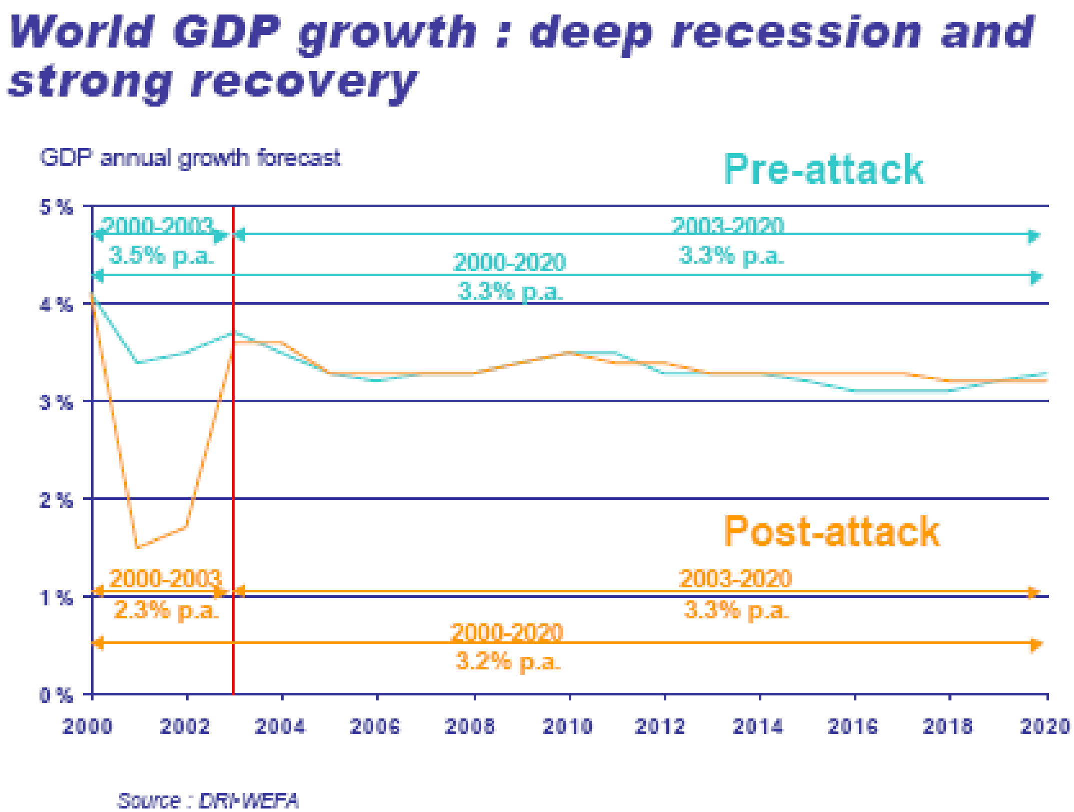
Back-up Slides

Motivation



Airbus Global Market Forecast, Sept 2002

- World GDP will average 3.2% growth per year
- World air cargo traffic will grow at 6.4% per year

Motivation

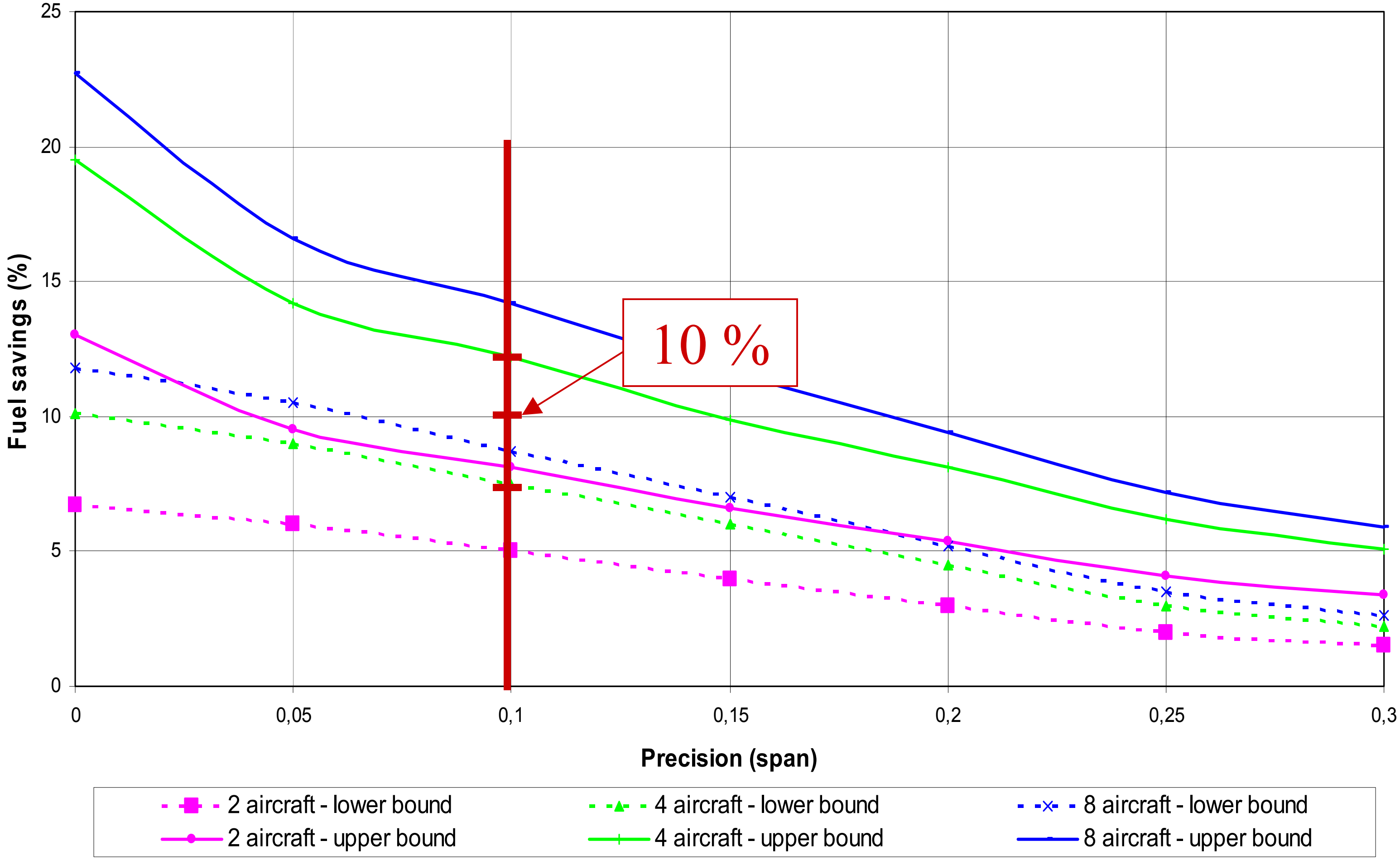
- Alaska Airlines saw average fuel price increase from 90 cents per gallon in 2003 to $1.10 per gallon in January to $1.30 per gallon in March of this year – a 44% increase over last year
- Airlines in the US have spent over $1 billion more on fuel during the first quarter of 2004 as compared to the same period in 2003
- American Airlines: Will spend $400 million more on fuel this year compared to last year
- United Airlines: Every penny increase in the price of a gallon of fuel costs $22 million per year
- Fuel is 2nd-largest airline expense next to personnel
- Fuel is 12-18% of total airline costs

