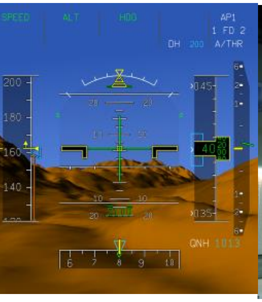
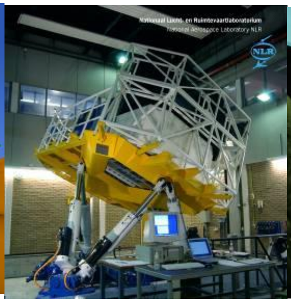
In Search of Positive Emergent Behaviour of Air Traffic

Henk Blom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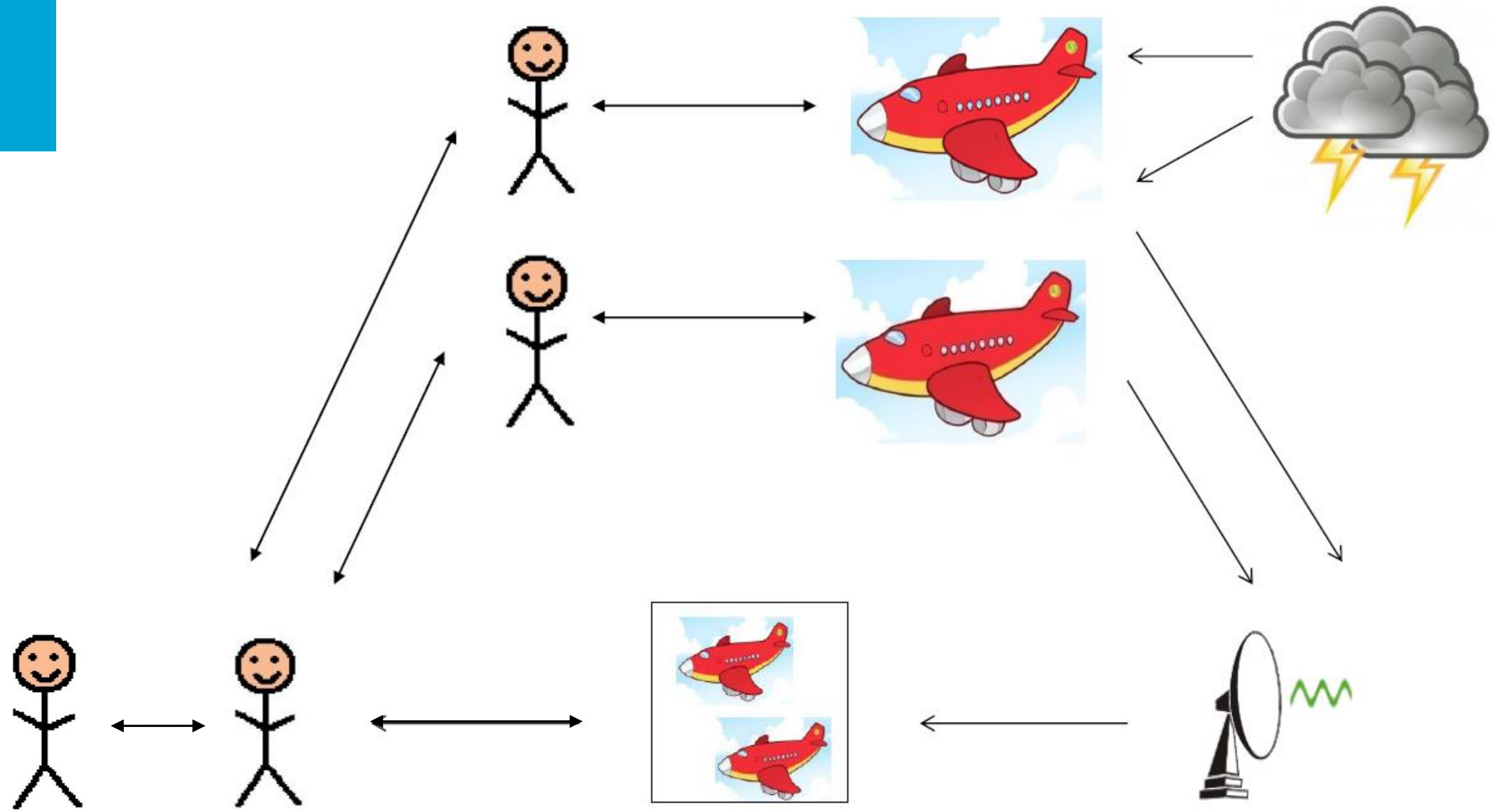
In Search of Positive Emergent Behaviour of Air Traffic

- ATM Design and Emergent Behaviour
- Agent Based Safety Risk Analysis
- Free Flight
- Concluding remarks

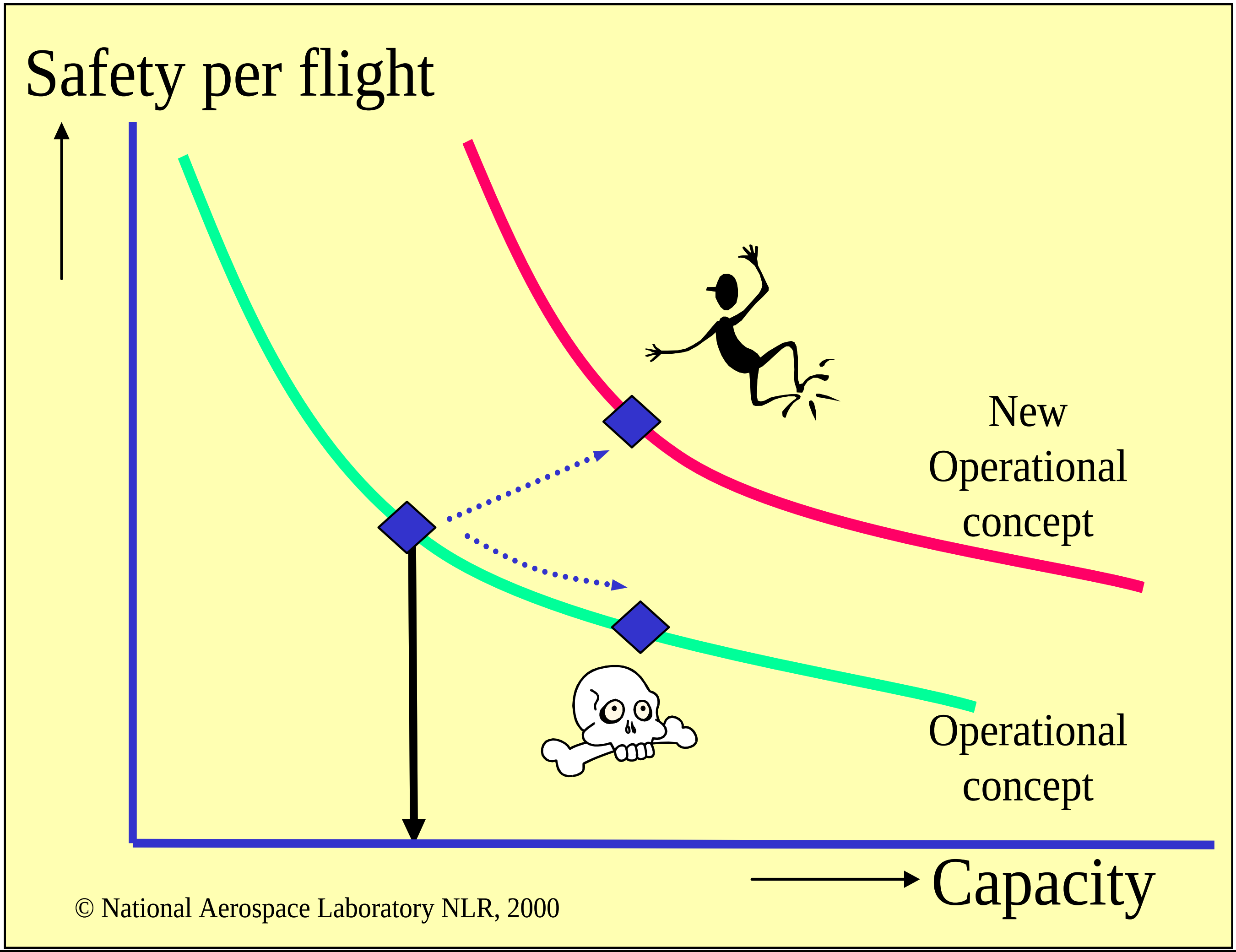
ATM is an Open Socio-Technical System



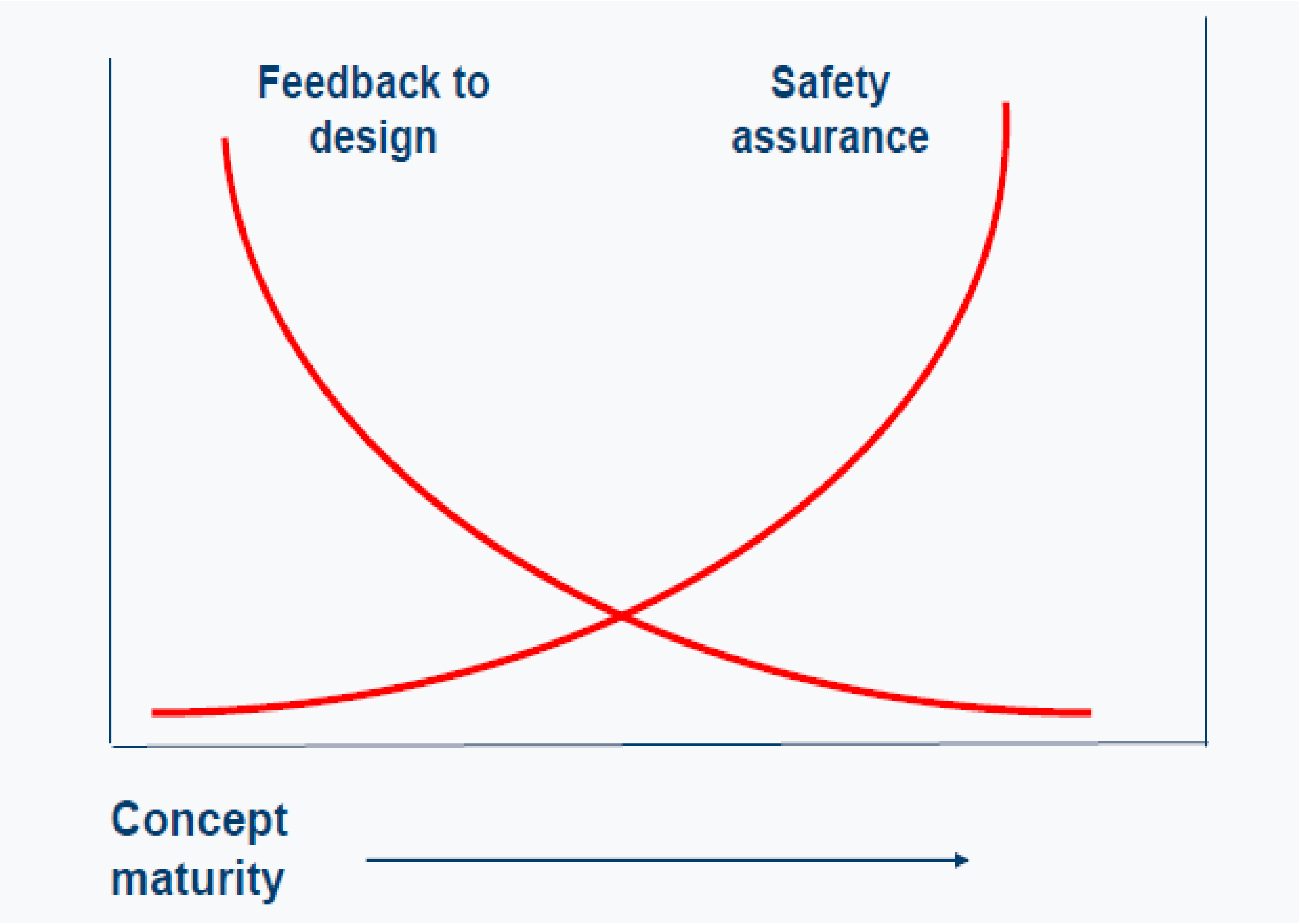
Future ATM design requires safety/capacity analysis

ATM performance improvement targets of SESAR programme

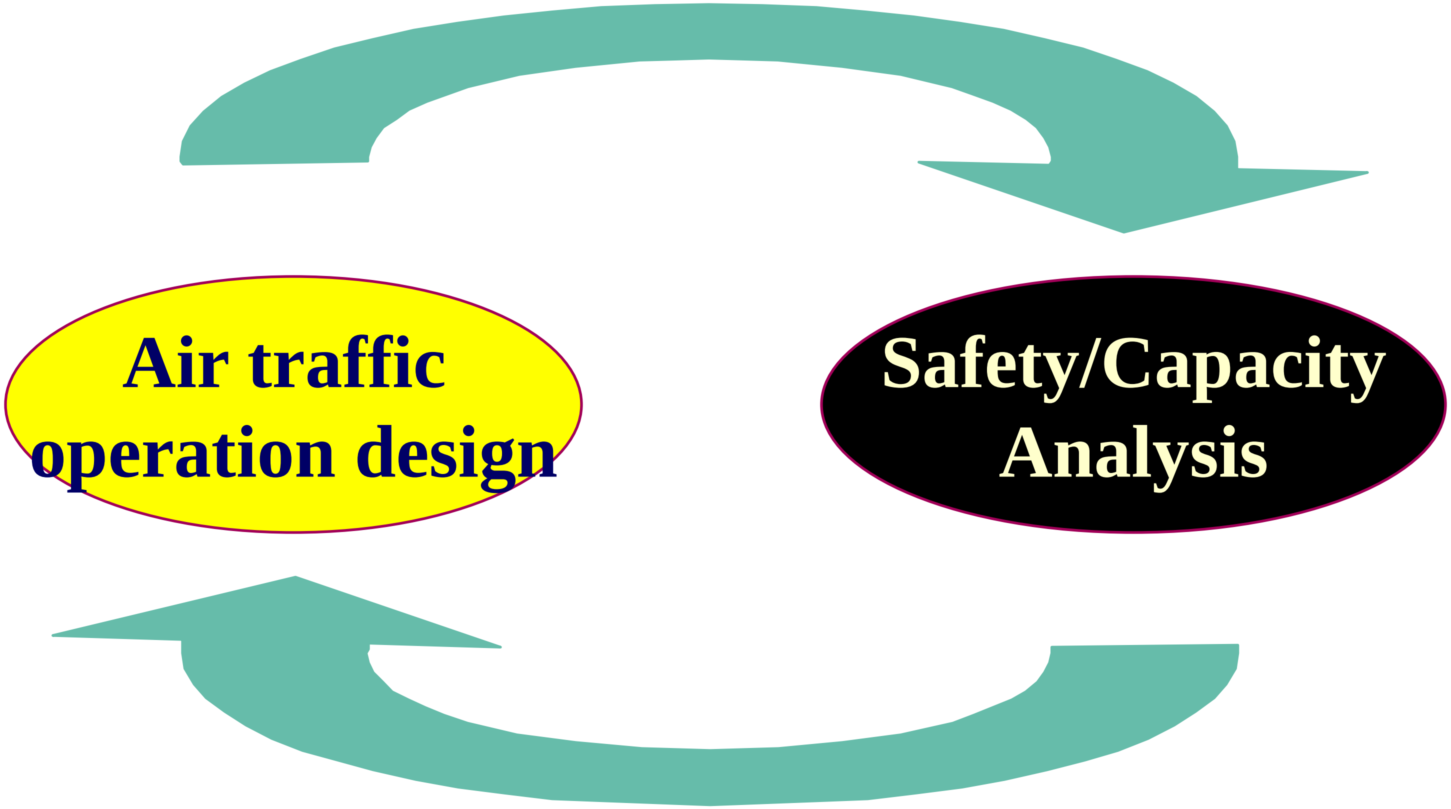
- Capacity: 3 x
- Safety: 10 x
- Economy: 2 x
- Environment: 10%



