Using Complexity Science in Analyzing Safety/Capacity of ATM Designs
Tutorial, Part 2

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Using Complexity Science in Analyzing Safety/Capacity of ATM Designs

- Motivation and background
- Complexity Science methods Part 1
- <u>Complexity Science methods Part 2</u>

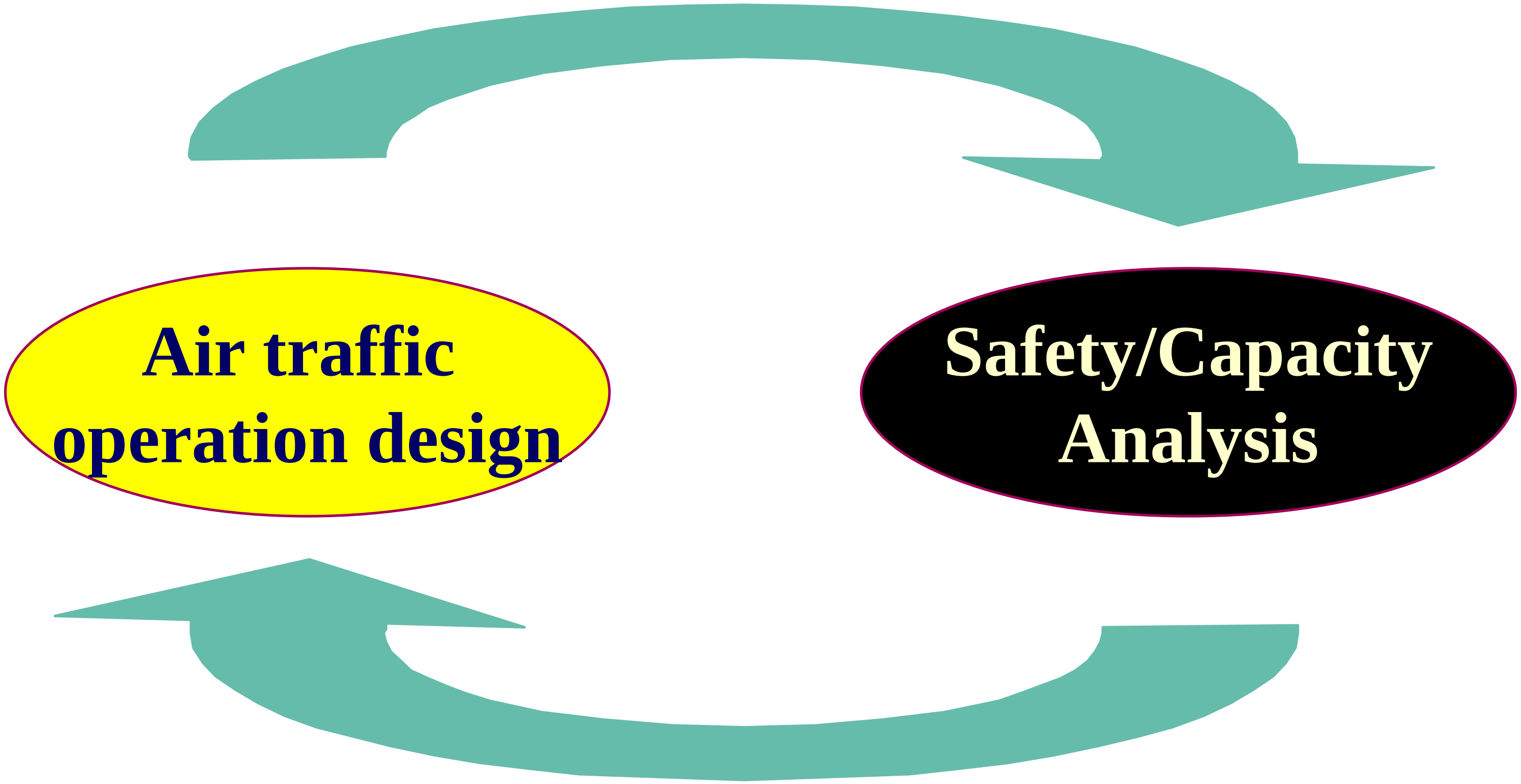
Key Free Flight Research Question

- Free Flight (or Airborne Self Separation) has been "invented" as a potential solution for high traffic demand airspace

- ATM community research trend has been to direct Airborne Self Separation research to situations of less demanding airspace (where mid-air safety risk is coming from pairwise encounters only)

- Key research question: Up to which traffic demand can Free Flight be designed sufficiently safe ?

Safety/capacity analysis feedback to future ATM design



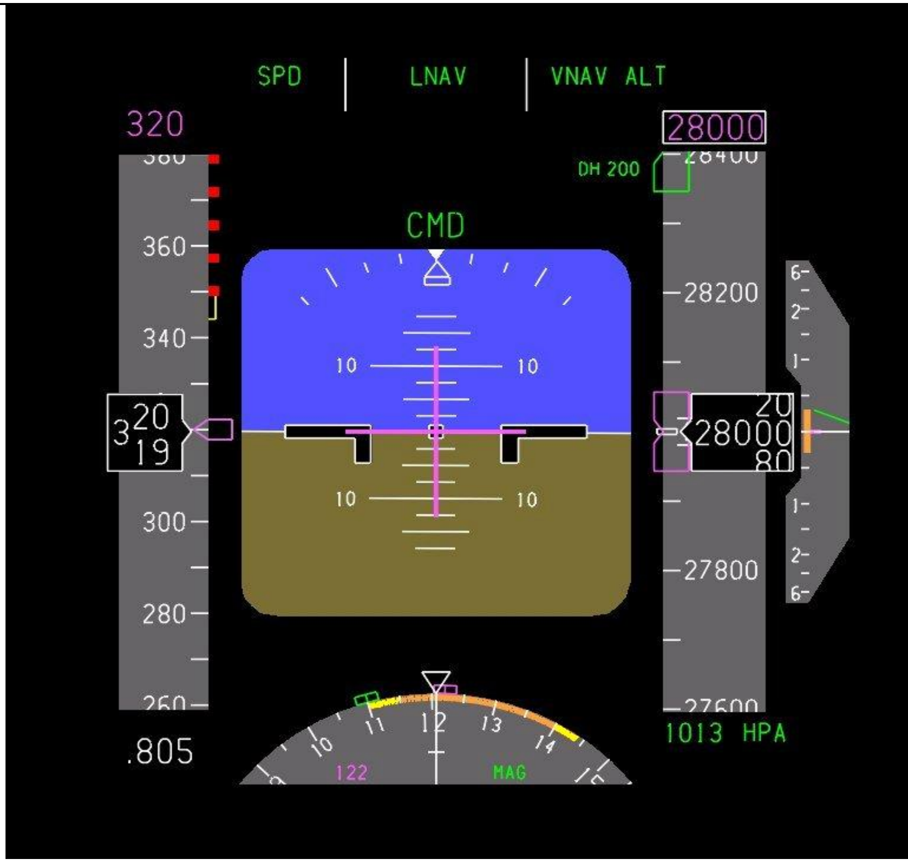
Tutorial Part 2

- Autonomous Mediterranean Free Flight (AMFF)
- Probabilistic Reachability Analysis
- Results for AMFF
- Advanced Airborne Self Separation (AASS)
- Results for AASS

Autonomous Mediterranean Free Flight (AMFF)

- Future concept developed for traffic over Mediterranean area
- Aircrew gets freedom to select path and speed
- In return aircrew is responsible for self-separation
- Aircraft broadcast their states without delay to other aicraft
- Each a/c equipped with an Airborne Separation Assistance System
- In AMFF, conflicts are resolved one by one (pilot preference)
  - Medium term: priority a/c does nothing
  - Short term: both aircraft resolve conflict

NLR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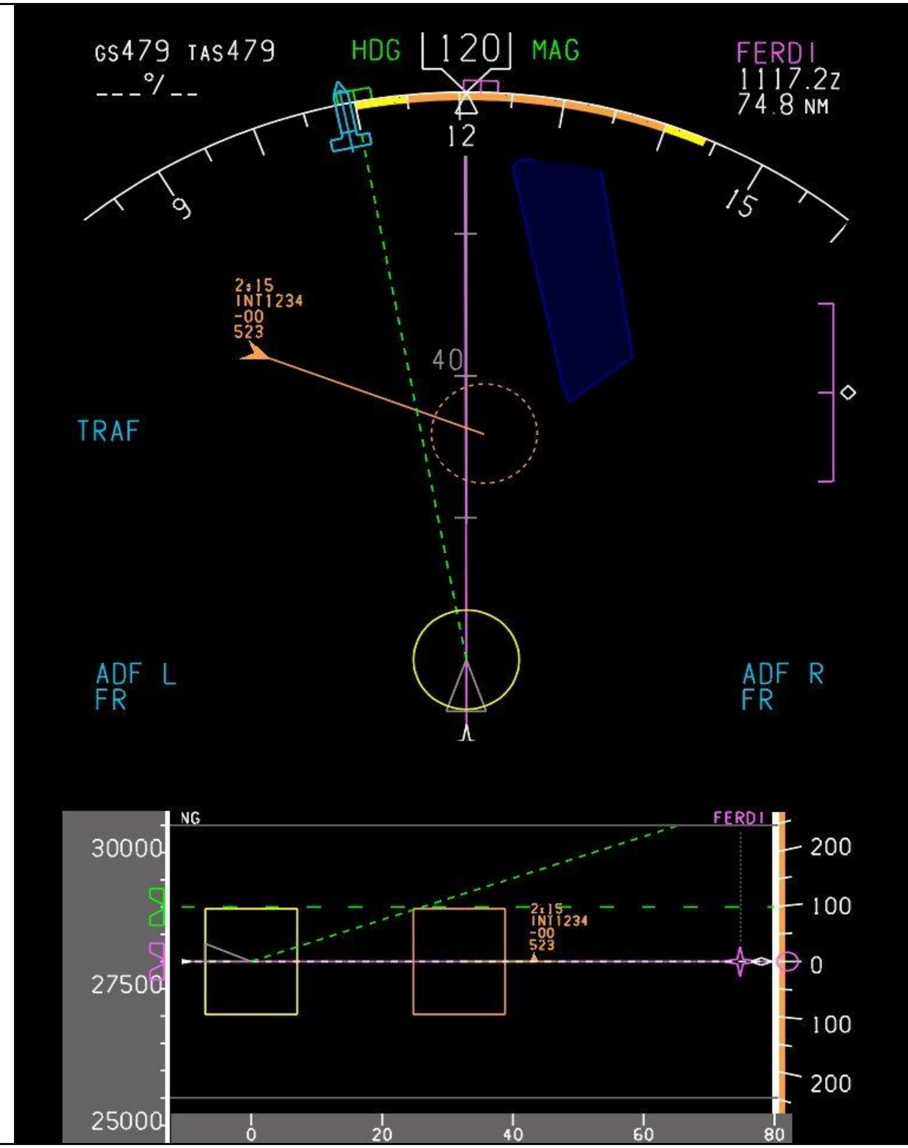
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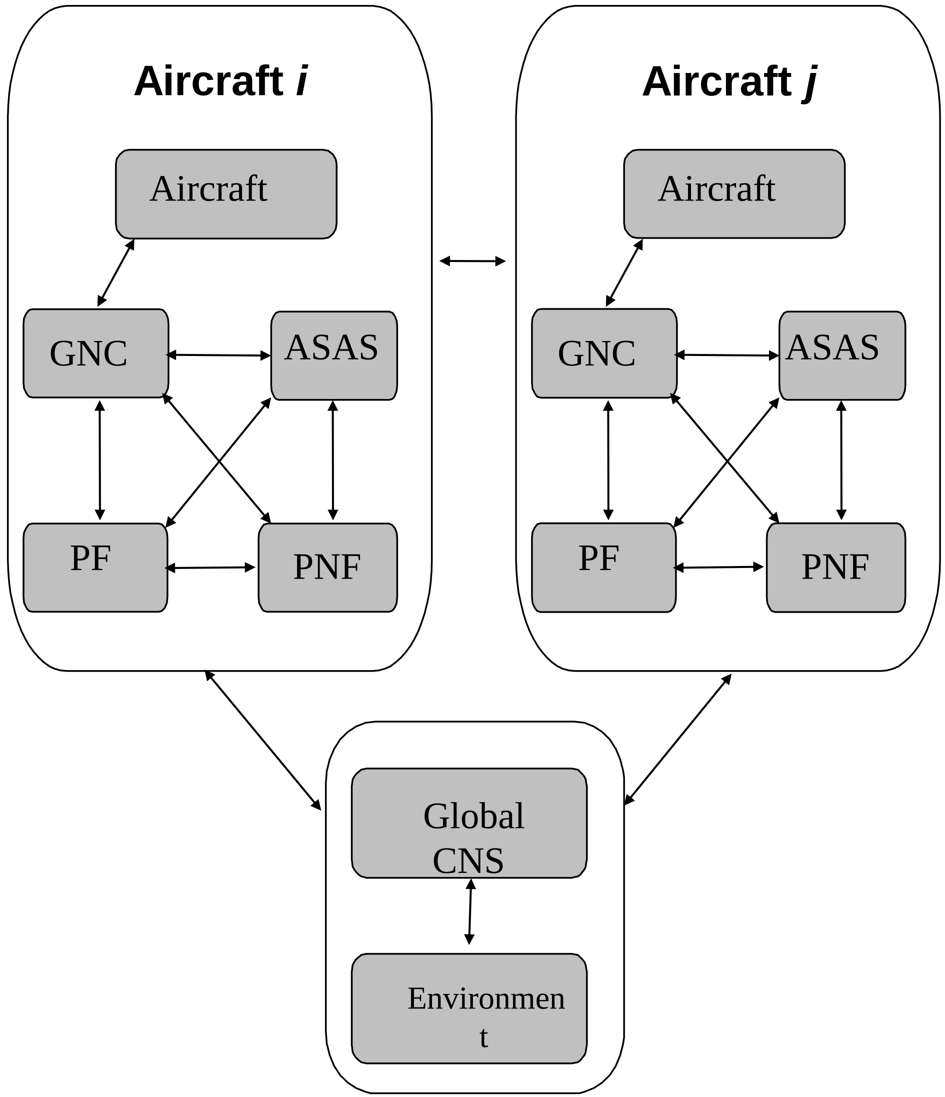
Evaluations performed for AMFF concept