New Aircraft Feasibility Study

- Innovative ideas for new aircraft
  - If formation flight becomes common, may be included
  - May open new missions to formation flight
- New ideas can increase range and fuel benefits
- Affordable used aircraft available for cargo carriers
- If a new aircraft development program already exists, the formation flight system can be integrated, would be same as modification programs.
- Even with optimistic assumptions, range and fuel benefits of an aircraft designed for formation flight, over a modified aircraft, do not offset new aircraft development costs

Mission Overview

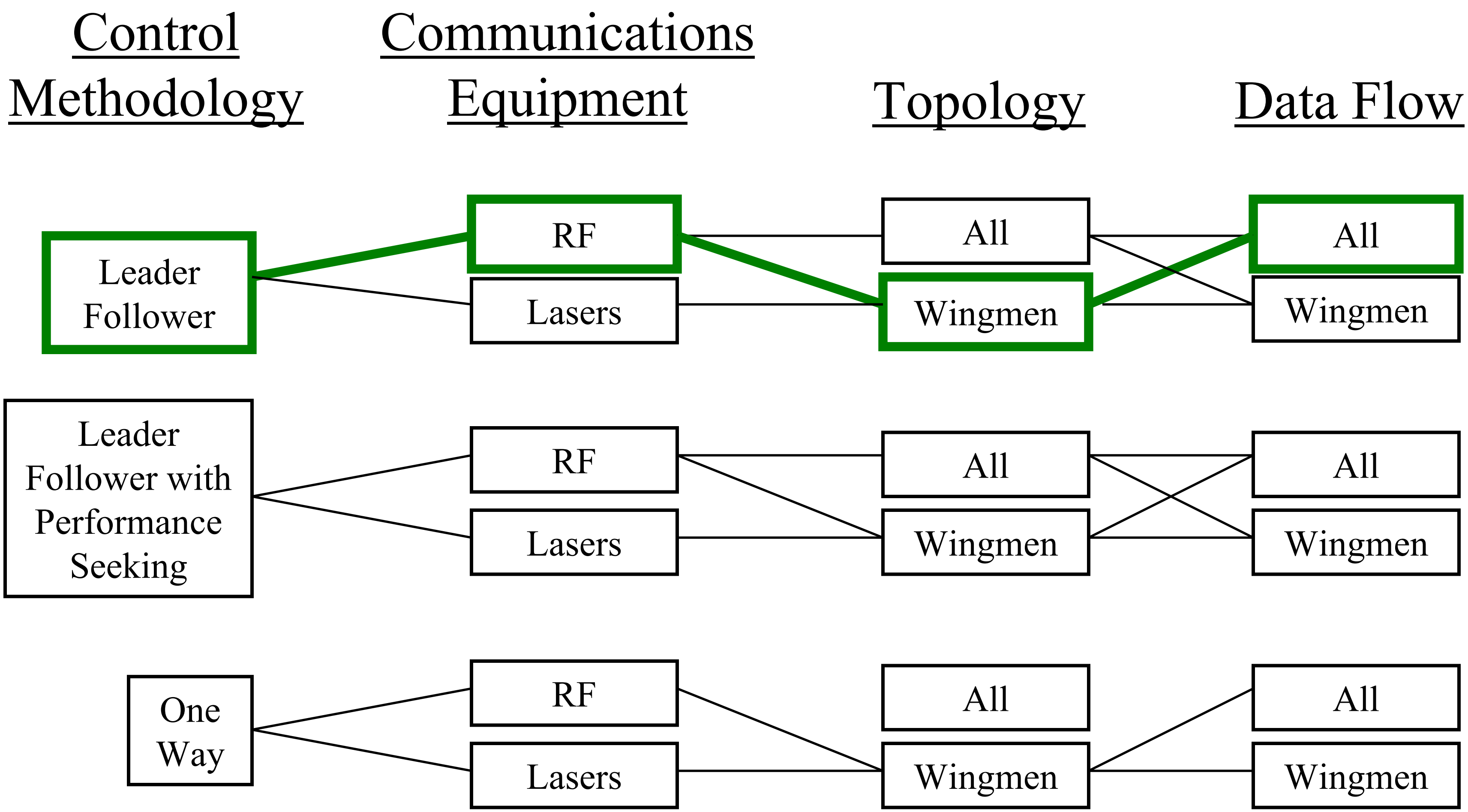
Minimum fuel savings upper and lower bound in function of the precision of the station-keeping