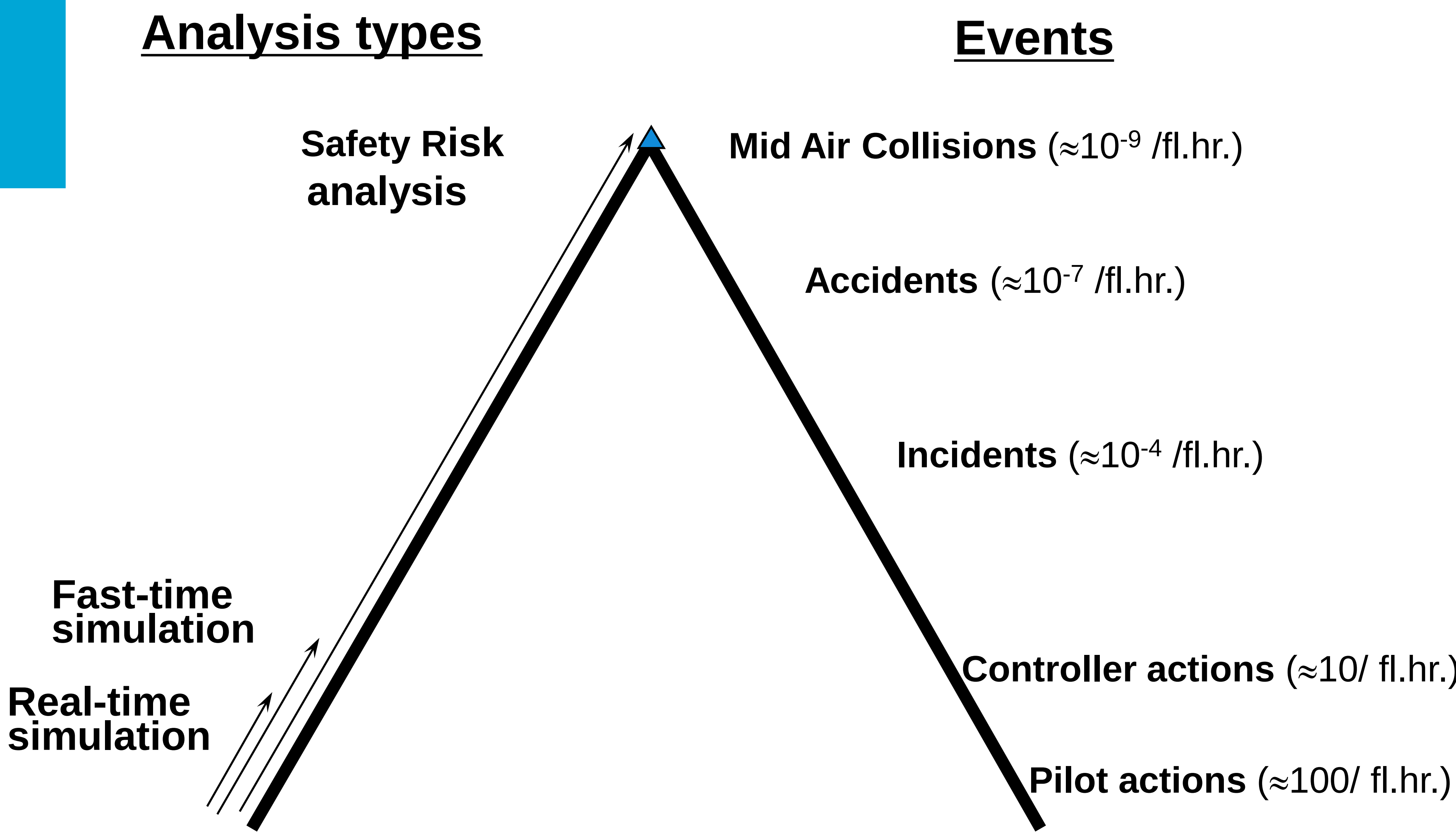
Feedback to Design vs. Safety Assurance



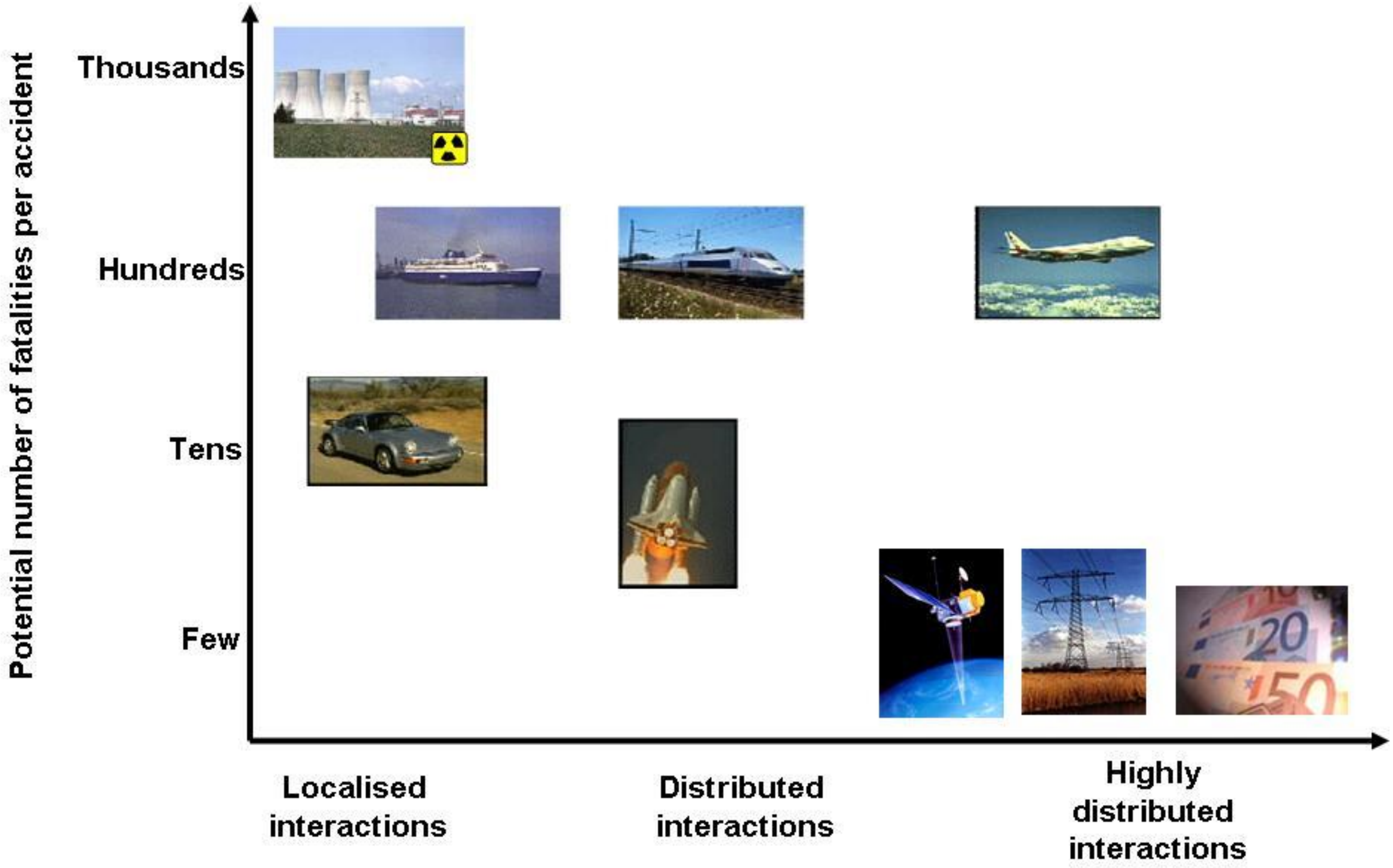
Safety/capacity analysis feedback to future ATM design



Air Traffic Safety Pyramid



ATM and other socio-technical systems



Emergent Behaviour

- Emergent behaviour is a result of interactions between local behaviours of many entities
- Emergent behaviour cannot be understood from the individual entity local behaviours alone

- Emergent behaviour examples in ATM:
  - Delay propagation over the traffic network due to a bad weather condition
  - Accidents due to combinations of events and misunderstandings in the socio-technical system
- Change in one part may change emergent behaviour unexpectedly

Emergent Behaviour and ATM Design

- Open en Socio- aspects of ATM are not well covered by established system engineering approach.
- No theory that tells how to improve emergent behaviours of a complex socio-technical system (Holland 2006)
- As long as emergent behaviour is not understood, then it is more likely to have a negative than a positive impact
- Hence early learning to understand potentially new emergent behaviours provide opportunities to improve ATM design:
  - to mitigate negative emergent behaviours found, and
  - to take advantage of any positive emergent behaviours.
- Network Flow Modelling and Agent-based Modelling and Simulation have the widest proven applicability in identifying potential emergent behaviours in complex critical infrastructures

Safety Modelling & Analysis Approaches

- Sequential accident modelling (e.g. fault/event trees)
  - Accident = Sequence of ordered events, such as failures or malfunctions of humans or machines
- Epidemiological accident modelling (e.g. Bayesian Belief Network)
  - Accident = Like spreading of disease: combination of failures and latent / environmental conditions, leading to degradation of barriers an defences
- Systemic accident modelling (e.g. FRAM, STAMP)
  - Accident = Emergent from the performance variability of a joint cognitive system, as a result of complex interactions and unexpected combinations of actions
- Agent-based Safety Risk Analysis
  - Accident Risk = Influenced by positive and negative dynamic and emergent behaviour of a complex distributed and open socio-technical system

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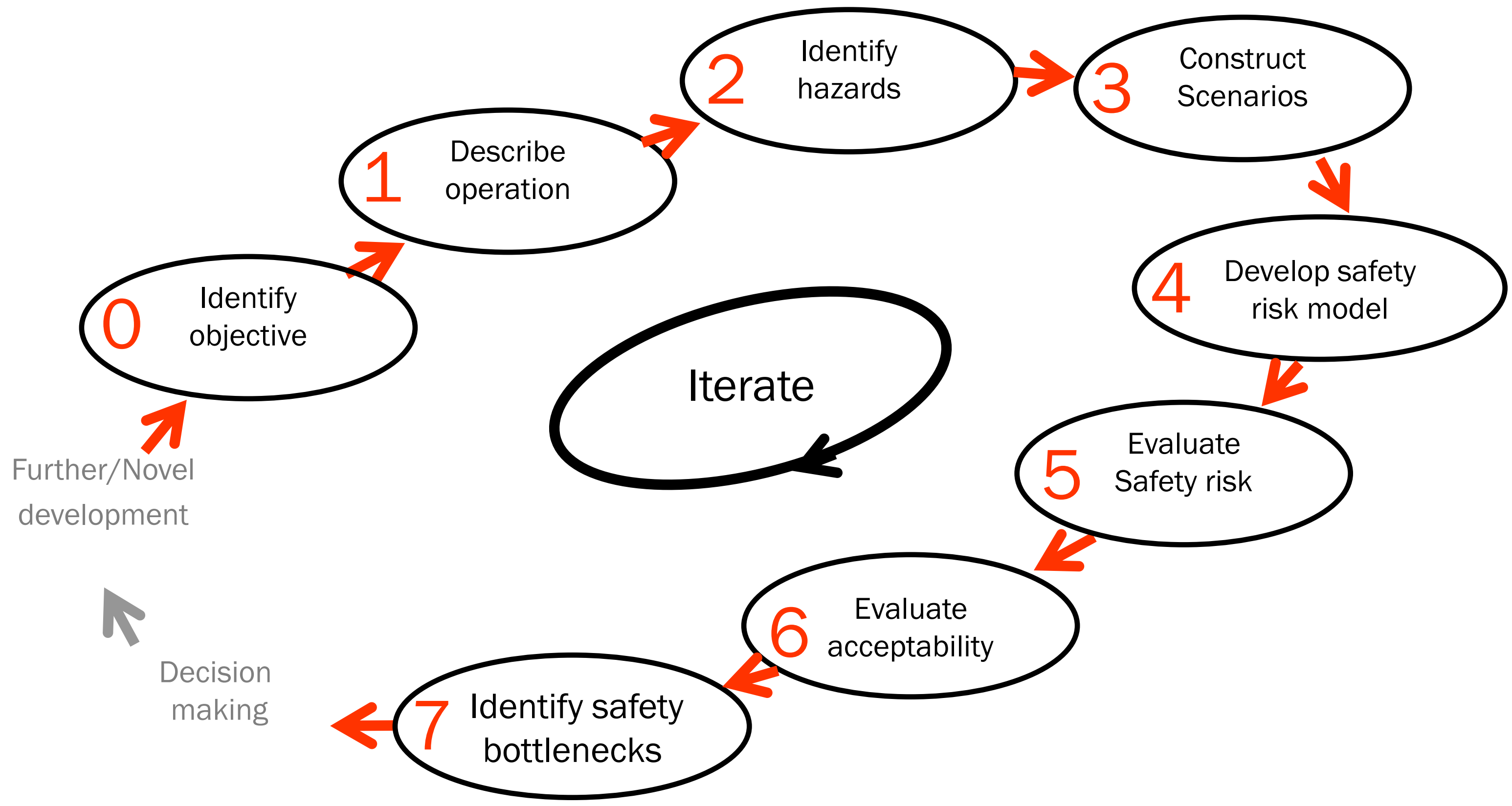
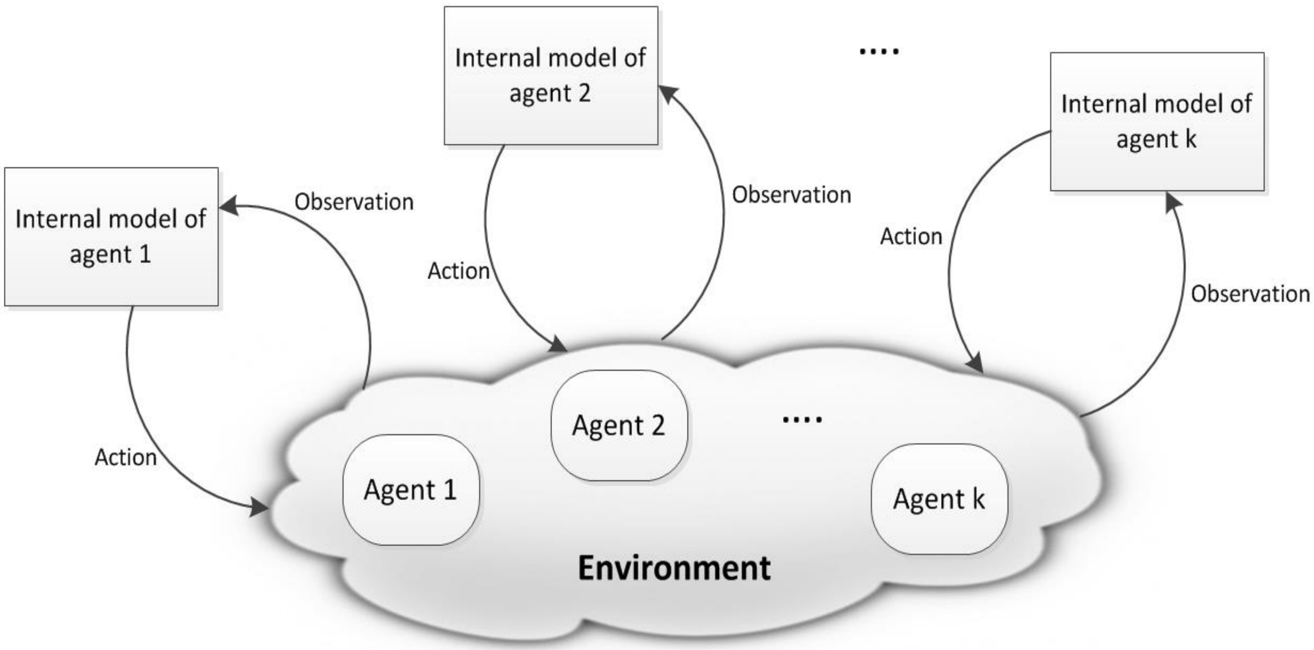
Safety risk assessment cycle



Agent Based Modelling and Simulation

Agents are autonomous entities that are able to perceive their environment and act upon this environment. Agents may be humans, systems, organizations, or another other entity that pursues a certain goal.