- Real-time pilot-in-the-loop evaluations
- Eurocae/RTCA ED78a safety assessment

Development of Agent Based Model

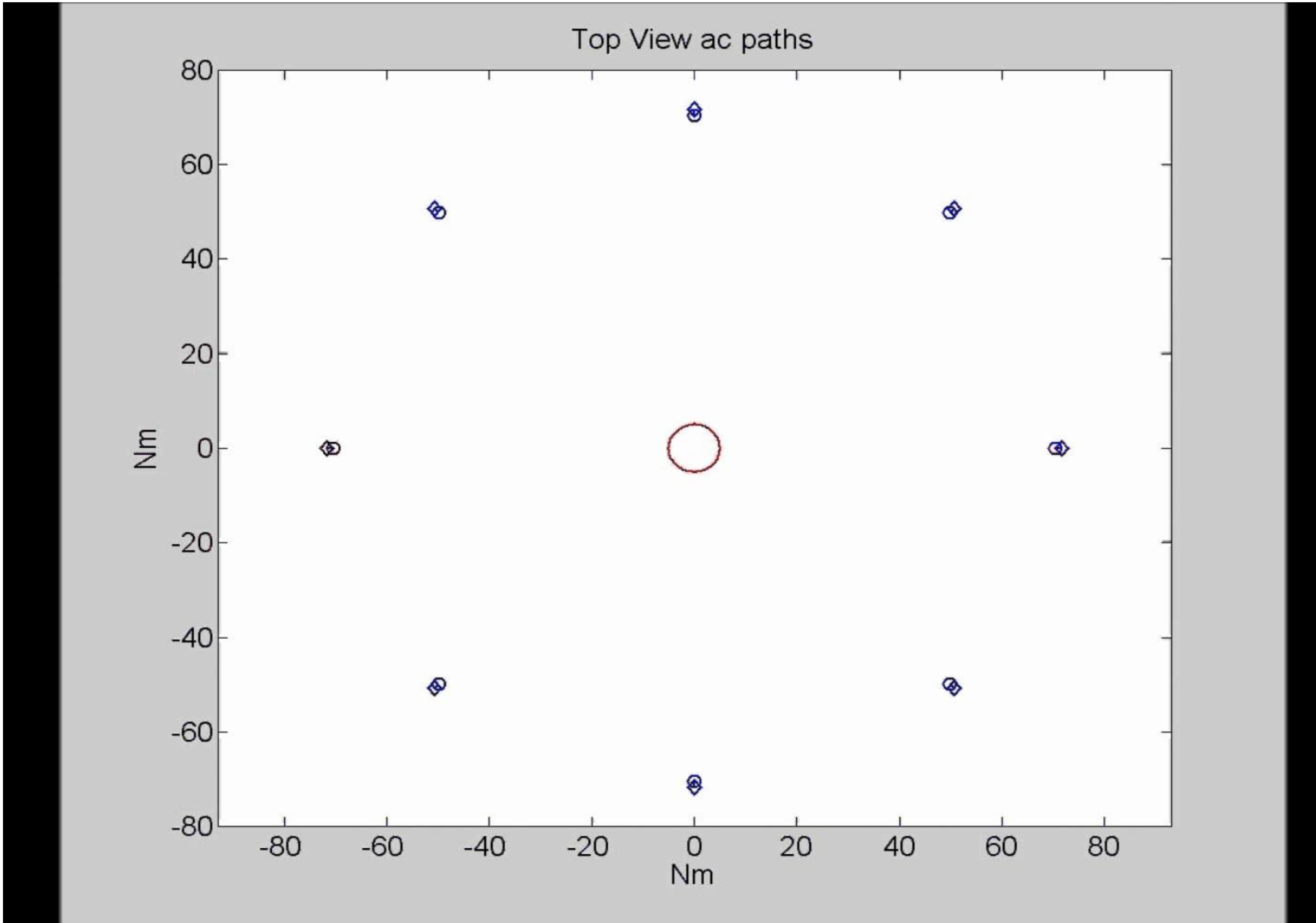
- Defining the relevant Agents
- Hazard identification
- Developing Petri net for each Agent
- Connecting Agent Petri nets
- Generate Monte Carlo simulation model
- Parametrization, Verification & Calibration

Agents in AMFF



AMFF

Run #1



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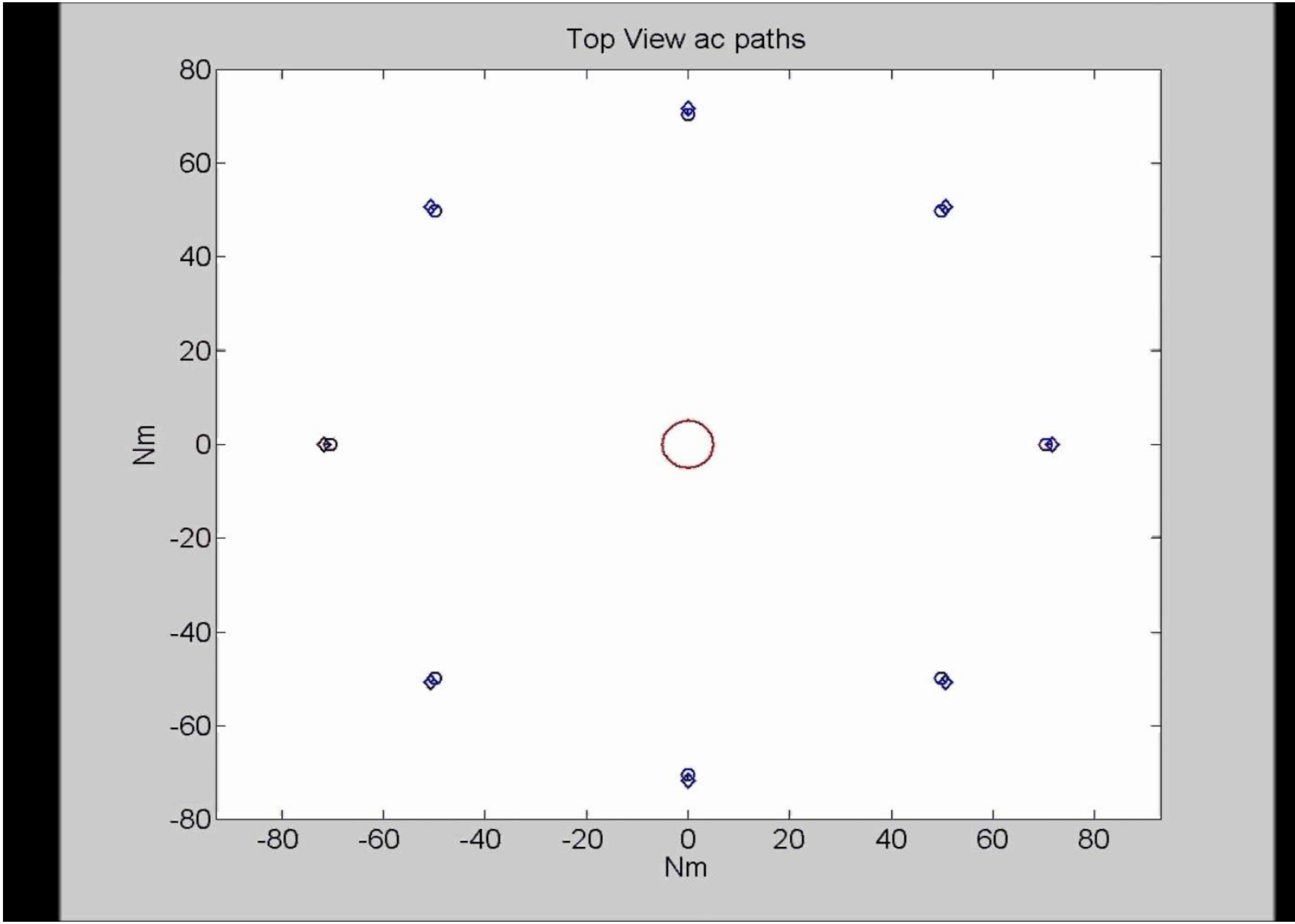
AMFF

Run #2



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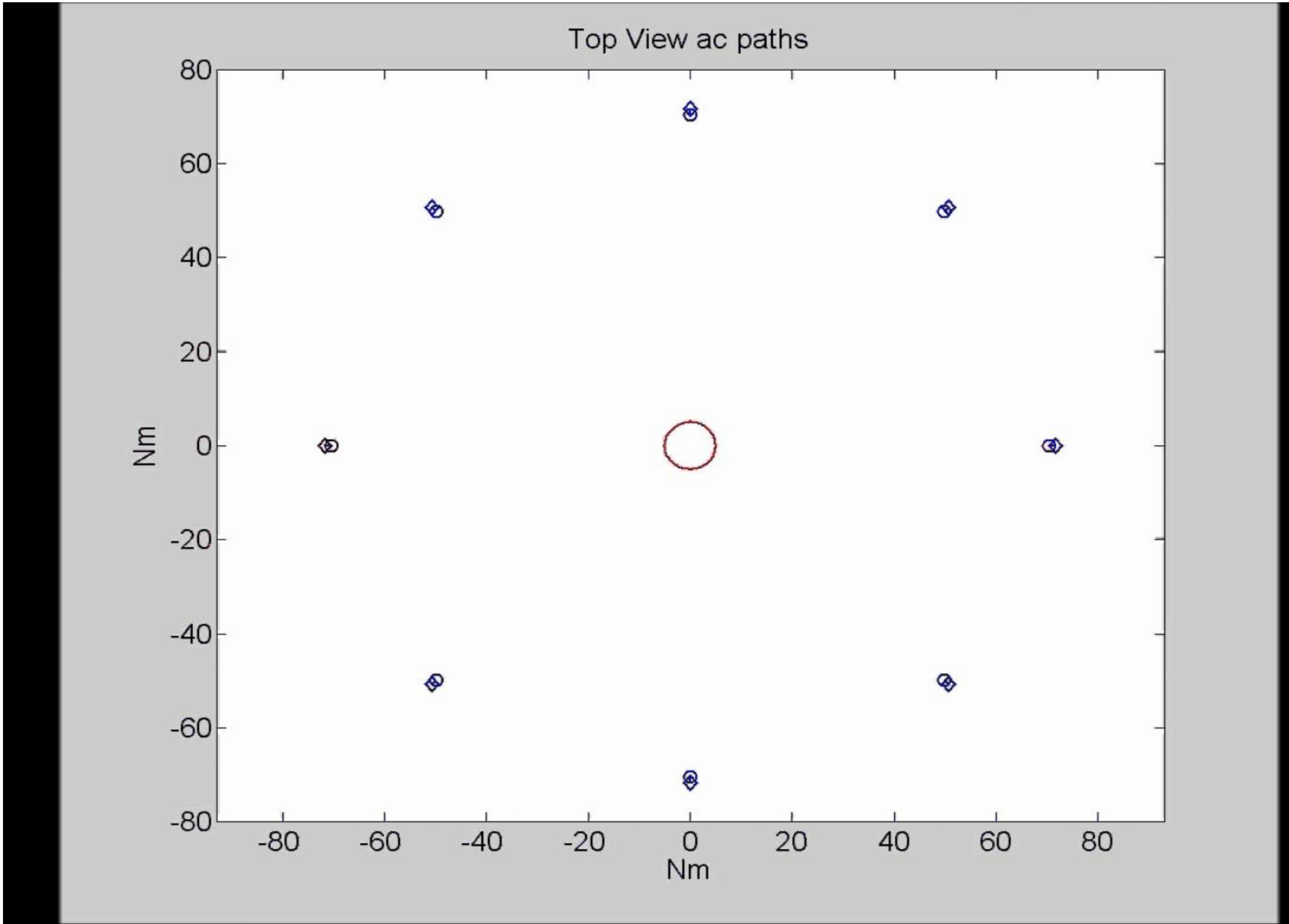
AMFF

Run #3



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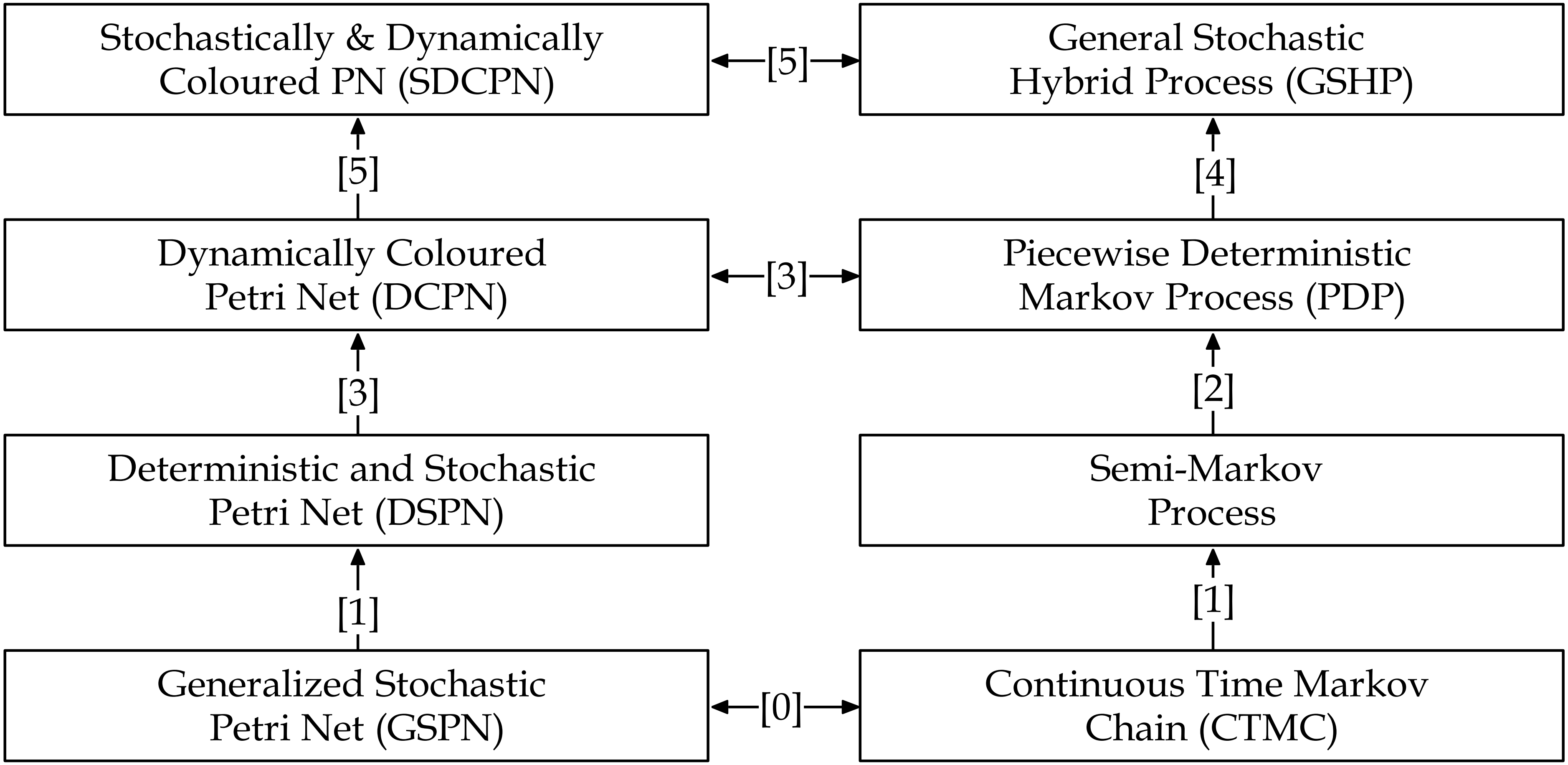
Size of AMFF agent-based model