System Goals

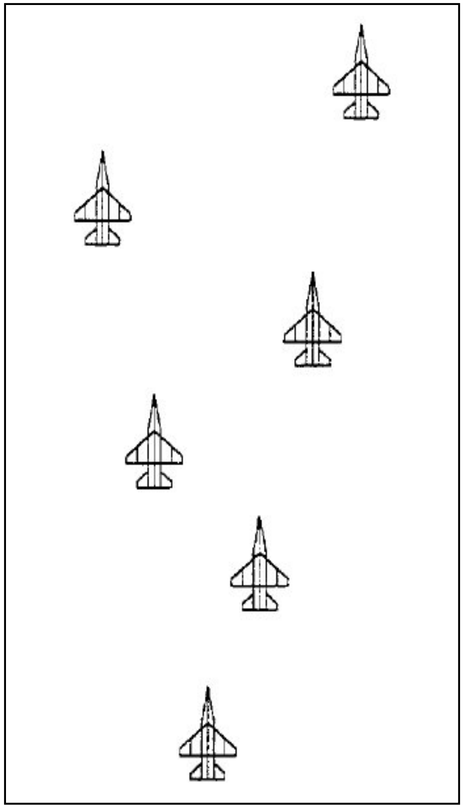
- The benefits of formation flight to the existing commercial cargo system are the easiest to quantify, VALUE = $$$
- The development and implementation would be similar across all applications
- Preliminary results are easier to obtain and can be applied to military or new aircraft programs
- Commercial missions are simple and scheduled
- Military:
  - Value is difficult to quantify
  - Missions are more variable and aircraft are less utilized than commercial aircraft
- Justification for development is easier to make in commercial terms
- Large share of the commercial cargo market is at stake

