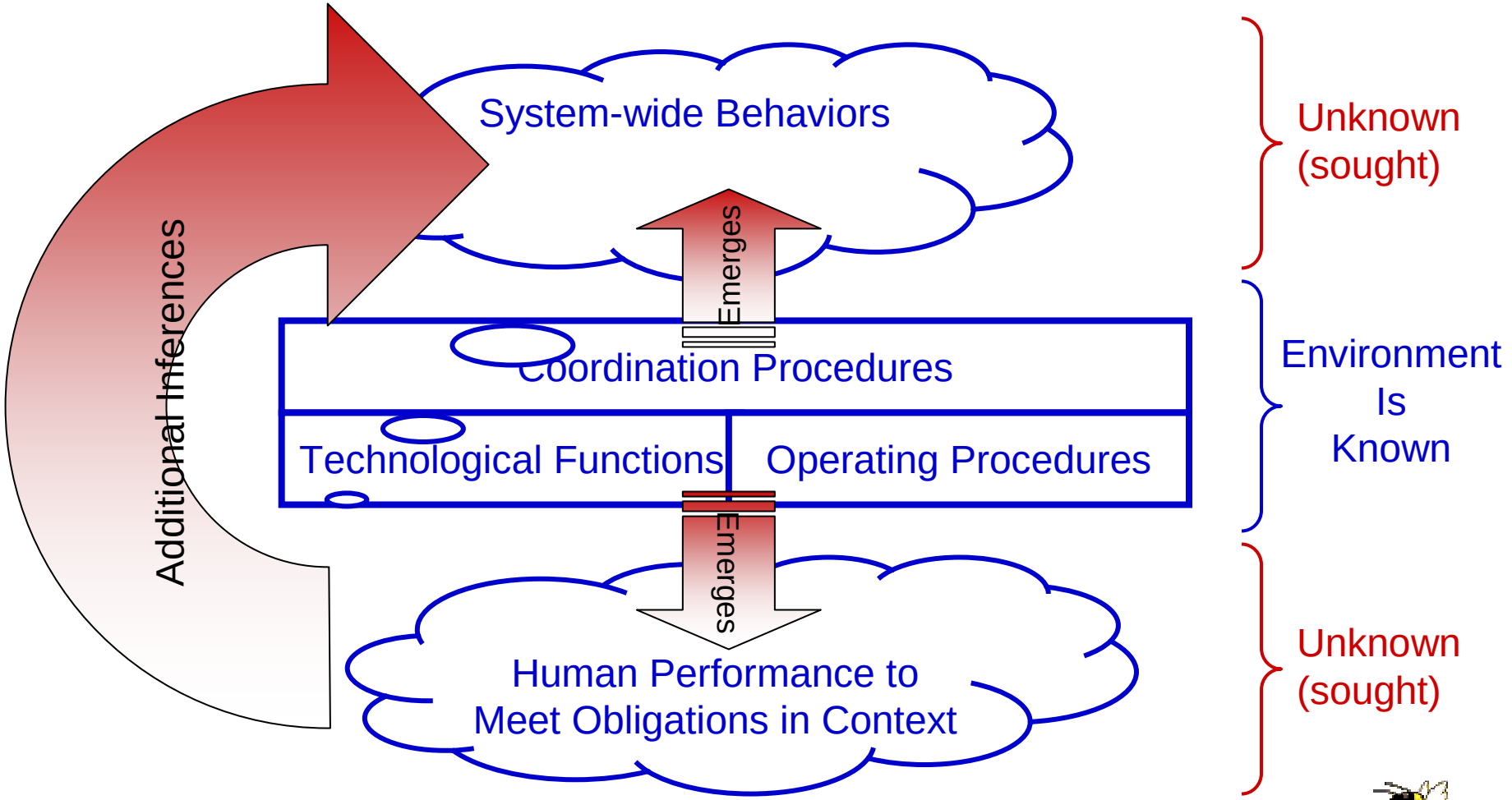
Agent-Based Modeling and Simulation

- Entities Are Modeled as *Agents*
  - Heterogeneous agents may behave differently and interact with each other
- Agents then act and interact within a rich environment
  - Generates individual behavior based on internal rules
  - Produces emergent phenomena from local interactions

Concept of Agent

- An ‘agent’ in ABMS may be defined as an simulated entity within a larger system with the following properties:
  - Some Degree Of Autonomy: The Capability To Carry Out Some Set Of Operations (I.e. work meeting its own purpose)
    - Flexible (Reactive, Pro-Active, Social) Behavior
  - Interactivity: The Ability To Interact With Other Agents To Accomplish Its Own Goals
    - Mutual influence (cooperative or competitive)
- In our case, our agents:
  - Have their own goals
  - Reference their behavior to established procedures
- Example: pilots, controllers, dispatchers, flow managers, schedulers, automated system

Known and Unknown During Design



Structure Preserving Representations

- Model maintains the form of reality
  - E.g., directly represent “knowns” in the world in same form as they are designed / implemented
  - Stream-lines all aspects of the process by minimizing translation and abstraction
    - Less model translation
    - Direct comparisons for validation
    - Direct applicability to implementation
- Thus, our model uses the structures used to describe:
  - Technological functions (e.g., aircraft dynamic models)
  - Information (e.g., same interfaces as used in reality)
  - Operational/ organizational factors (e.g., procedures specified to human and automated agents)

Agent Models of Human Performance

- Computational Agent Model With Cognitive Abilities
  - Observe and Sense Its Simulated Environment
  - Reasoning, Planning, and Problem Solving
  - Take Actions To Perform

- Why?
  - Humans are integral system components
  - Cost-effective, detailed simulation early in design
    - Consideration of human capabilities and limitations
  - Evaluation of changes of human behavior on safety and performance of the system at the system-level
    - Procedures, interfaces, new technologies
    - Sensitivity analyses (impacts of human errors)

RFS-WEA Simulation Architecture

RFS-WEA Framework

- Built Upon Cognitive Engineering Principles
  - Describes the work environment in a task-relevant, structure-preserving form
  - Proactive Agents
  - Dynamic Environmental Components
- Declarative Models of System Components and Their Interrelations
- Computational Models of The Complex, Dynamic Behaviors of Those Components

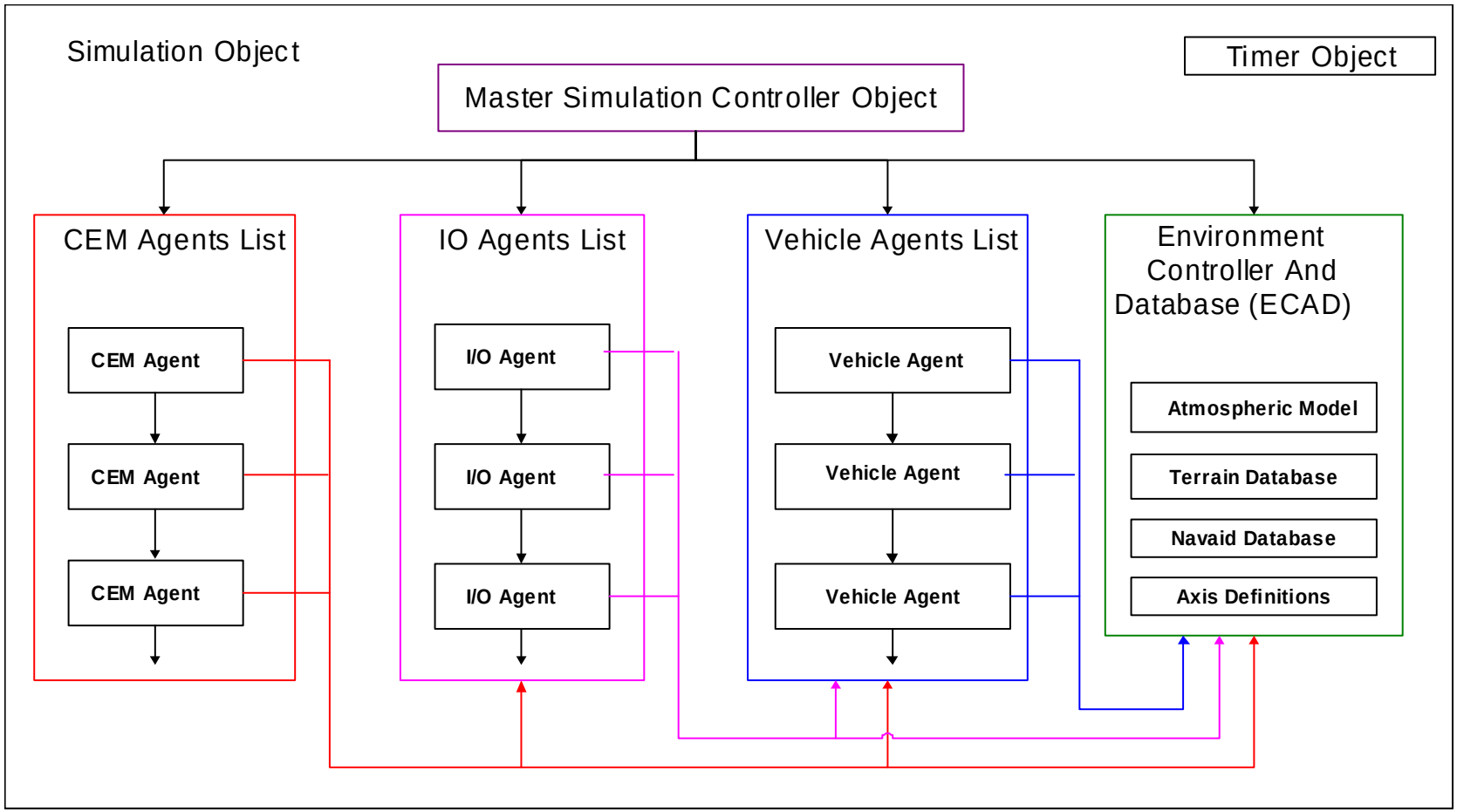
Agent-Based Simulation Architecture

- Easily Incorporates Different Types of Models
- Accepts Any Types of Agents with Varying Fidelity and Resolution
- Easily Added and Removed As Needed
- Easily Modified and Reused
- Easily Extendible and Sharable
- Computationally Efficient Timing Methods

Component-Based Architecture

- Abstraction of Simulation Components
  - Object-Oriented Framework (C++)
  - Interface Inheritance from Parent Class
- Modularity (Configurable, Robust, Sharable)
  - Implementation of Components Completely Isolated from the RFS Executable
  - Each Module is a Dynamically-Linked Library (dll)
  - Modules Configured Through Run-Time Interface and/or Scripts

Simulation Architecture



Interactions and Communications

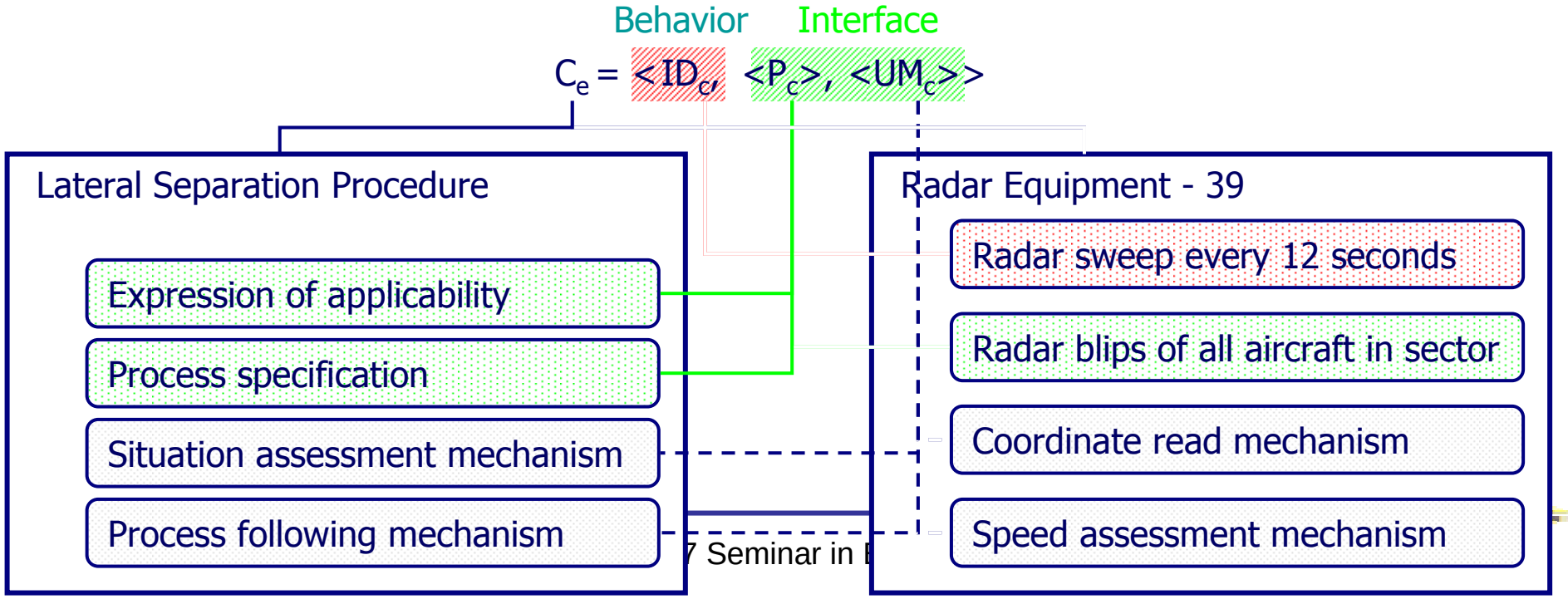
- Most Interactions Between Agents Can Be Supported By Accessing Pointers To Other Agents
- Base Standard Interfaces Handle The Interactions and Communications Between Agents
  - Standard Event Messages (Creation and Removal of Agent)
  - Basic Attributes and Methods
- Additional Interfaces (Attributes and Methods) Can Be Provided By Using the Object Data/Methods Extensions (OD/ME) Protocol.
  - Allow to Share With Other Agents
  - Allow to Facilitate the Communications Between Agents

The Environmental Component

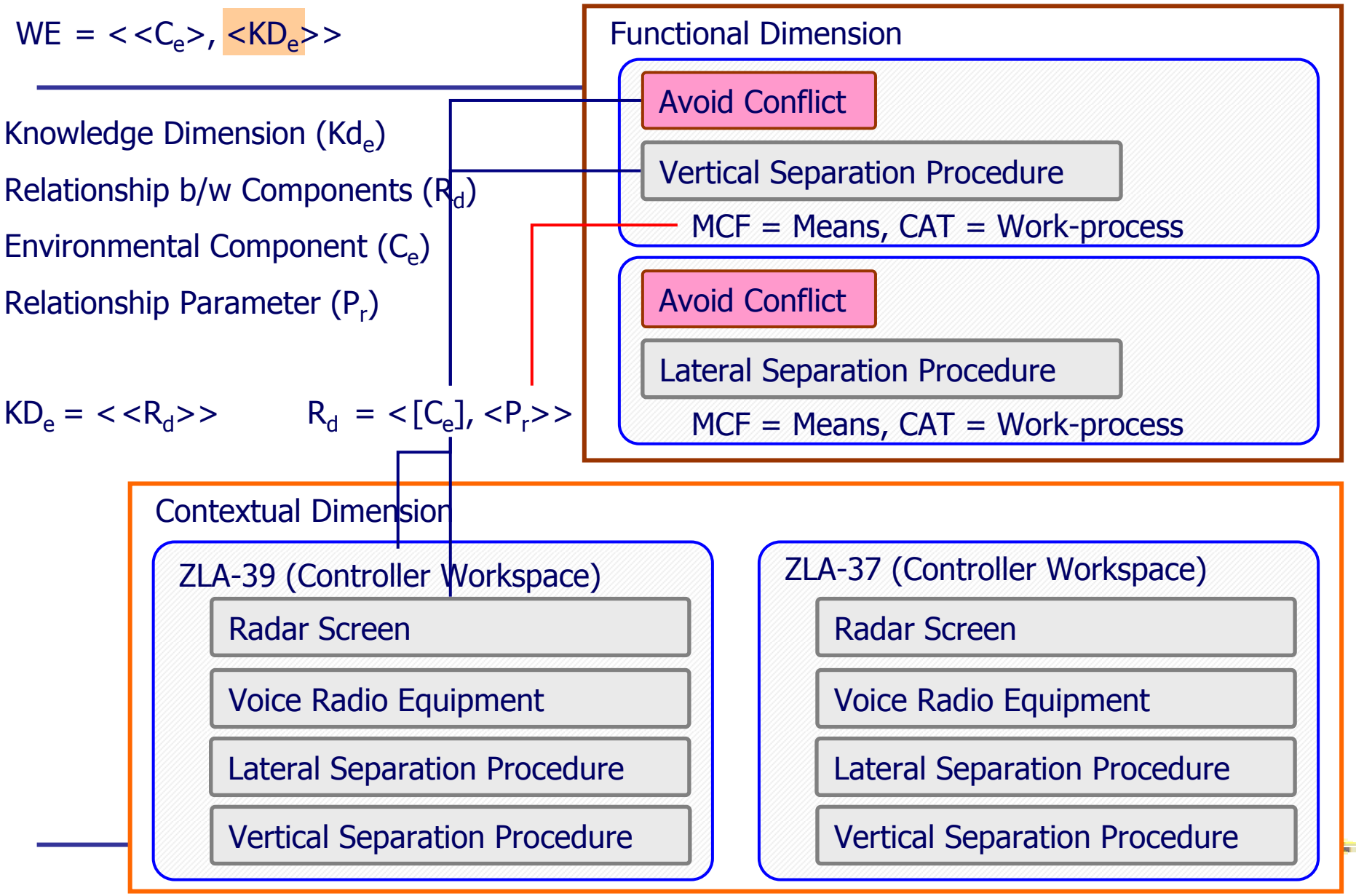
WE = <<C_e>, <KD_e>>

Environmental component (C_e): Any thing, physical or not, that affects work activities of workers, independent of any particular worker