Agent	# of product places	Maximum colour Product state space
Aircraft	24^N	R^{13N}
Pilot-Flying (PF)	490^N	R^{28N}
Pilot-not-Flying (PNF)	7^N	R^{3N}
AGNC	$(15\times 2^{16})^N$	R^{45N}
ASAS	48^N	$R^{37N+21N^2}$
Global CNS	16	R^0
PRODUCT	$\approx 16\times(3.88\times 10^{12})^N$	$R^{126N+21N^2}$

Model Power Hierarchy



[0]: [Ajmone Marsan et al, 1984]

[1]: [Malhotra & Trivedi, 1994], [Muppala et al, 2000]

[2]: [Davis, 1984]

[3]: [Everdij & Blom, 2005]

[4]: [Bujorianu & Lygeros, 2006]

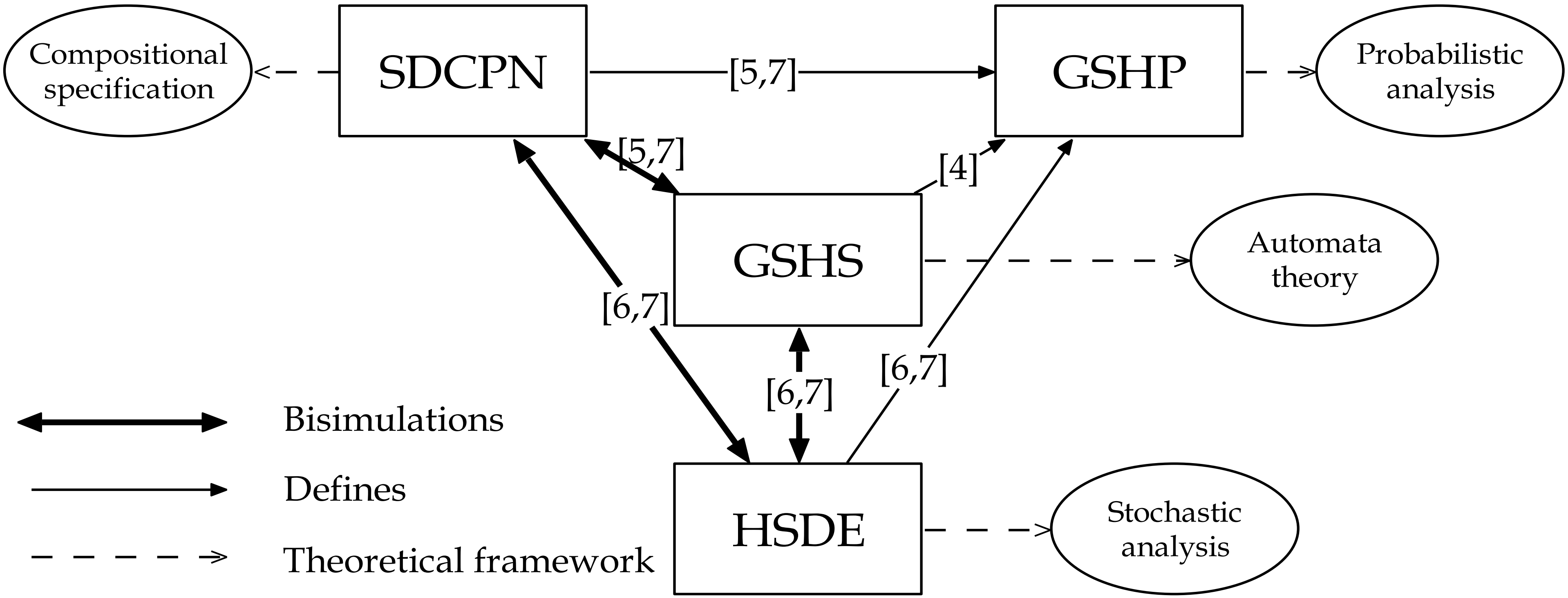
[5]: [Everdij & Blom, 2006]

Bisimulation

- **Two systems are bisimulations when their executions are equivalent in probabilistic sense**
  - VanDerSchaft, 2004; Bujorianu et al., 2005

- **Systems with GSHP executions:**
  - SDCPN = Stochastically and Dynamically Coloured Petri Net
  - GSHS = General Stochastic Hybrid System
  - HSDE = Hybrid Stochastic Differential Equation

SDCPN inherits analysis power of SDE's and formal verification power of automata



[4]: [Bujorianu & Lygeros, 2006]

[5]: [Everdij & Blom, 2006]

[6]: [Everdij & Blom, 2010]

[7]: [Everdij, 2010]

Approaches in Reach Probability Computation

- Markov Chain (MC) approximation (Prandini&Hu, 2006)
- Dynamic Programming (DP) approach (Abate, Amin, Prandini, Lygeros & Sastry, 2006)
- Interacting Particle System (IPS) approach (Cerou et al., 2005)

Interacting Particle System (IPS)

- Define a sequence of conflict levels decreasing in urgency $(D_k\text{'}s)$
  - Most urgent level represents collision $(D_m = D)$
- Simulate N_p particles; initially all outside D_1 (less urgent level)
- Freeze each particle that reaches the next urgent level before T
- Make N_p copies of frozen particles
- Repeat this until the most urgent level has been reached
- Count the simulated fraction $\tilde{\gamma}_k$ that reaches level k
- Estimated collision risk = $\tilde{\gamma}_1 \times \tilde{\gamma}_2 \times \tilde{\gamma}_3 \times \ldots \times \tilde{\gamma}_m$

IPS convergence

Cerou, Del Moral, Legland and Lezaud (2002, 2005) have shown that the product of these fractions $\tilde{\gamma}_k$ forms an unbiased estimate of the probability of $\{s_t\}$ to hit the set D within the time period $[0,T)$, i.e.

$$\mathbb{E}[\prod_{k=1}^{m} \tilde{\gamma}_k] = \prod_{k=1}^{m} \gamma_k = P(\tau < T)$$

In addition there is a bound on the L^1 estimation error, i.e.:

$$\mathbb{E}(\prod_{k=1}^{m} \tilde{\gamma}_k - \prod_{k=1}^{m} \gamma_k) \leq \frac{c_p}{\sqrt{N_p}}$$

Hybrid IPS versions

1. Importance switching (Krystul&Blom, 2005)

2. Rao-Blackwellization, using exact equations for $\{\theta_t\}$ and particles for Euclidian state (Krystul&Blom, 2006)

- Both handle rare mode switching well
- Large scale SHS scalability problem remains
  - Huge number of discrete product places

Hierarchical Hybrid IPS (HHIPS)
(Blom, Bakker & Krystul, 2007, 2009)

- ✓ Define an aggregated mode process $\{\kappa_t\}$ with $\{\mathbb{M}_k, \kappa \in \mathbb{K}\}$ a partition of $\mathbb{M}$

$$\kappa_t = \kappa \text{ if } \theta_t \in \mathbb{M}_k$$

- ✓ Apply Importance switching to $\{\kappa_t\}$
- ✓ Rao-Blackwellization, i.e. use exact equations for $\{\kappa_t\}$ and particles for the other process elements $\{x_t, \theta_t\}$

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Scenarios

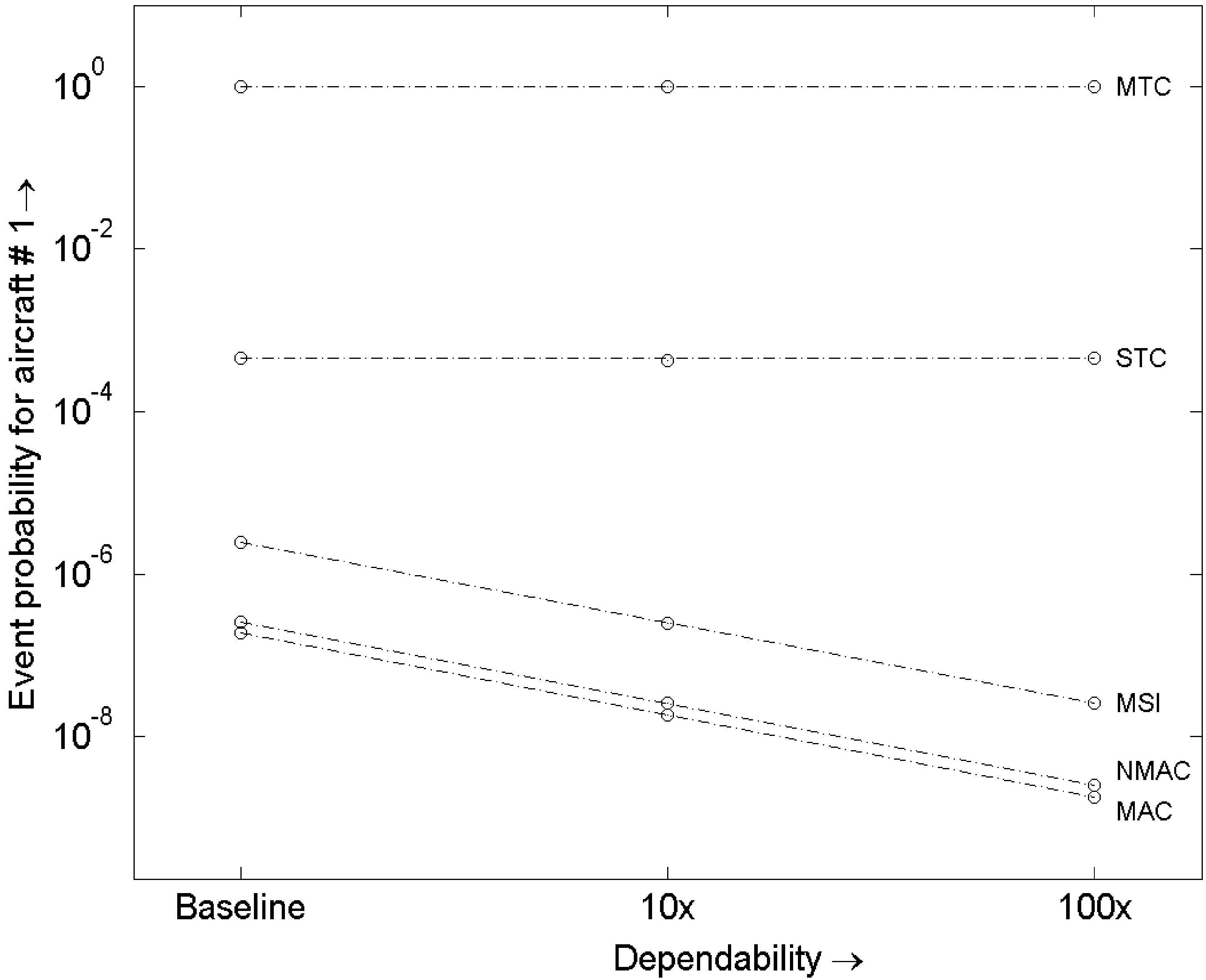
- Two aircraft encounter
- Eight aircraft encounter
- Random traffic

Sequence of conflict levels for air traffic

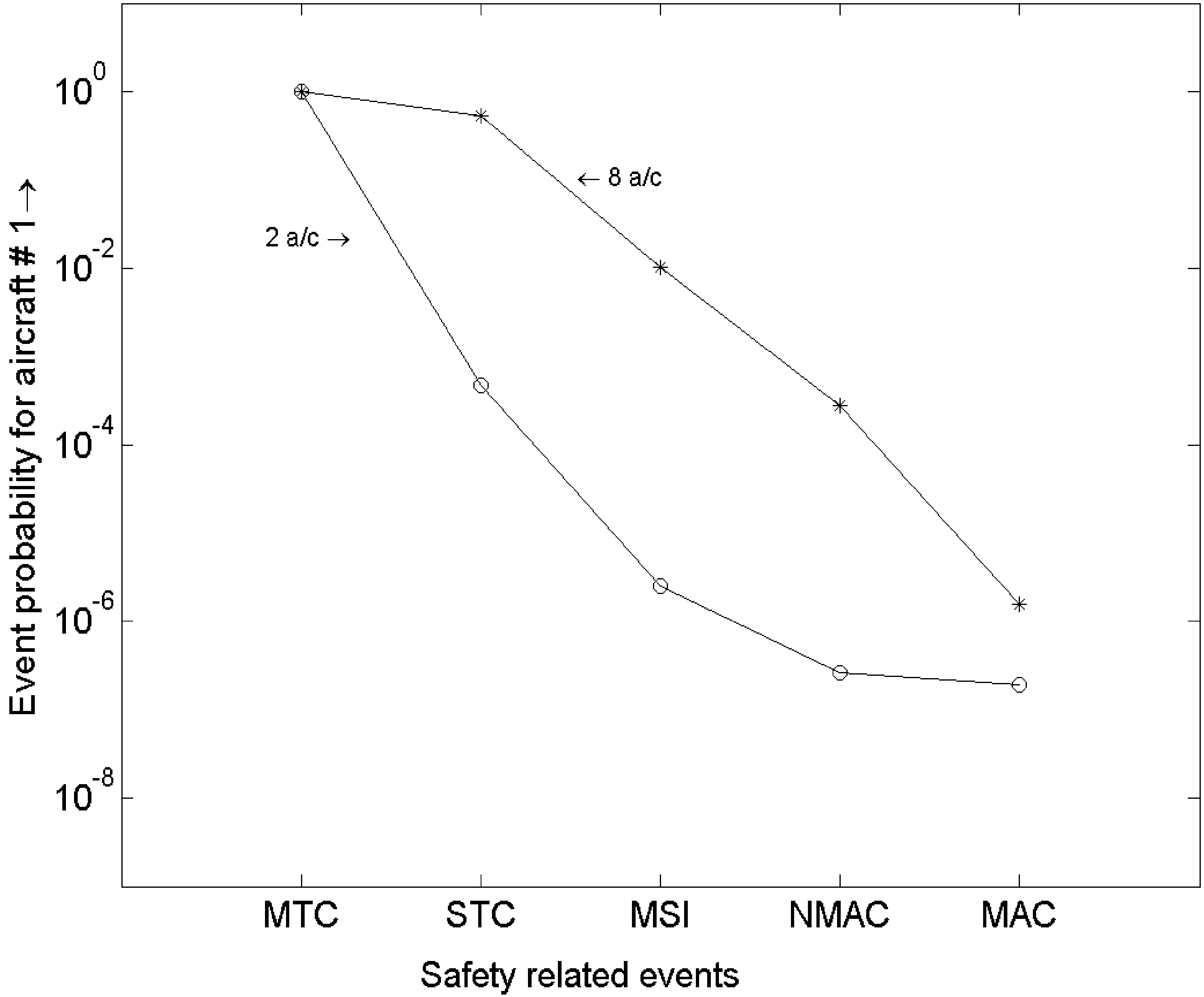
k	1	2	3	4	5	6	7	8
D_k (Nm)	4.5	4.5	4.5	4.5	2.5	1.25	0.5	0.054
h_k (ft)	900	900	900	900	900	500	250	131
Δ_k (min)	8	2.5	1.5	0	0	0	0	0