Architecture Decisions

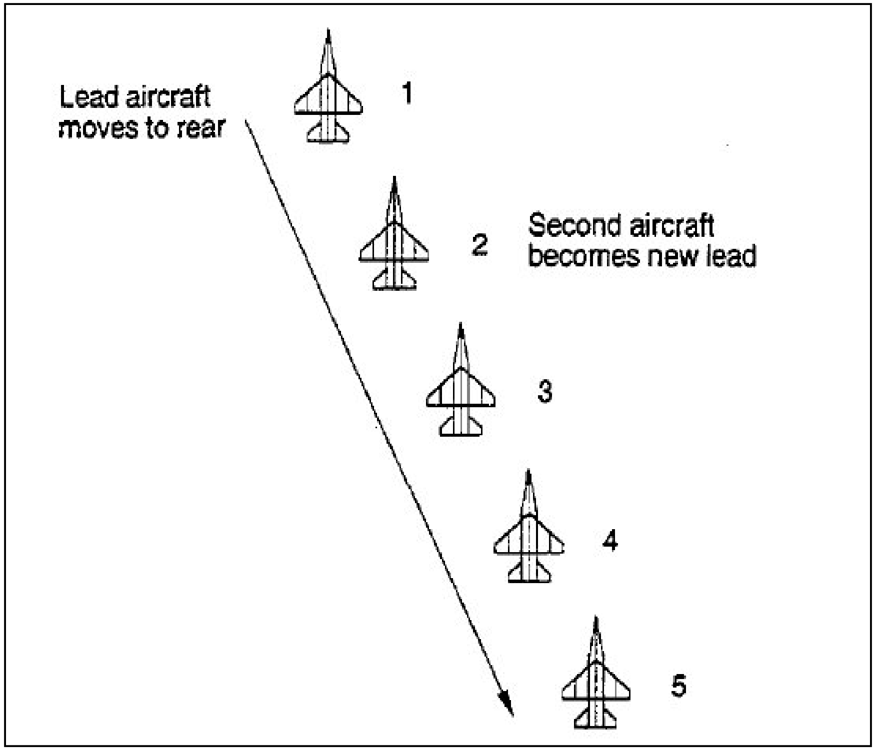


Architectures - Formation Shapes

Staggered chevron



Rotating echelon

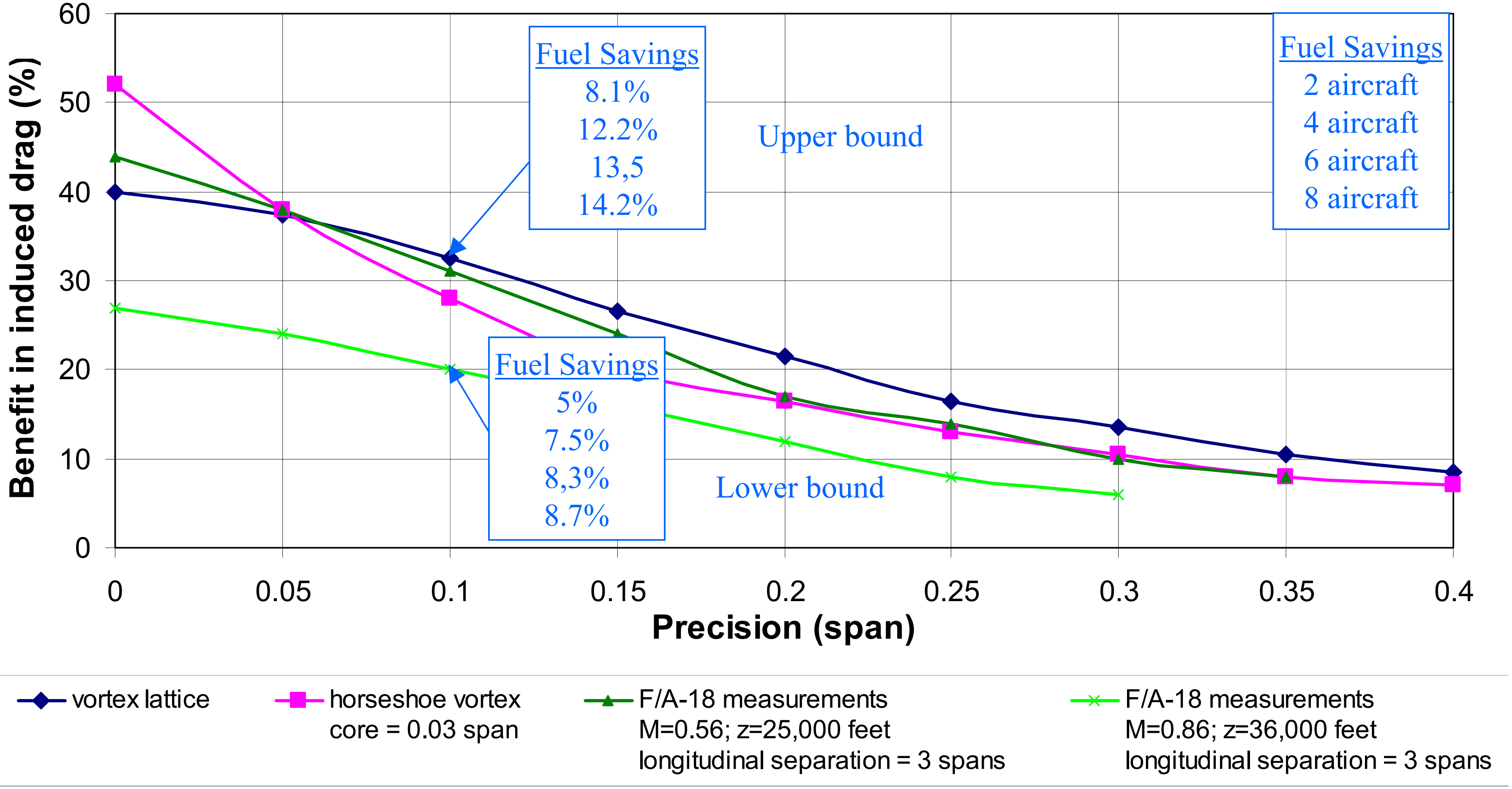


Both optimum in terms of fuel savings

If we want range increase: need for rotation

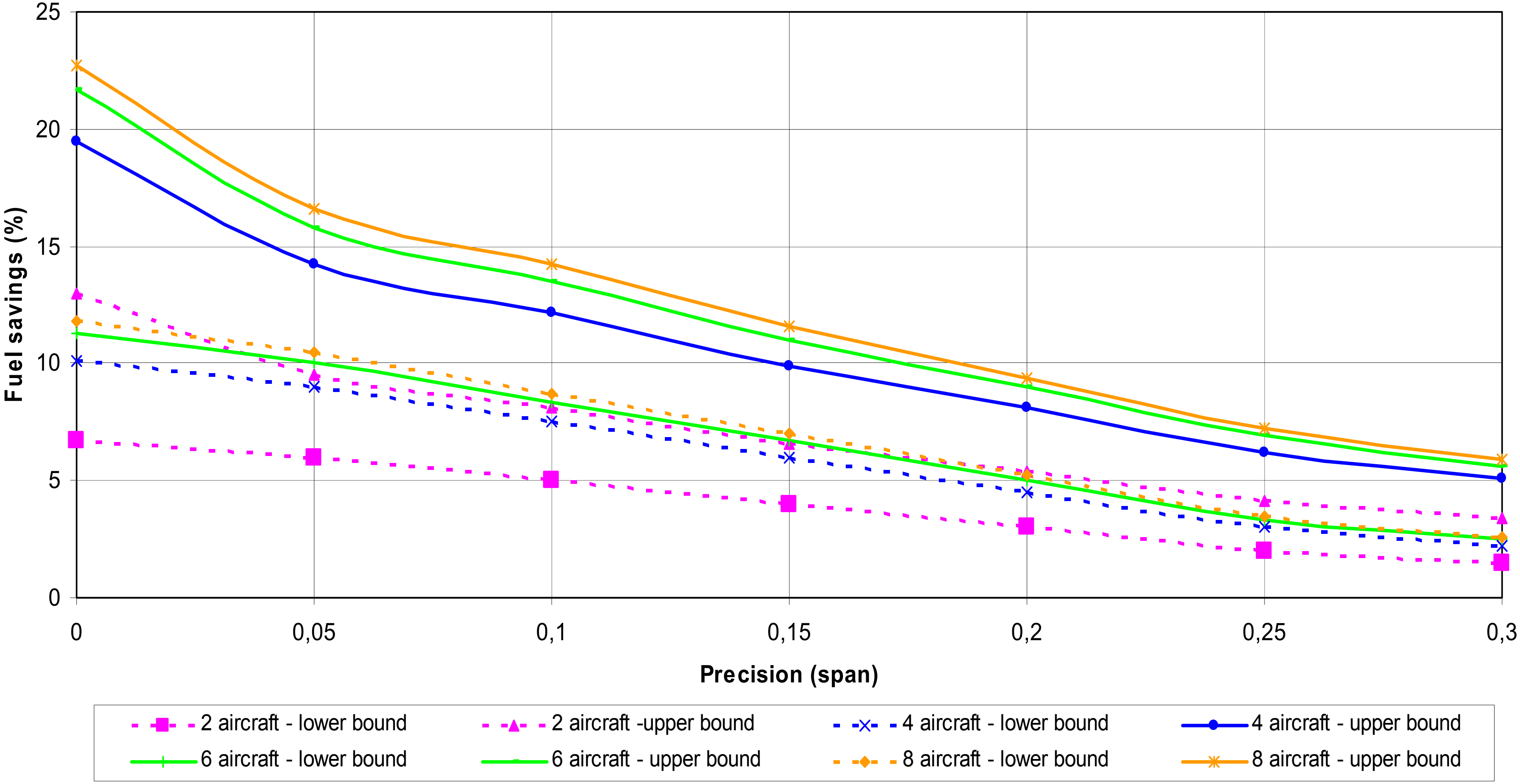
Evaluation – Performance Benefits

Minimum induced drag benefit in function of the precision for the follower in a two- aircraft formation