Interacting Agents applications in:

- Ecology
- Political science
- Social science
- Economics
- Evolutionary biology
- Biomedical science
- Computer science

Use of agent sub-models in capturing hazards (non-nominal events) [1]

Top 5 sub-models	% of hazards
1. Multi Agent Situation Awareness differences [2]	41.4 %
2. Technical System Modes (Configurations, Failures)	19.9 %
3. Basic Human Errors (Slips, Lapses, Mistakes)	18.0 %
4. Human Information Processing	14.3 %
5. Dynamic Variability (e.g. aircraft dynamics)	8.6 %

[1] Blom et al. (2013)   [2] Stroeve et al. (2003)

Top-5 Model constructs/types: use in aviation studies (1/2)

Rank 1 (41.4%): Multi-Agent SA (MA-SA):

- Multi Agent extension of Endsley's (1995) SA model
- Allows to capture SA differences between agents

Rank 2 (19.9%): System mode:

- RAMS: Reliability, Availability, Maintainability and Safety of technical systems

Rank 3 (18.0%): Basic Human error

- Slips, Lapses and Mistakes only (Reason, 1990)

Top-5 Model constructs/types: use in aviation studies (2/2)

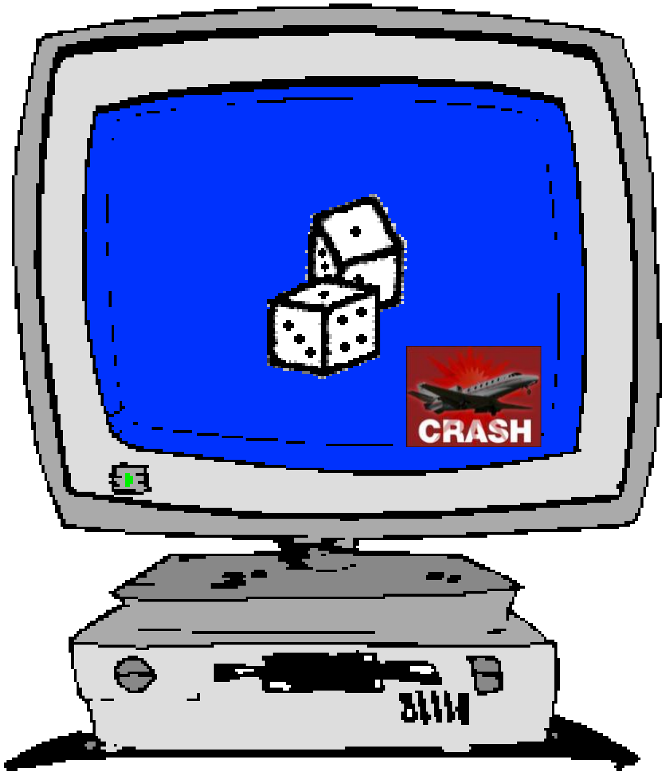
Rank 4 (14.3%): C1 - Human Information Processing

- Human performance simulation, e.g. MIDAS, Air-MIDAS, PUMA, ACT-R, IMPRINT/ACT-R, D-OMAR

Rank 5 (8.6%): C11 - Dynamic Variability

- Simulation of aircraft dynamical behaviour:
  - Aircraft performance models
  - Human-In-The-Loop simulations
  - Fast Time simulations

Monte Carlo simulation of an Agent Based Model (ABM)



- Conduct N simulation runs with ABM
- Per run: use independent random numbers
- Count number C of runs with a crash

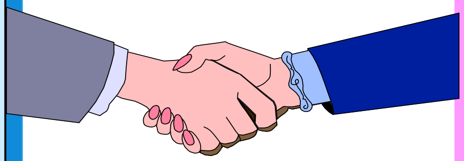
- Estimated crash risk = C/N per ABM run
- Analyse simulated trajectories of each crash

- Advantage over classical risk assessment:
  - Safety relevant event sequences follow from Monte Carlo simulation
  - No need to identify early on which event sequences are safety relevant

- Challenge: Straightforward Monte Carlo simulation takes extremely much time

Integrating ABM and Mathematical tools

Agent Based Modelling and Simulation



Mathematical Tools

↓

Agent Based Safety Risk Analysis

Mathematical Tools

- **Stochastically & Dynamically Coloured Petri Nets**
- **Fokker-Planck-Kolmogorov evolution**
- **Probabilistic Reachability Analysis**
- **Conditional Monte Carlo Simulation**
- **Particle Swarm Intelligence**
- **Importance Sampling**
- **Sensitivity/Elasticity Analysis**
- **Uncertainty Quantification**

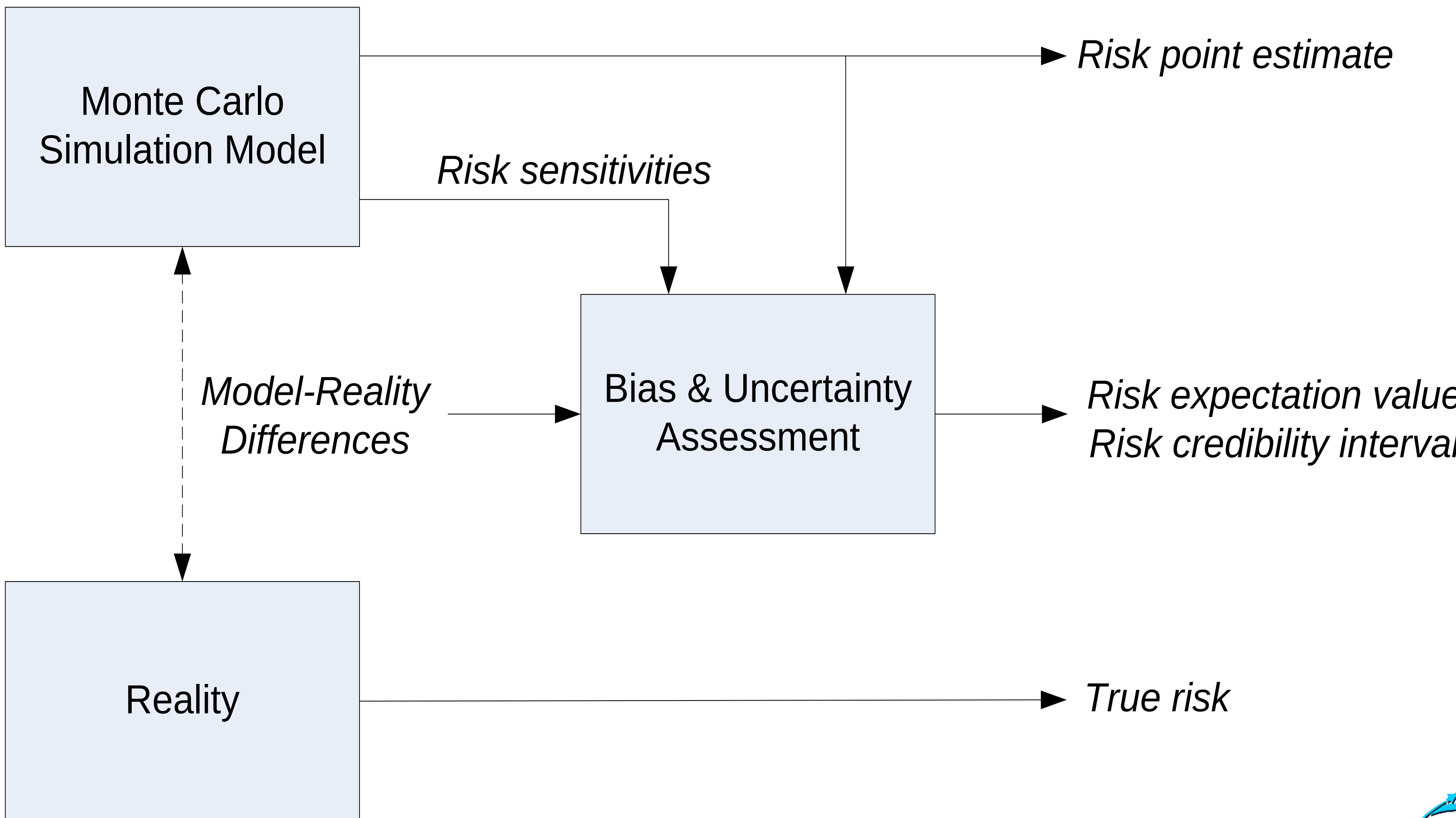
Bias and uncertainty assessment

- By definition: Model ≠ Reality
  - Numerical approximations
  - Parameter values
  - Model structure
  - Hazards not covered
  - Operational concept

- Bias and uncertainty assessment
  - Identify differences between model and reality
  - Assess the size of these differences (operational expert interviews)
  - Assess the sensitivities of the model
  - Assess the impact of these differences at the risk level

- Typical output: expected risk and 95% bracket

Risk assessment through MC simulation + bias & uncertainty assessment



Agent-based Safety Risk Analysis in TOPAZ

Human Performance Modelling

Mathematical model integrating state-of-the-art psychology in human cognition/performance modeling. Based on SA (Endsley, 1995), the multiple resources model (Wickens 1998), the contextual control mode model (Hollnagel 1993), and human error modelling (Kirwan 1994)

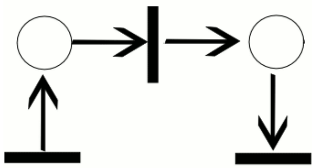
TOPAZ: Traffic Organization & Perturbation AnalyZer

Sensitivity, Bias, and Uncertainty Analysis

Assessment of the impact of potential differences between the true operation and the agent-based model such as errors in paramter values, model structure differences from reality, etc.

Agent-Based Modeling and Simulation

Capability to integrate hetregonous components of the ATM system such as cognitive models, technological models, and working procedures



Stochastically & Dynamically Colored Petri Net Formalism

Advanced Modelling language to develop the agent-based model in a compositional way, and conduct MC simulations enabling powerful stochastic analysis.

Rare Event Monte Carlo Simulation

Application of probabilistic reachability analysis to stochastic hybrid systems, providing a framework to capture uncertainty and dynamics of the ATM system,

Agent Based Safety Risk Analysis: ATM applications

- Conventional ATM: Reduction of separation minima [1]
- Simultaneous use of converging runways [2]
- Runway Incursion Risk [3],[4]
- Initial TBO operations in TMA [5],[6]
- <u>Free Flight</u>

[1] Blom et al., 2003 [2] Blom et al., 2003 [3] Stroeve et al., 2008
[4] Stroeve et al., 2013 [5] Everdij et al., 2012 [6] Teuwen et al., 2014

Free Flight

- “Invented” in 1995 [RTCA, 1995]

- With support of an Airborne Separation Assistance System (ASAS) pilots are allowed to do separation management themselves

- Ongoing dispute between two schools of researchers:
  - Believers: Free Flight can safely accommodate high traffic demand
  - Non-believers: Free Flight is unsafe under high traffic demands

- Scientific need to resolve this dispute through safety/capacity analysis

- Two well developed Free Flight designs:

1. <u>Autonomous Mediterranean Free Flight (AMFF)</u>

2. <u>Advanced Airborne Self Separation (AASS)</u>

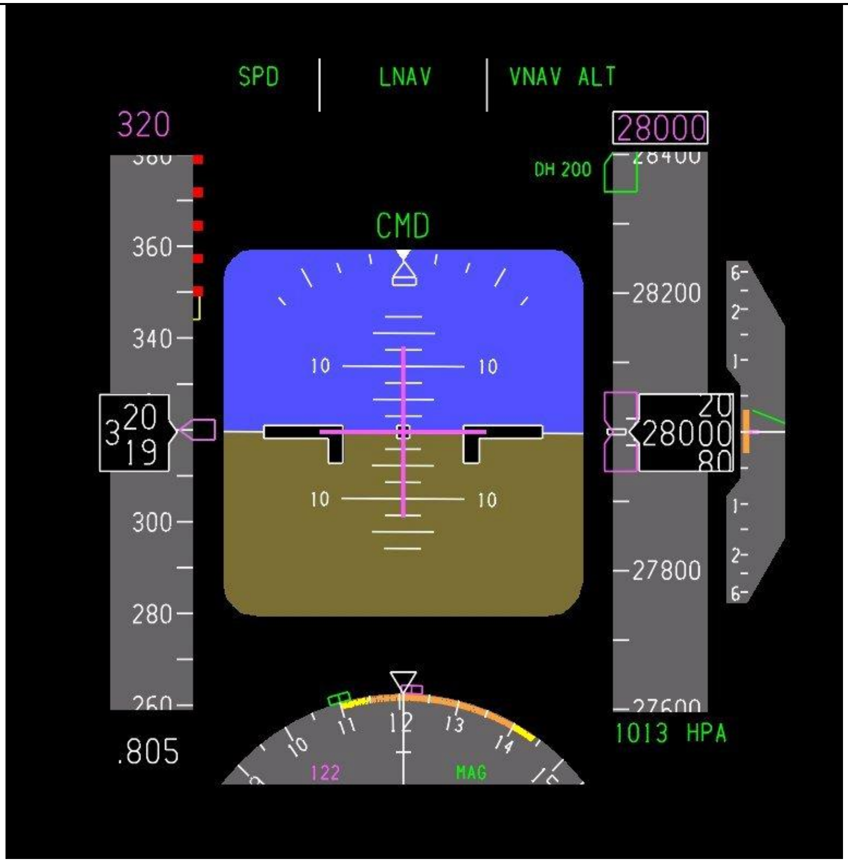
1. AMFF [1]

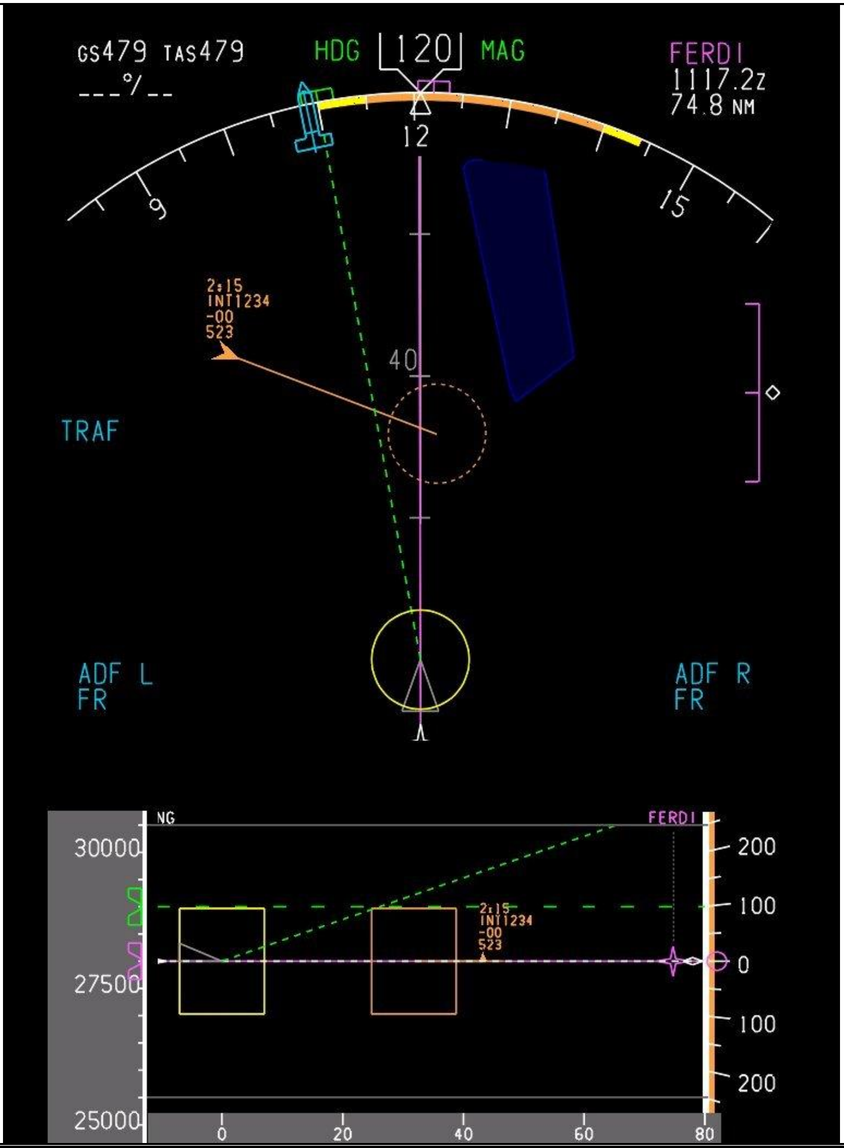
- Conflict detection and resolution
  - Nearest aircraft only
  - Priority based plan (5-10 mins)
  - Tactical resolution (3-5 mins)