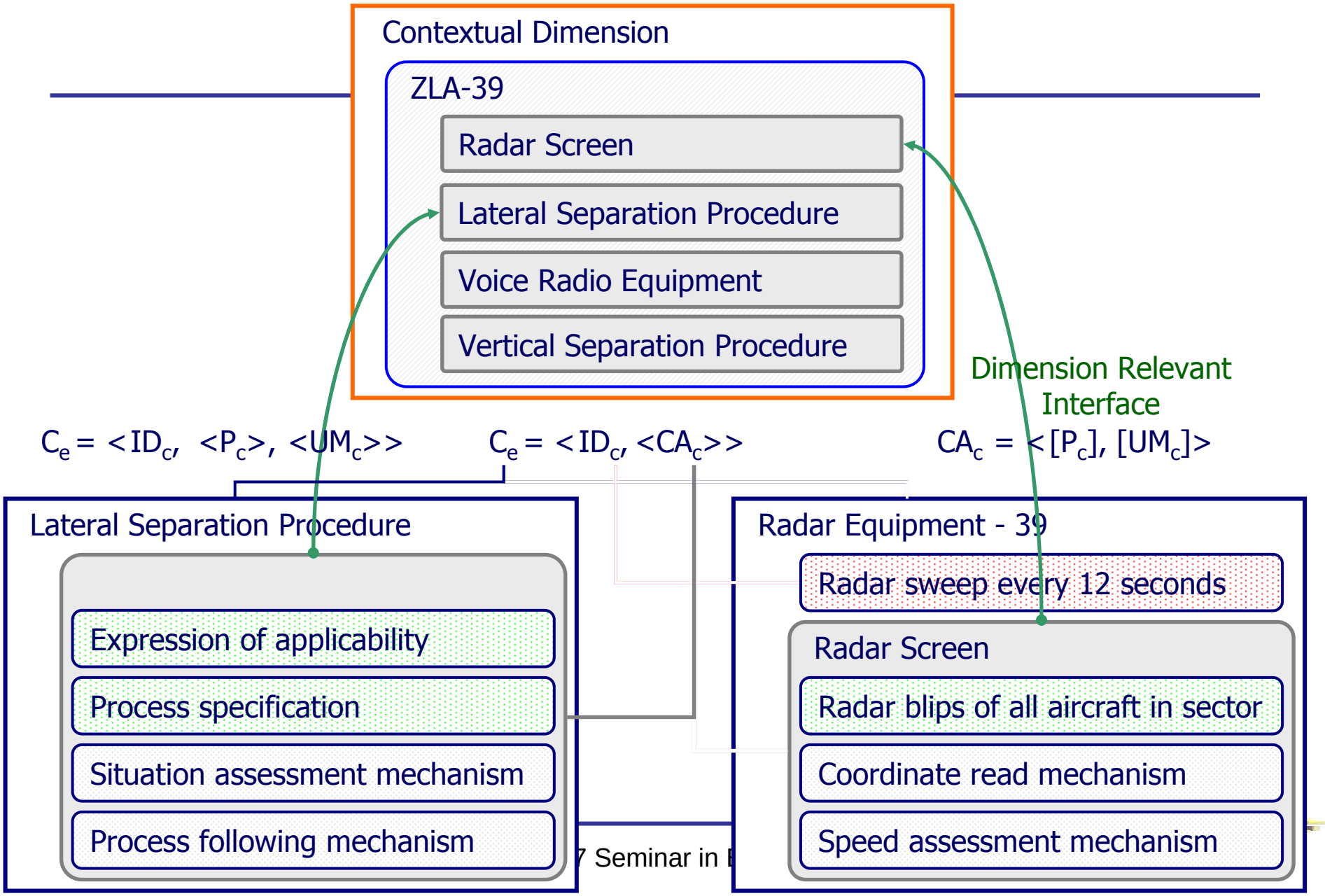
- Internal Dynamics (ID_c): Any internal mechanism that governs the autonomous or responsive behavior of the C_e
  (Developed as separately-compiled software)
- Properties (<P_c>): The set of properties of the C_e that represents its state
- Usage Mechanisms (<UM_c>): The set of mechanisms by which a C_e can be used

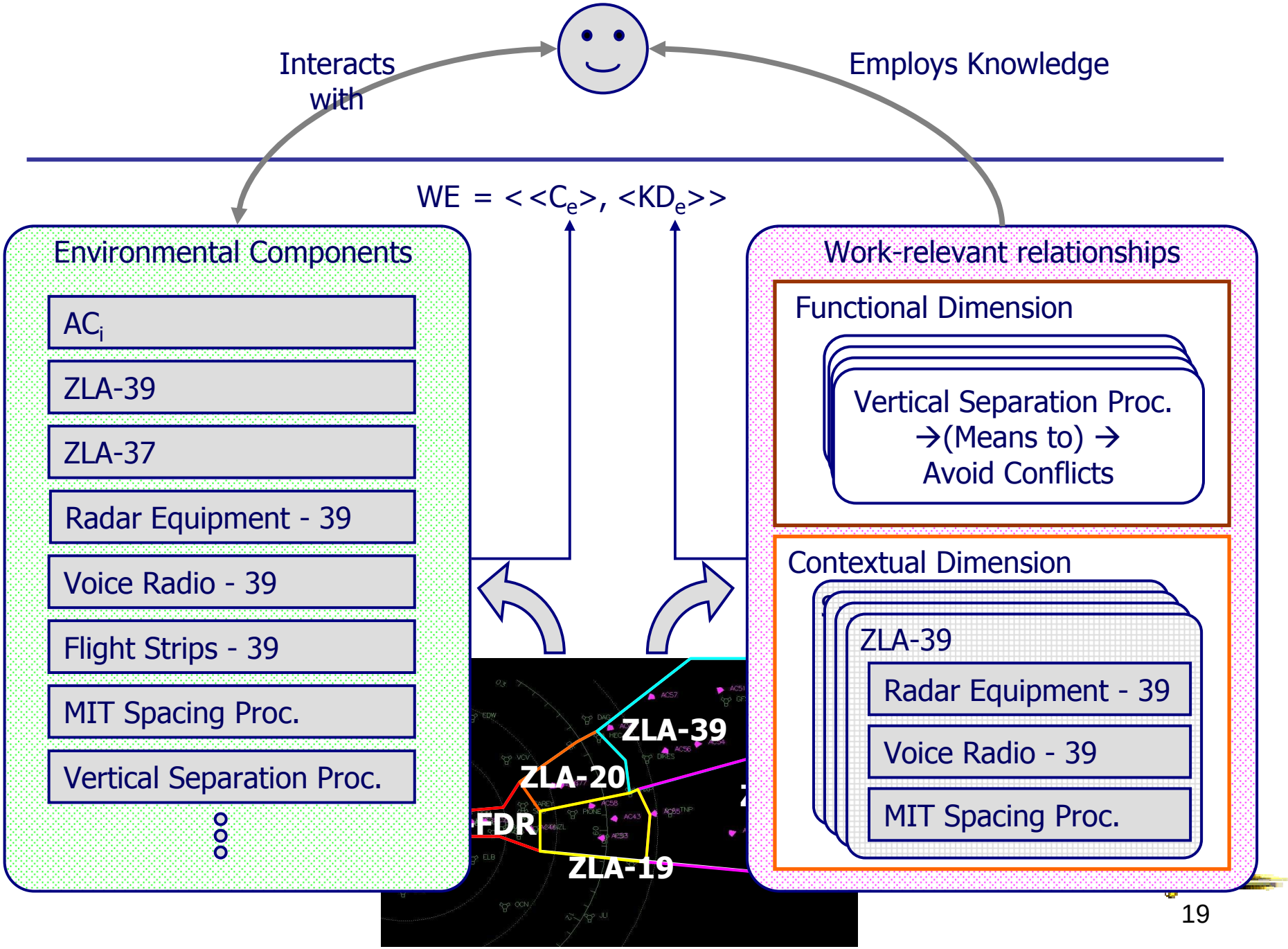


Dimensions and Relationships

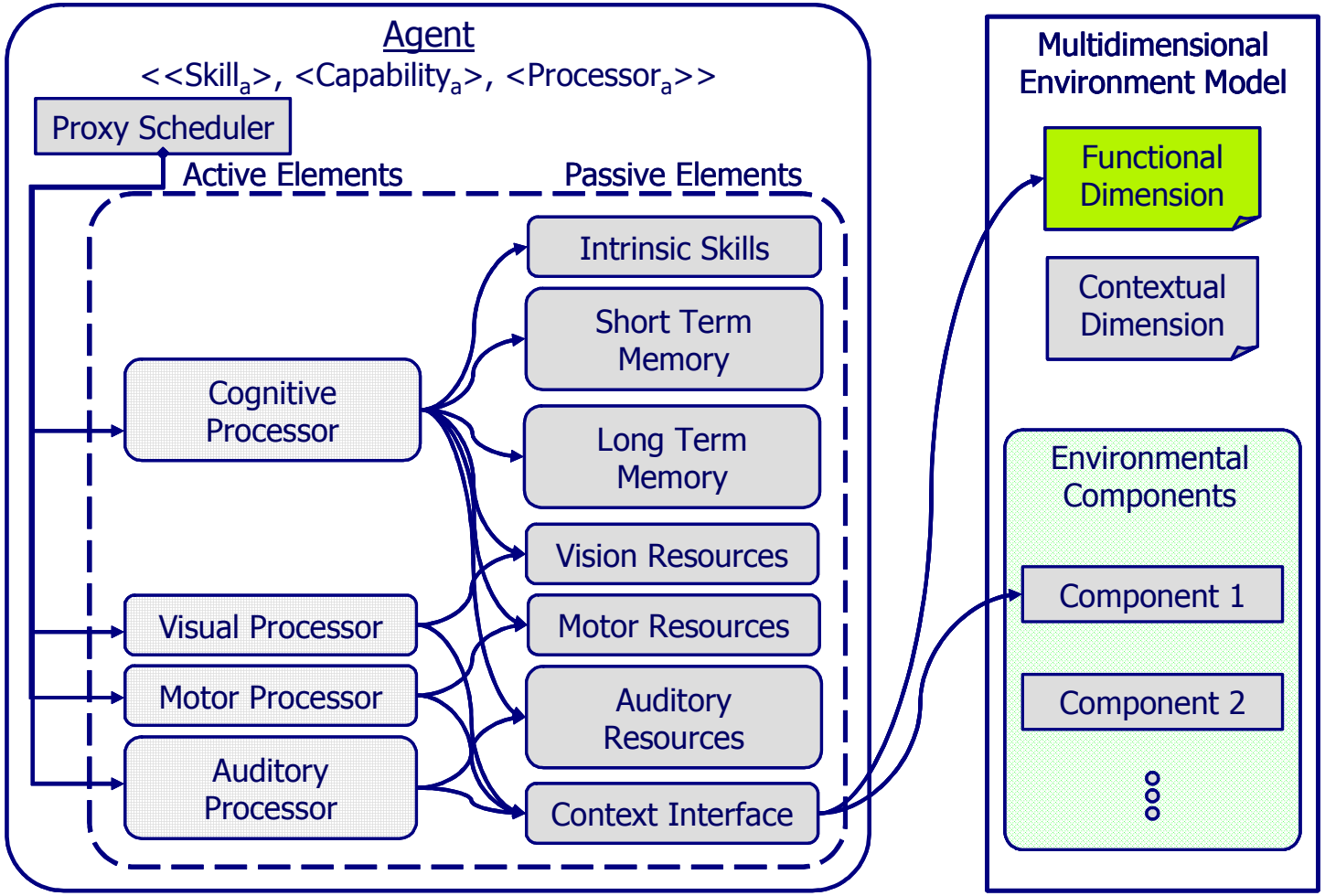


Component Aspects and Dimensions

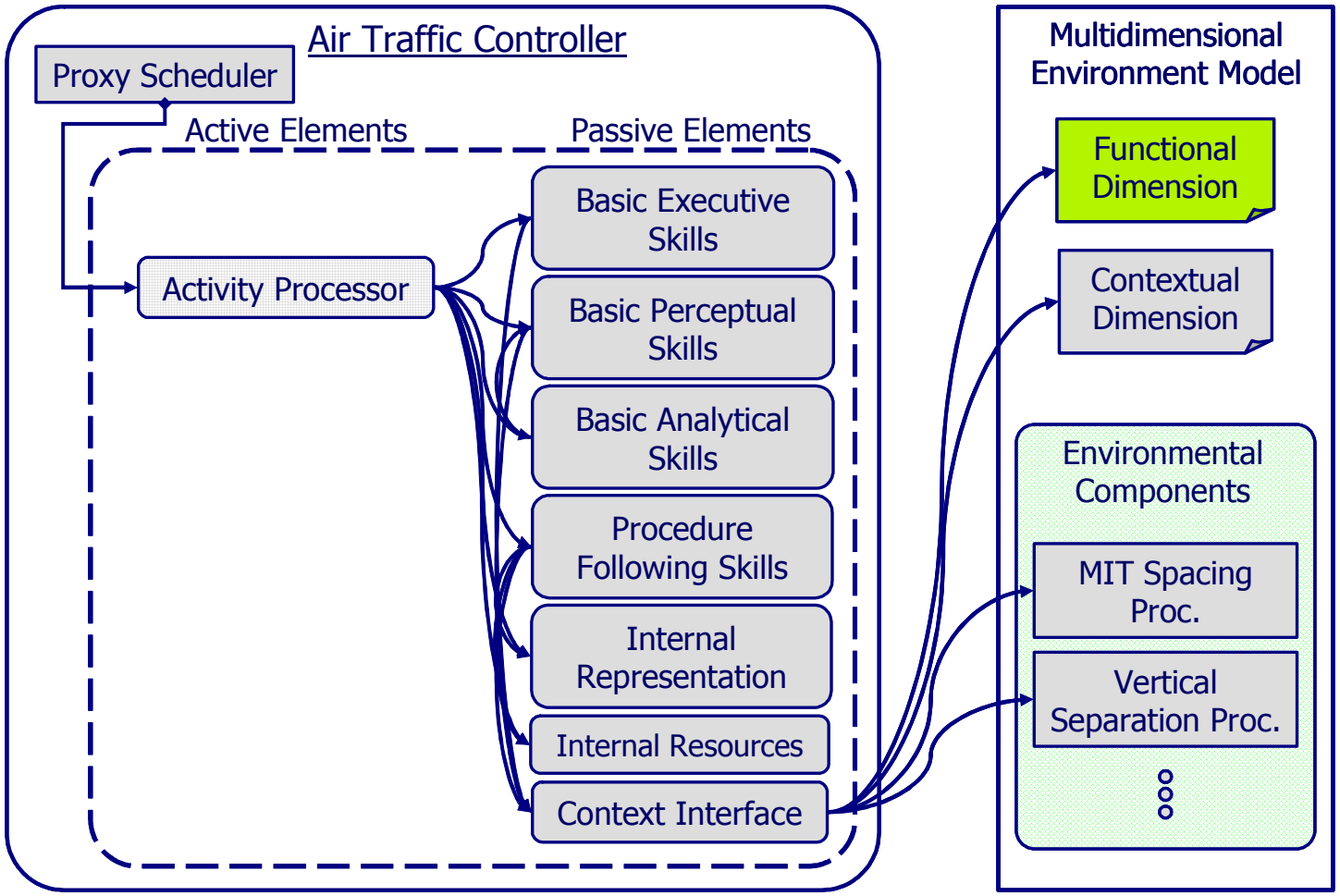



Interacts with
Employs Knowledge
WE = <<Ce>, <KDe>>
Environmental Components
ACi
ZLA-39
ZLA-37
Radar Equipment - 39
Voice Radio - 39
Flight Strips - 39
MIT Spacing Proc.
Vertical Separation Proc.
Work-relevant relationships
Functional Dimension
Vertical Separation Proc.
→(Means to) →
Avoid Conflicts
Contextual Dimension
ZLA-39
Radar Equipment - 39
Voice Radio - 39
MIT Spacing Proc.
ZLA-39
ZLA-20
FDR
ZLA-19