Evaluation – Performance Benefits

Minimum fuel savings upper and lower bound in function of the precision of the station-keeping



Control Architectures - Options

- Model-based Methods
  - More traditional, proven in other applications
  - Smaller development effort & risks to implement
  - **Types**
    - Trajectory Tracking
      - Simplest to implement and predict behavior
      - Operationally inflexible
    - Leader-Follower
      - Proven outside of vortex in flight tests
      - Theoretically modeled optimal position not necessarily so in practice
      - Many different ways of implementing
        - » Leader, front and hybrid modes
        - » Centralized or decentralized

Control Architectures - Options

- Non Model-based Methods
  - Generally experimental, some use in loosely related applications
  - Larger development effort & risks to implement
  - Potentially greater performance benefits than model-based methods

  - **Types**
    - Performance Seeking
      - If working correctly will actually find the minimum drag location based on actual flight data
      - Easily side-tracked by local minima
      - Works better in conjunction with position-hold algorithm

    - Neural Networks
      - Relative position sensing not required
      - Requires comprehensive training set
      - Tough to certify due to unpredictability when a condition outside of the training set is encountered

    - Vortex Shaping
      - Requires extensive wing modifications (plus related development cost) to existing aircraft
      - Theory not yet well developed enough to predict effects of changing wing geometry on vortex position

Control Architectures - Most Promising

- Leader-Follower Methods
  - Some obvious problems with all other methods, including:
    - Certification issues
    - Large uncertainty/risks associated with unproven technologies
    - Simply cannot meet performance requirement
- Three better implementations of this method
  - Centralized Leader-Follower
  - Centralized Leader-Follower with Performance Seeking
  - De-Centralized Leader-Follower

Centralized vs. Decentralized

- Centralized
  - Higher level system decision-making
    - Enhanced coordination
    - Greater performance level
  - Lower algorithm complexity
  - Preferred for simple missions where performance is a priority
    - Commercial flight
- Decentralized
  - Distributed decision-making can result in conflicting decisions
  - Robust, flexible
  - Formation reconfiguration is easier
  - Lower information requirements
  - Preferred for complex missions, particularly where # of airplanes in formation is expected to change
    - UAVS
    - Other manned military operations such as bombing multiple targets

Control Architectures - Decision

- Centralized Leader-Follower:
  - Single leader aircraft within the formation that issues commands to all other aircraft
  - Leader:
    - Receives relative & absolute state information from all planes
    - Acts as DGPS base station
    - Issues commands designed to:
      - Maintain overall formation shape with planes offset by required amount
      - Anticipate planned future maneuvers (feed-forward)
  - Followers:
    - Receives state commands from leader, computes how to execute them
    - Sends aircraft state information to leader

Expected Control Performance

- Autonomous formation flight in the wingtip vortex has never been done!
- Expectation:
  - Control within 0.1b of required relative position may be achieved with this method
  - If not, performance-seeking control may be pursued as a further refinement
- Baselines:
  - NASA AFF project
    - Flight test with two F/A-18s, decentralized leader-follower
    - Out of vortex lateral/vertical accuracy +/- 9ft (~0.2b)
    - Algorithm NOT tweaked or optimized
  - Proud, Pachter, D'Azzo
    - Simulation with two F-16s, decentralized leader-follower
    - Met 0.1b performance requirement for level flight and maneuvering flight under the following changes:
      - Lead heading change of +/- 20 degrees
      - Lead velocity change of +/- 50ft/s
      - Lead altitude change of +/- 400ft
  - Centralized leader-follower would have similar results for these 2 aircraft configurations
  - Many other simulations using leader-follower strategies within this range
  - Subject matter experts (Deyst, How) optimistic method can achieve 0.1b accuracy based on experience with UAVs

Position and Velocity Sensing - Options

- Possible solutions with required accuracy

Solution	Advantages	Disadvantages
Coupled Carrier-Phase Differential GPS and IMU	• Most conventional solution • Proven to work in NASA AFF flight tests and other formation applications	• Complexity in achieving desired accuracies • Occasional large errors when formation aircraft observe different satellite sets
Lasers	• Low observability • Best accuracy, used as 'truth case' baseline for comparison to other methods • Small size • Already in use on all C5's, many potential space applications	• Highest cost • Level of accuracy really is not required • Unless omni-directional, must be directed • Reliability difficulties in some weather conditions
Optical Camera	• Once aimed, does not require continuous communications link	• Camera must be initially aimed using rougher position data • Requires target to have specially placed markings
Electromagnetic Pulses	• Low complexity • Sub-foot accuracies easily achieved • Possibly low cost, but a question mark	• Most unconventional, unproven solution • More development required, though can leverage existing radar technologies

- Can have multiple systems for backup
  - Collision avoidance, loss of primary sensors

Position and Velocity Sensing - Decision

- Primary system: Carrier-phase differential GPS and IMU
  - 0.2 in accuracy theoretically possible for surveying applications
  - 1 foot accuracy in relative position in practice for formation flight (NASA Dryden experiment)
  - Leader acts as DGPS base station for relative positioning and sends satellite errors through intra-formation communications system
- Backup system: Optical Camera
  - Different technology than primary system for robustness
  - Machine vision tracks markings placed on adjacent aircraft and uses size to determine separation