- Each aircraft broadcasts its 3D position and destination to others

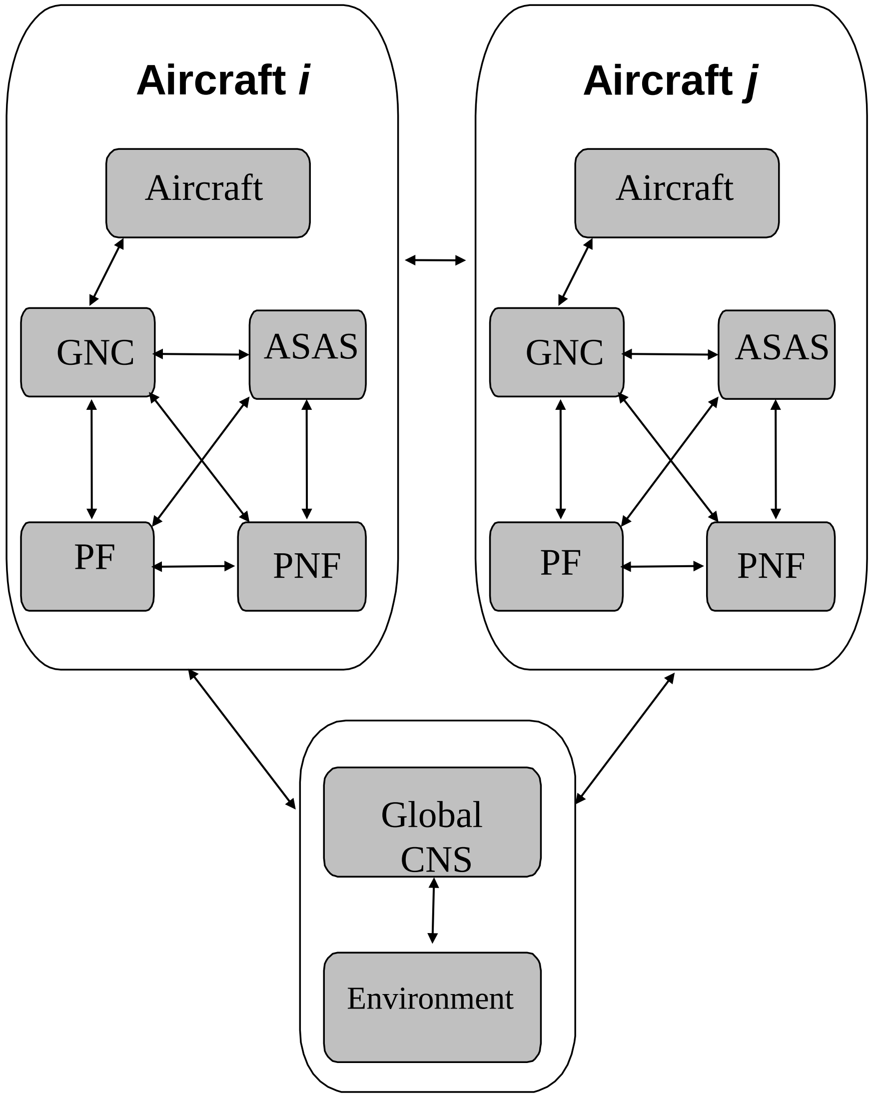
[1] Gayraud et al. (2005)

AMFF Pilot view





Agent Based Model of AMFF



GNC = Guidance, Navigation & Control

ASAS = Airborne Separation Assistance System

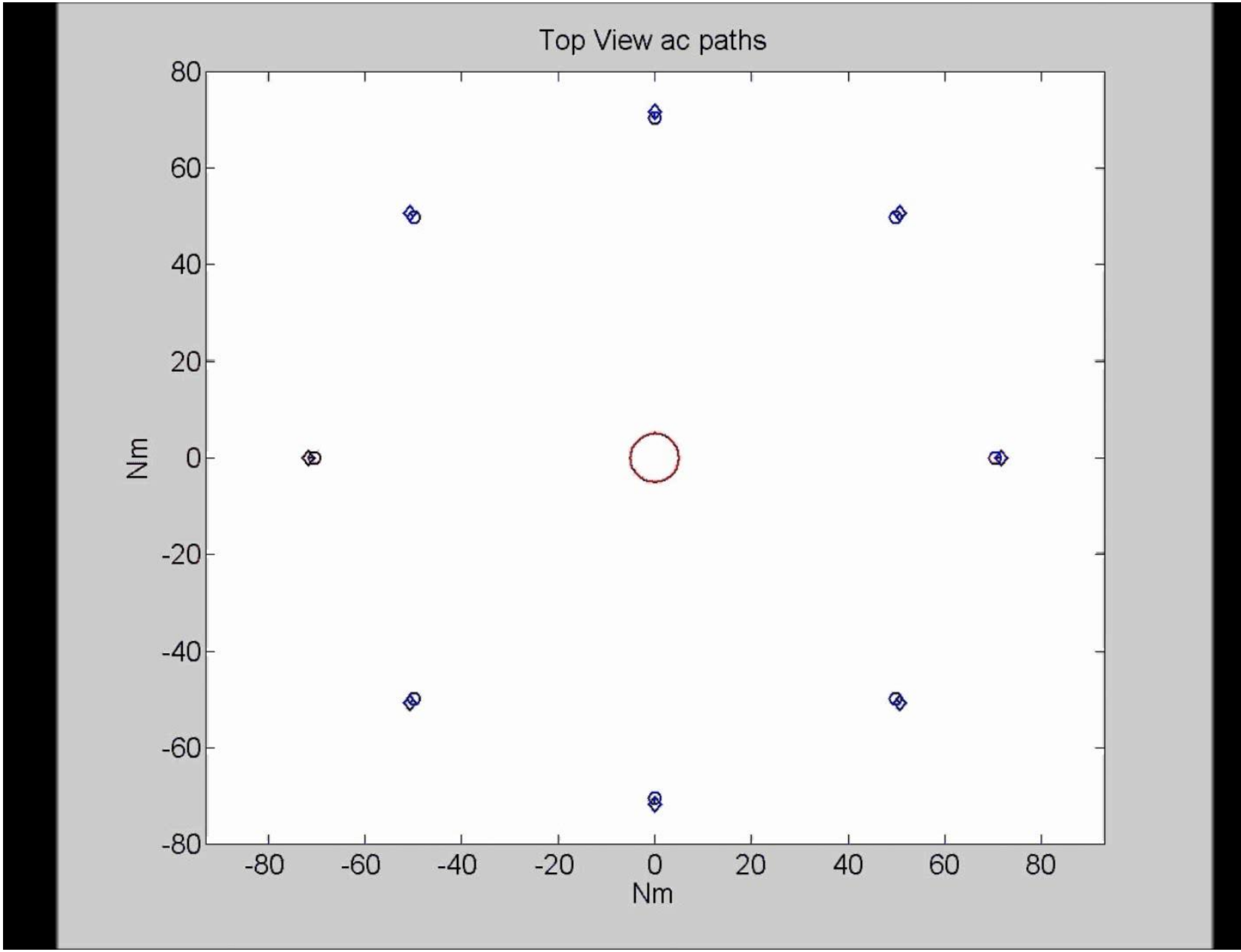
PF = Pilot Flying

PNF = Pilot Non Flying

CNS = Communication, Navigation & Control

AMFF

Run #1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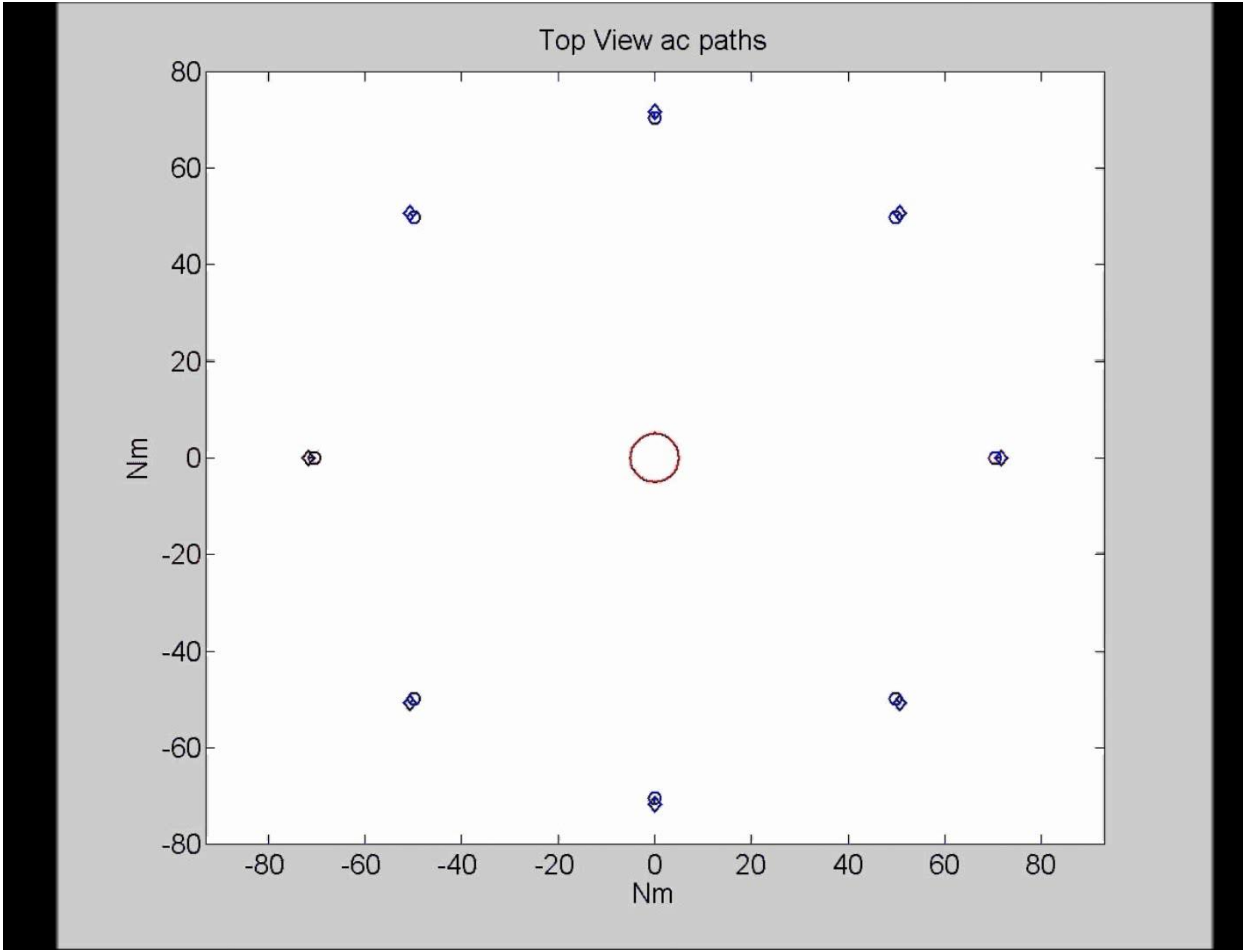
AMFF

Run #2



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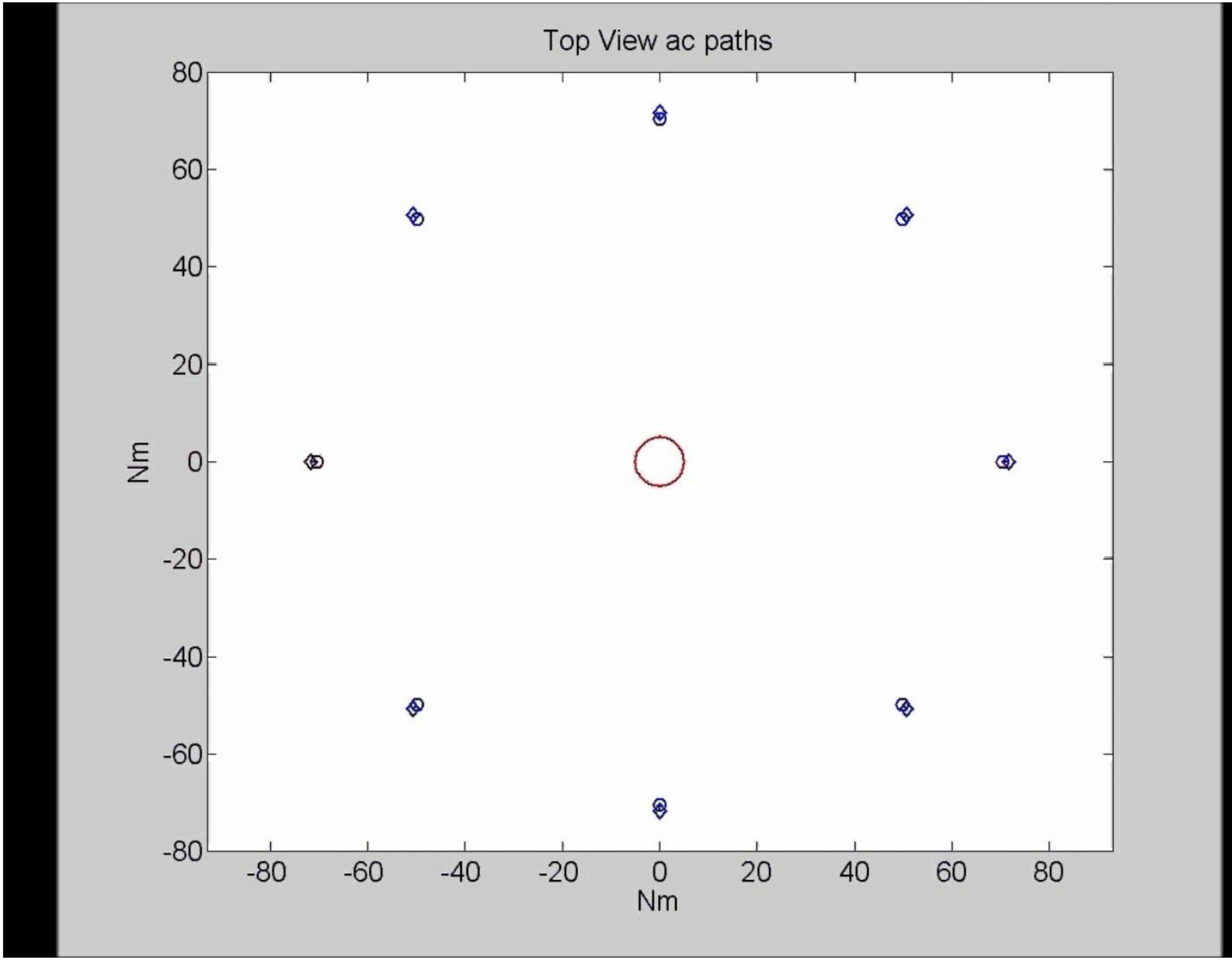
AMFF