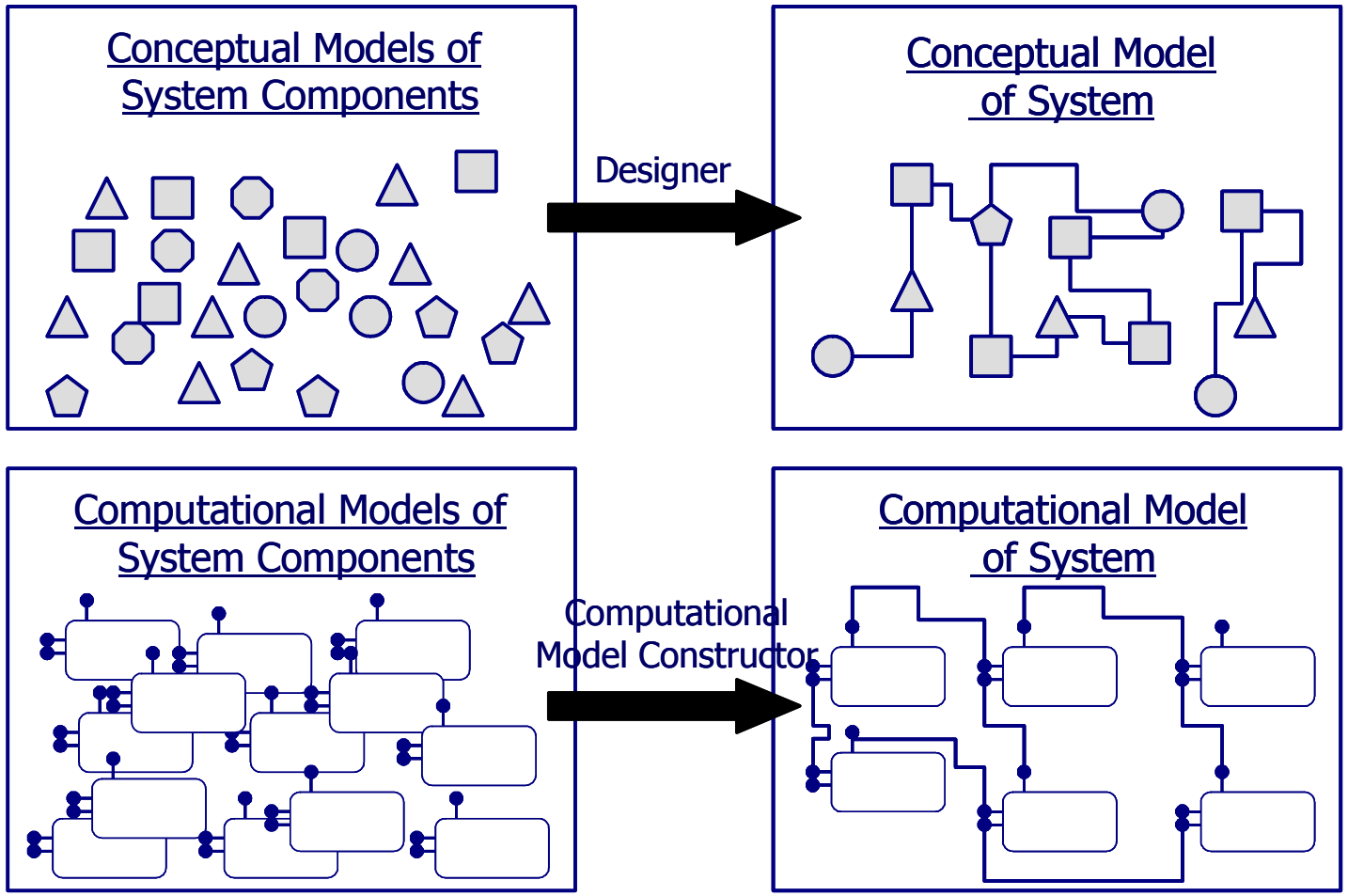
Agent Model of Worker



Worker Example – Air Traffic Controller

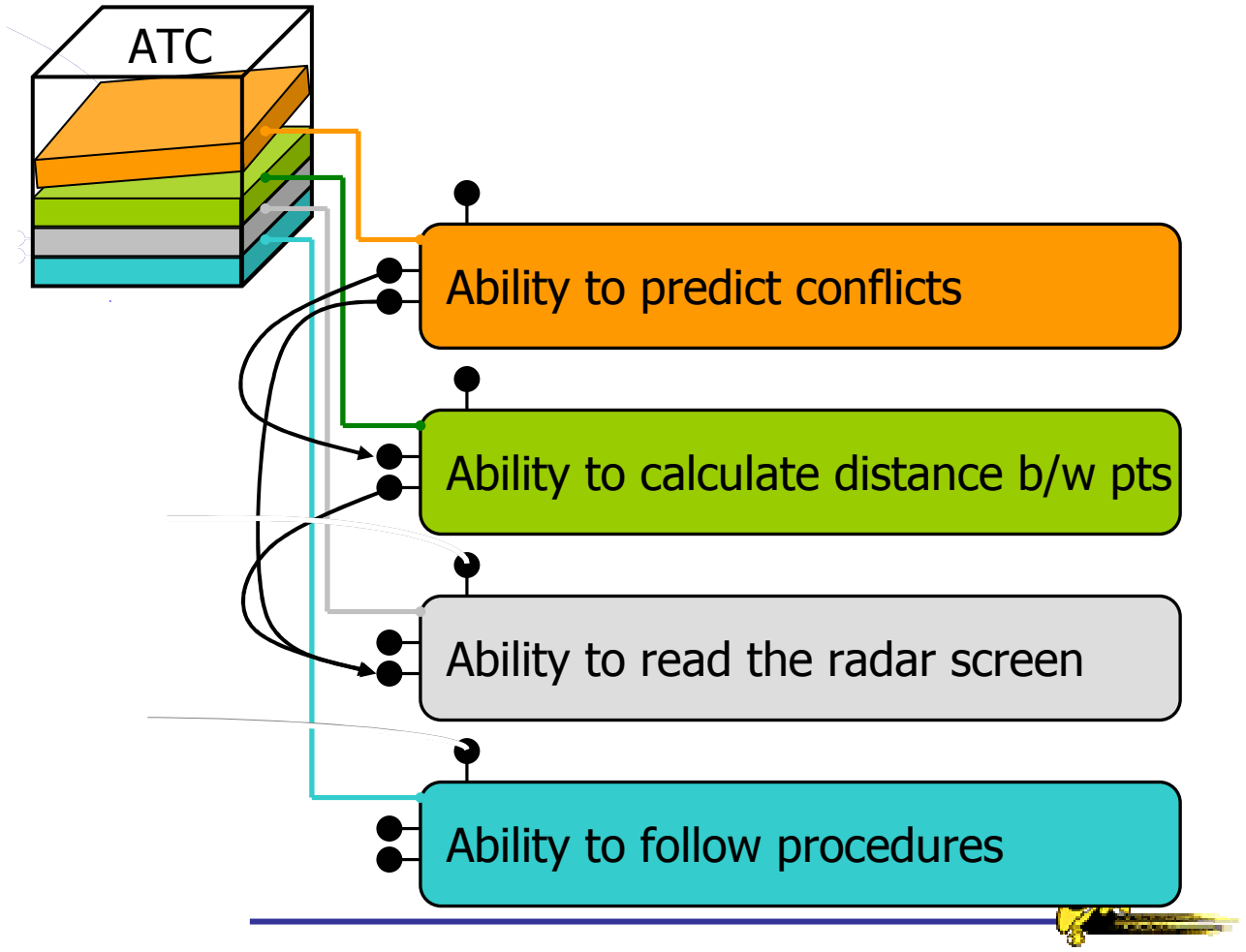


Building a Computational Model of System

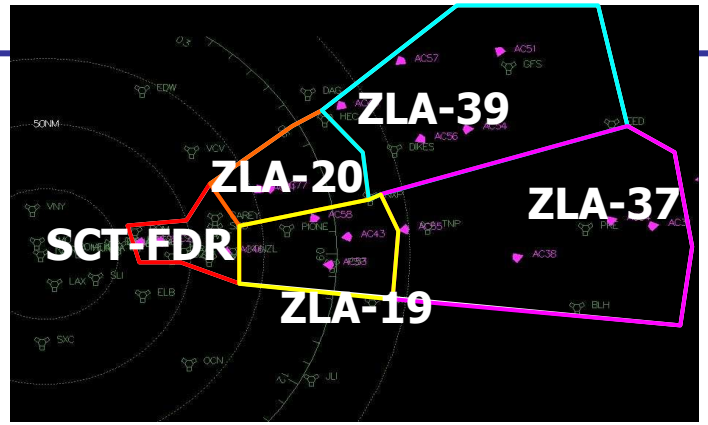


Constructing Models of Worker

Agent = <<$Skill_a$>, <$Capability_a$>, <$Processor_a$>>



Putting The Models Together



Contextual Dimension

ZLA-39

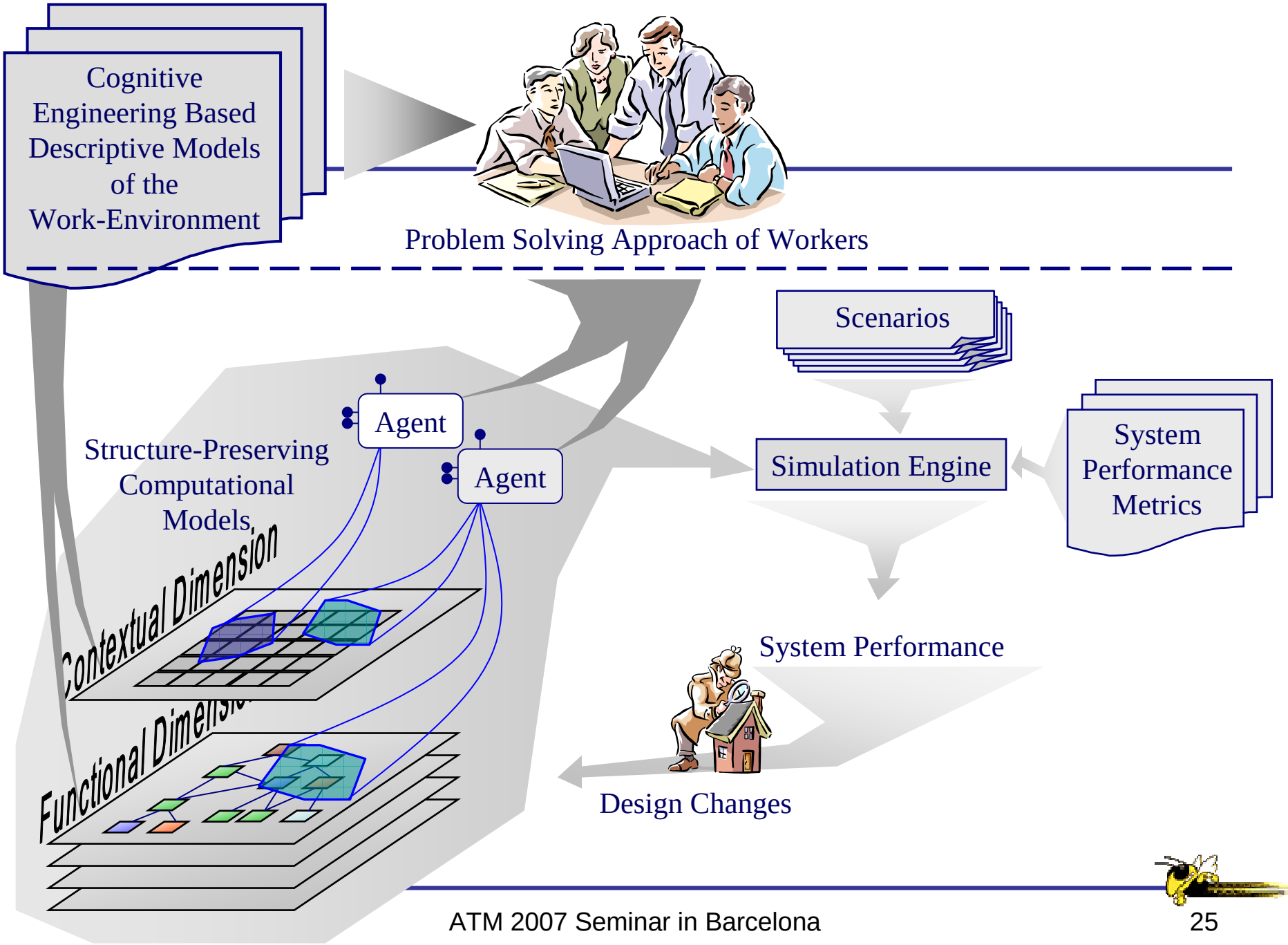
- Radar screen
- Lateral separation procedure
- Voice radio equipment
- Vertical separation procedure

Radar Equipment - 39

- Radar sweep every 12 seconds
- Radar screen
  - Radar blips of all aircraft in sector
  - Coordinate read mechanism
  - Speed assessment mechanism