- $k = 1$: Medium Term Conflict (MTC)
- $k = 2$: Short Term Conflict (STC)
- $k = 4$: Minimum Separation Infringement (MSI)
- $k = 6$: Near Mid-Air Collision (NMAC)
- $k = 8$: Mid-Air Collision (MAC)

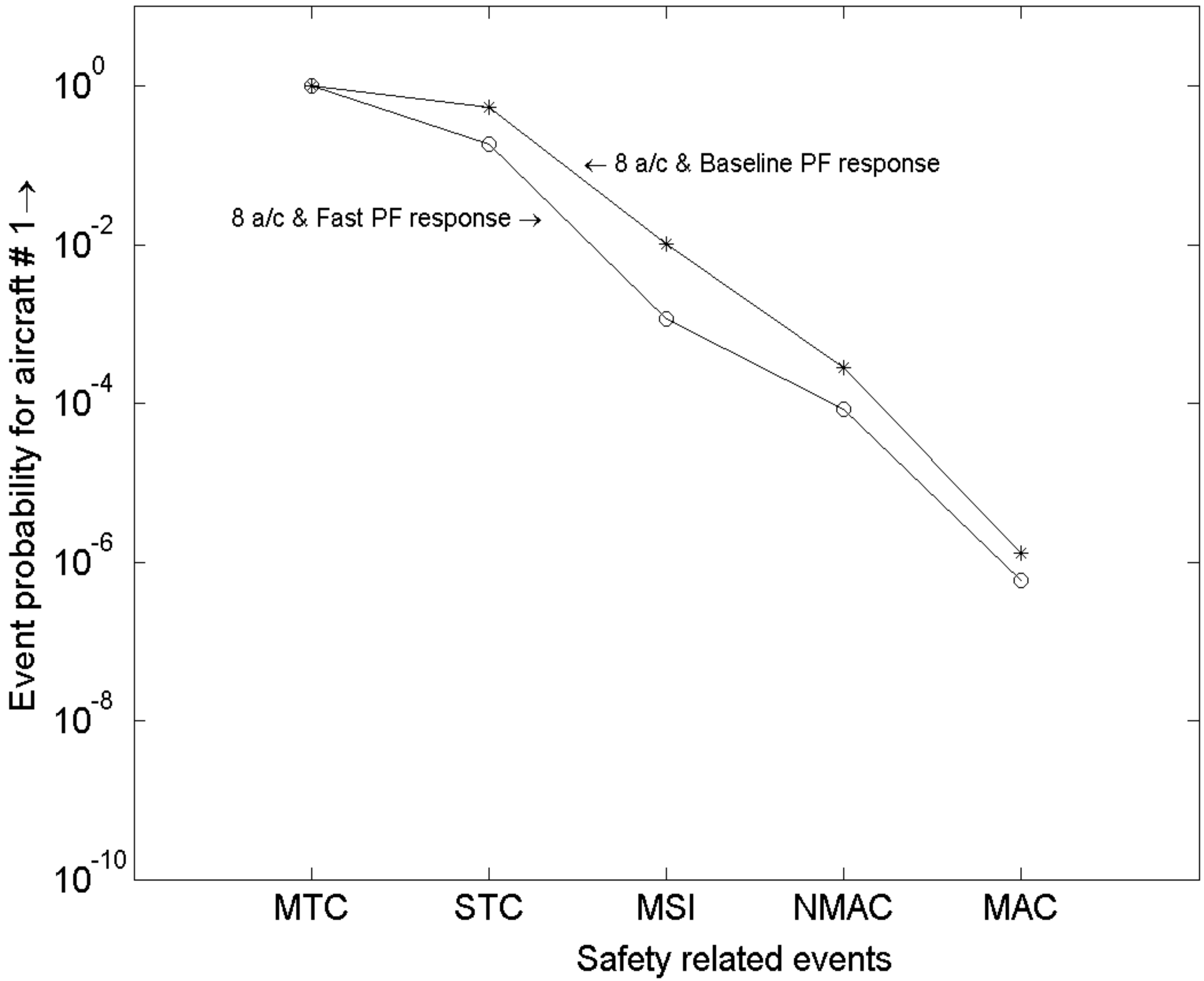
Two-aircraft encounter and dependable technical systems



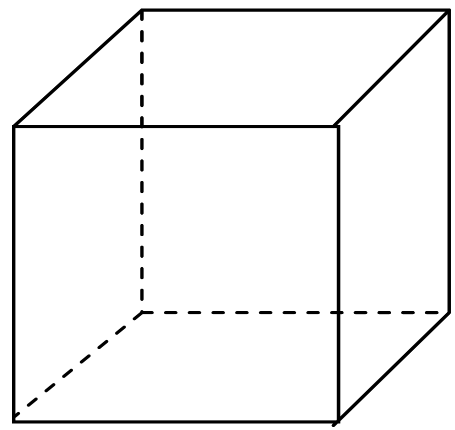
Two-aircraft vs. eight-aircraft encounter



Eight-aircraft encounter: Baseline PF response vs. Fast PF response

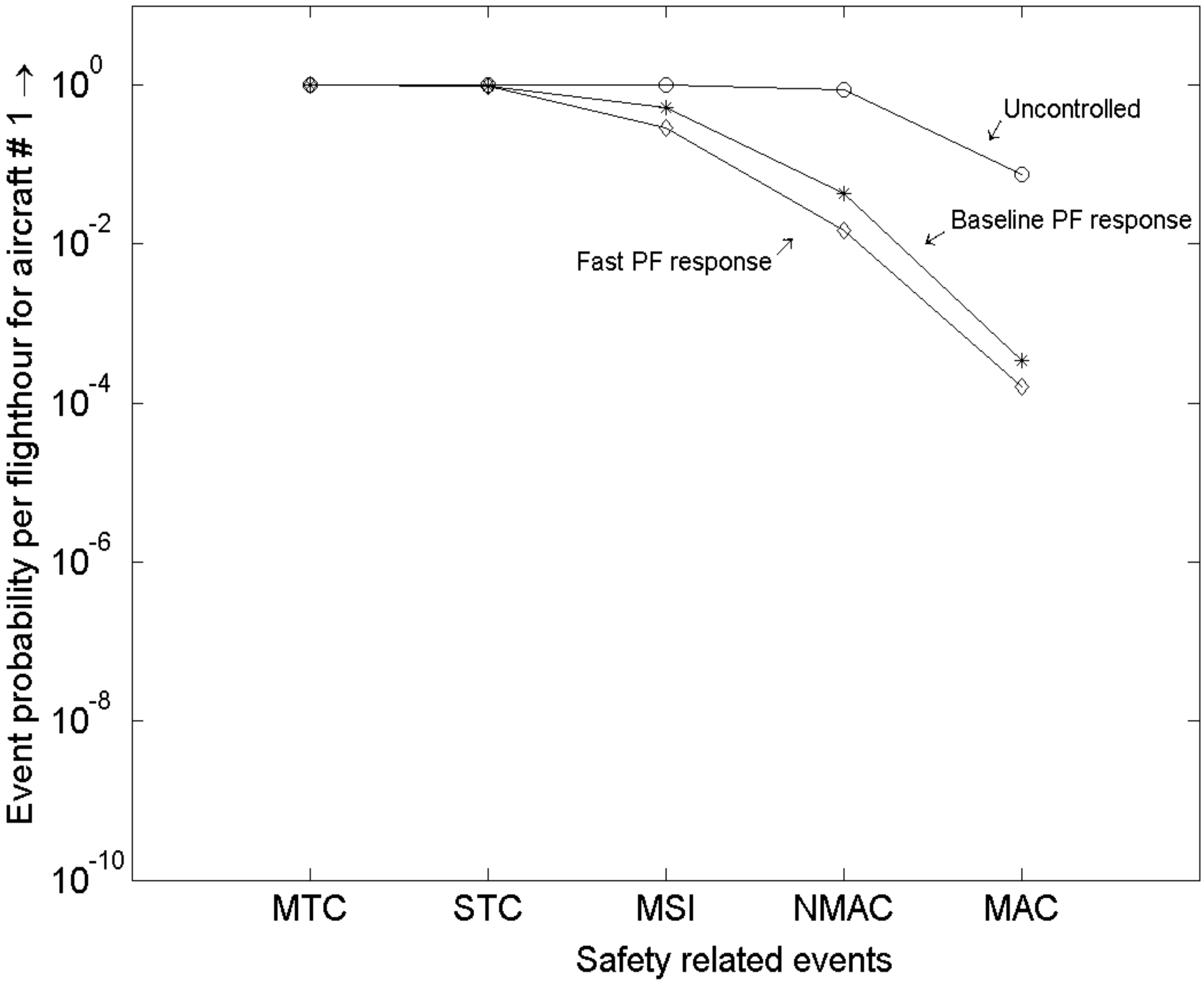


Random traffic, high density



- **Eight aircraft per packed container**
  - 3 times as dense above Frankfurt on 23rd July '99

Random high traffic: Uncontrolled vs. AMFF controlled



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Advanced Airborne Self Separation ConOps considered

- Aircraft plan conflict-free 4D trajectories
  - Reference Business Trajectory (RBT)
- Each a/c broadcasts its current RBT and its destination to other aircraft
- SWIM transfers this over-the-horizon.
- Conflict detection and resolution take all aircraft into account
  - Medium Term (5-15 mins)
  - Short Term (3-5 mins)
- Tactical Separation Minima is down from 5Nm to 3 Nm
  - Stemming from RESET project

NASA research on Advanced Airborne Self Separation ConOps

- **Basic concept has been developed by NASA [NASA, 2004]**
  - This includes ConOps extension for non-equipped aircraft
  - Has recently been published [Wing and Cotton, ATIO-2011]

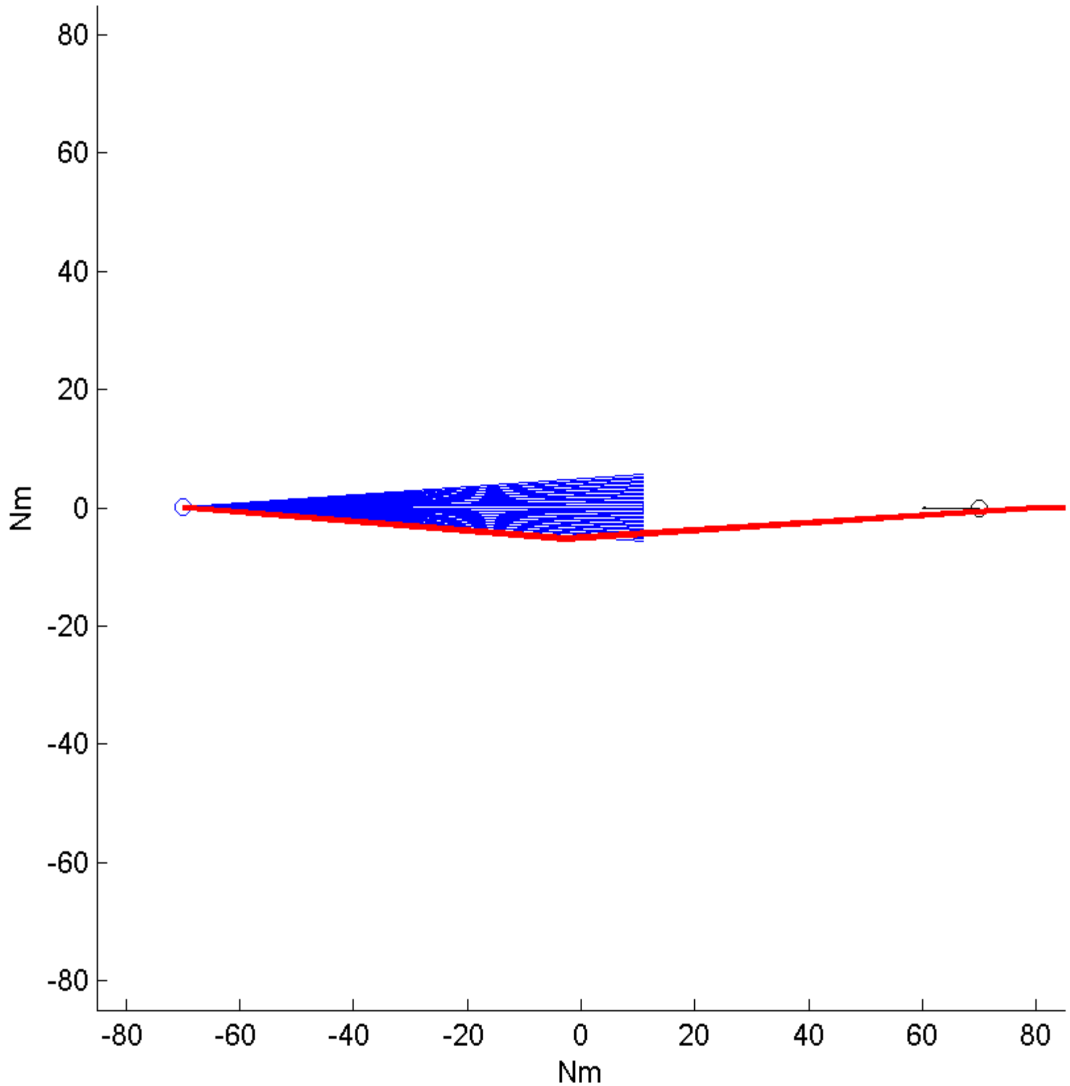
- **Extensive study of planning layer**
  - Under nominal conditions [Consiglio et al., ATIO-2007]
  - Effect of pilot response delays [Consiglio et al., ATIO-2008, ICAS-2010]
  - Effect of large wind deviations [Consiglio et al., ATM-2009]
  - Planning layer absorbs all but large wind deviations (60 kts)

- **Follow-up Research Question:**
  - Can the tactical layer resolve this safely?