Run #3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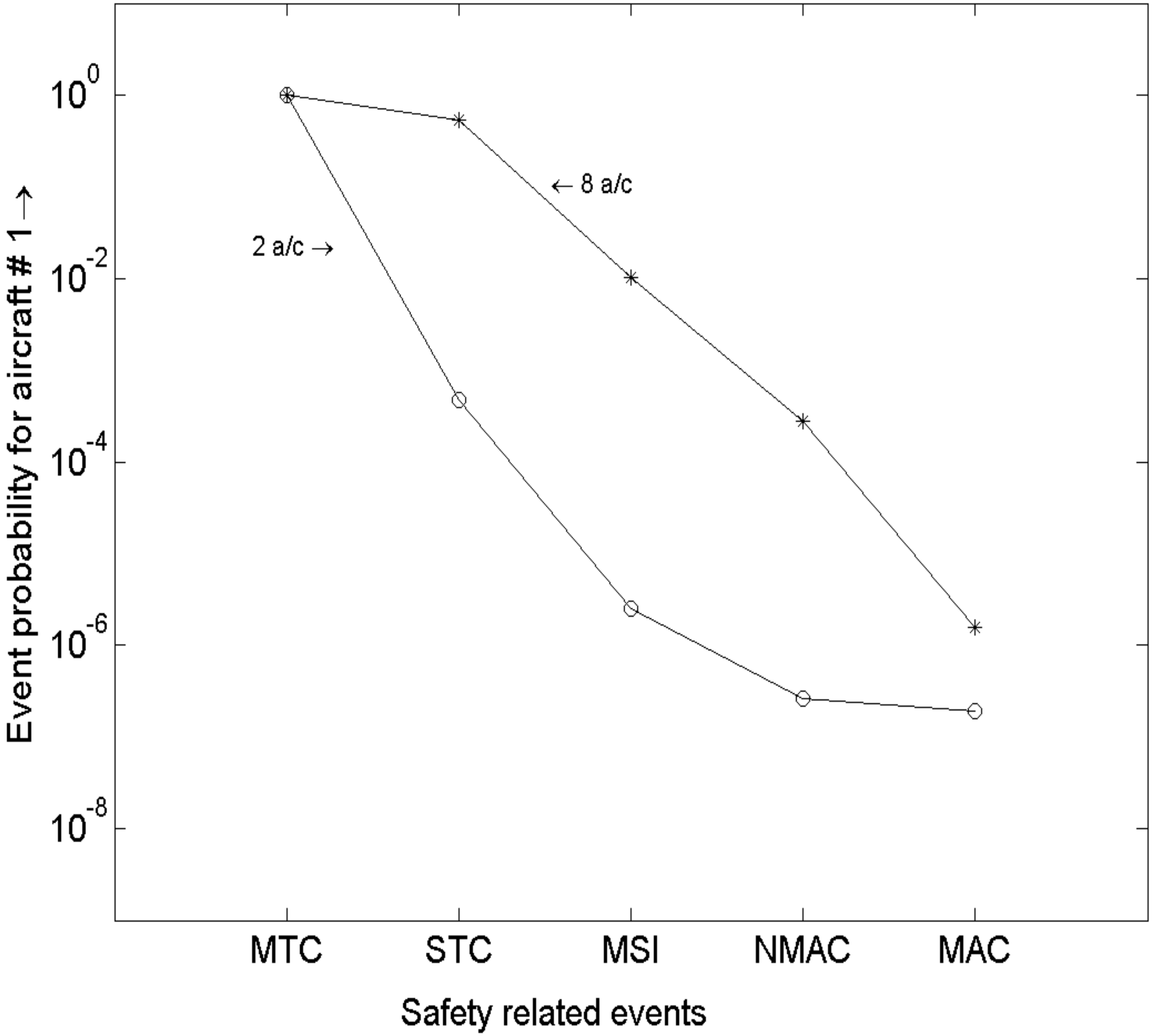
Rare event Monte Carlo Simulation

- Start with N initial traffic scenarios
- Simulate from one conflict level to next conflict level
- Fraction of N scenarios reaches next conflict level
- Multiply fractions of these simulations
- Conditions for convergence [Cerou et al., 2002,2007]
- Systematic way to adhere to these conditions in a stochastic Multi Agent model [Everdij & Blom, 2006]

8 aircraft vs. 2 aircraft encounters under AMFF



MAC = Mid Air Collision

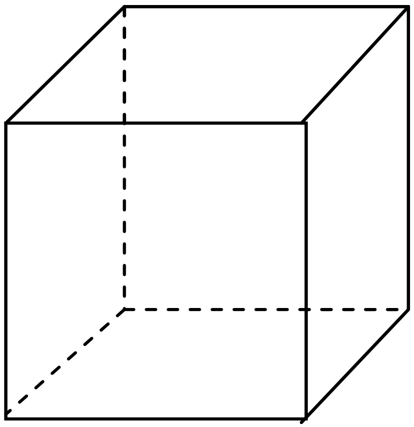
NMAC = Near MAC

MSI = Minimum Separation Infringement

STC = Short Term Conflict

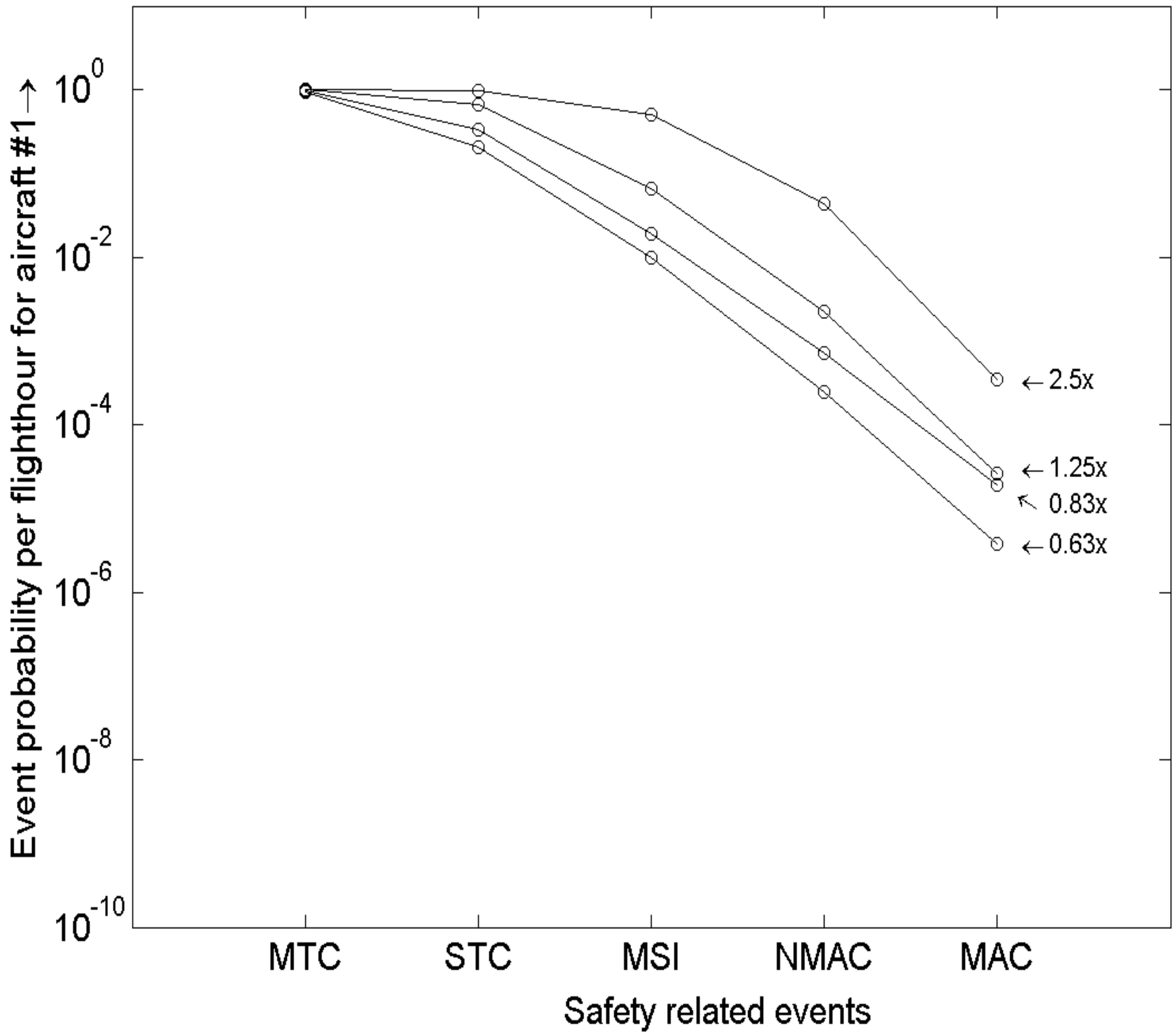
MTC = Medium Term Conflict

Random Traffic Scenarios



- Periodic Boundary Condition
- Eight a/c per packed box/ no climbing or descending a/c
- Varying traffic density by varying the box size
  - 0.63x till 2.5x the en-route density above Frankfurt on 23rd July 1999

High density en-route random traffic under AMFF



Findings for AMFF under very high en route traffic demand

<u>Findings</u>

• Agent Based Safety Risk Analysis [Blom et al., 2009]	–
• Real-time pilot-in-the-loop simulations [Ruigrok and Hoekstra, 2007]	+
• ASAS Requirements Analysis [Klein Obbink et al., 2005]	+

2. AASS [1]

- Much in common with [2], [3]

- Conflict detection and resolution:
  - Takes all aircraft into account
  - Priority based 4D plan (>5 min)
  - Tactical resolution (3-5 min)

- Each aircraft broadcasts its 3D position, 4D plan, and destination to others
- SWIM transfers information over the horizon

[1] Cuevas et al., 2010
[2] NASA, 2003
[3] Wing & Cotton, 2011

RESET and NASA findings regarding separation criteria under very high en route traffic demand

- RESET project findings (2007)
  - TBO spacing should go down from 8 Nm to 5 Nm and Minimum Separation should go down from 5 Nm to 3 Nm in order to accommodate very high en-route traffic demands.

- NASA findings [Consiglio et al., ATM2009]
  - TBO layer can accommodate realistic large wind prediction errors only when the distance between 4D trajectory plans is 8 Nm

- Question: How well is the Tactical decision-making layer able to abridge the difference between the 5 Nm requirement of RESET versus the 8 Nm requirement of NASA ?

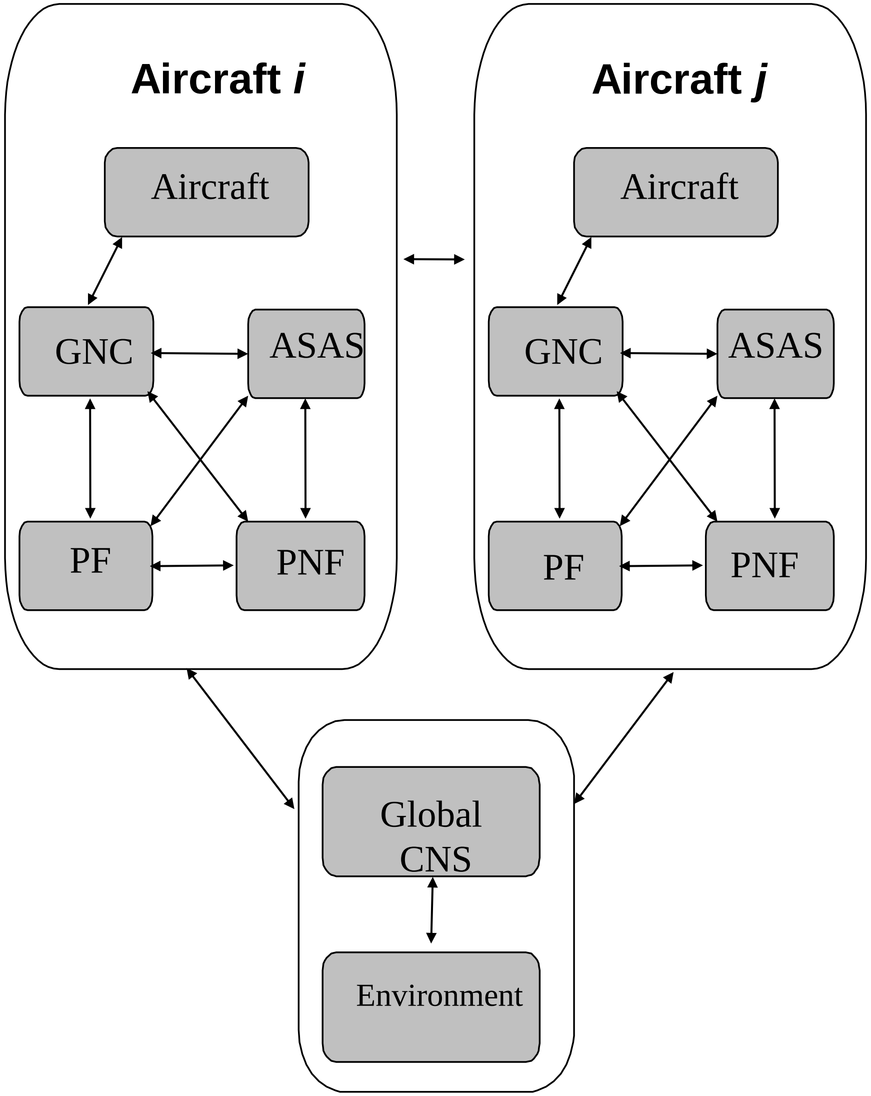
Medium Term CD&R approach

- Each aircraft detects conflicts (5NM/1000ft) 10 min. ahead.
- a/c nearest to destination has priority over other a/c.
- a/c with lowest priority has to make its 4D plan conflict free (15 min ahead) with all other plans.
- However, undershooting of 5Nm/1000ft is better than doing nothing if there is no feasible conflict free plan. It should not create a short term conflict.
- Then, the aircraft broadcasts its non-conflict-free 4D plan together with a message of being “Handicapped” (which is priority increasing).

Short Term CD&R approach

- a/c which detects conflict is obliged to resolve the conflict without awaiting any of the other aircraft.
- Course change is identified using Velocity Obstacles (3 min. ahead).
- Conflict free means 3Nm/900ft minimal predicted miss distance.
- However, undershooting of these values is better than doing nothing if there is no feasible alternative.
- Then, the a/c broadcasts its new course or rate of climb/descend.