Air Traffic Controller

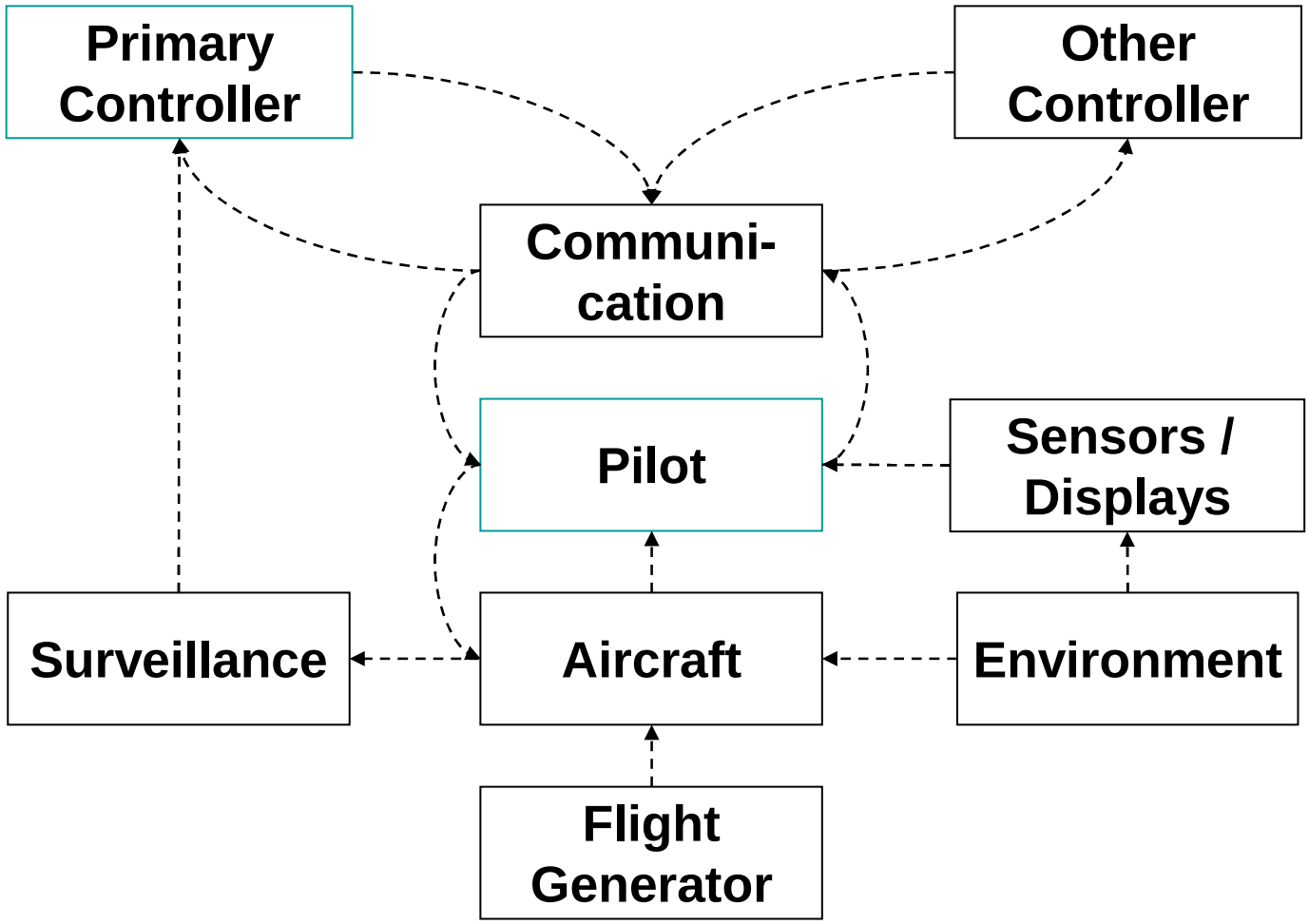
- Coordinate Reading Skill
- Context Understanding Skill


Cognitive Engineering Based Descriptive Models of the Work-Environment
Problem Solving Approach of Workers
Scenarios
Agent
Agent
Structure-Preserving Computational Models
Simulation Engine
System Performance Metrics
Contextual Dimension
Functional Dimension
System Performance
Design Changes

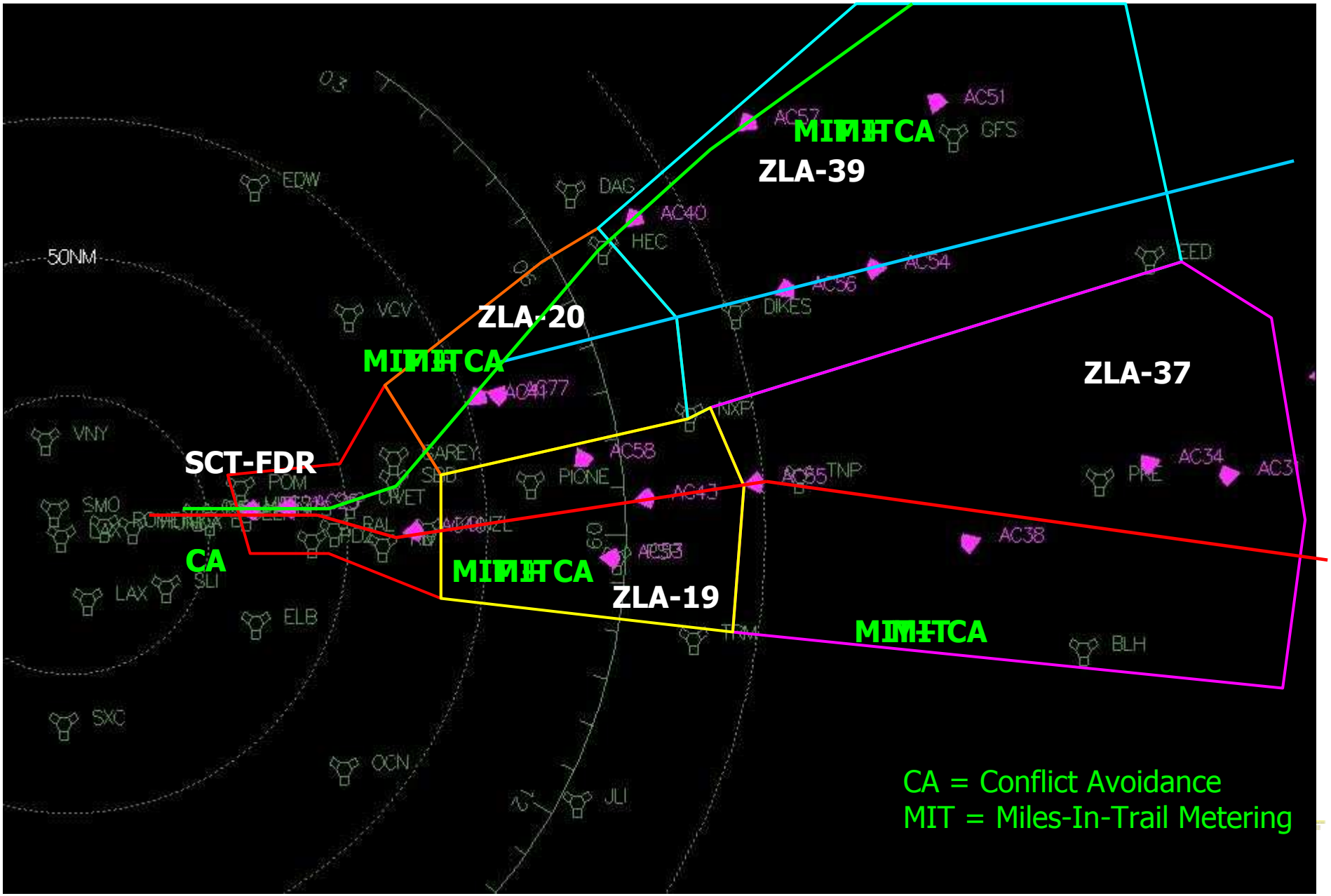
Demonstration

- Model arrivals into Los Angeles International Airport (LAX) with the following procedures
  - Conflict Avoidance (CA)
  - Miles-In-Trail Metering (MIT)
  - Time-Based-Metering (TBM)

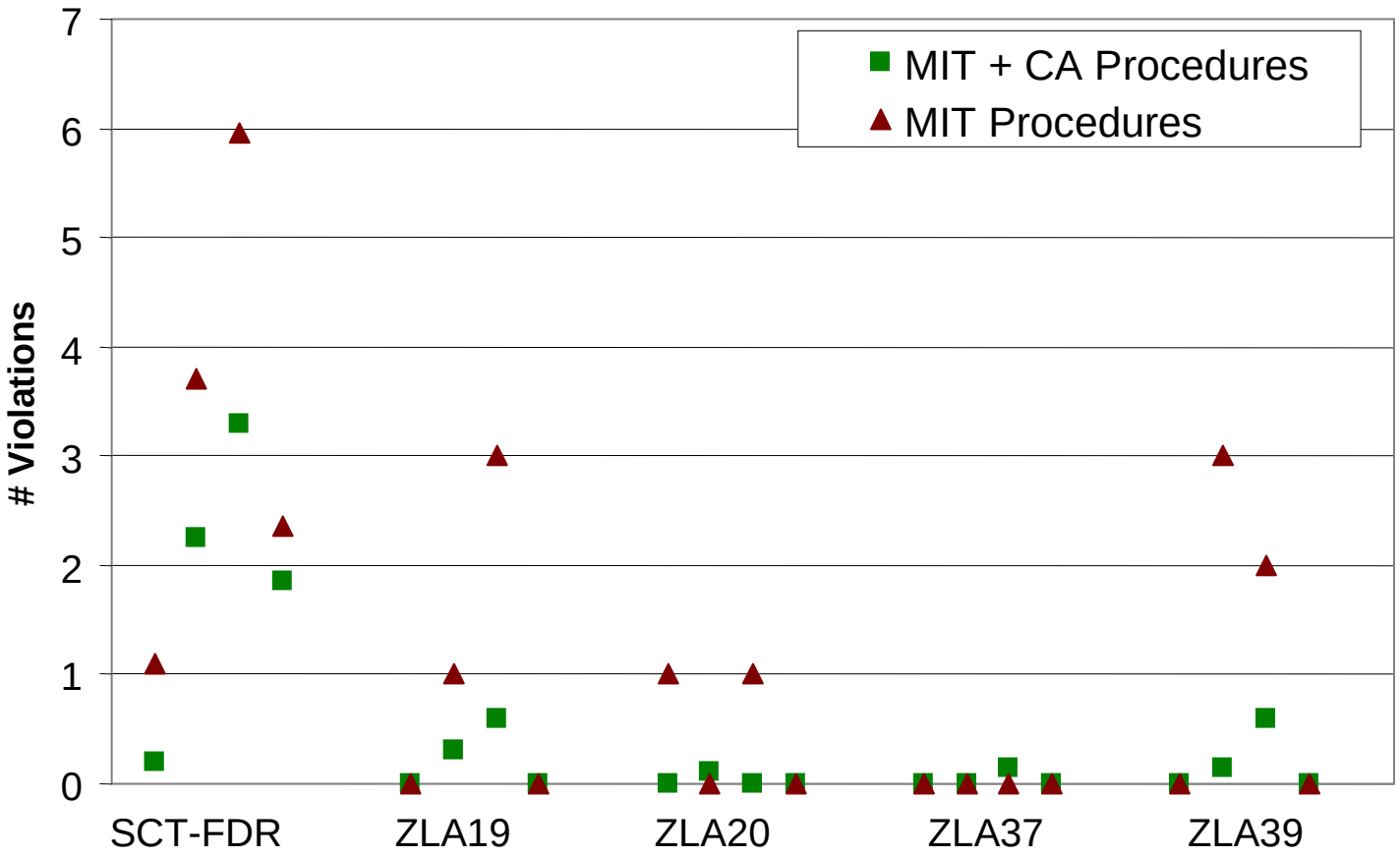
Agents


Primary Controller
Other Controller
Communi-cation
Pilot
Sensors / Displays
Surveillance
Aircraft
Environment
Flight Generator