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.
- Undershooting of 5Nm/1000ft is allowed if there is no feasible conflict free plan and it does not create a short term conflict.
- Then such aircraft broadcasts its non-conflict-free 4D plan together with a message of being “Handicapped” (which is priority increasing)

Velocity Obstacles (Collision Cones)
Medium Term (10 min & 5 Nm)



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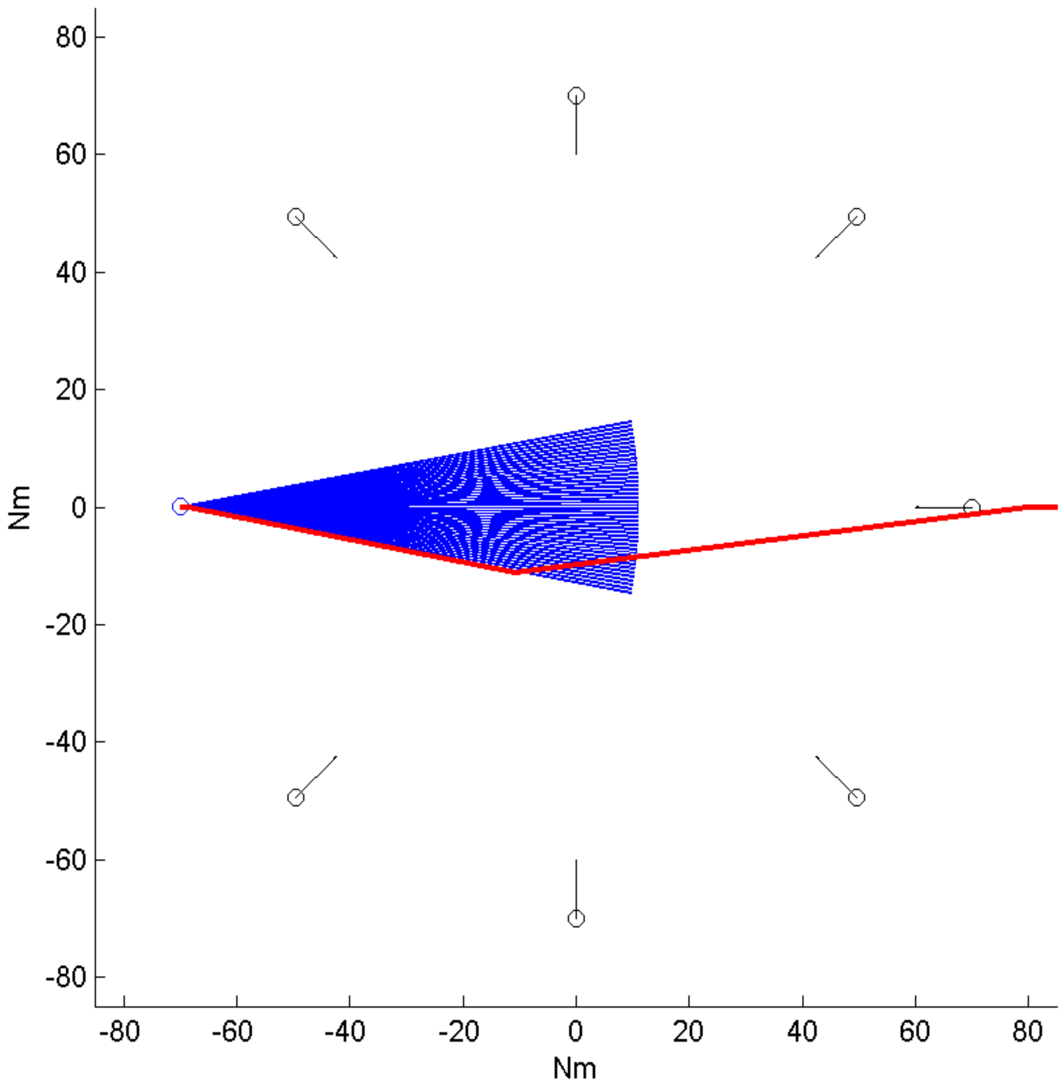

Velocity Obstacles (Collision Cones)
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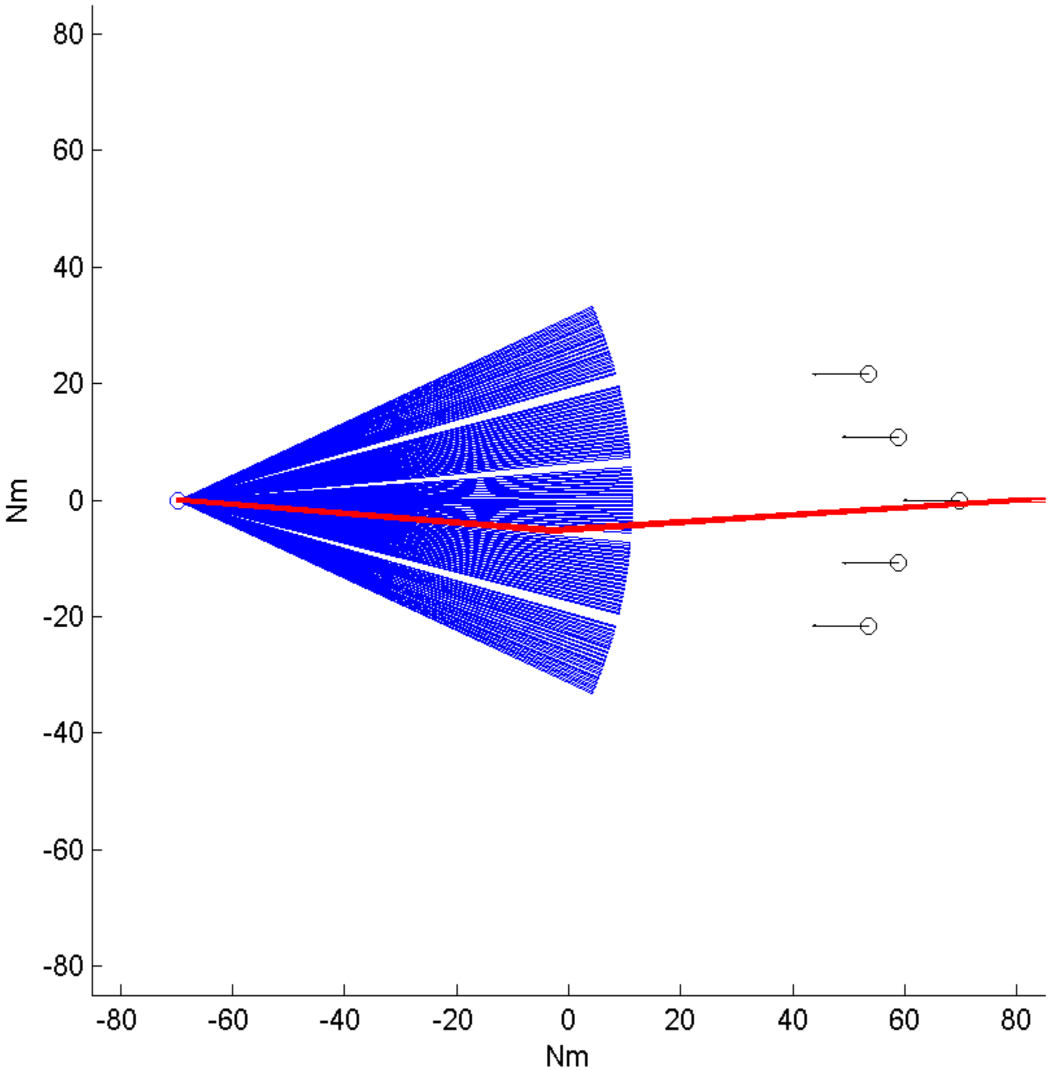
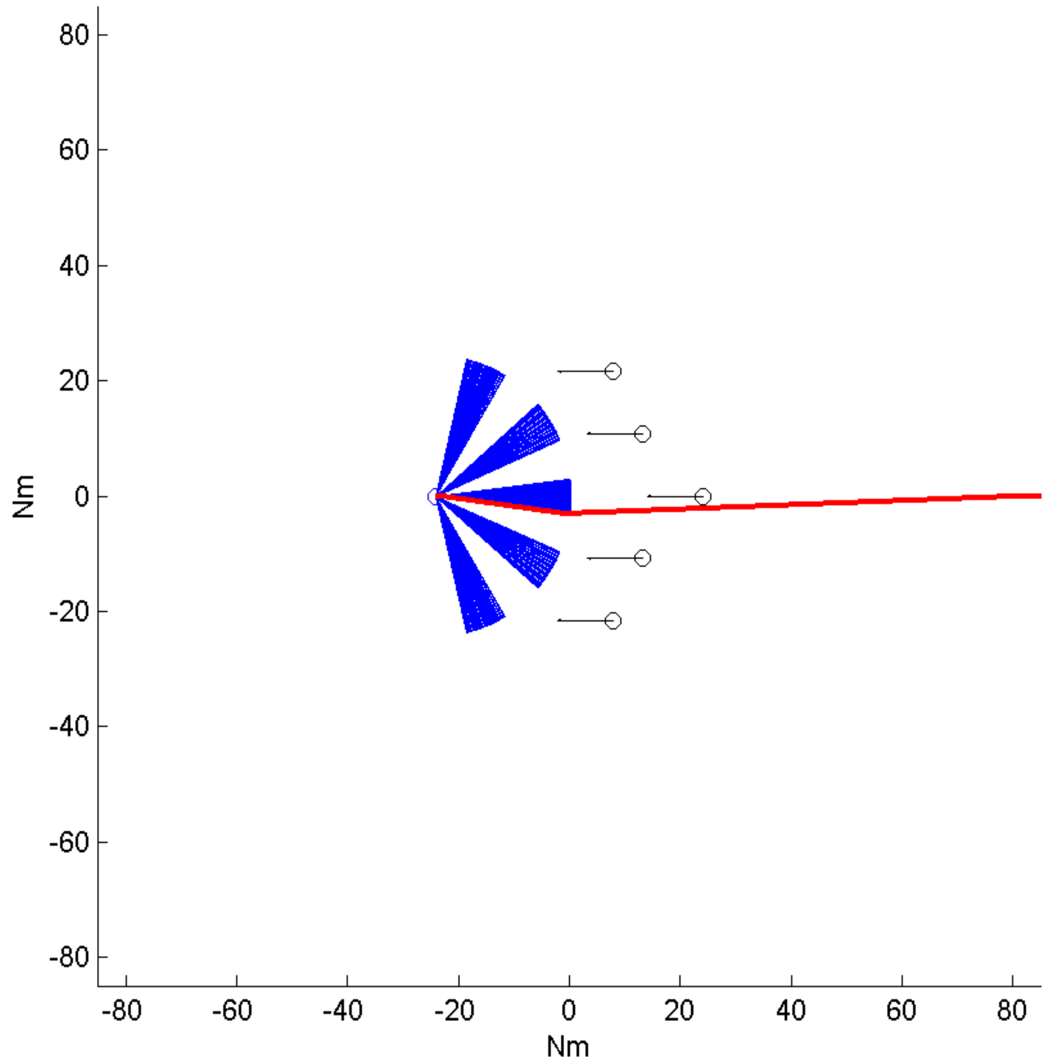


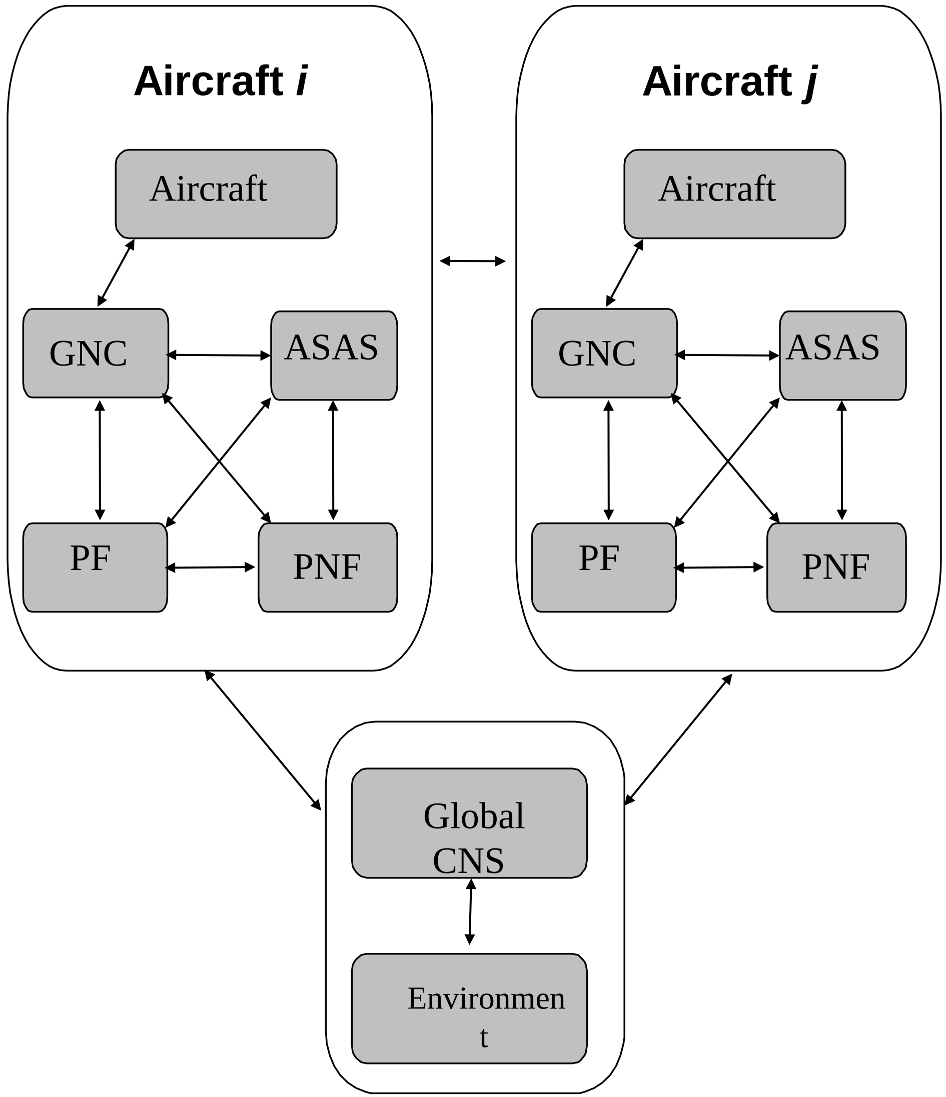
Short Term CD&R approach

- 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
- Undershooting of these values is allowed if there is no feasible alternative
- a/c broadcasts its new course or rate of climb/descend