Agent Based Model of Airborne Self Separation TBO



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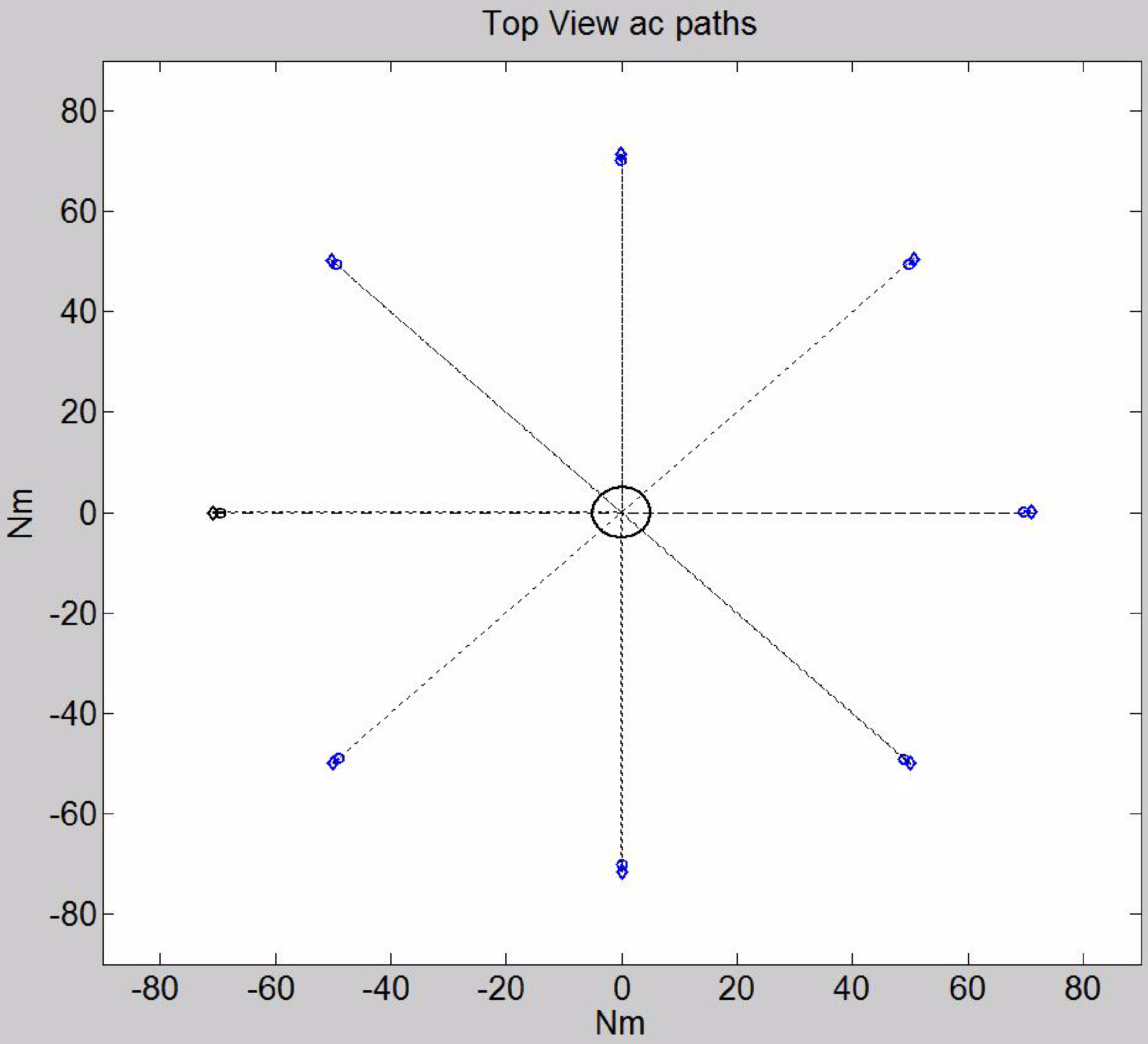
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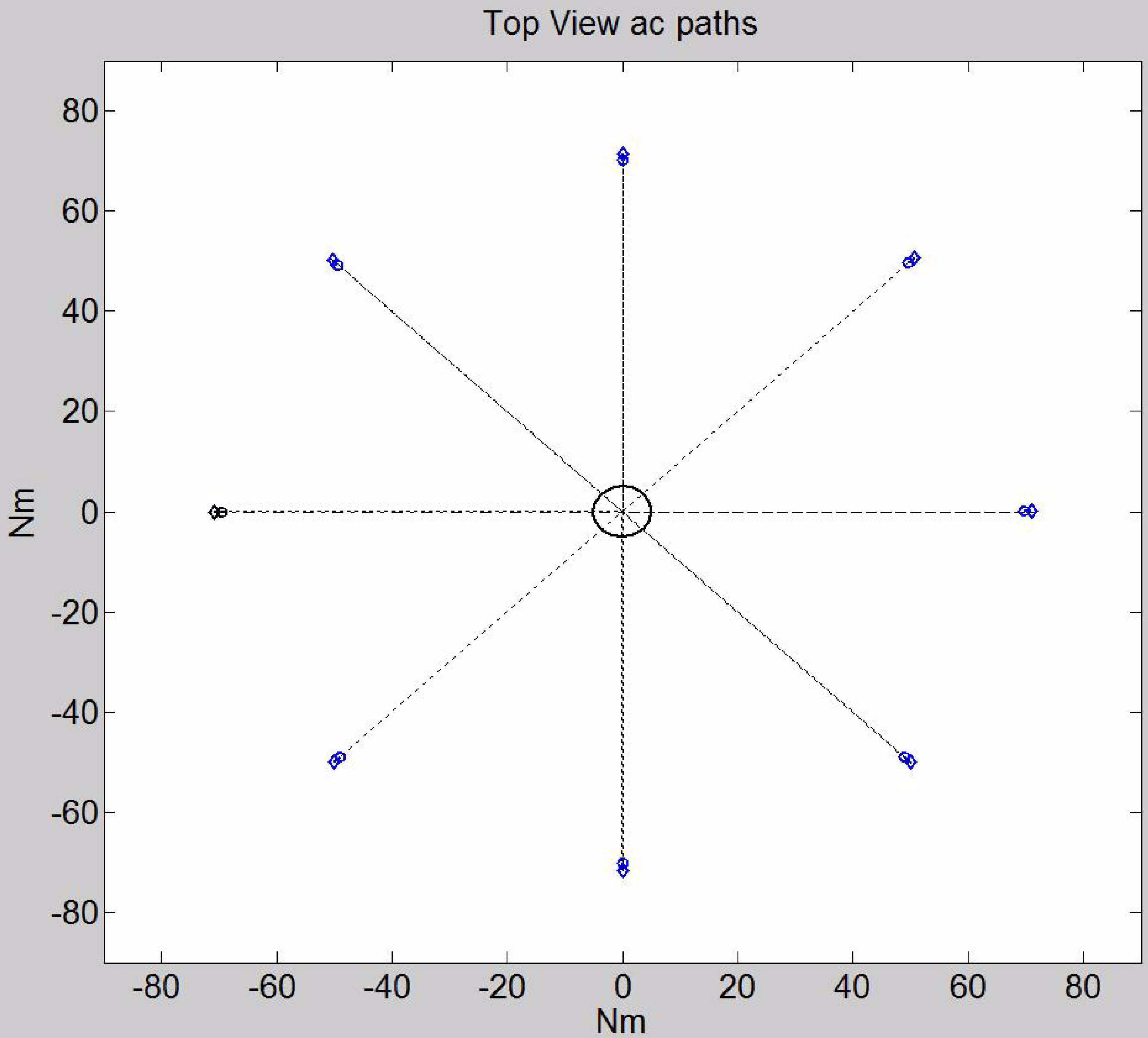
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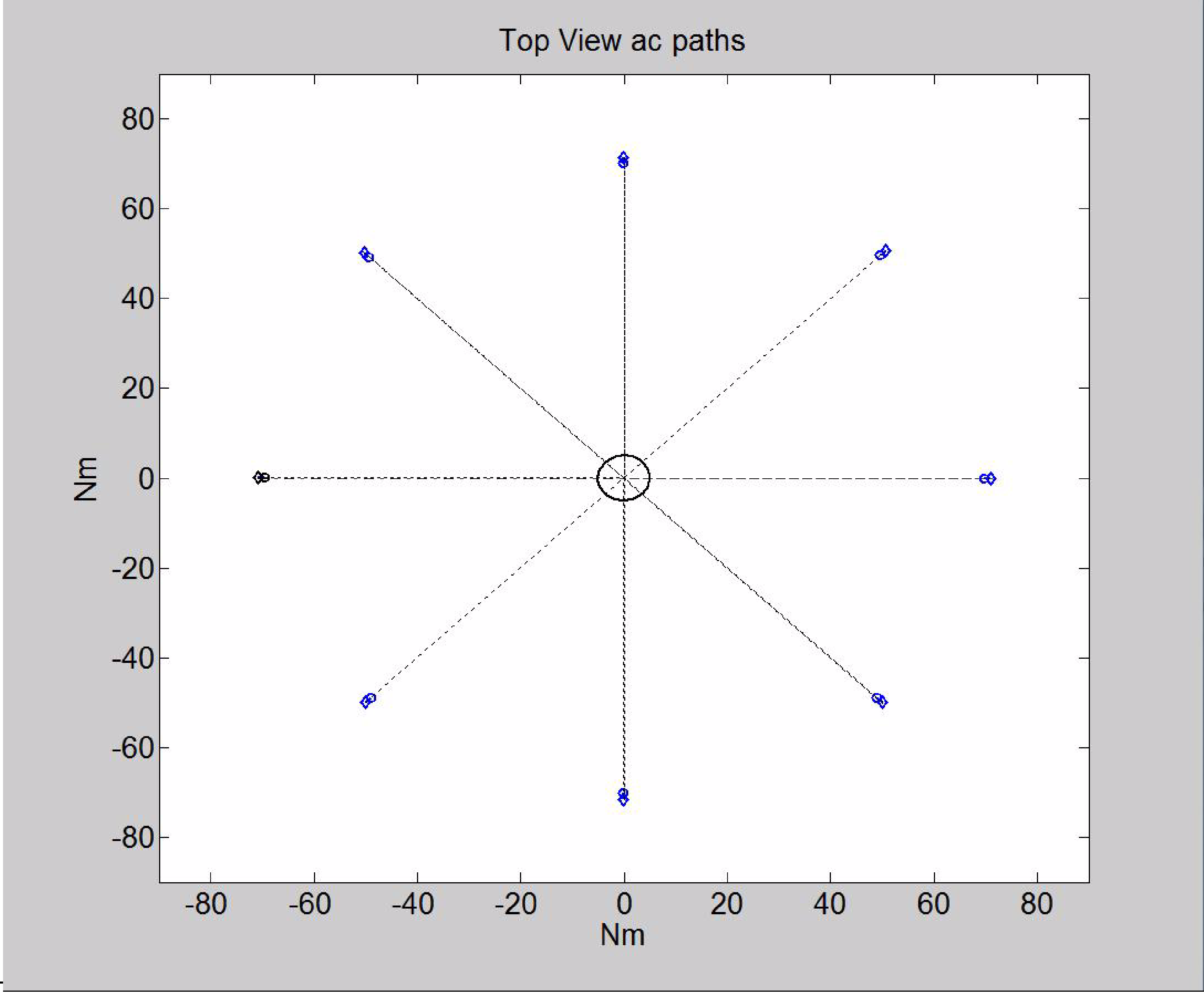
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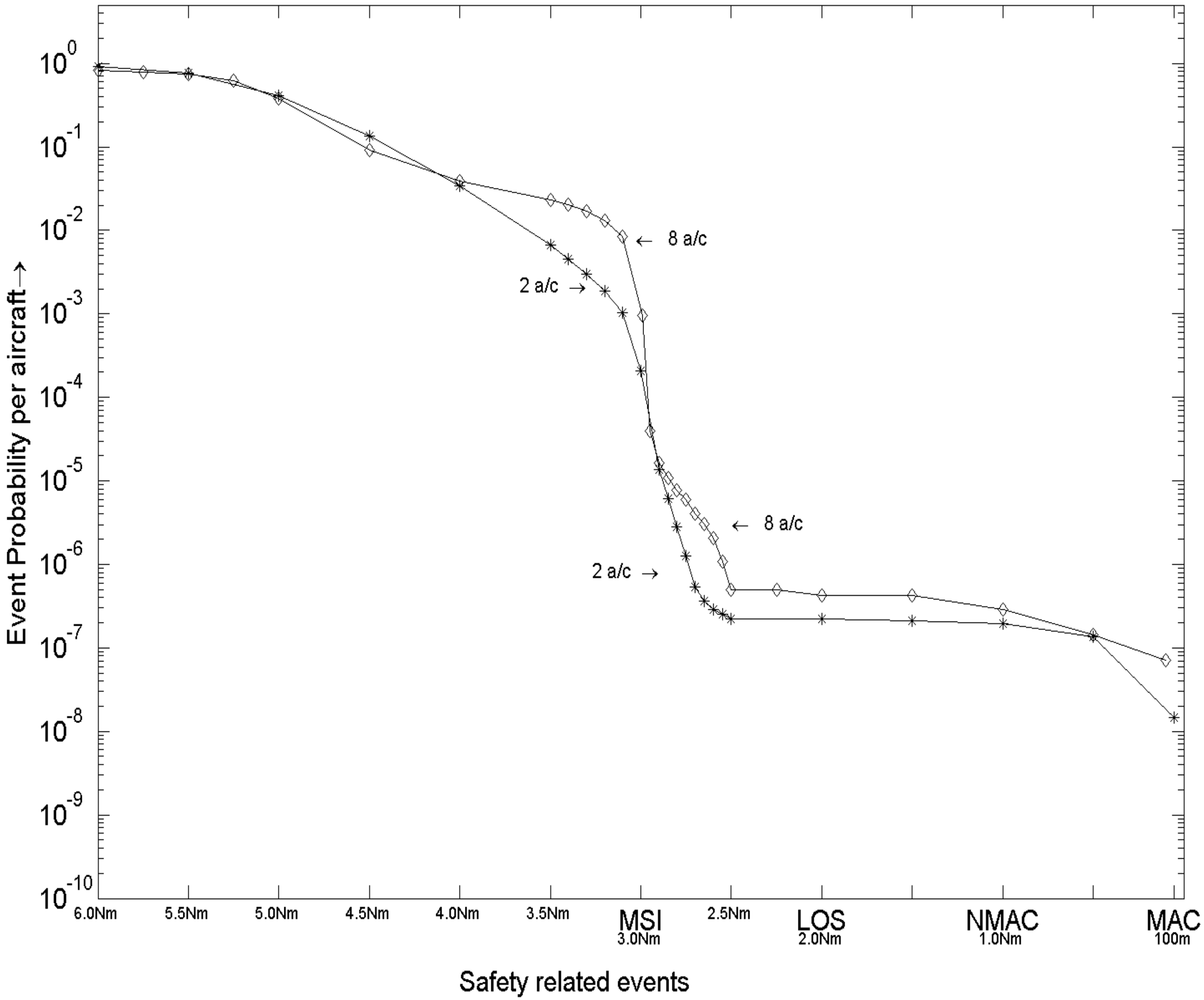
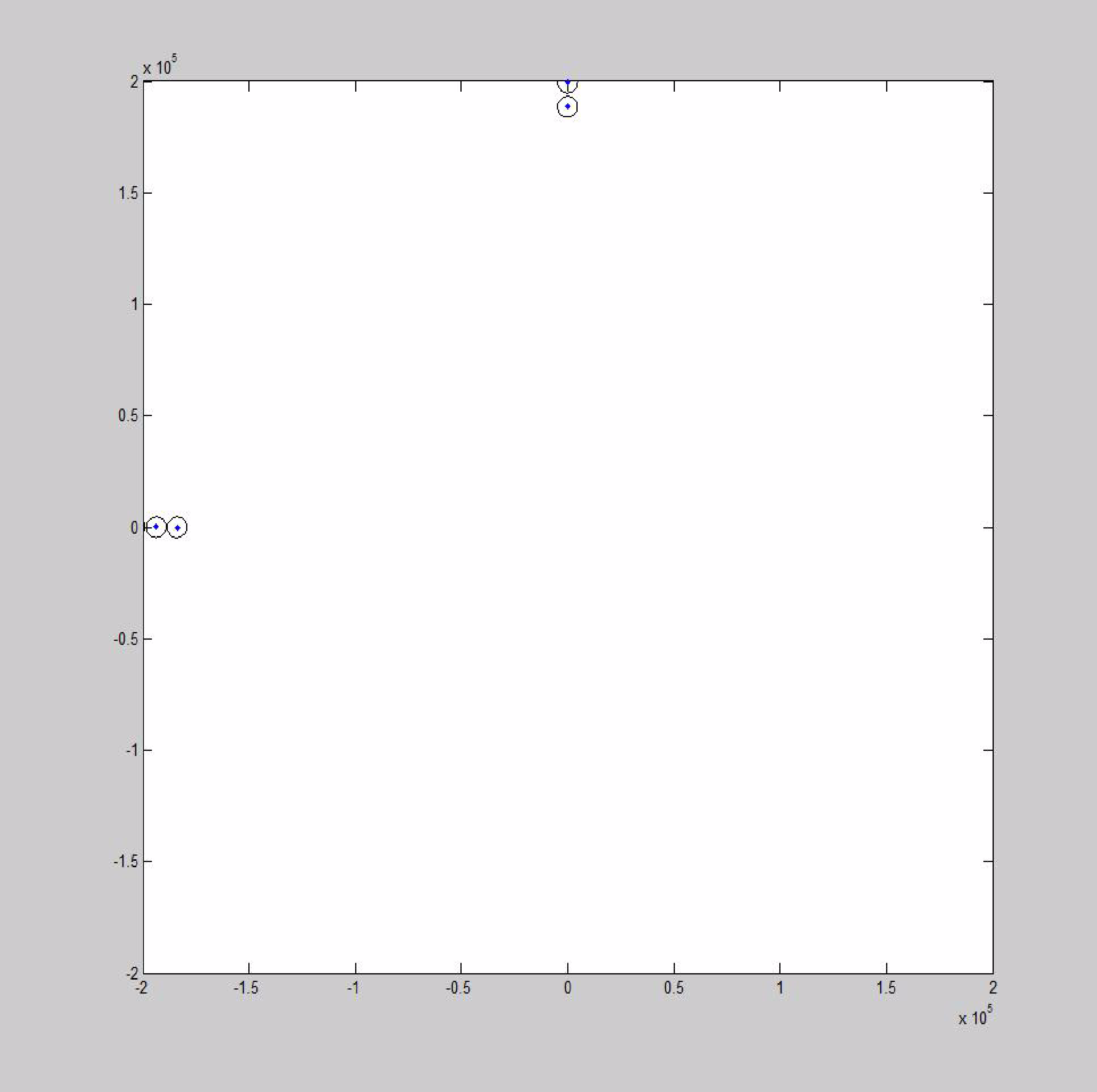
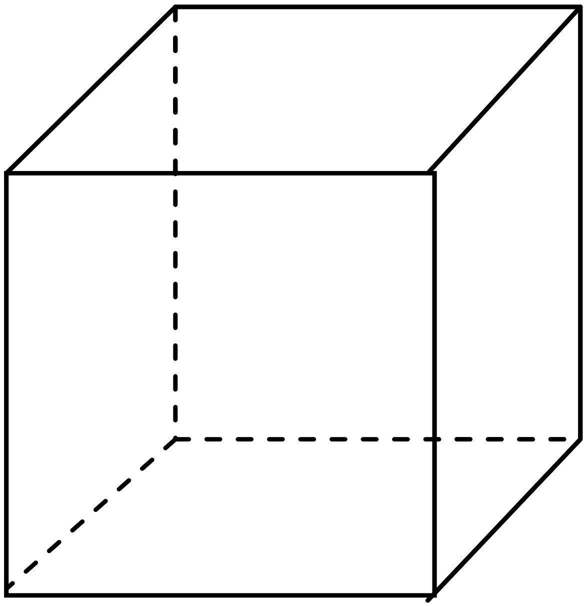
8 a/c versus 2 a/c