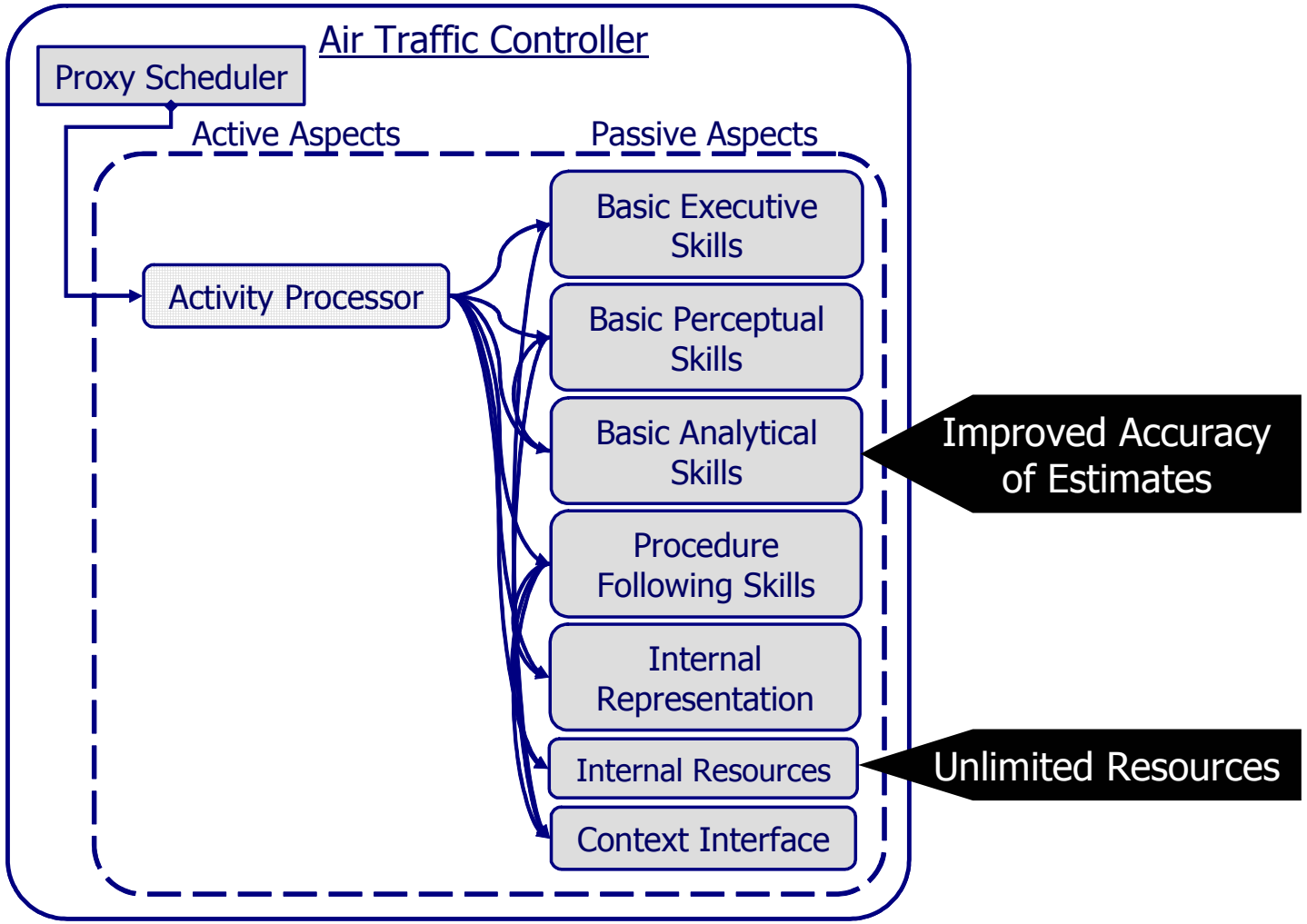
Changing Allocations in Tasks



Effect of Change in Procedures



Impact of Human Performance

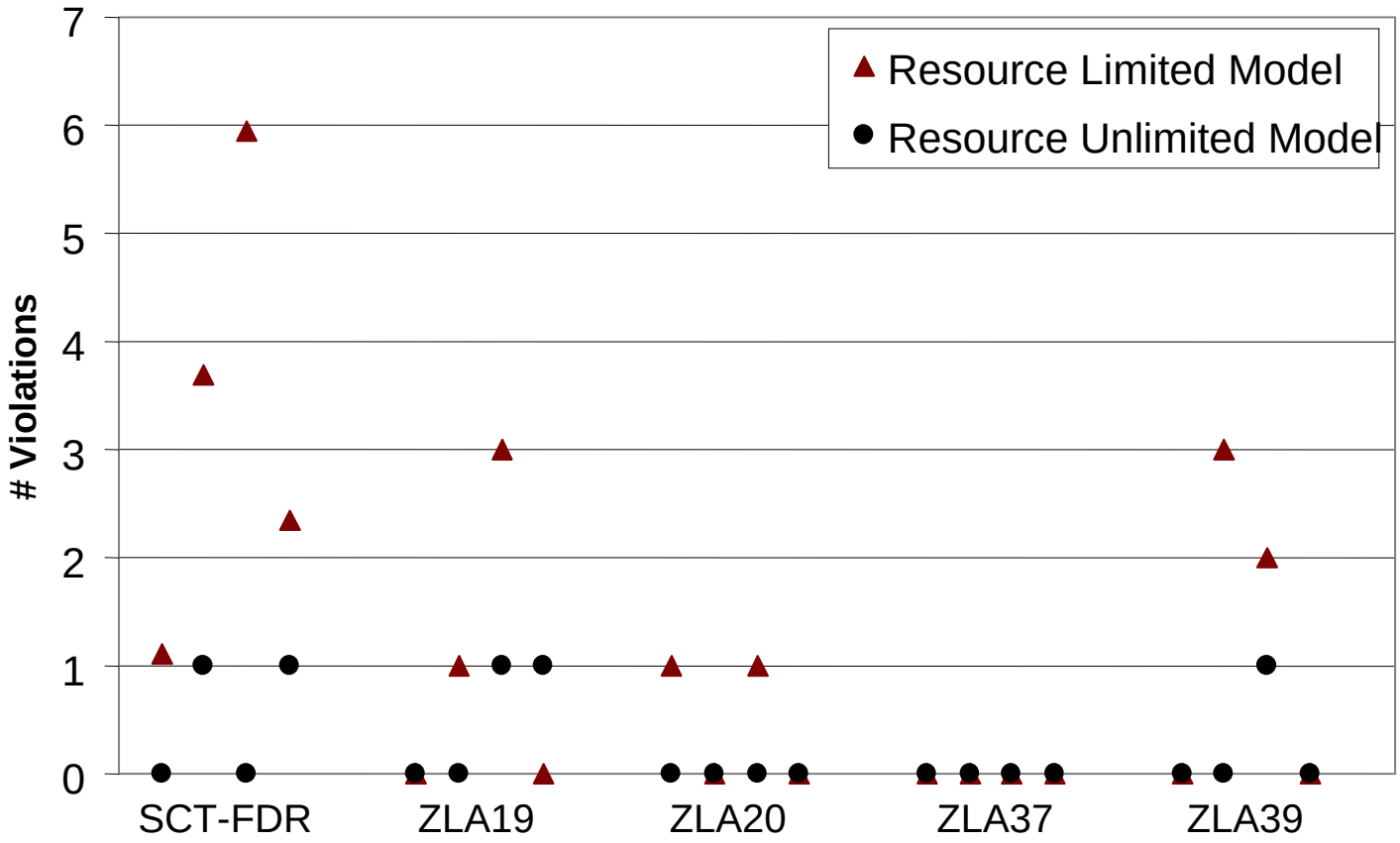


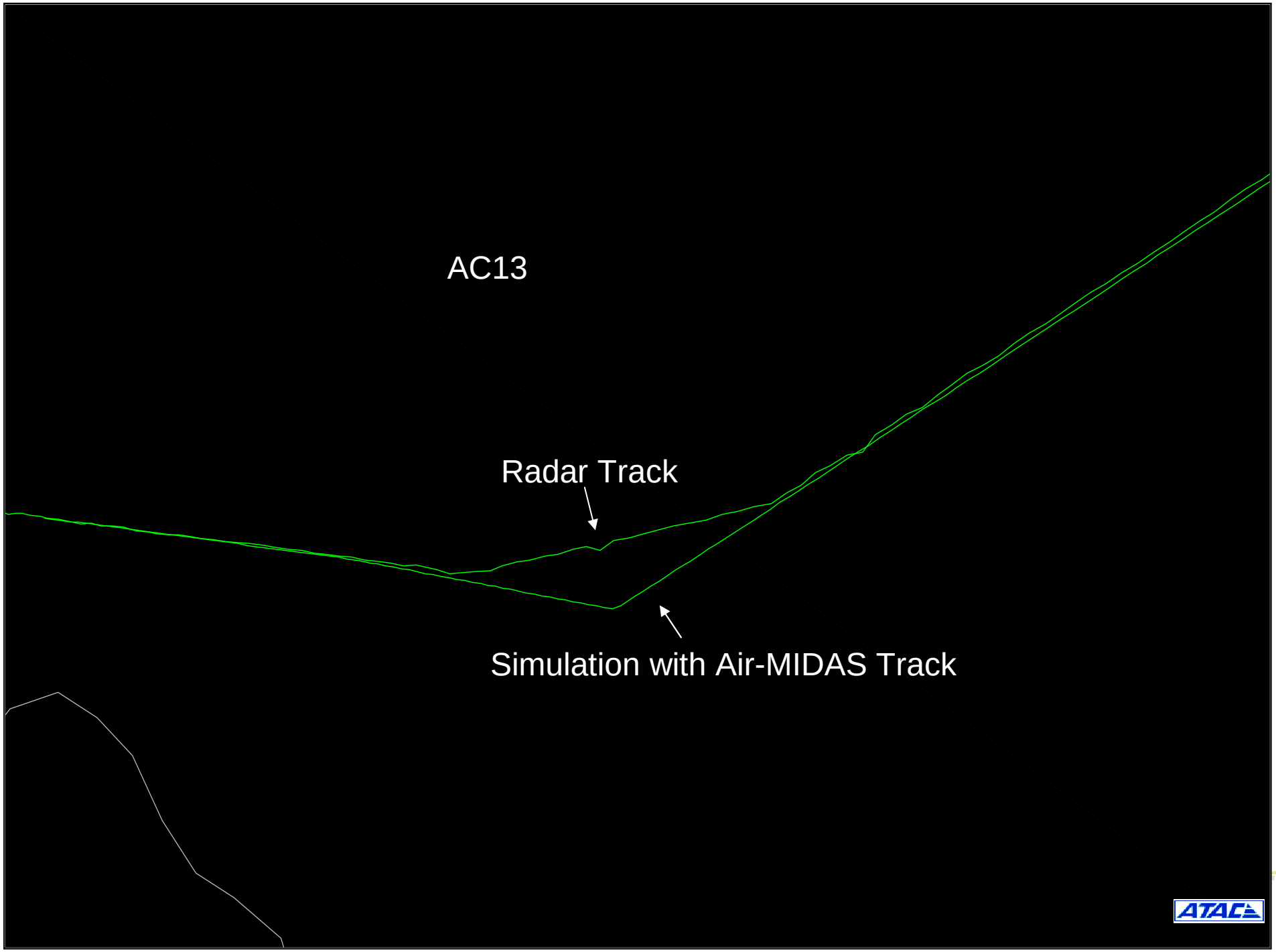
Transformation in Air Traffic Controller

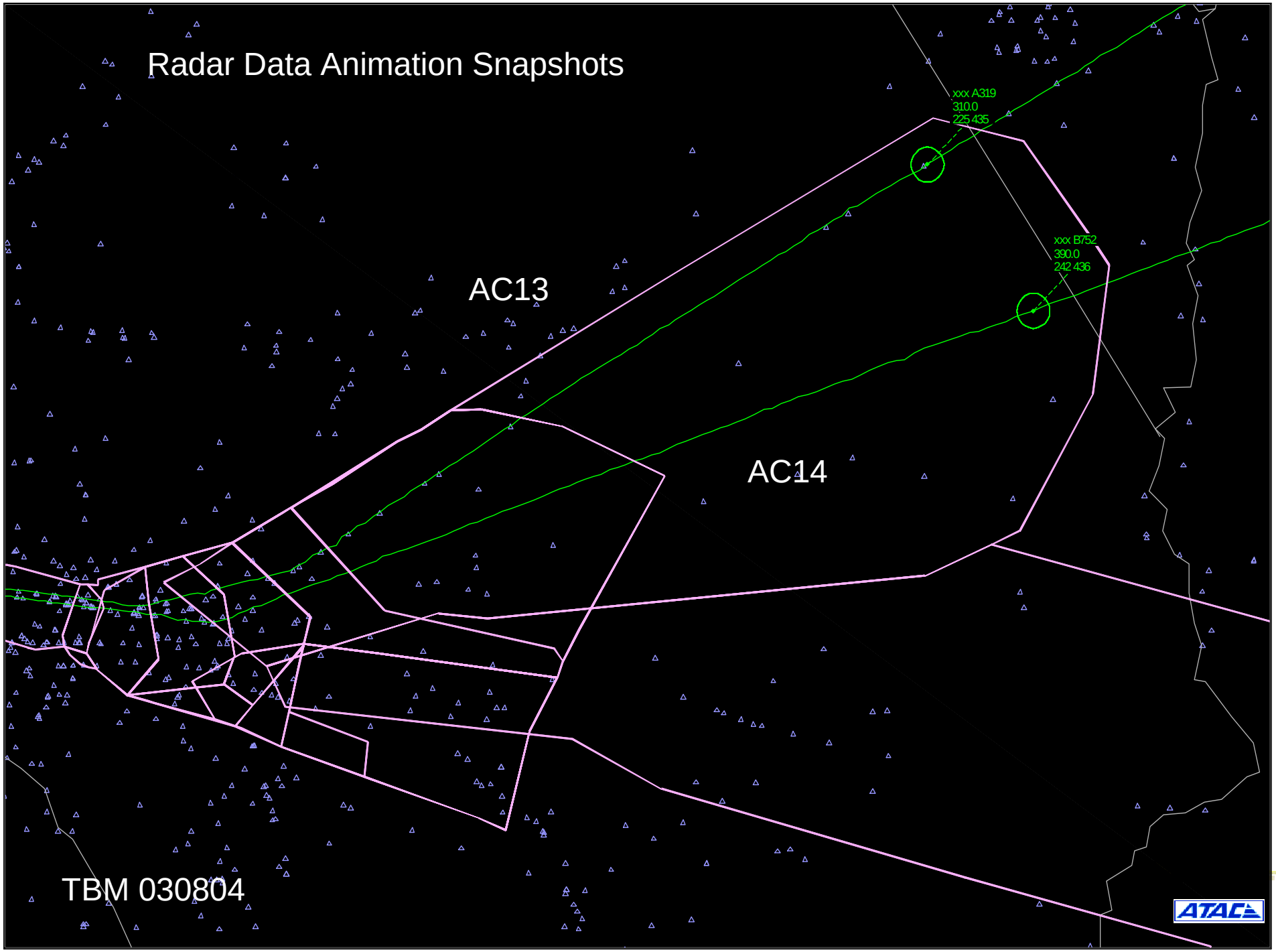
Variability Matrix - Air Traffic Controller Activities							
Agent Type	Unlimited resources		Limited resources (Max Resources = 7)				
Source of Variability	Accuracy		Accuracy		# Resources		Resource Acquisition Priority Rating
Distribution	Uniform		Uniform		Normal		
Activity	Prob		Prob		Mean	Stdev	
Monitor Traffic for Conflicts	1	N/A	0.8	N/A	3	1	5
Monitor Traffic for MIT Spacing	1	N/A	0.8	N/A	3	1	4
Monitor Traffic for TBM Compliance	N/A	N/A	N/A	N/A	2	1	4
Change Speed	N/A	N/A	N/A	N/A	4	1	8
Change Heading	N/A	N/A	N/A	N/A	4	1	8
Change Altitude	N/A	N/A	N/A	N/A	4	1	8
Resume Course	N/A	N/A	N/A	N/A	4	1	8
Resume Speed	N/A	N/A	N/A	N/A	4	1	8
Monitor Sector Boundary Conformance	N/A	N/A	N/A	N/A	2	1	10
Wait	N/A	N/A	N/A	N/A	1	1	1
Follow Procedures	N/A	N/A	N/A	N/A	2	1	3

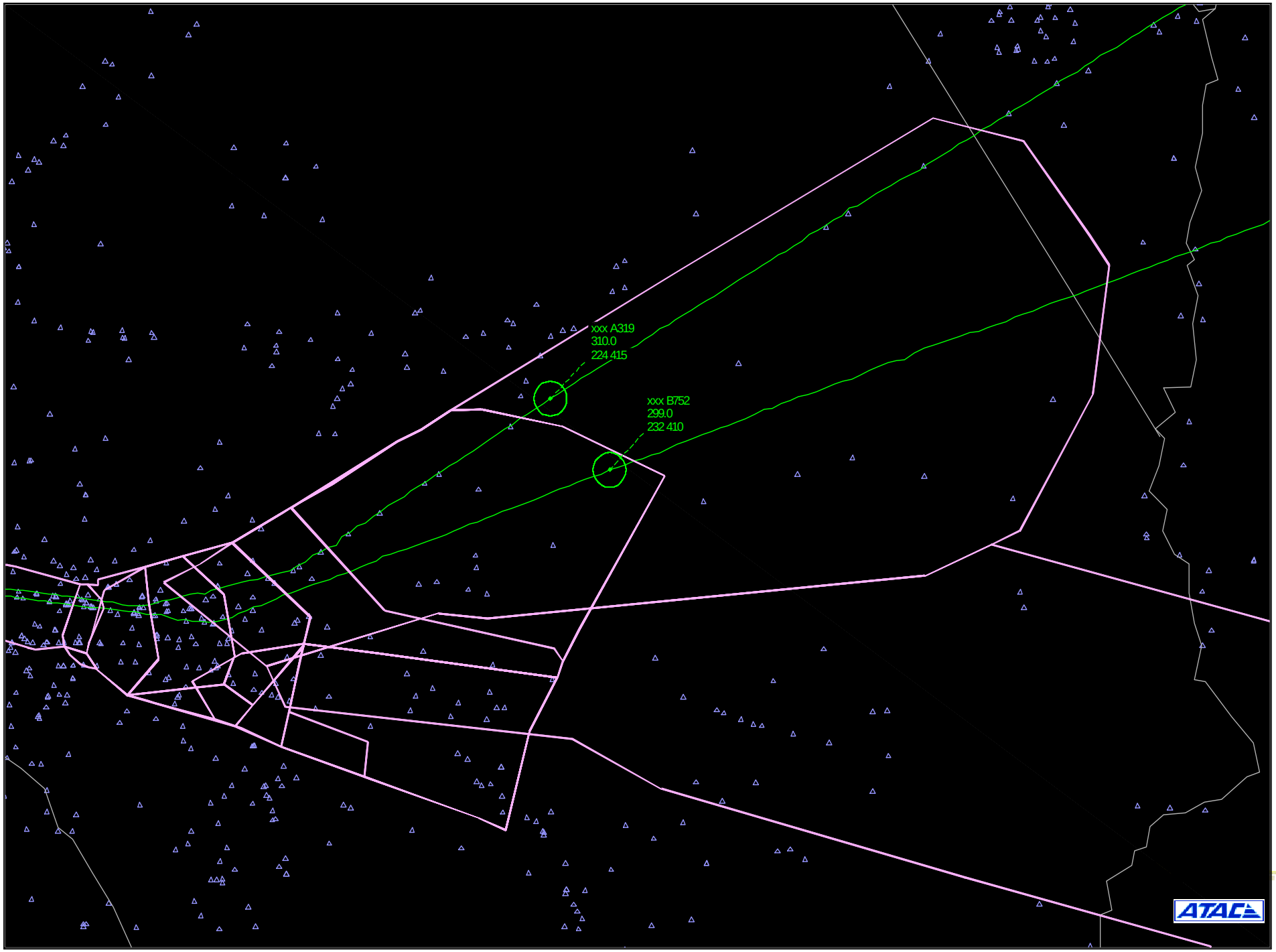
Accuracy: Probability of detecting a conflict on each scan. That is, with a 'prob' of 0.8 there is 98.4% chance that the air traffic controller, would have detected the conflict by the End of the 3rd scan