Velocity Obstacles = Collision Cones
Short Term (3 min & 3 Nm)



Agents in Airborne Self Separation



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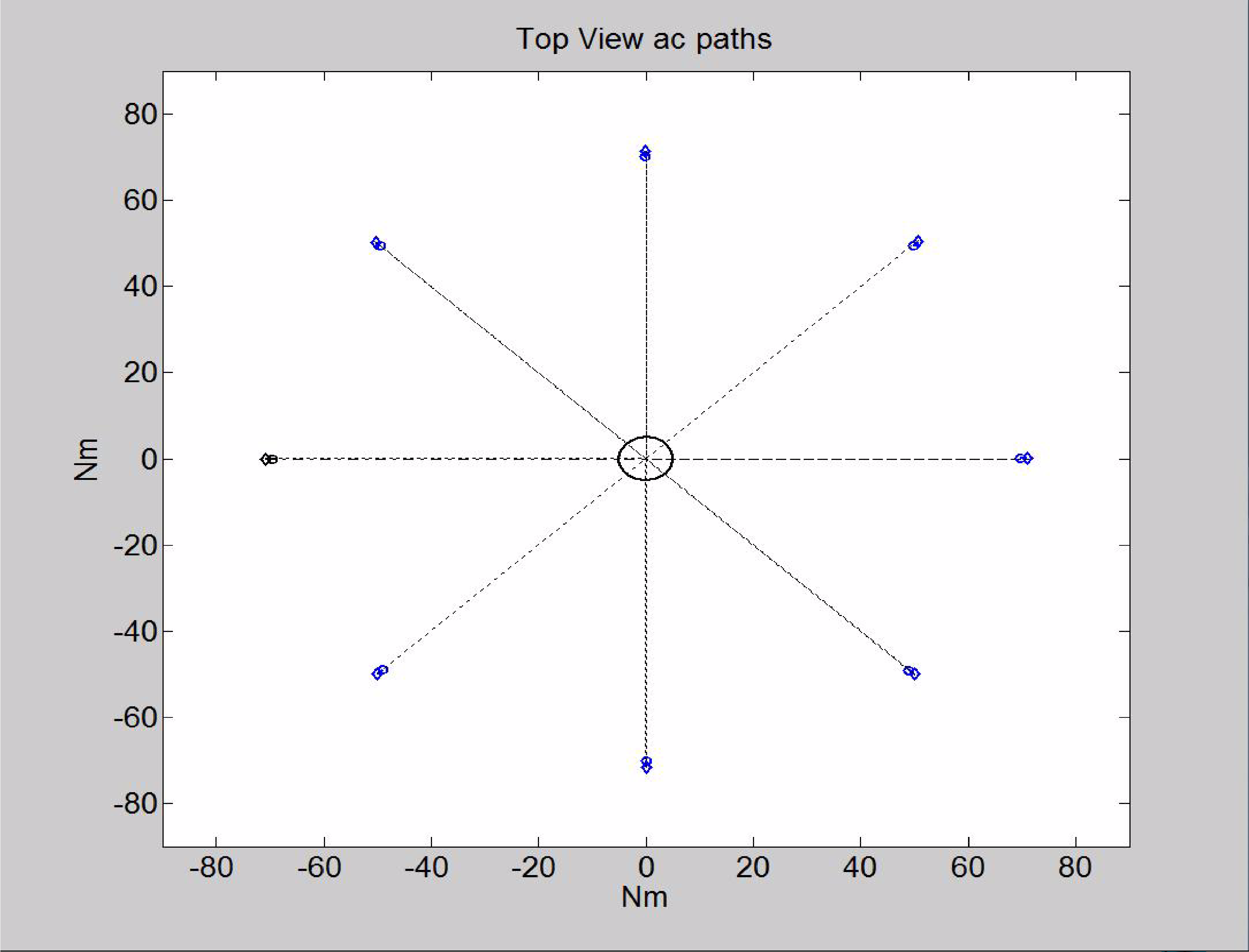

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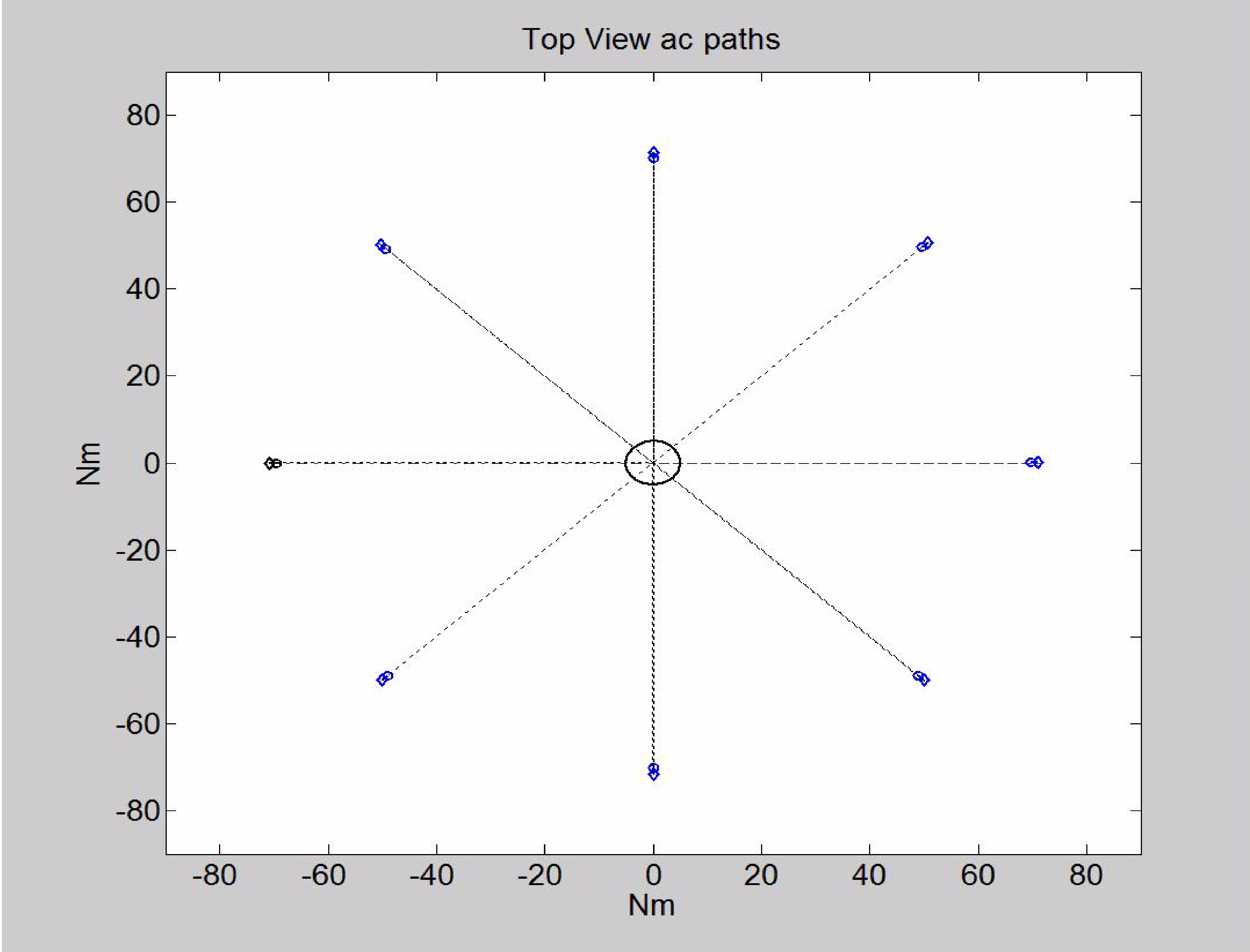
Run #2



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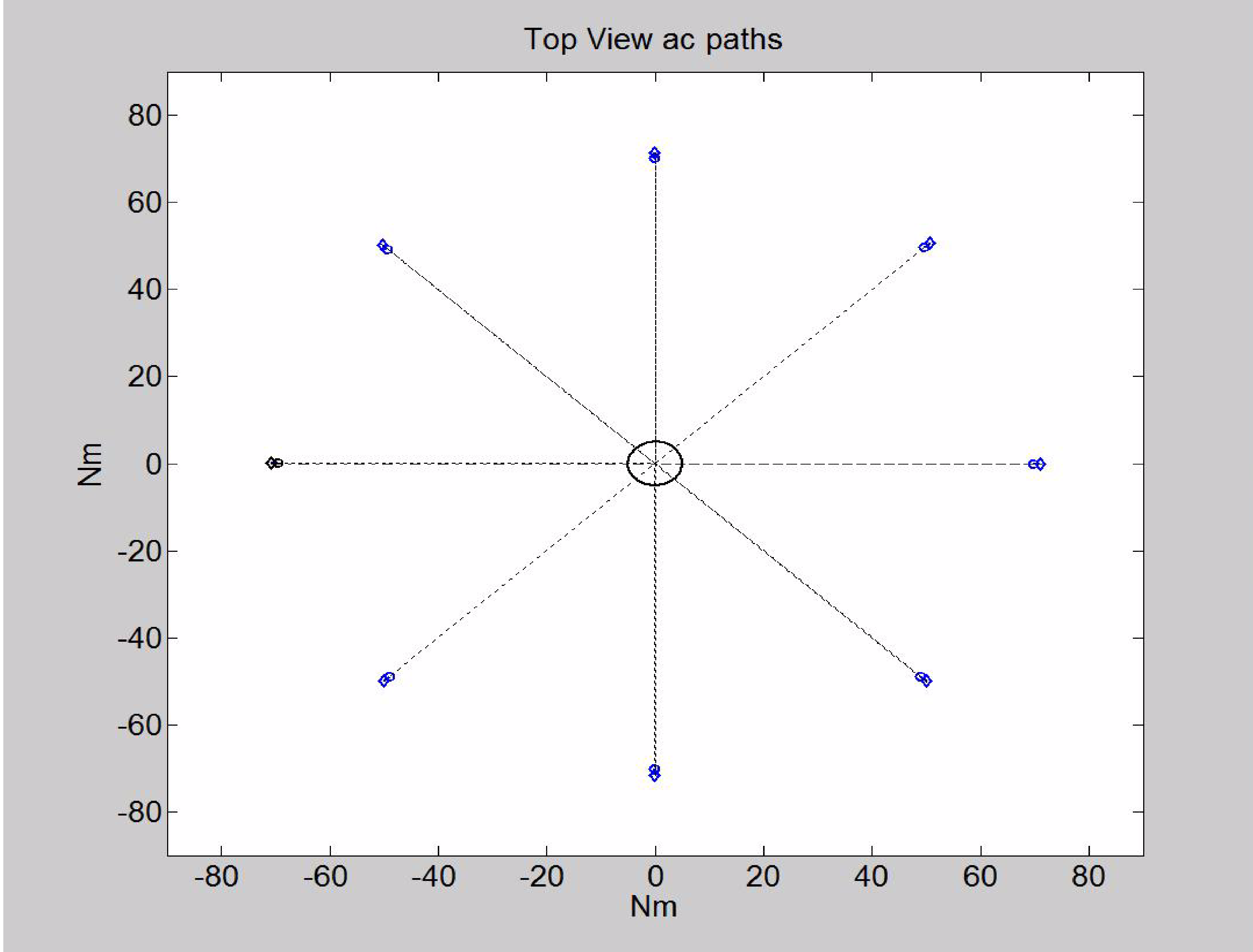
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Traffic Scenarios