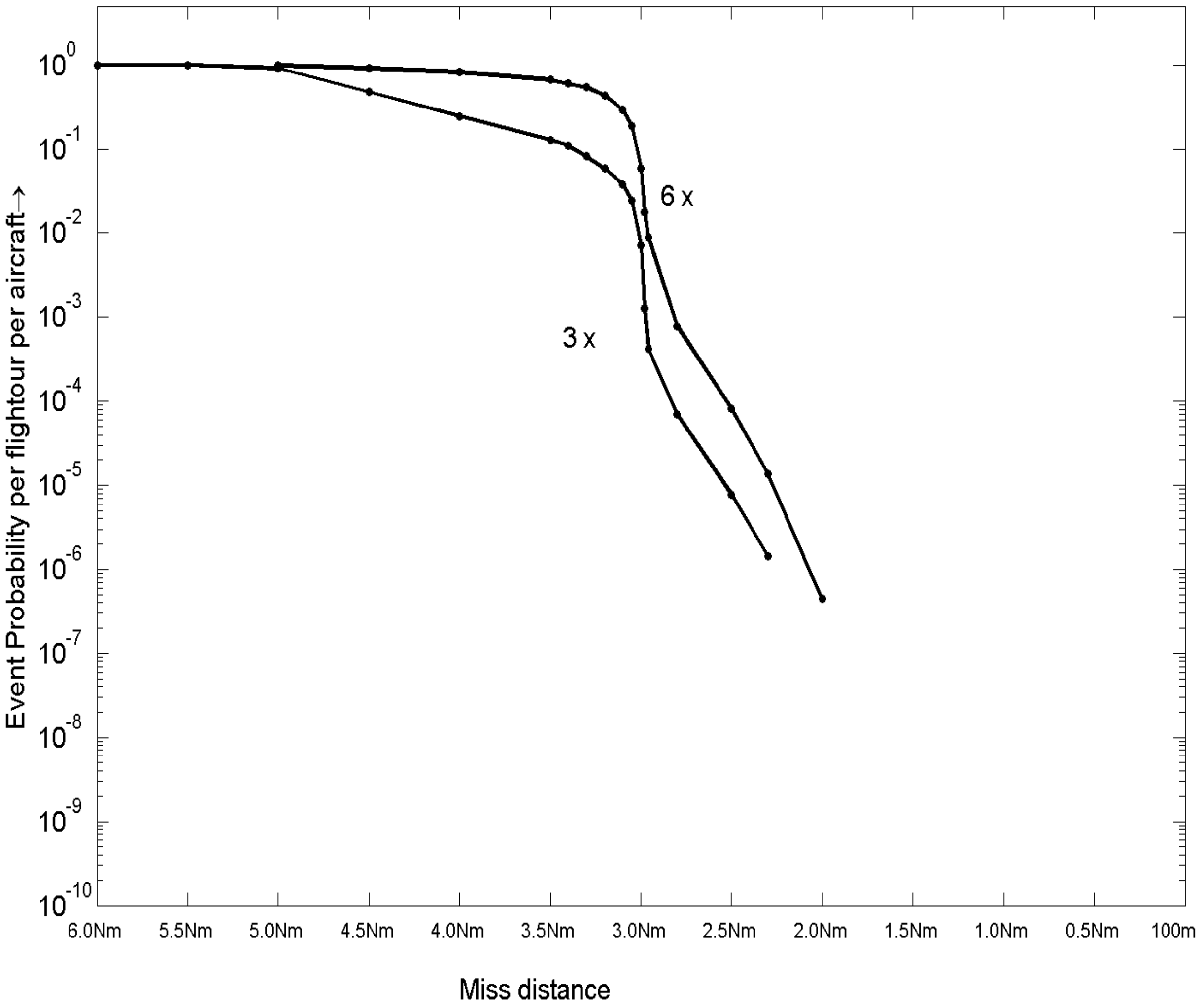
Two crossing traffic flows



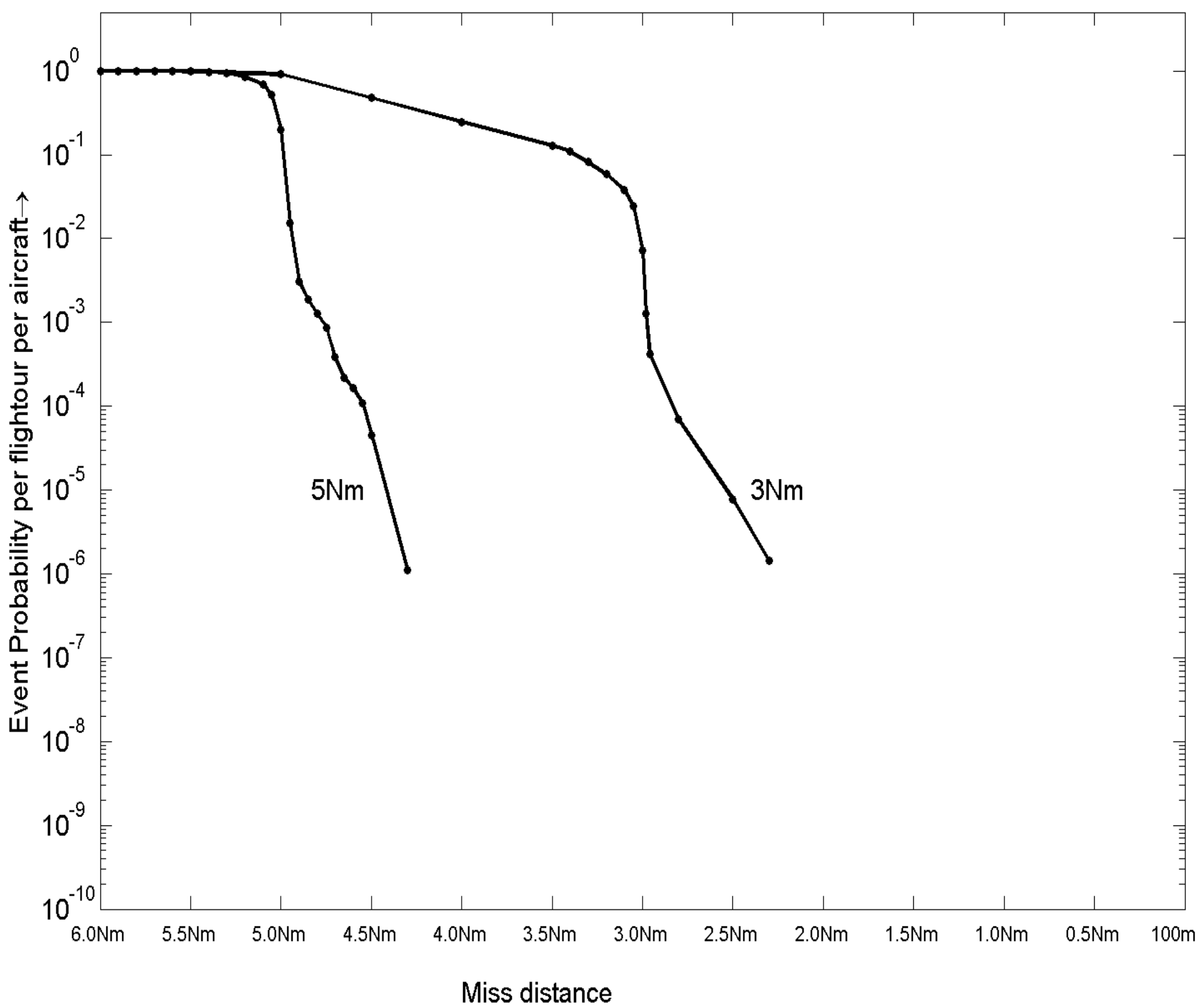


- Periodic Boundary Condition
- Eight a/c per packed box/ no climbing or descending a/c
- Vary container size in order to simulate:
    - 3x as dense as high density area in 2005
    - 6x as dense as high density area in 2005

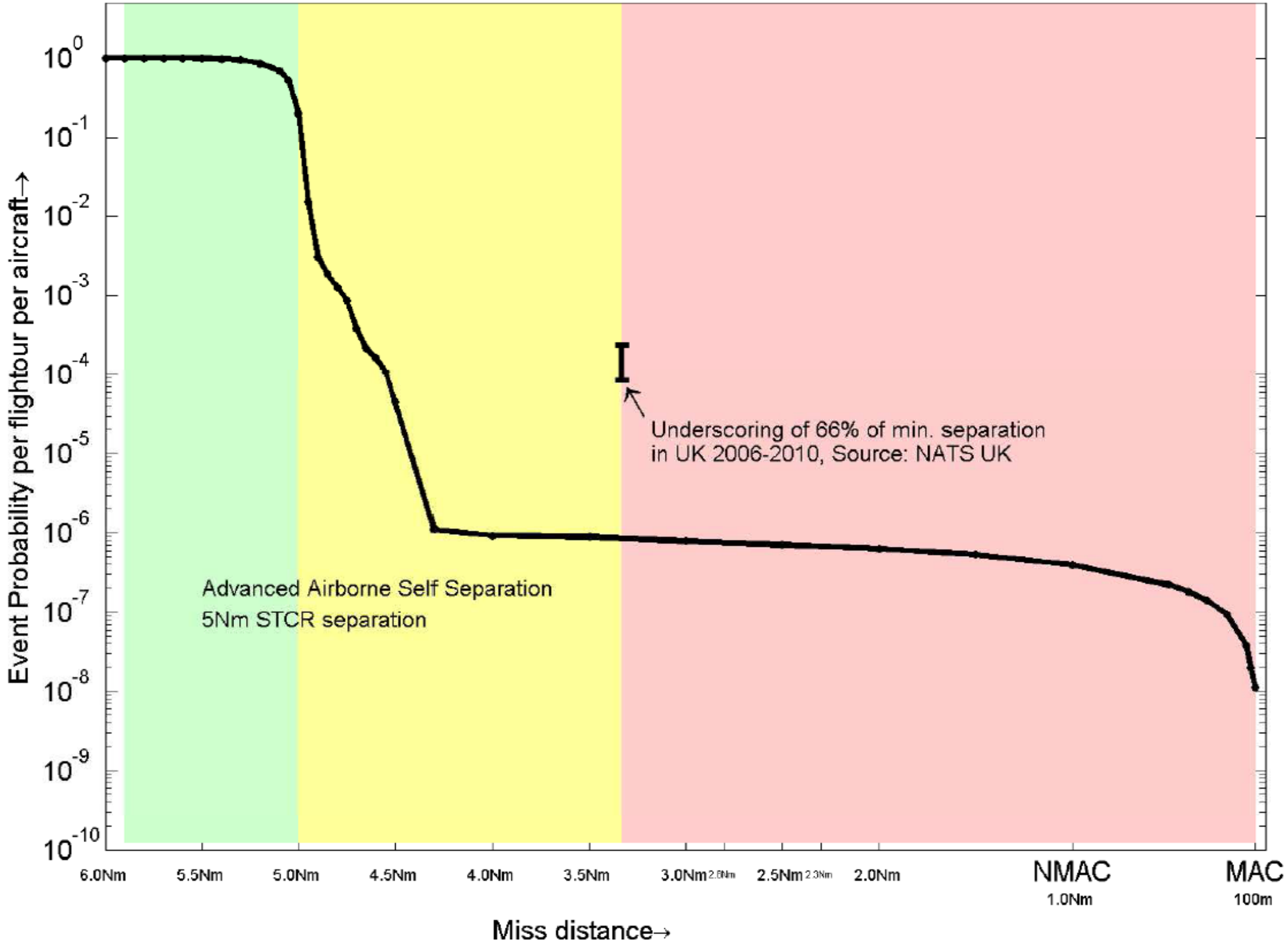
Very High Random Traffic Demand (3x and 6x 2005)