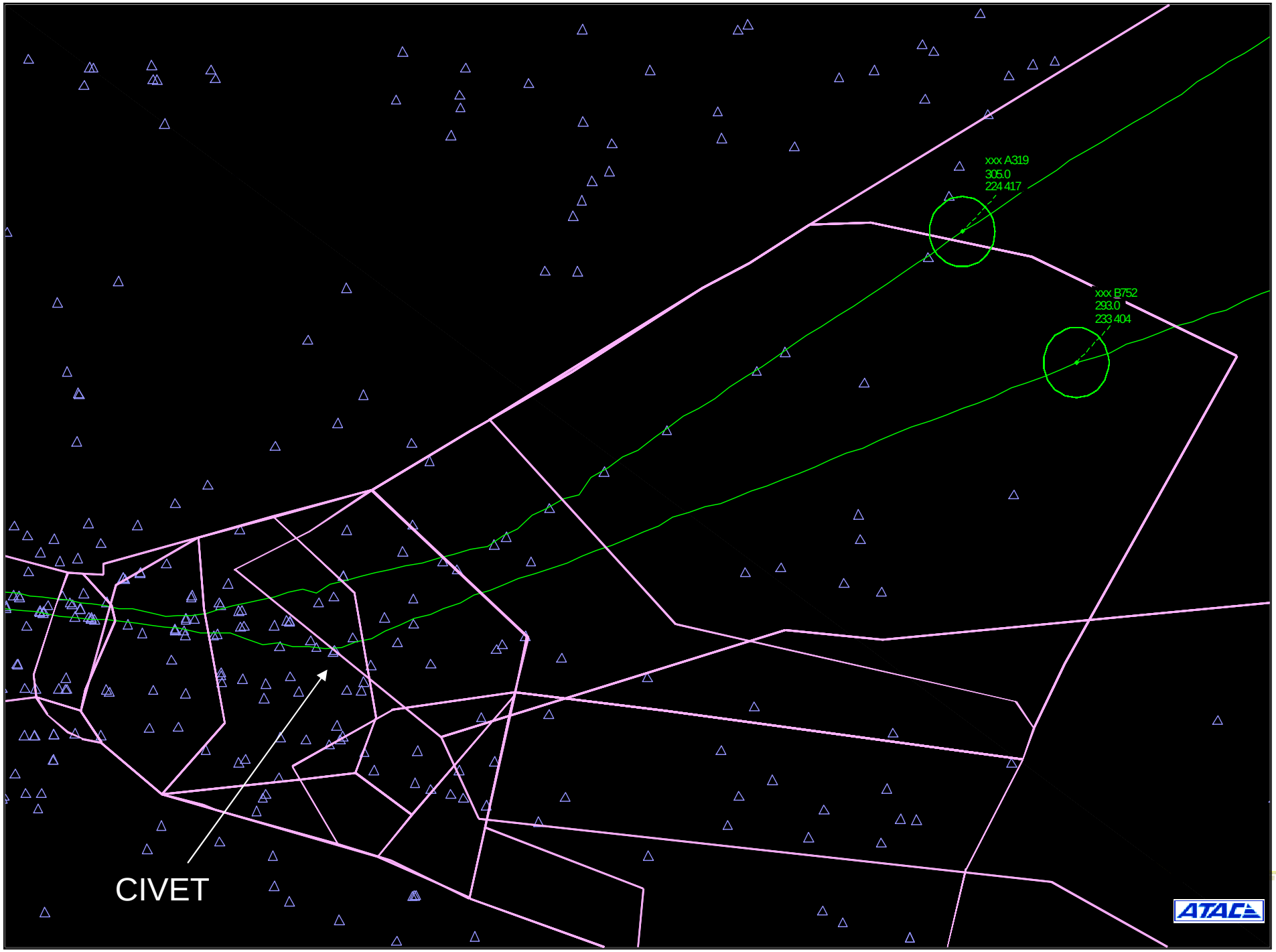
Impact of Human Performance Variables

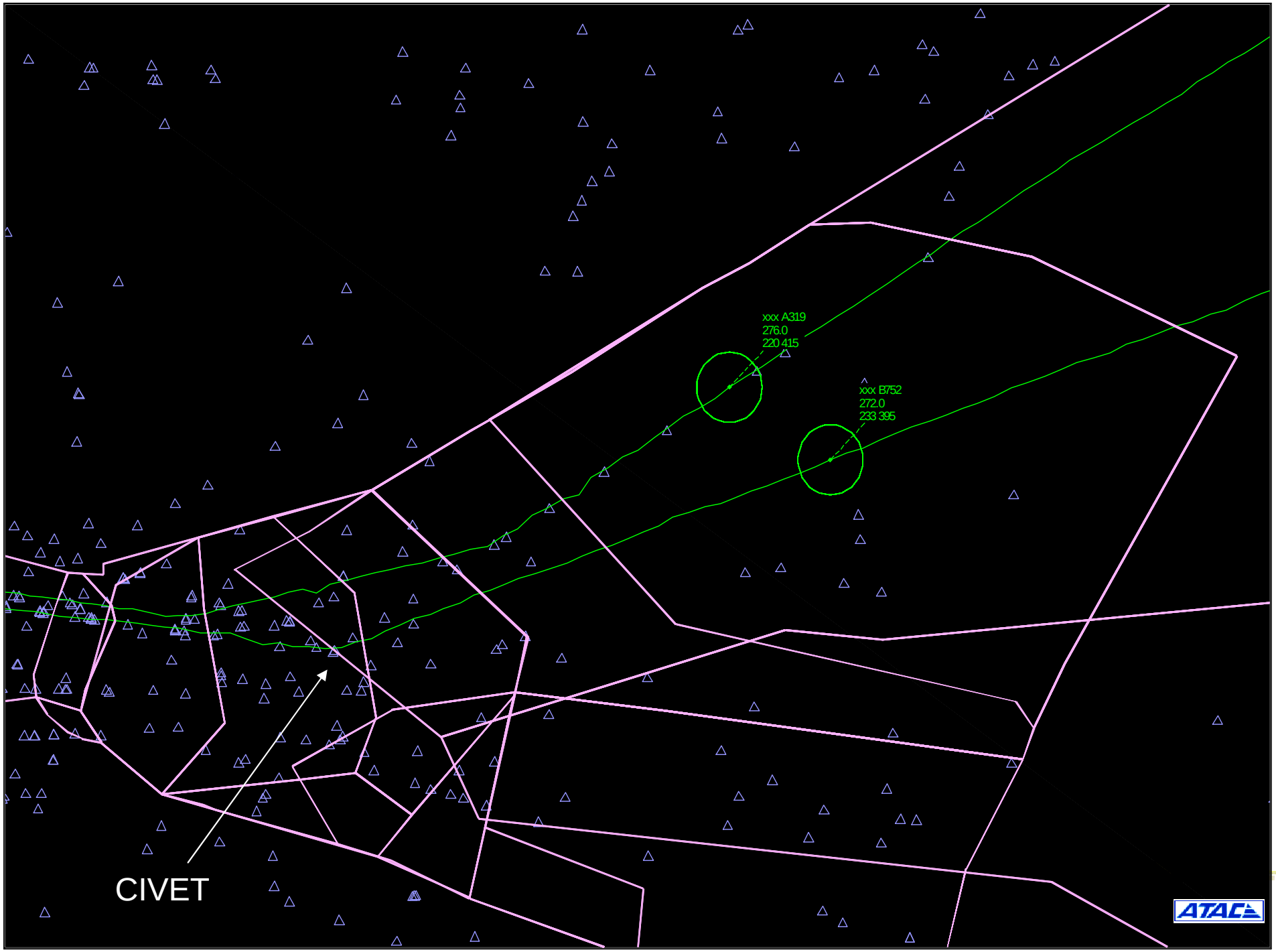


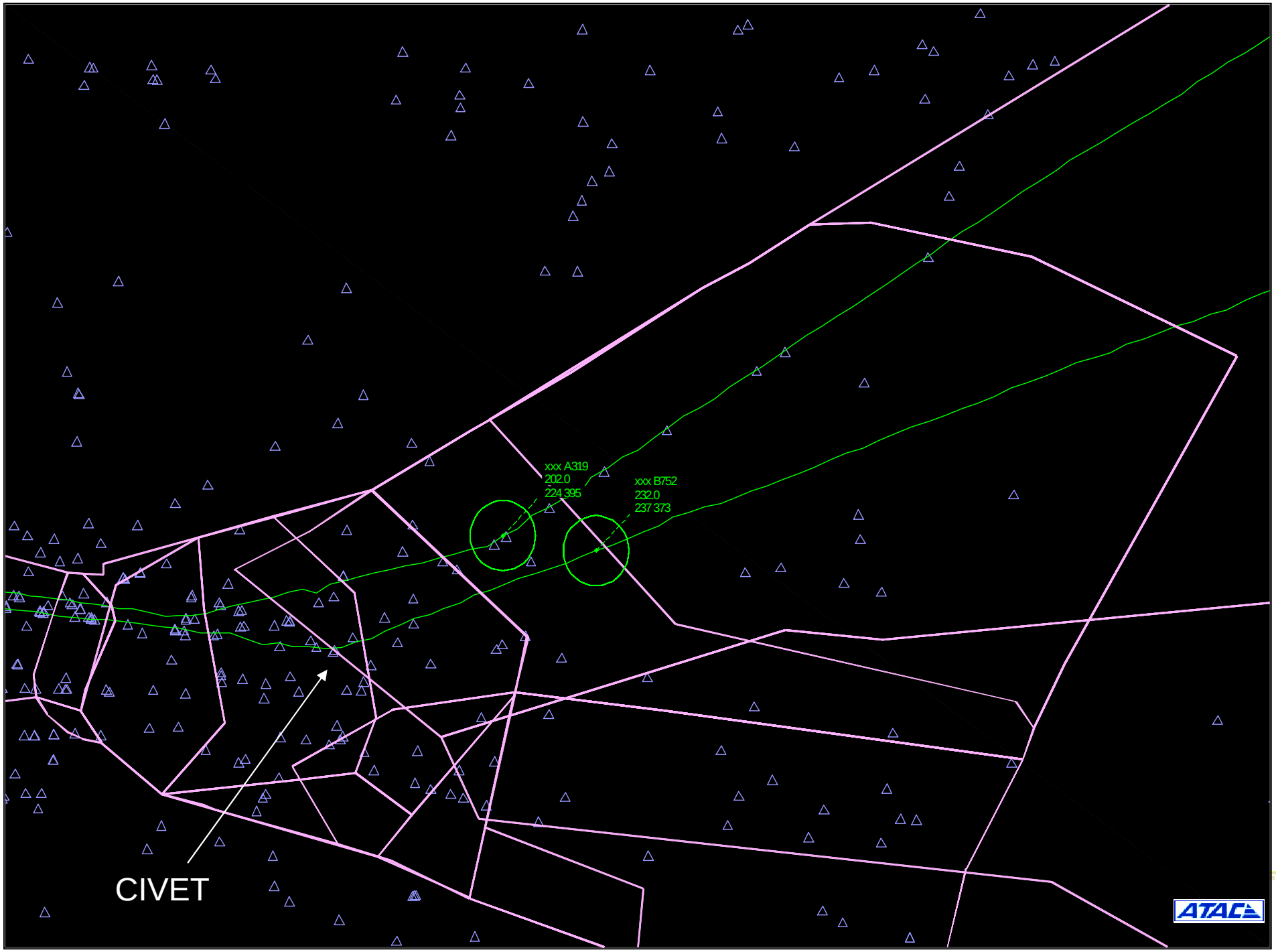

AC13
Radar Track
Simulation with Air-MIDAS Track

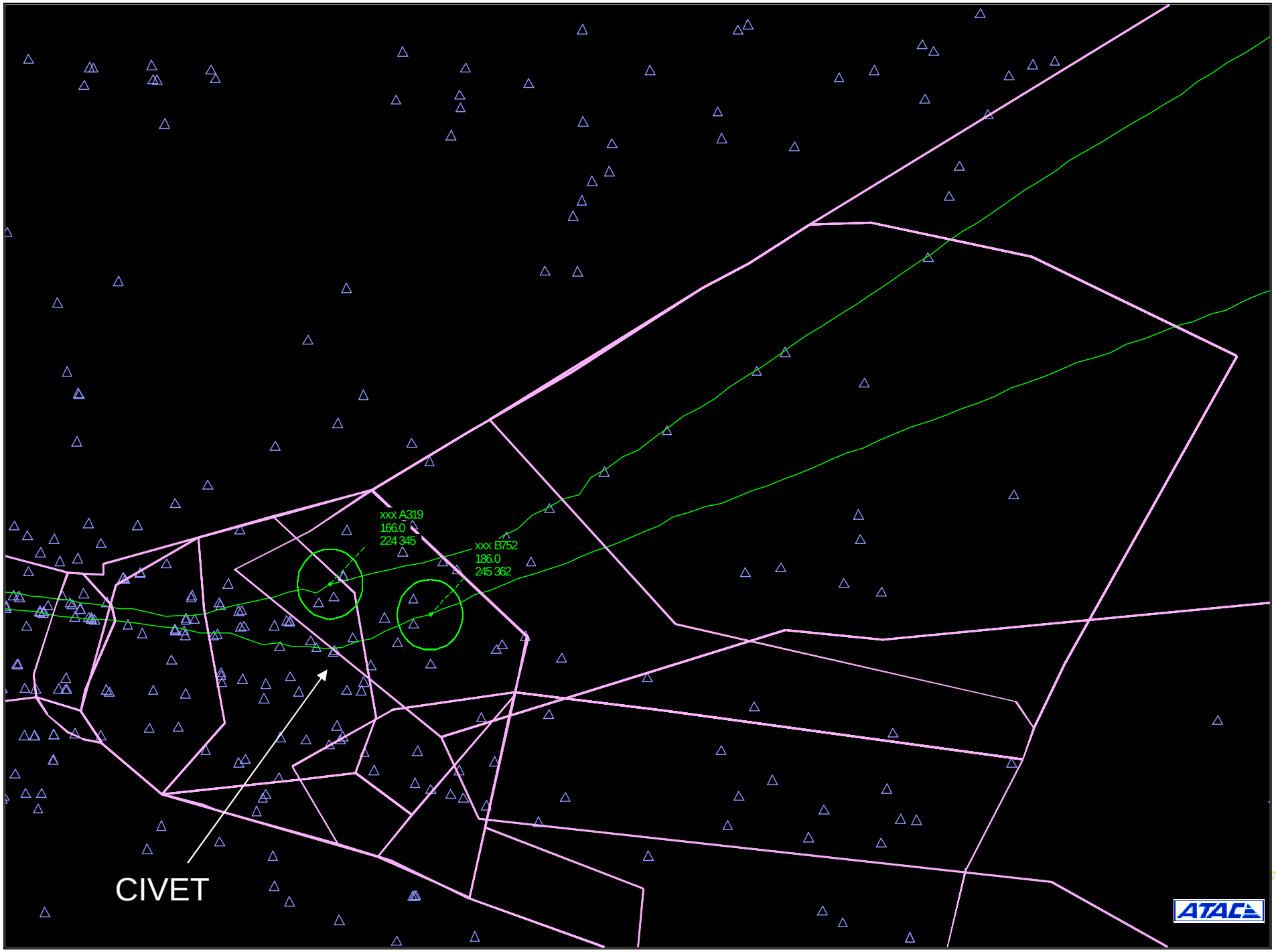

Radar Data Animation Snapshots
xxx A319
310.0
225 435
xxx B752
390.0
242 436
AC13
AC14
TBM 030804