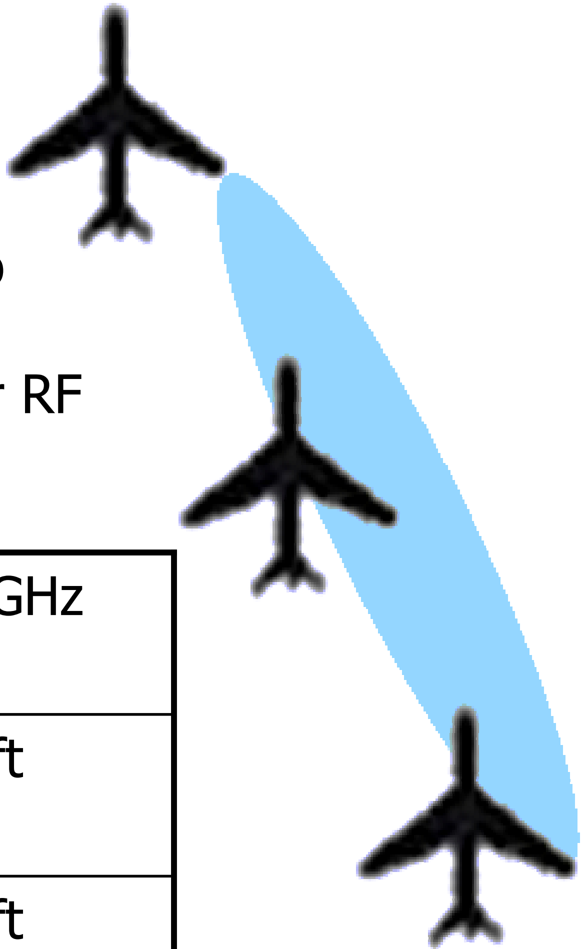
Communications - Options

- Possible solutions able to meet requirements

Transmission Technology	Advantages	Disadvantages
RF Line of Sight	• Used for other many other common applications • Transmitters and receivers commercially available • Low cost	• Additional antennas need to be installed on exterior of A/C • May have conflicts with other equipment or frequencies • Line of sight required for transmission
RF Satellite	• Currently in use for other commercial applications • Avoids line of sight requirement	• Higher cost • Half-second delay • Requires use of external satellite system
Laser, Infrared, Other	• Low observability • Less likely to conflict with existing equipment	• Higher cost to implement • Shorter range for infrared • May have weather issues

Communications: Why relay?

- Non-adjacent aircraft cannot be connected via direct RF links because aircraft in between block the Fresnel clearance zone necessary for radio transmission
- HF band, which bounces off ionosphere, already too saturated, and has low data rate
- Table shows size of 60% Fresnel zone necessary for RF comm for aircraft in configuration to the right with adjacent aircraft 7 spans apart



(Lateral offset is assumed to be small compared to longitudinal distance for purposes of estimate)

A/C \ Freq.	2.4 GHz	5.8 GHz
B757 (125 ft span)	10.4 ft	6.7 ft
A380 (262 ft span)	15.0	9.7 ft

Calculated using Fresnel Zone calculator at:
http://www.firstmilewireless.com/cgi-bin/fresnel-calc.pl

Data Update Rate Available

- Calculation of available data rate:
  - Let each "message" contain data about one aircraft
  - Assume 20 32-bit numbers need to be transmitted per message to cover all data transfer
    - Includes approximately 9 aircraft states, DGPS errors for up to 5 satellites, aircraft ID, time of measurement, 4 control commands
  - Assume data rate at long distances at high altitude degraded from 11 Mbps on ground for commercial wireless technology to 3 Mbps = 3,000,000 bits per second (not 2^{20} bits)
  - For n aircraft in formation, if only one can transmit at a time, n*(n-1) messages must be sent to update all aircraft with all other aircraft information
  - Total of 20*32*n*(n-1) bits to update all aircraft
  - n*(n-1)/5000 seconds for full system update

# of aircraft in formation	2	3	4	5	6	7	8	9	10
Full system update time	0.4 ms	1.2 ms	2.4 ms	4.0 ms	6.0 ms	8.4 ms	11.2 ms	14.4 ms	18.0 ms

Required Data Update Rate

- Function of how dynamic environment is
  - How quickly the vortex is moving around
- Want to update faster than the frequency of actual movement
- Basic range: 1-100Hz
- NASA AFF program had 40Hz local and 10Hz relative position and state rates
  - Starting point for the proposed system

Pilot Interface

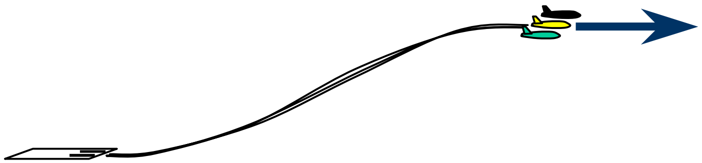
- Flight Display on ND 1 & 2:
  - Same functions as the standard ND with a close-up view on the formation
  - Predictive display of the position of the surrounding planes with safety distance thresholds associated to alarms
  - Flying mode (leader/follower)
  - Graphical display of the route followed by the formation

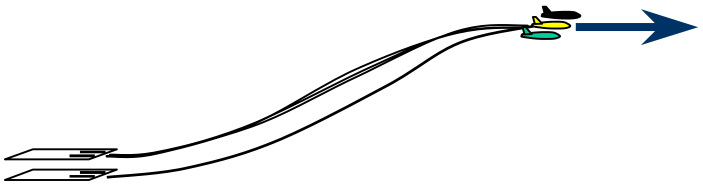
Pilot Interface

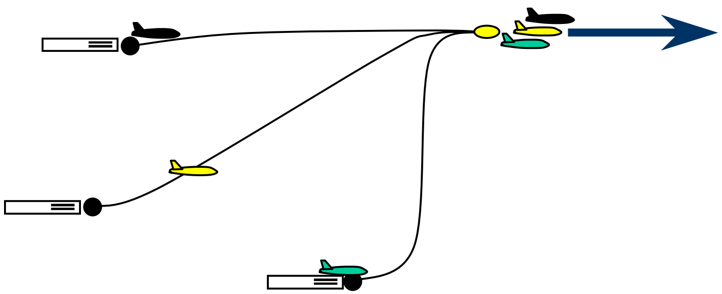
- CDU pages dedicated to formation flight
  - Status and route of the formation:
    - Input set by the leader in "leader mode"
    - Updated automatically from the leader for planes in "follower mode"
  - Status of the formation software characteristics and the associated alarms (shown on the System Display)
    - Possibility to check how the system is running
    - Display of visual and acoustic alarms

Those pages can be similar to the ones already in use. It all depends on the autopilot system chosen for our concept.