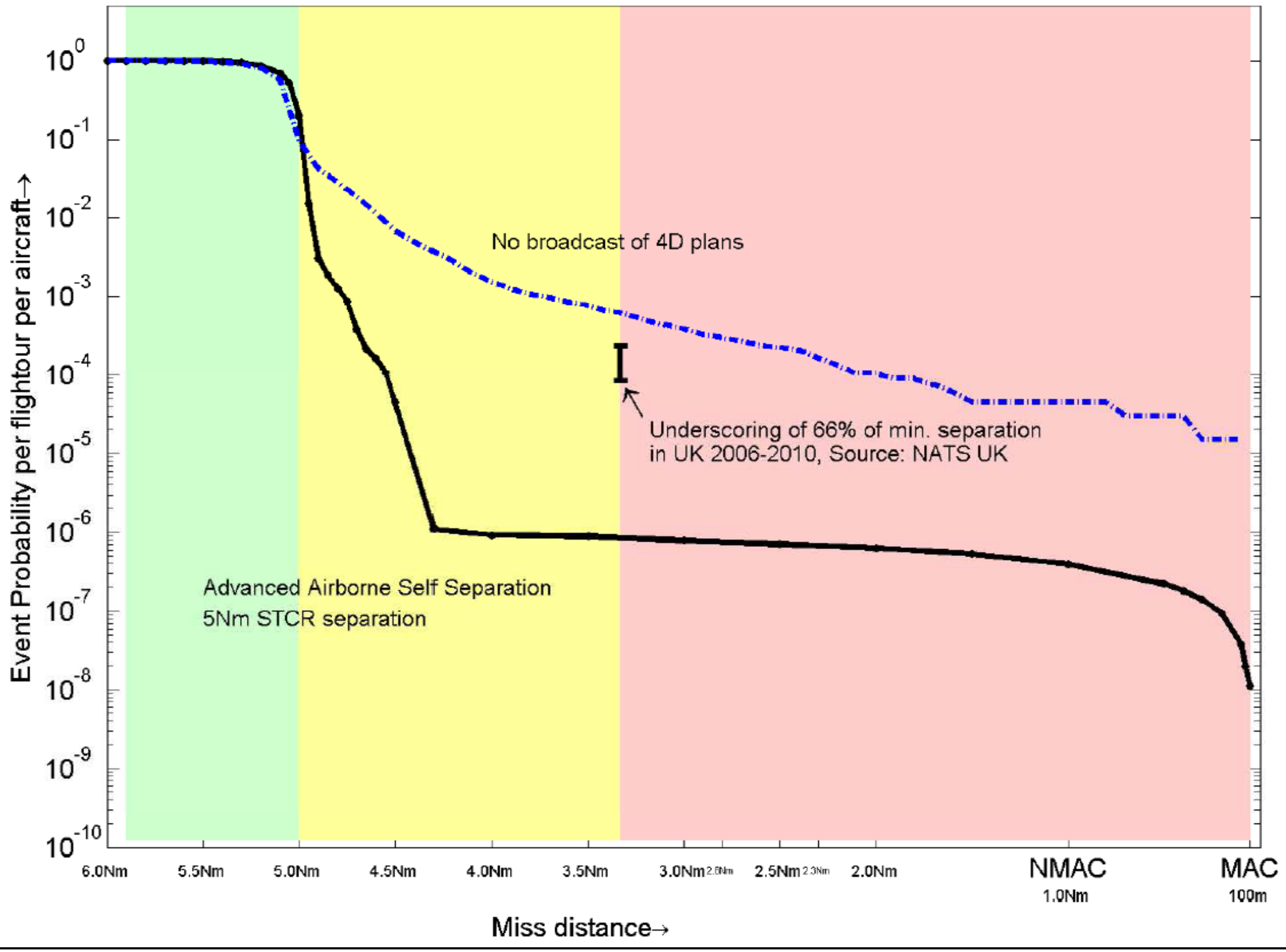
3x 2005: 5Nm vs. 3Nm tactical separation minimum



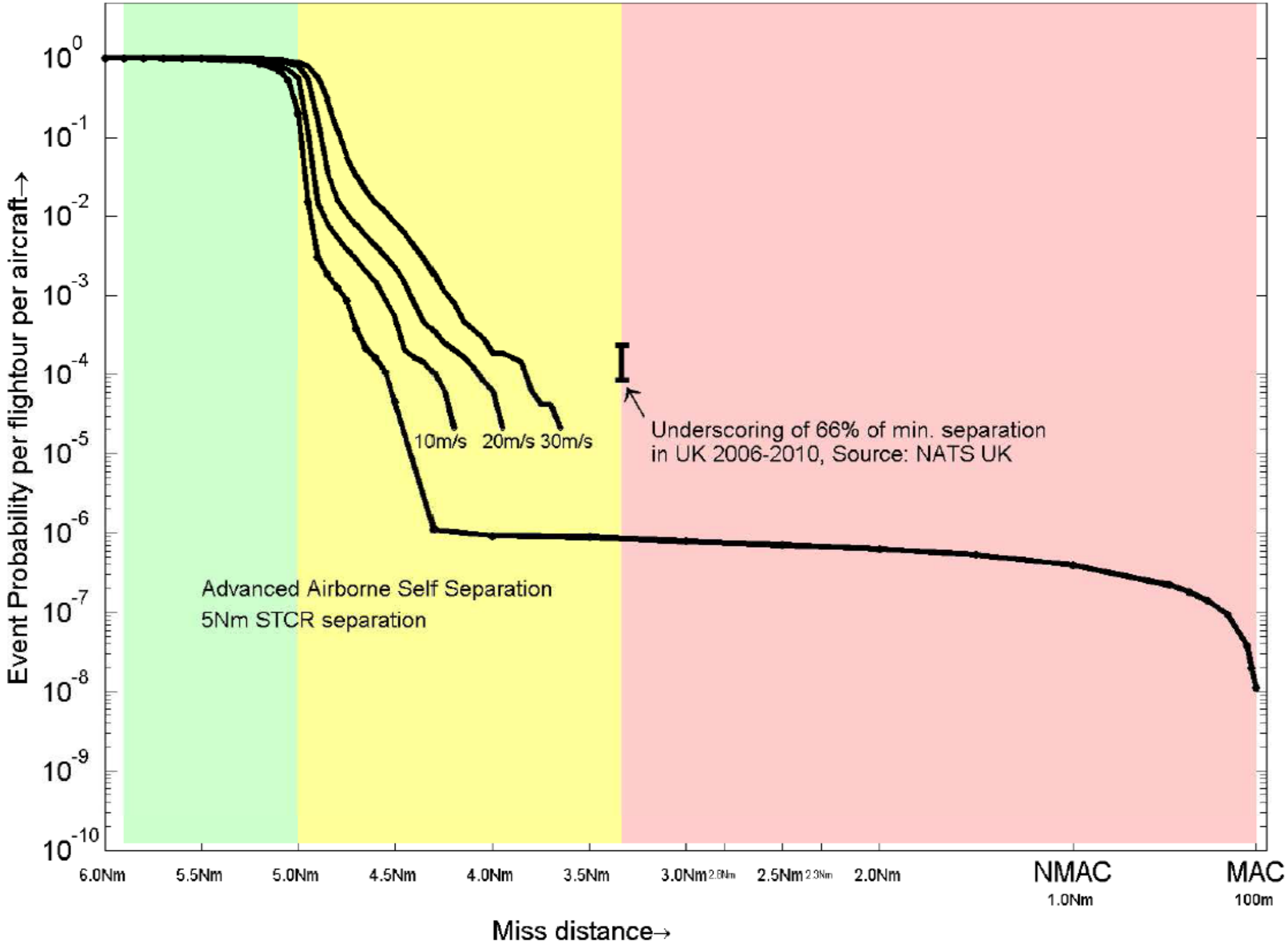
3x 2005 high random traffic and 5NM



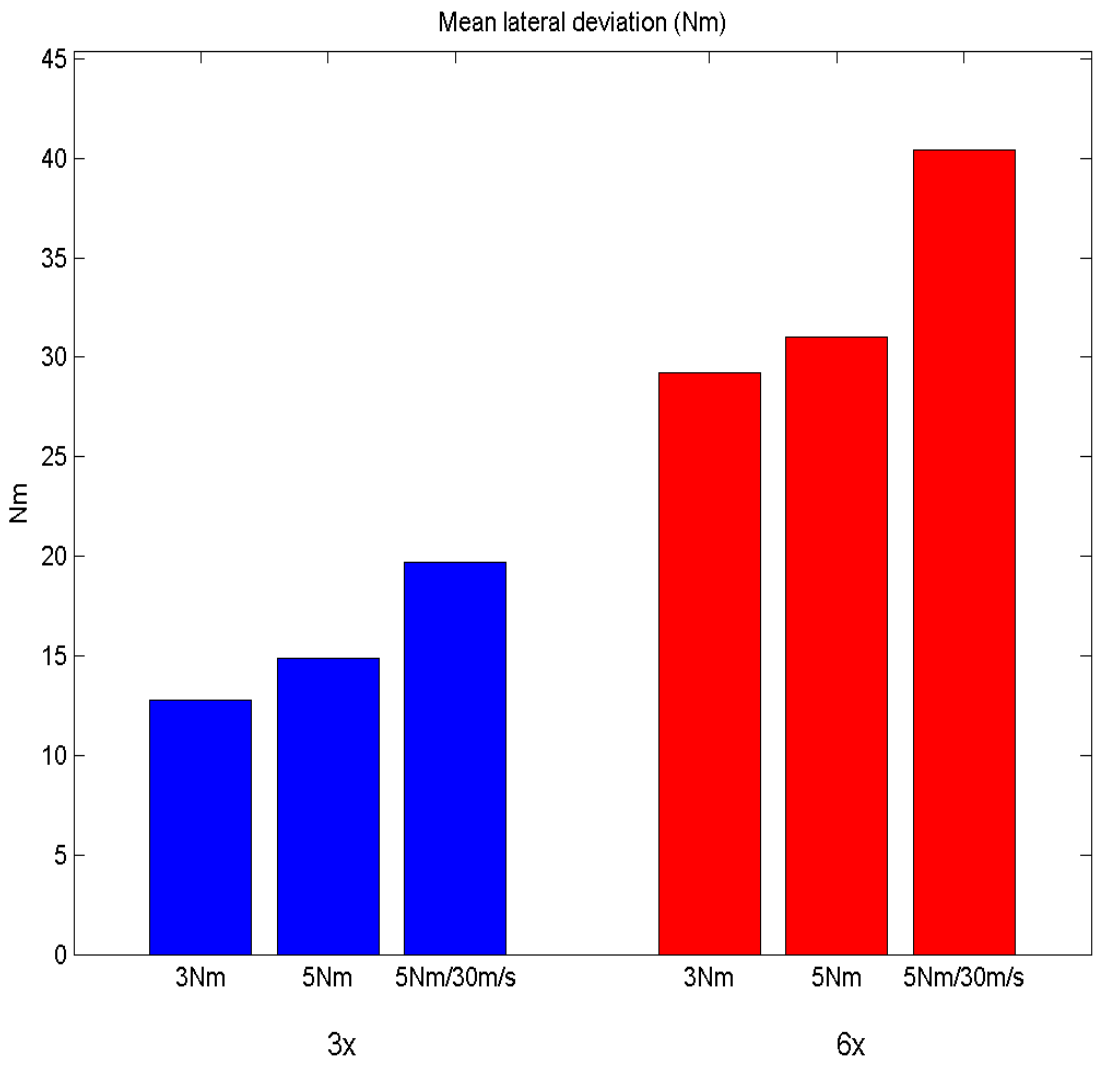
4D plans not broadcasted



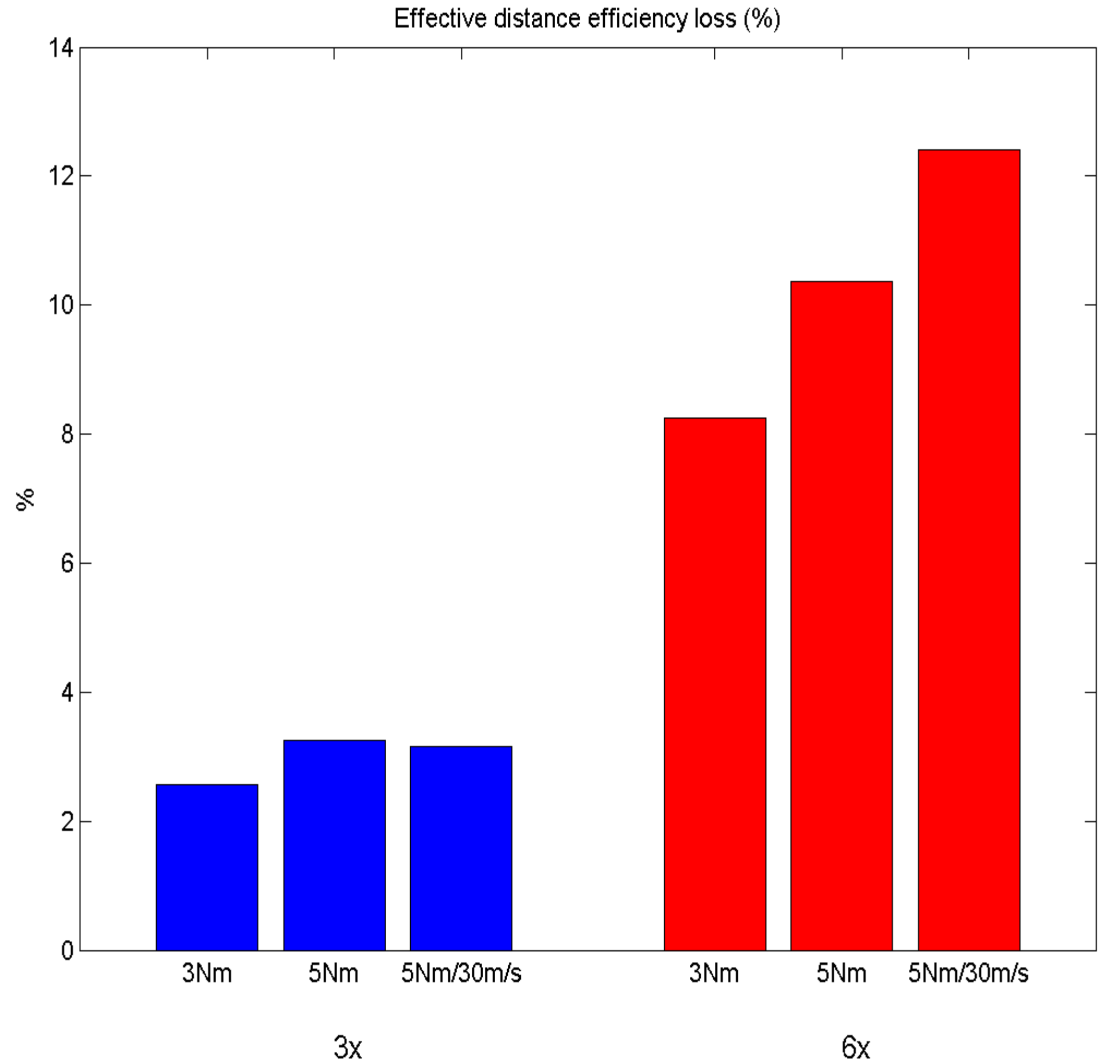
Systematic wind errors 10, 20, 30 m/s



Mean absolute value of lateral deviation



Mean loss in effective distance travelled



Findings for AASS under very high en route traffic demand

	Findings
• Agent Based Safety Risk Analysis [Blom & Bakker, 2012]	+
• Real-time pilot-in-the-loop simulations [Consiglio et al. , 2010]	+
• ASAS Requirements Analysis [Casek & Romani, 2011]	+

These findings decide the dispute between the two schools of researchers in favour of the believers !

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Conclusions

- ATM is a complex socio-technical system which cannot escape from emergent behaviours;
- Emergent behaviour that is not well understood is likely to have a negative impact.
- ATM design can benefit from identifying emergent behaviour: adopting the positive, and mitigating the negative;
- Agent Based Modelling and Simulation (ABMS) and Network Flow approaches have a proven records for this;
- Handshake with mathematical tools allows extension of ABMS to agent-based safety risk analysis;
- Application to Free Flight designs has revealed formerly unknown emergent behaviours; both negative and positive;
- Feedback of findings to Free Flight design team allowed to strengthen the positive and mitigate the negative emergent behaviours.

Positive Emergent Behaviours/Properties Identified

1. A proper tactical conflict detection and resolution layer makes it possible for the pilot to resolve tactical situations under which its 4D trajectory plan has lost the conflict-free quality.

2. There appears to be no need to keep centerlines of conflict-free 4D plans further away from each other than the tactical separation minimum; hence both can be 5 Nm

3. In addition to safely accommodating 3x busy en-route 2005 traffic demand flight efficiency is OK, and detoriates in a gradual way above this demand level; i.e. no nearby phase transition !

Follow up: EMERGIA project; SESAR WP-E In search of positive emergent behaviour

1. Develop an ATM ground based version of the AASS model

2. Evaluate and compare the emergent behaviours of this novel model (100% TBO equipped aircraft) with those found for the AASS model

3. Inform an ATM design team of these outcomes, and let them develop an improved ATM design (100% TBO equipped aircraft)

4. Develop an agent-based stochastic model of this improved ATM design, evaluate it on emergent behaviours and compare this with the results for AASS and for the novel model under 2

Findings are expected to support development of a suitable transition path from 0% TBO equipped aircraft to 100% TBO equipped aircraft situation.