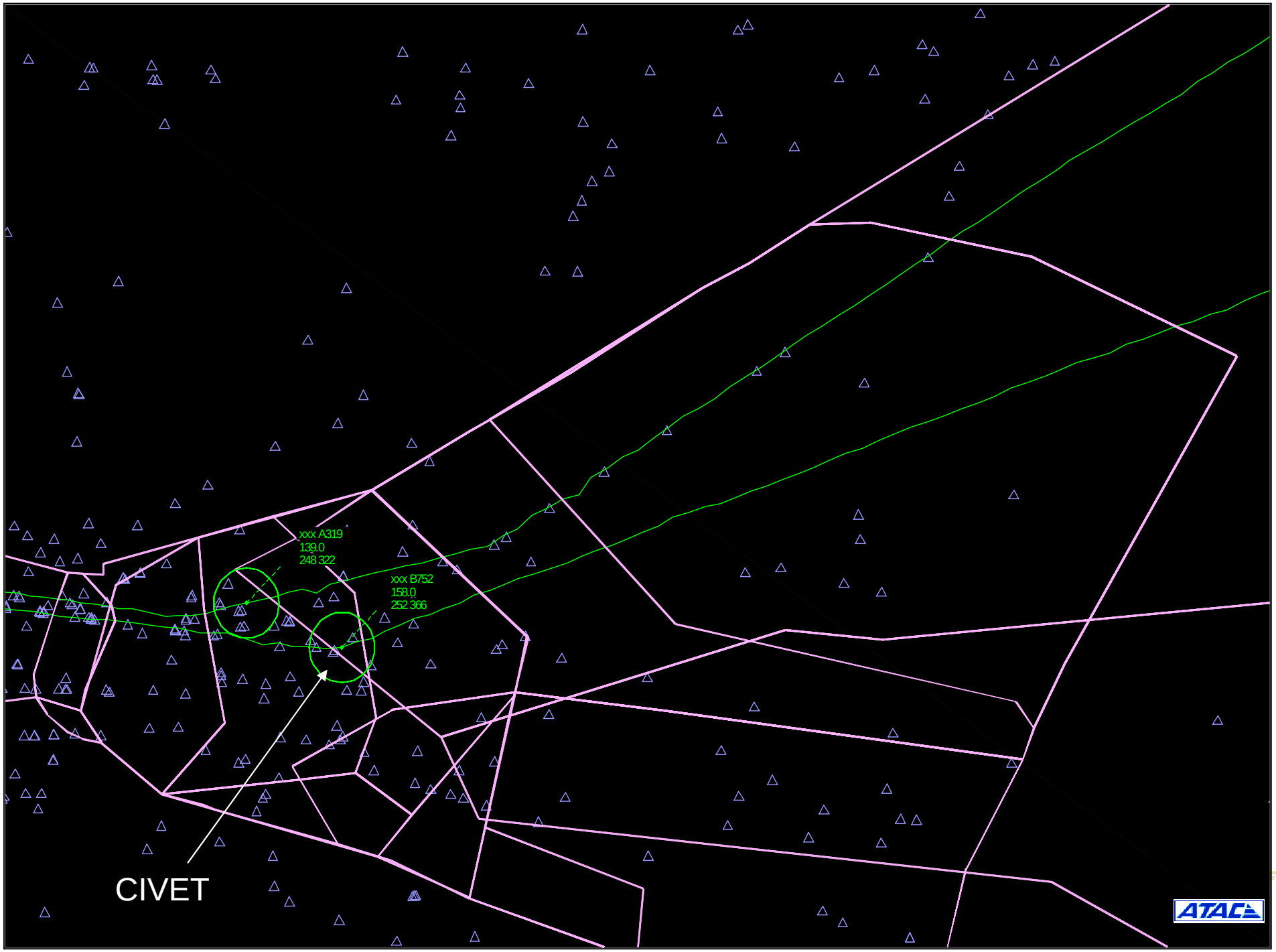

xxx A319
310.0
224 415
xxx B752
299.0
232 410
ATAC

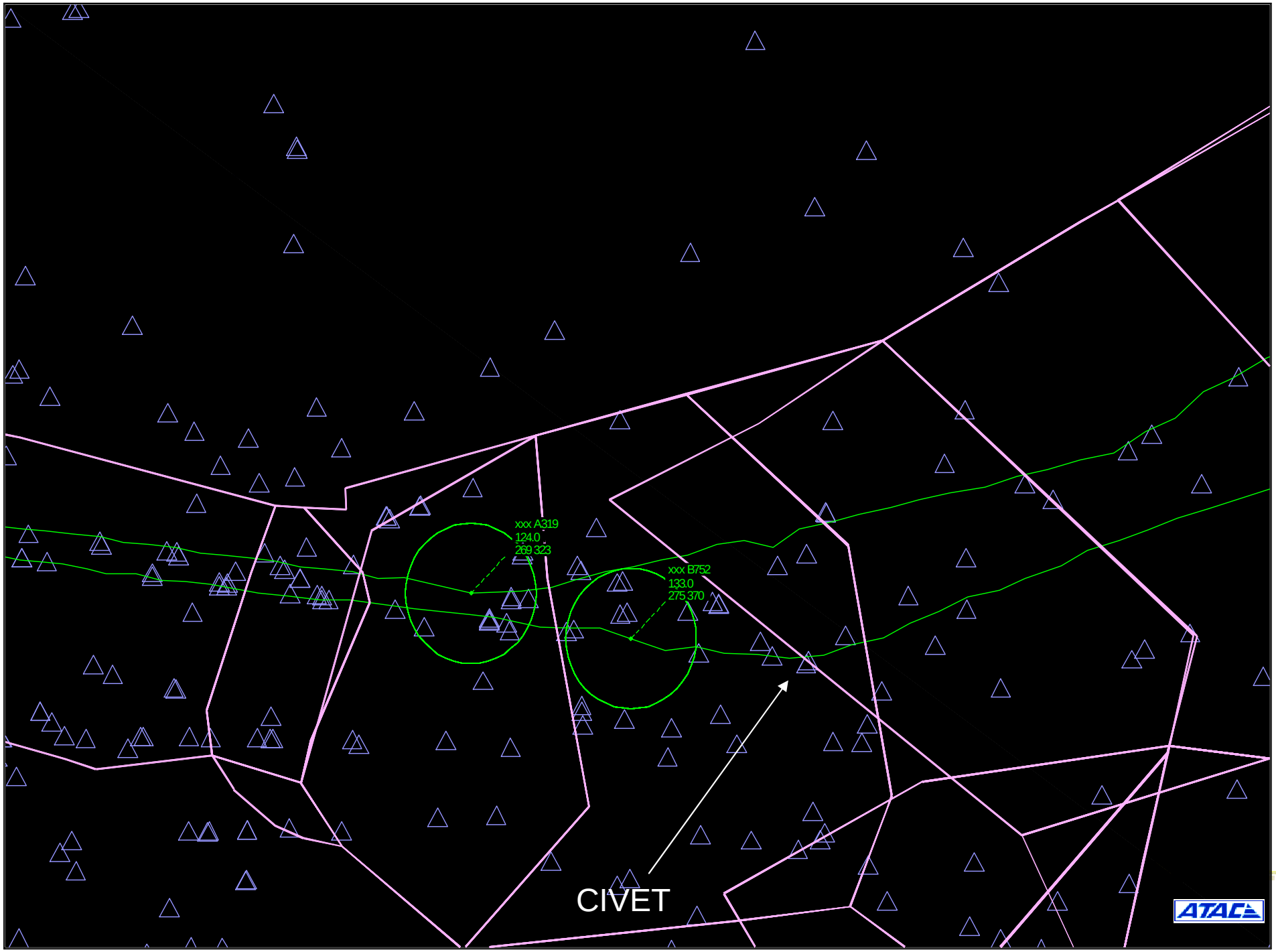

xxx A319
305.0
224 417
xxx B752
293.0
233 404
CIVET

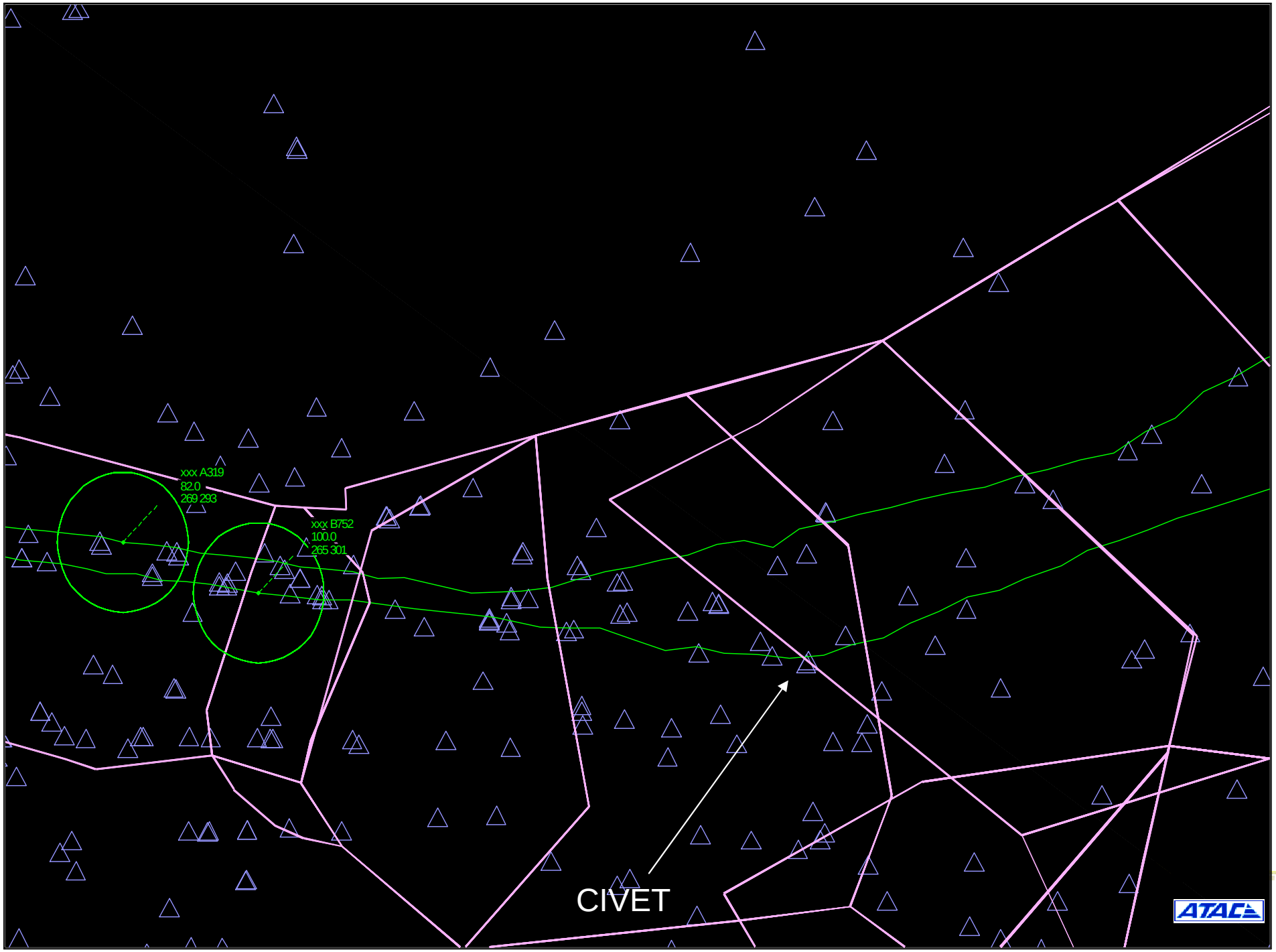

xxx A319
276.0
220 415
xxx B752
272.0
233 395
CIVET
ATAC


xxx A319
202.0
224 395
xxx B752
232.0
237 373
CIVET
ATAC


xxx A319
166.0
224 345
xxx B752
186.0
245 362
CIVET
ATAC


xxx A319
139.0
248 322
xxx B752
158.0
252 366
CIVET
ATAC


xxx A319
124.0
269 323
xxx B752
133.0
275 370
CIVET


xxx A319
82.0
269 293
xxx B752
100.0
265 301
CIVET

Summary of Results

- Modelled arrivals into Los Angeles International Airport (LAX) with the following procedures
  - Conflict Avoidance (CA)
  - Miles-In-Trail Metering (MIT)
  - Time-Based-Metering (TBM)
- Constructed and compared design alternatives
- Explained emergent behavior that could not previously be explained

Overall Thoughts

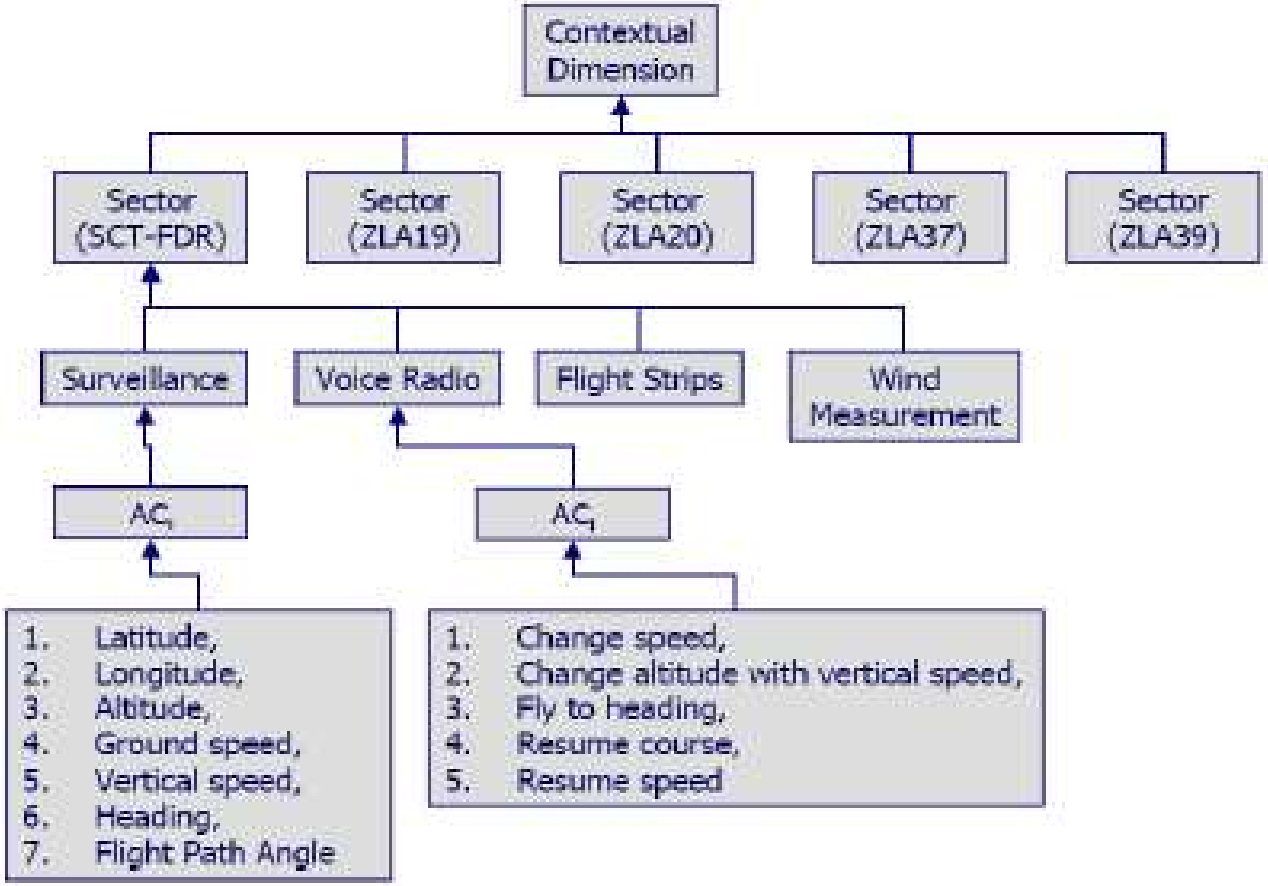
- Agent-based Simulation Can Examine Many Different Types of Operational Concepts Involving Interaction / Coordination of Agents
- Measures / High-level Behaviors Examined can Include:
  - Safety (‘emergent error’ as well as ‘emergent behavior’?)
  - Efficiency / throughput
  - Others? (Demand/scheduling...)
- Translation Between ‘Micro’ and ‘Macro’ Viewpoints