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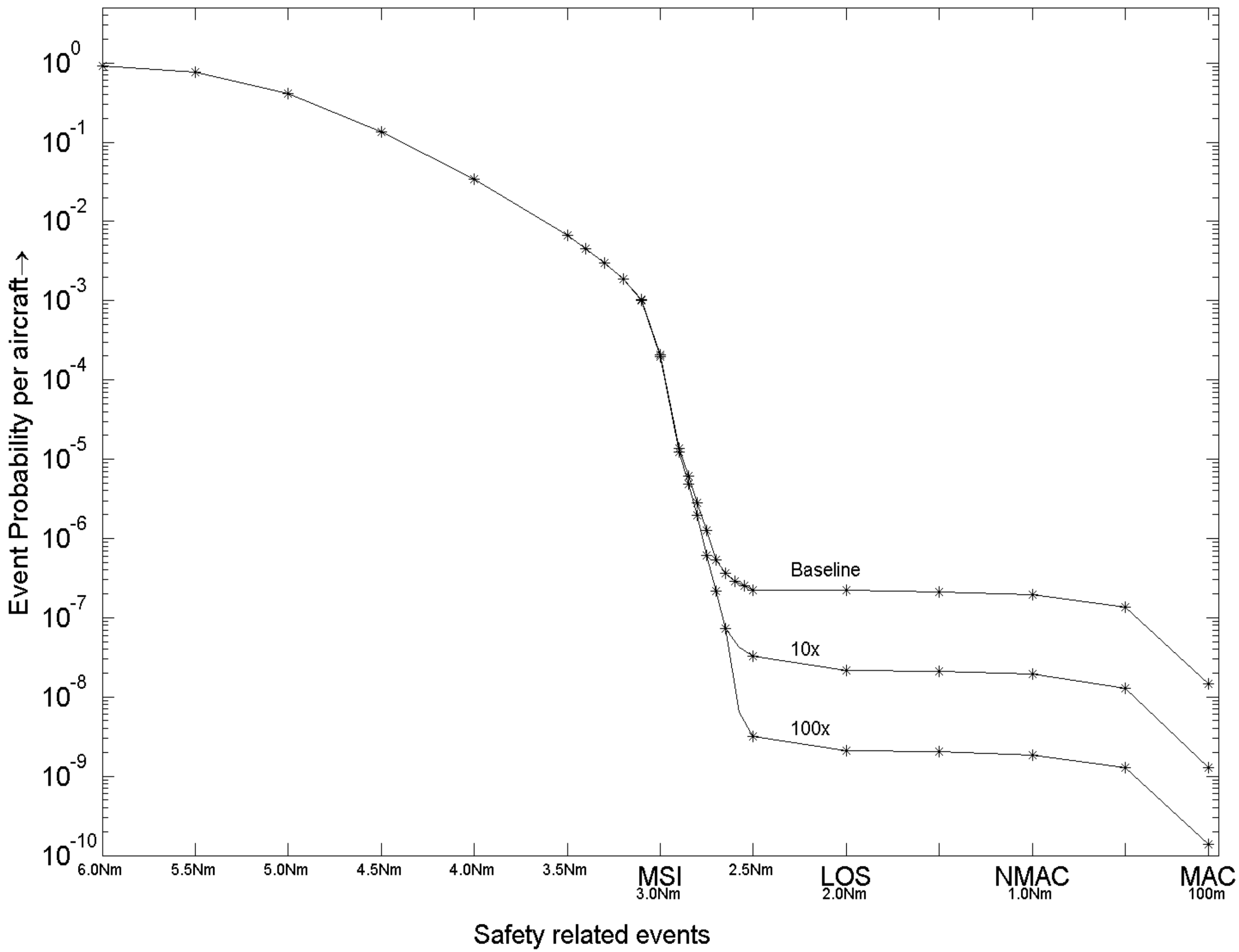
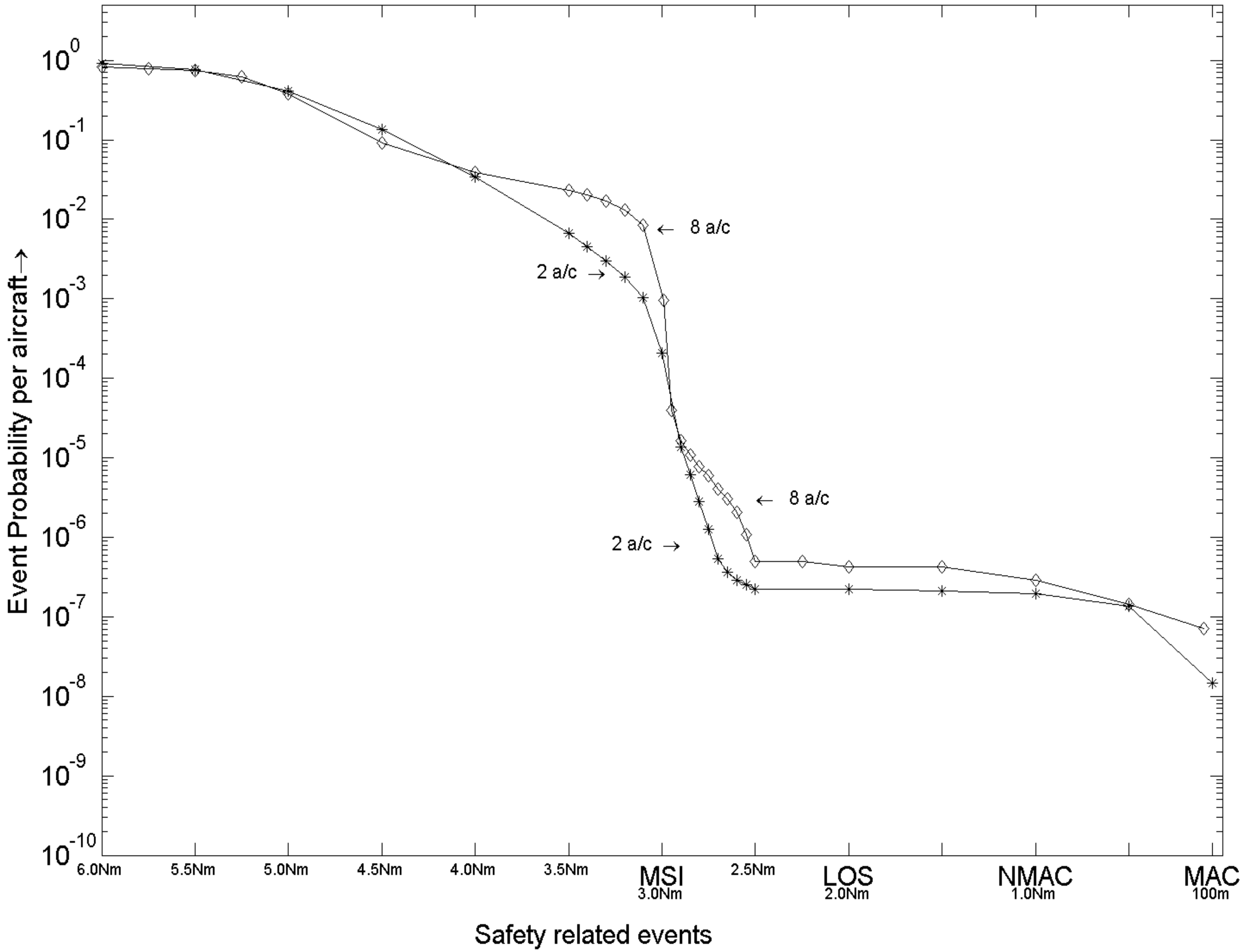
- Eight aircraft encounter
- Random traffic high density

2 a/c, varying ASAS dependability



8 a/c versus 2 a/c



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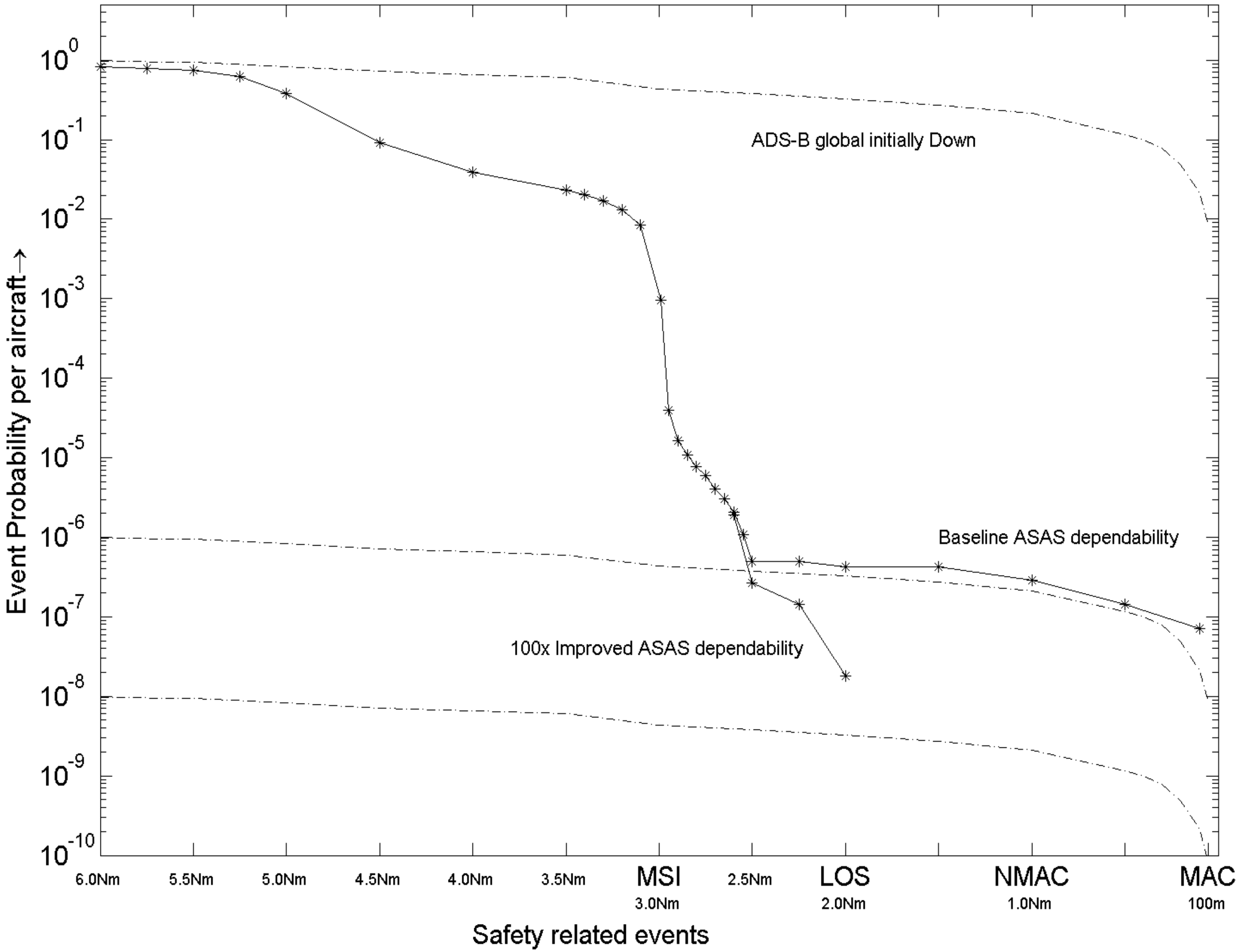
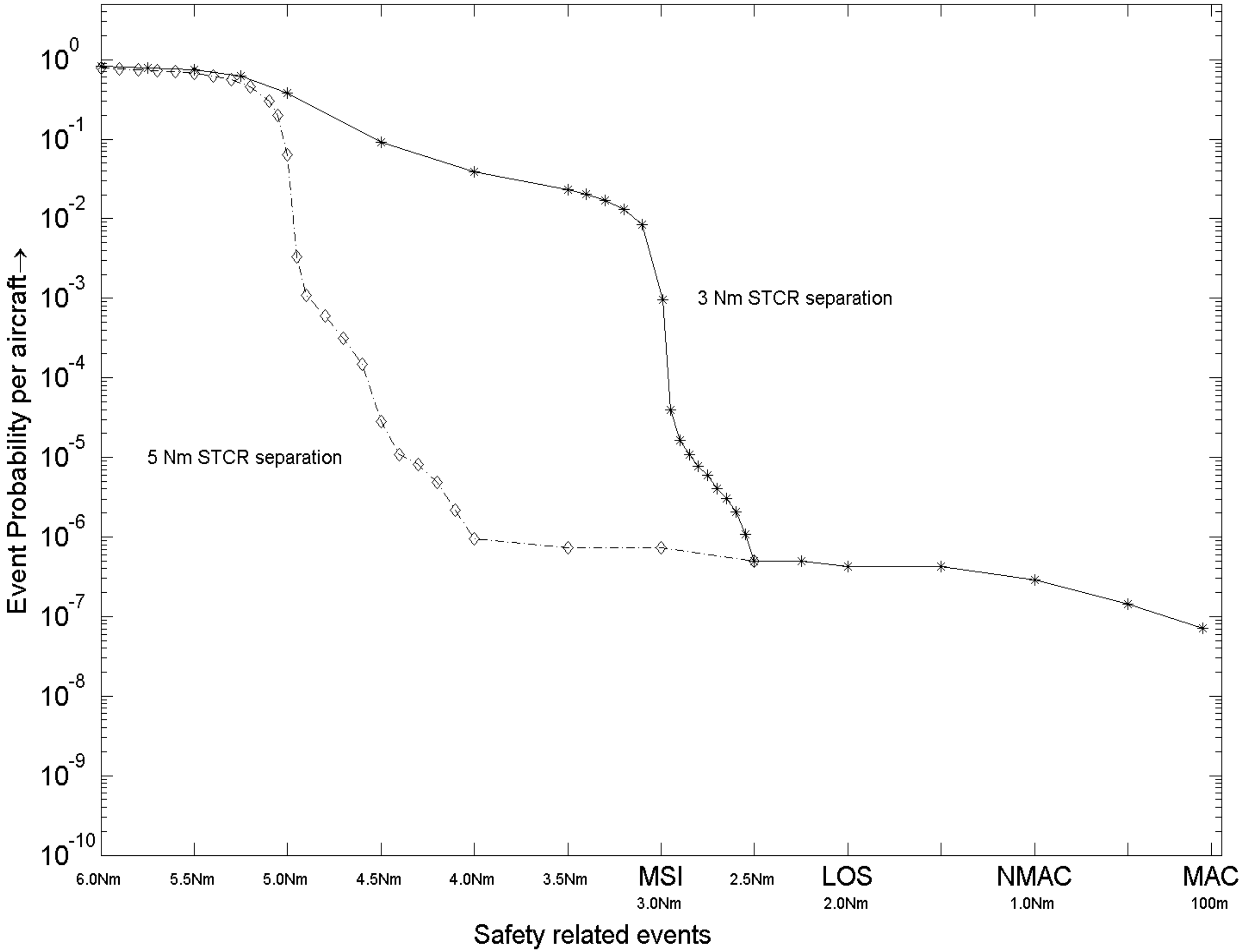
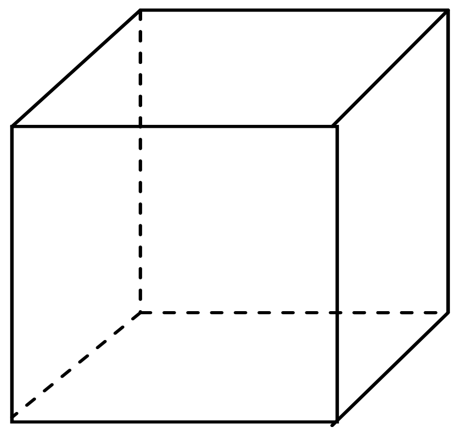