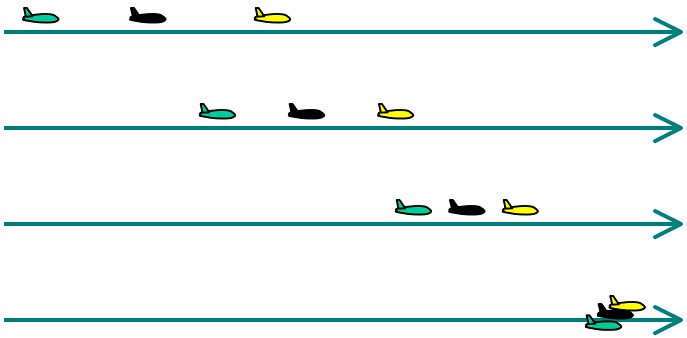
Take-off configurations

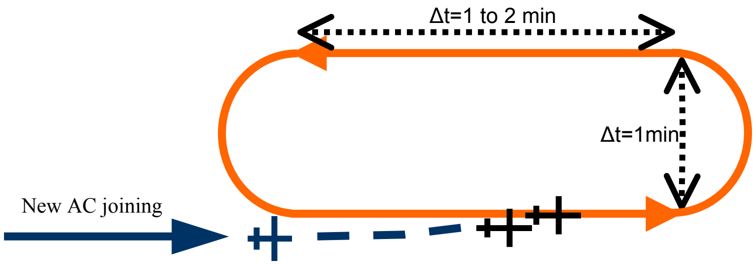


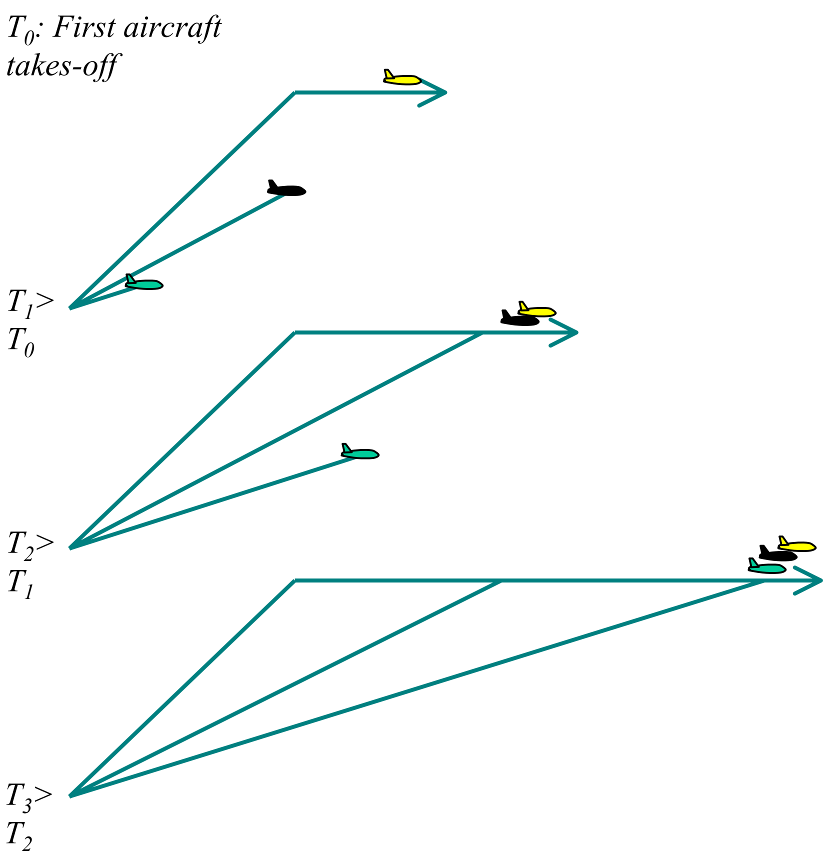