Summary

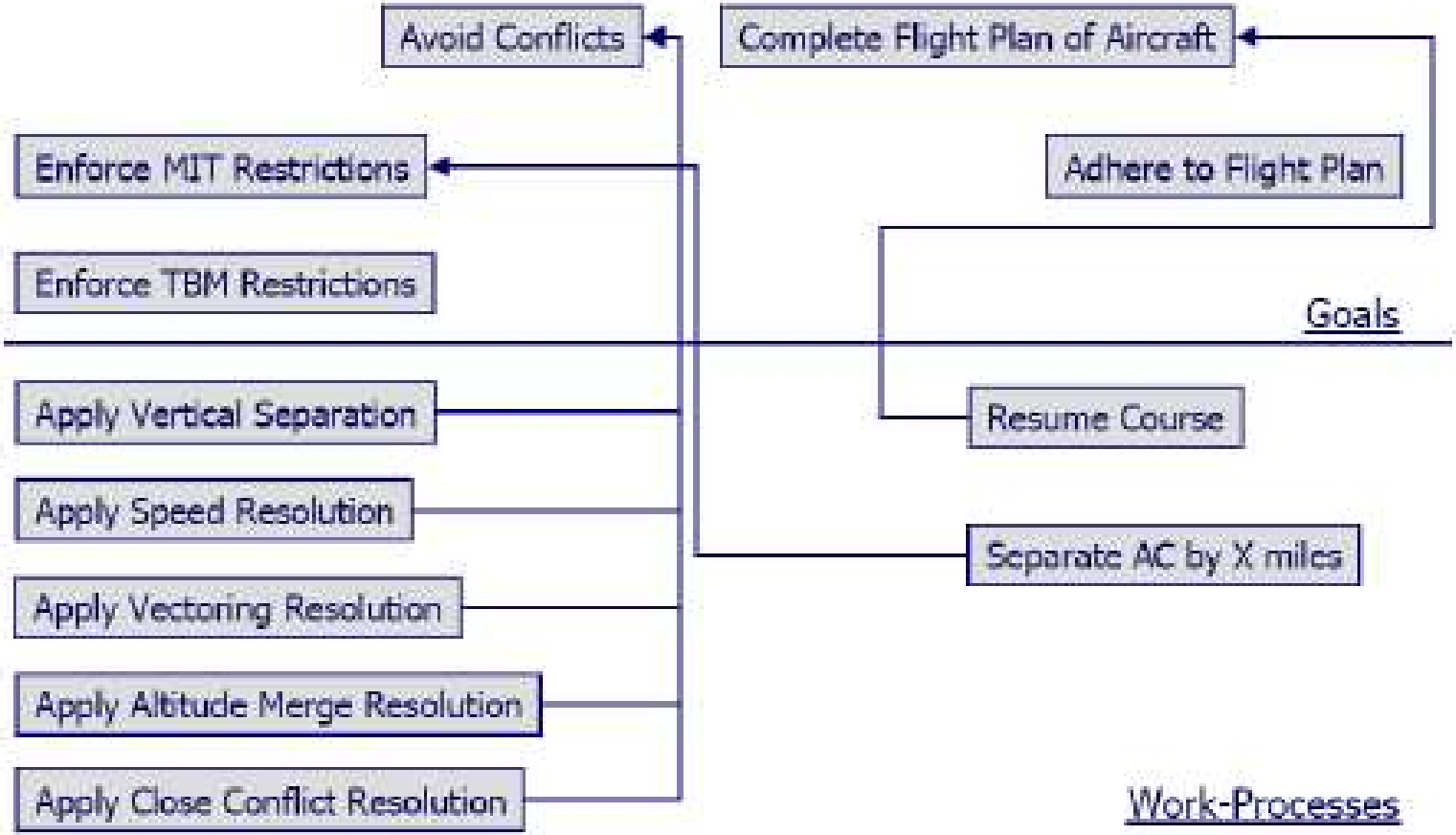
Ideal	RFS-Agent Based
Predictive	Based on known properties of physics and cognition, in response to proposed procedures and technologies
Detailed	As detailed as standard operating procedures and technology specifications
Broad Scope	Several sectors / center no problem. Wider is possible
Available	Yes, immediately
Easy to Configure	Airborne aircraft and ‘standard’ controllers already in place. Most other behaviors easily scripted into place
Fast to Run	On small compute cluster (11 machine) recently ran almost 1 million aircraft arrivals into LAX
Relevant to Design	***Uses same language as procedure design and technology requirements***

Discussion

Contextual Dimension

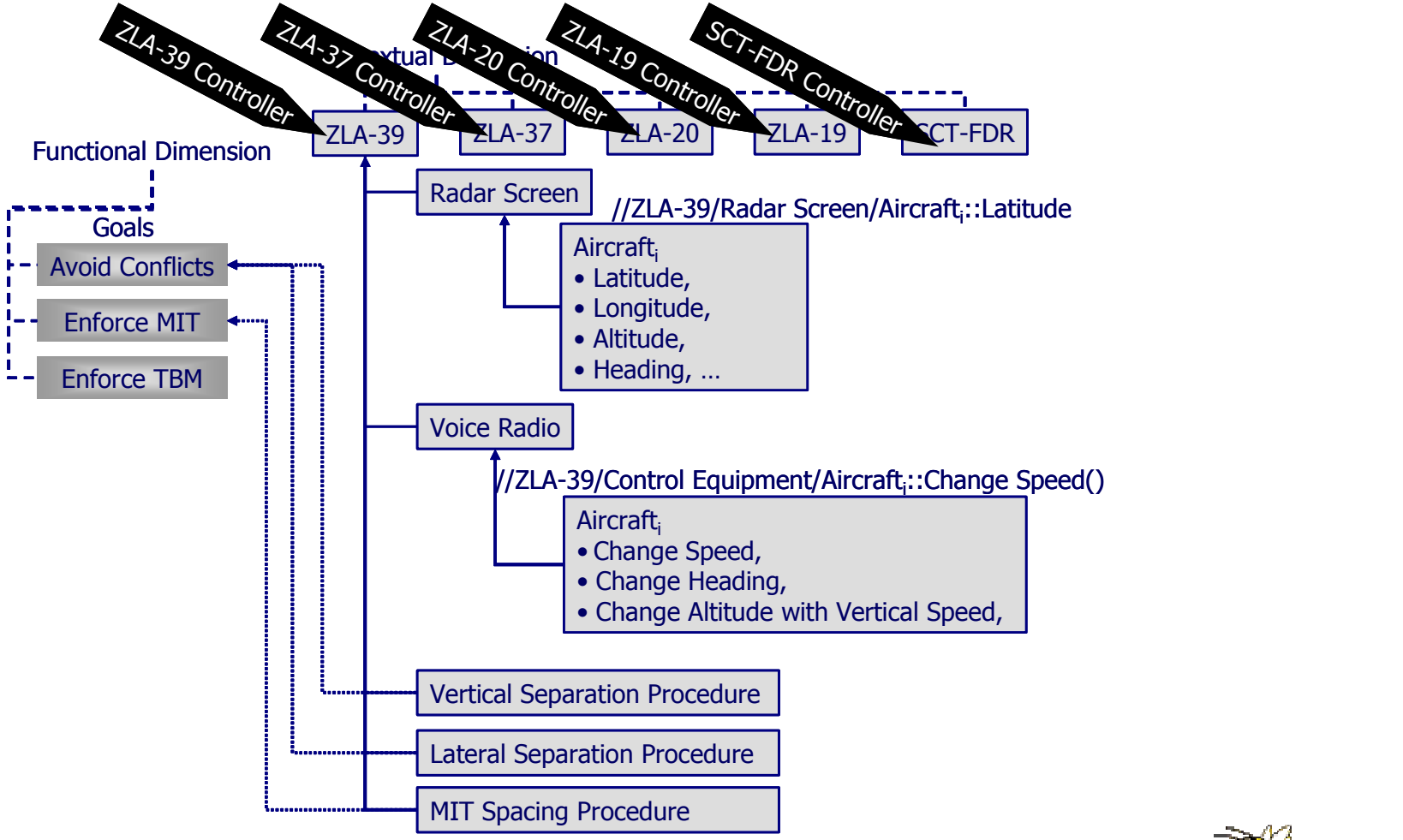


Functional Dimension



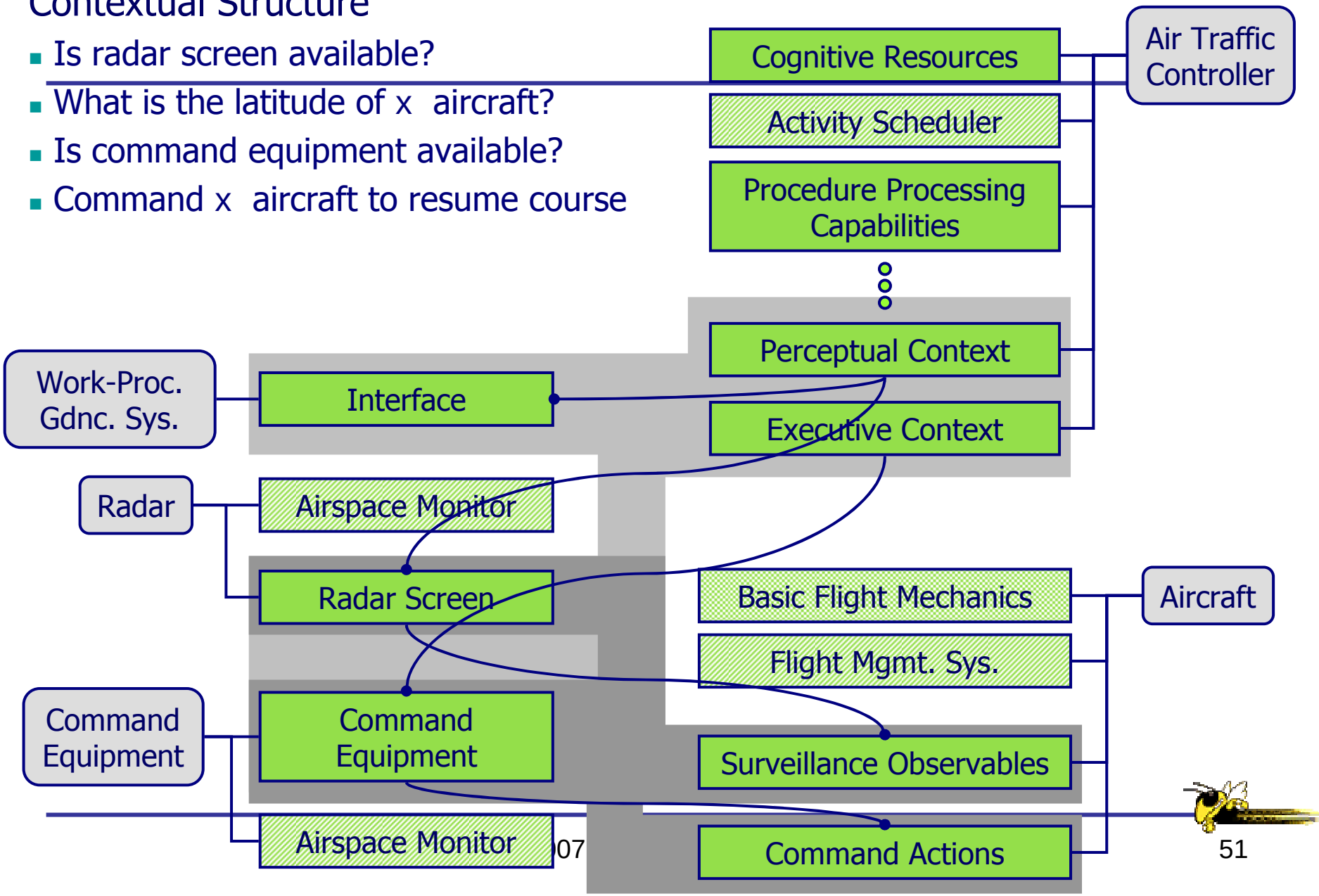
Summary of Conceptual Framework

$WE = <<C_e>, <KD_e>>$	Work-environment
$KD_e = <<R_d>>$	Knowledge Dimensions
$R_d = <[C_e], <P_r>>$	Work-relevant Relationship
$C_e = <ID_c, <P_c>, <UM_c>>$	Environmental Component
$C_e = <ID_c, <CA_c>>$	Dimension-oriented Representation of the Component
$CA_c = <[P_c], [UM_c]>$	Aspect of a Component
$Agent = <<Skill_a>, <Capability_a>, <Processor_a>>$	Agent


ZLA-39 Controller
ZLA-37 Controller
ZLA-20 Controller
ZLA-19 Controller
SCT-FDR Controller
ZLA-39
ZLA-37
ZLA-20
ZLA-19
SCT-FDR
Functional Dimension
Goals
Avoid Conflicts
Enforce MIT
Enforce TBM
Radar Screen
//ZLA-39/Radar Screen/Aircraft$_i$::Latitude
Aircraft$_i$
• Latitude,
• Longitude,
• Altitude,
• Heading, …
Voice Radio
//ZLA-39/Control Equipment/Aircraft$_i$::Change Speed()
Aircraft$_i$
• Change Speed,
• Change Heading,
• Change Altitude with Vertical Speed,
Vertical Separation Procedure
Lateral Separation Procedure
MIT Spacing Procedure

Contextual Structure

- Is radar screen available?
- What is the latitude of x aircraft?
- Is command equipment available?
- Command x aircraft to resume course



Constructing The Situational Dimension - XML

```
<WEAObject Name="ZLA39" ClassID="WEAObject"
DLL=".\modules\WEA\WEAObject.dll">
  <Initialization><![CDATA[
    <Dimension type="SituationalDimension">
       <SituationalAspect Name="ZLA39"/>
    </Dimension>
  ]]></Initialization>

  <WEAAspects>
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DLL=".\modules\WEA\WEASituationalAspect.dll">
      <Initialization><![CDATA[
        <ParentContext Name="//"/>
      ]]></Initialization>
    </WEAAspect>
  </WEAAspects>
</WEAObject>
```

XML Representation of Air Traffic Controller

```
<WEAObject Name="ATC39" DLL=".\modules\WEA\WEAATC-RL.dll"
       ClassID="BaseWEAObject">
<WEAAspects>
  <WEAAspect Name="ATCData" DLL=".\modules\WEA\WEAATC-RL.dll"
       ClassID="ATCData">
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      <Initialization>
        <SectorID Value="39"></SectorID>
      </Initialization>
    ]]></Initialization>
  </WEAAspect>

  <WEAAspect Name="SectorRadar"
       DLL=".\modules\WEA\WEASituationAccessor.dll">
    <Initialization><![CDATA[
      <WEASituationAccessorInitData>
        <CurrentContext ObjectName="Radar39" AspectName="RadarData"/>
      </WEASituationAccessorInitData>
    ]]></Initialization>
  </WEAAspect>
```

```
<WEAAspect Name="ActivityProcessor"
      DLL=".\modules\WEA\WEAATC-RL.dll" ClassID="ActivityProcessor">
   <Initialization><![CDATA[
     <Initialization>
       <ActivityLogFile Value="../../Simulation Outputs/PhaseIII
              /ActivityLog/ActivityLog_MIT_1205_030804.csv"/>
     </Initialization>
   ]]></Initialization>
 </WEAAspect>

 <WEAAspect Name="ProcedureProcessor"
      DLL=".\modules\WEA\WEATestProcessor.dll"
      ClassID="WEAProcedureProcessor">
     <Initialization><![CDATA[
       <Initialization>
         <DefaultContextAspect AspectName="//ZLA39"/>
         <StartProcedure ProcedureName="MonitorTraffic"/>
       </Initialization>
     ]]> </Initialization>
 </WEAAspect>
```

```
<WEAAspect Name="PerceptualCapabilities"
       DLL=".\modules\WEA\WEAATC-RL.dll"
       ClassID="CBasicPerceptualCapabilities">
  <Initialization><![CDATA[
    <Initialization>
      <DefaultAccessor Value="SectorRadar"/>
    </Initialization>
  ]]></Initialization>
</WEAAspect>

<WEAAspect Name="AnalyticalCapabilities"
       DLL=".\modules\WEA\WEAATC-RL.dll"
       ClassID="CBasicAnalyticalCapabilities">
  <Initialization><![CDATA[
    <Initialization>
      <ATCDataAspect Value="ATCData"/>
      <CBasicPerceptualCapabilities Value="PerceptualCapabilities"/>
    </Initialization>
  ]]></Initialization>
</WEAAspect>

<WEAAspect Name="ResourceProvider"
       DLL=".\modules\WEA\WEAATC-RL.dll" ClassID="ResourceProvider">
  <Initialization><![CDATA[
    <Initialization>
      <MaxResources Value="7"/>
    </Initialization>
  ]]></Initialization>
</WEAAspect>
```

```
 <WEAAspect Name="ExecutionCapabilities"
        DLL=".\modules\WEA\WEAATC-RL.dll"
        ClassID="CBasicExecutionCapabilities">
    <Initialization><![CDATA[
      <Initialization>
        <ATCDataAspect Value="ATCData"/>
        <ATCControlAspect Value="SectorChannel"/>
        <BasicAnalyticalCapabilities Value="AnalyticalCapabilities"/>
        <ActivityProcessor Value="ActivityProcessor"/>
        <ProcedureProcessor Value="ProcedureProcessor"/>
        <ResourceProvider Value="ResourceProvider"/>
        <RandomNumberGenerator Name="RandomNumberGenerator"/>
      </Initialization>
    ]]> </Initialization>
  </WEAAspect>
  … …
</WEAAspects>

<WEAProcessors>
  <WEAProcessor Name="SwitchableProcessor"
        DLL=".\modules\WEA\WEAATC-RL.dll" ClassID="SwitchableProcessor">
      <Initialization><![CDATA[
        <Initialization>
          <Processor Value="ActivityProcessor"/>
        </Initialization>
      ]]> </Initialization>
  </WEAProcessor>
</WEAProcessors>
</WEAObject>
```