8 a/c, STCR separation back to 5 Nm

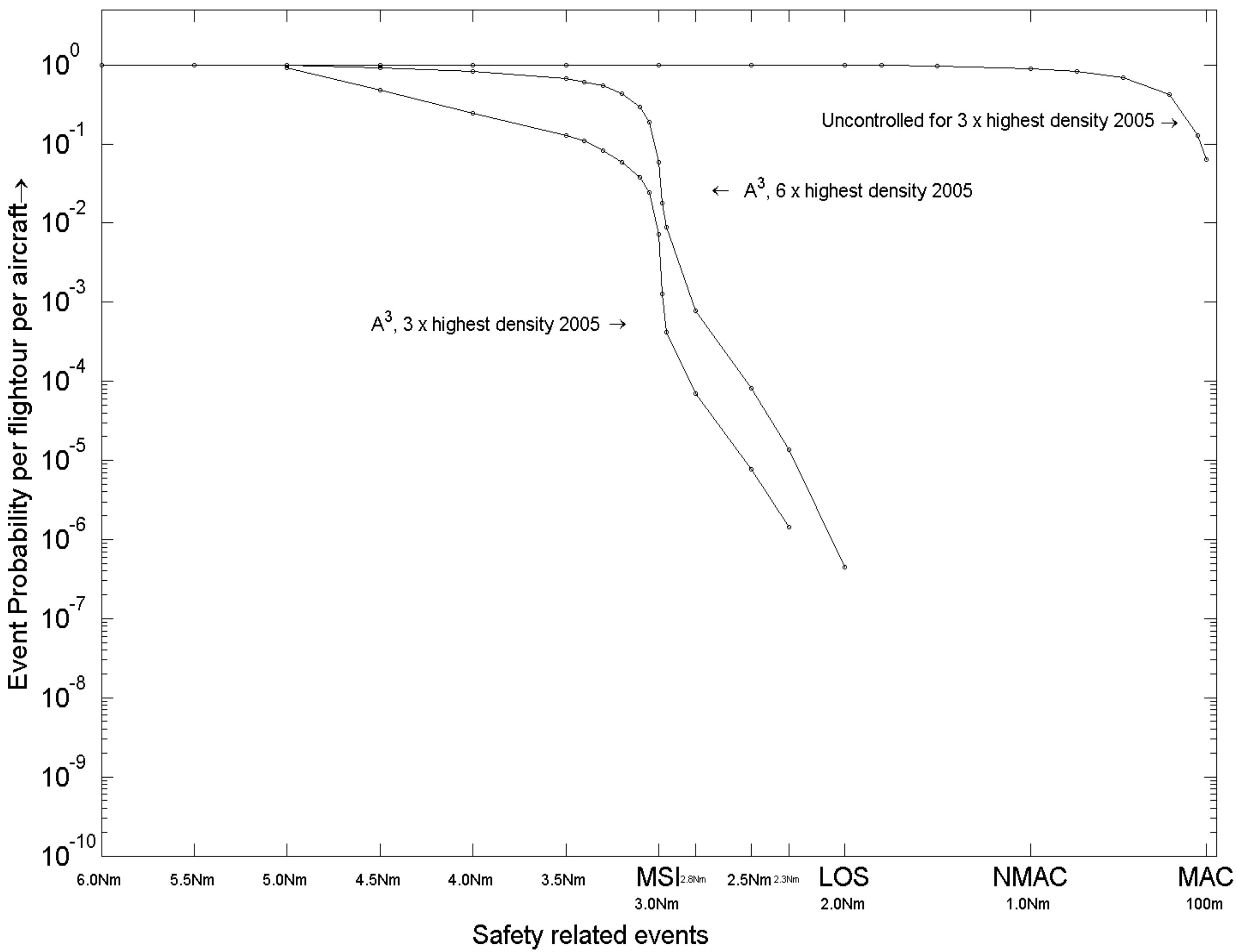


Random Traffic Scenarios

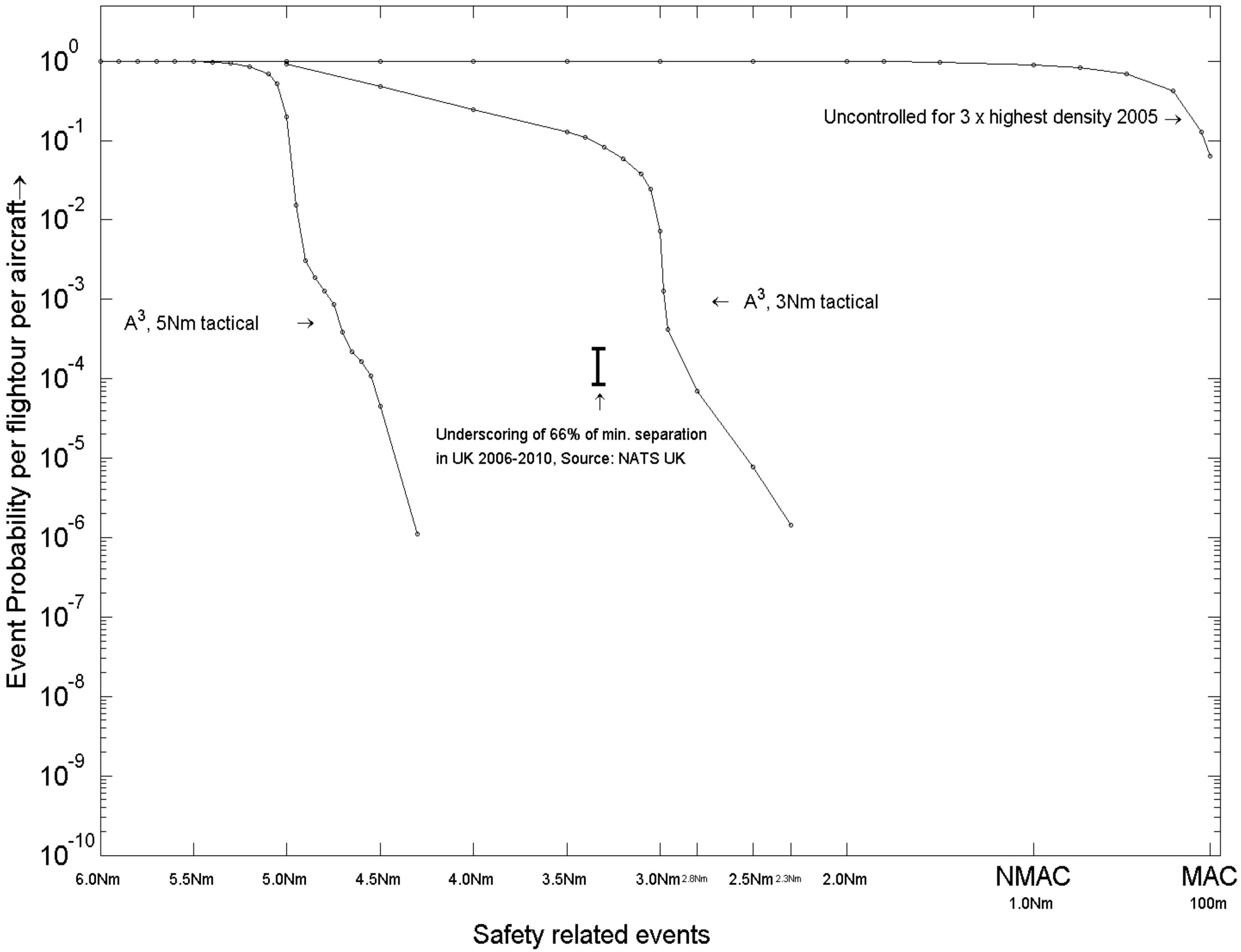


- Periodic Boundary Condition
- Eight a/c per packed box/ no climbing or descending a/c
- Vary container size in order to simulate:
  - 3x as dense as high density area in 2005
  - 6x as dense as high density area in 2005

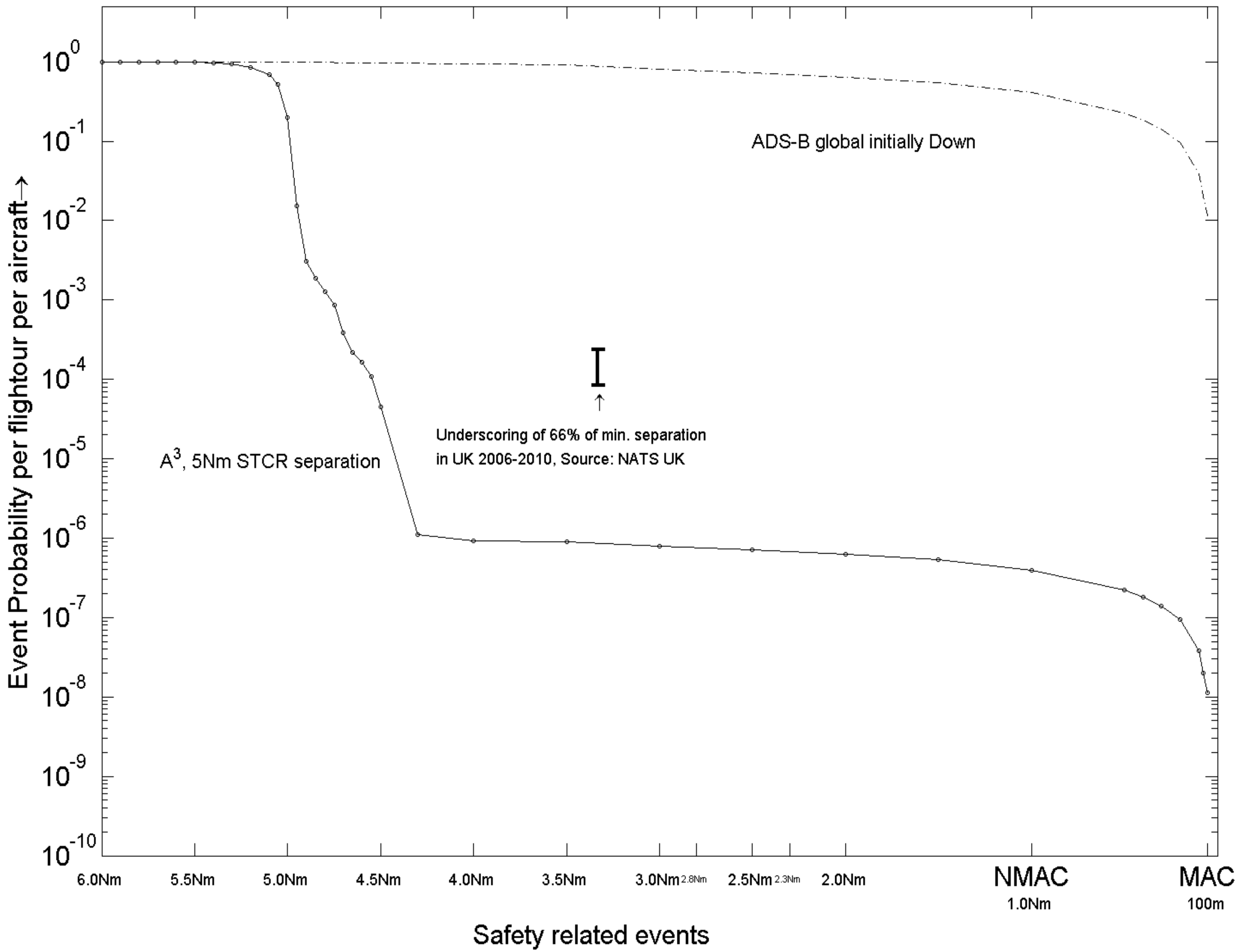
Random traffic: 3x and 6x 2005



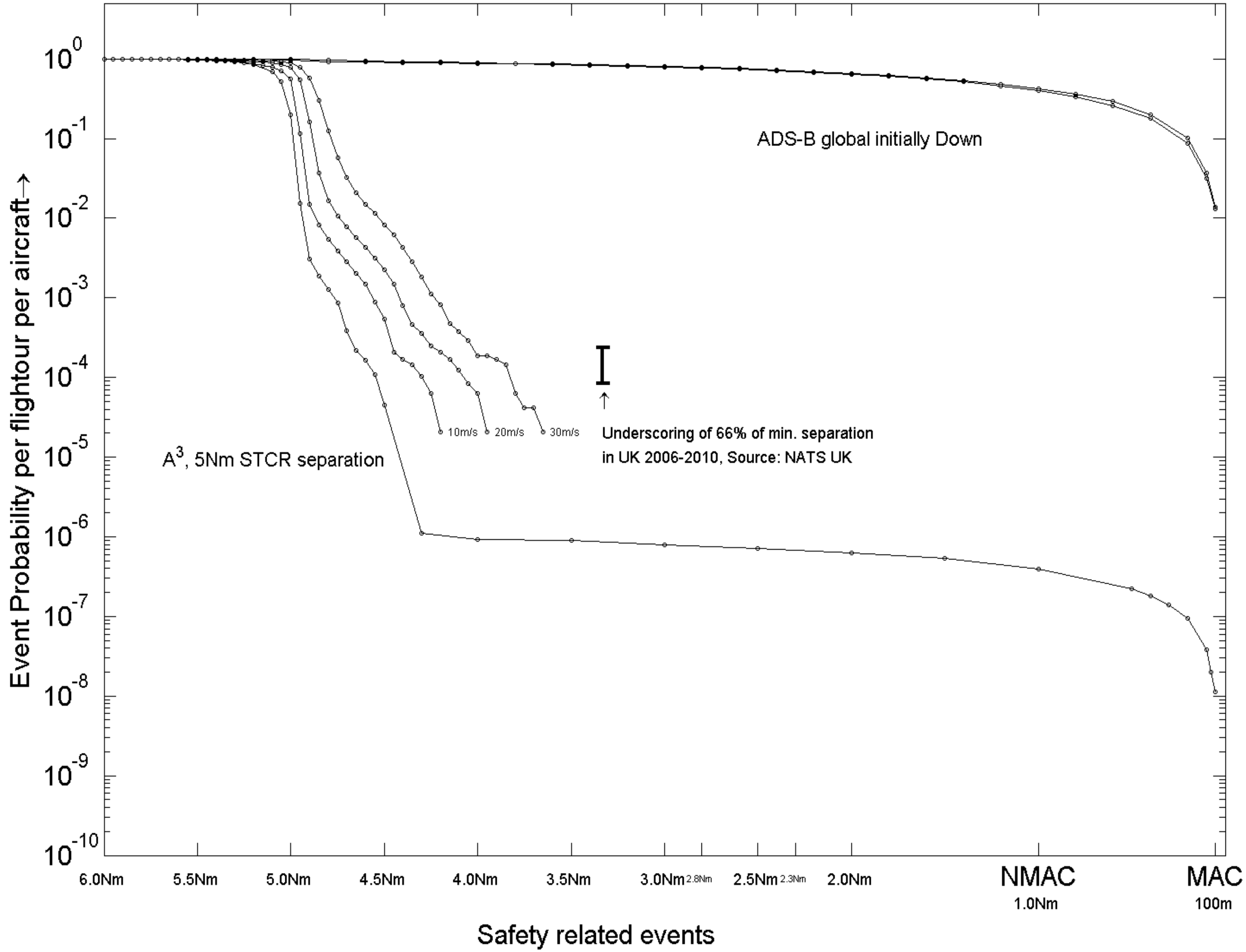
Tactical Separation: 5Nm and 3Nm



3x high 2005 random traffic



3x high 2005 traffic + wind error 10/ 20/ 30 m/s



Conclusions

- MFF project showed: Pilots like it, if they know that ASAS supporting systems are dependable
- Dependability requirements have been identified using RTCA DO-264 (=EurocaeED78a) and rare event MC simulations
- Agent Based Modelling & Simulation shows: It can safely accommodate very high en route traffic demands at current separation minima
- To safely accommodate 3x traffic of 2005, Tactical Separation distance can stay at 5 Nm
- Other aspects have been addressed in complementary studies
  - CD&R algorithms more advanced than Velocity Obstacles
  - Cost Benefit

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Questions / Discussion

Validation of assessed risk level

- **Simulation model ≠ Reality**
- Identify the differences
- Assess each difference individually (and conditionally)
  - use of statistical data and expert knowledge
- Assess model parameter sensitivities by Monte Carlo simulations
- Evaluate effect of each assumption at simulated risk level
  - use of statistical data and expert knowledge
- Evaluate combined effects of all model assumptions
  - Typical output: expected risk and 95% area
- Improve simulation model for large differences