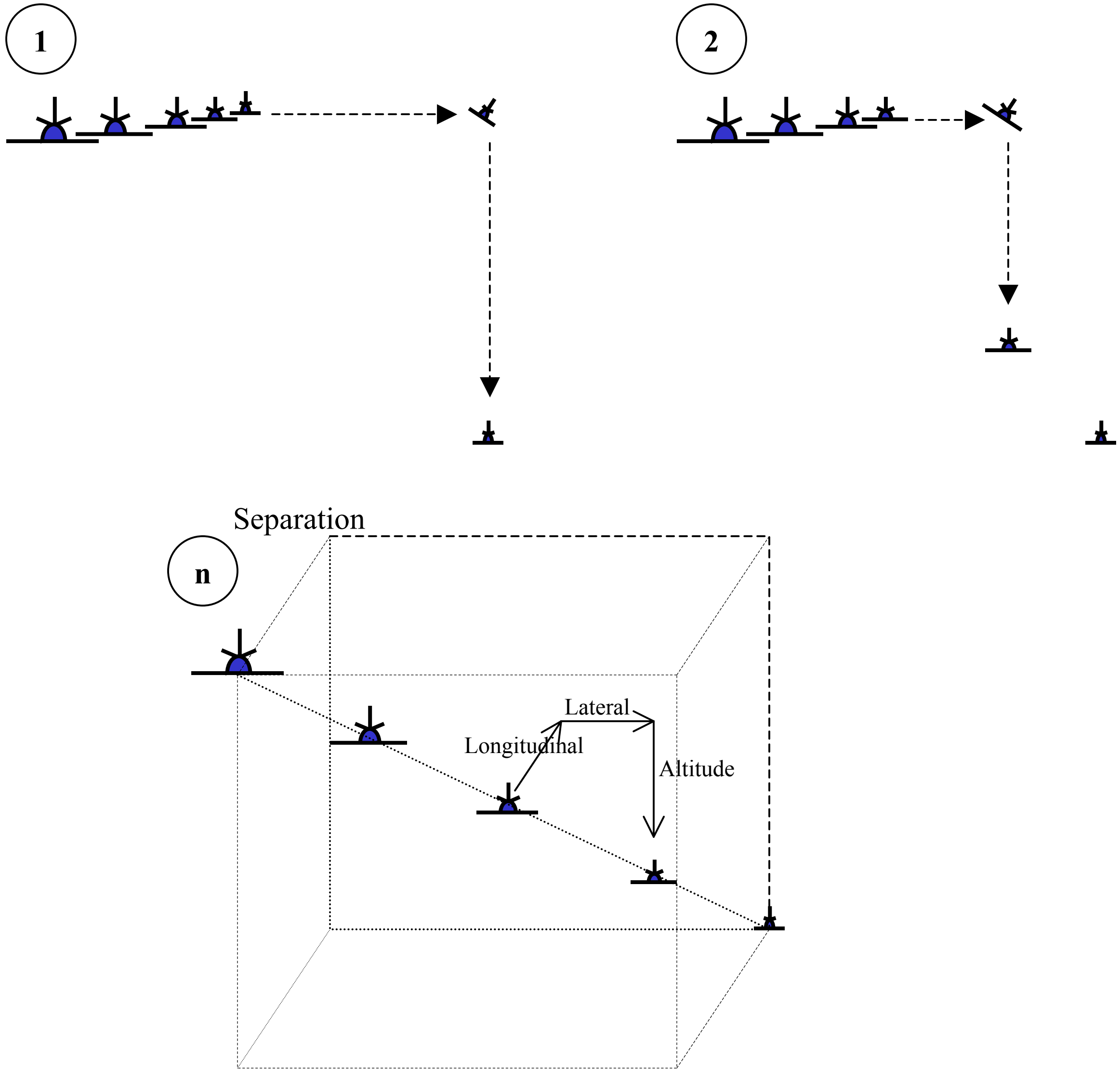
Join-up configurations



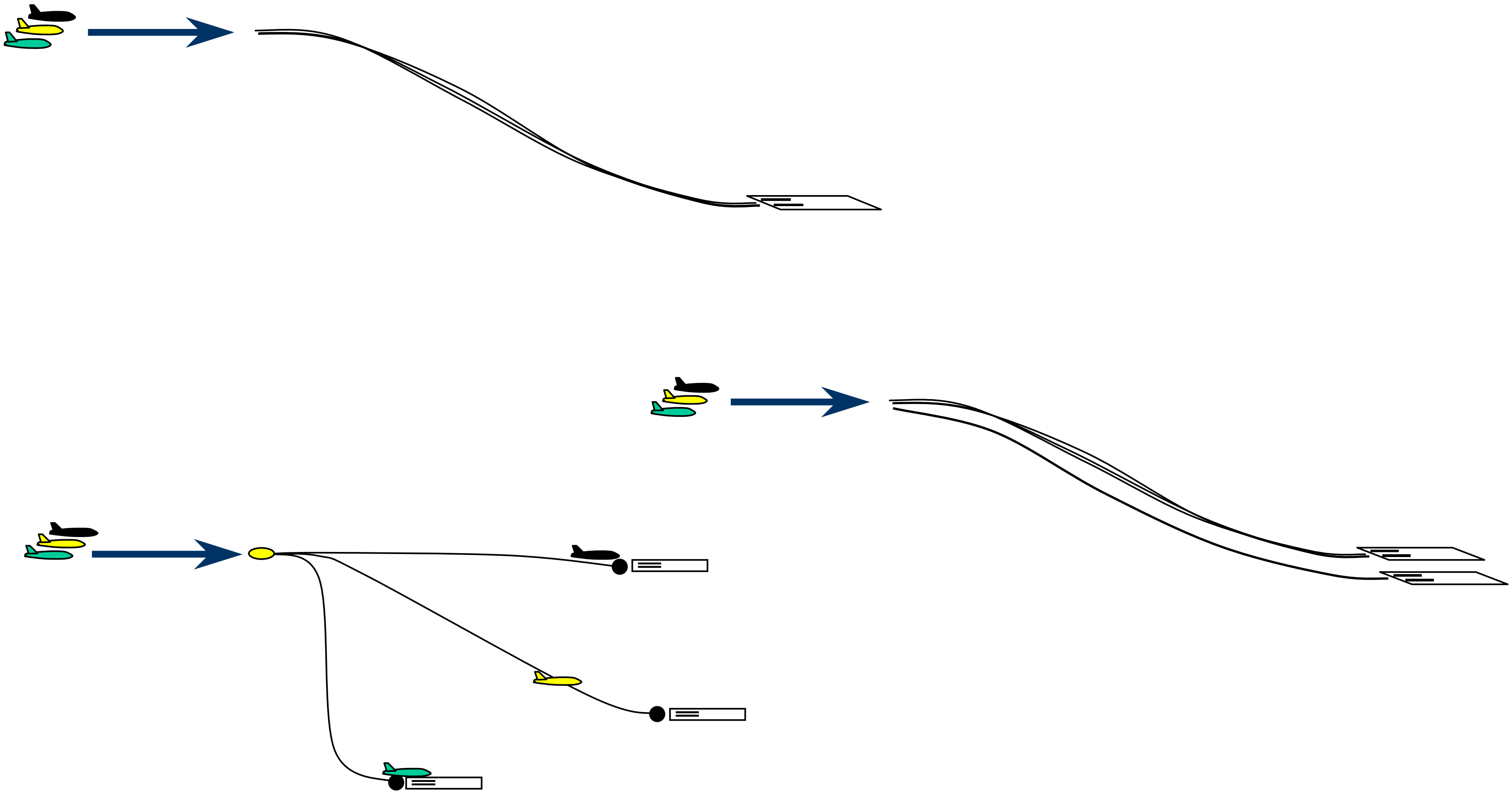




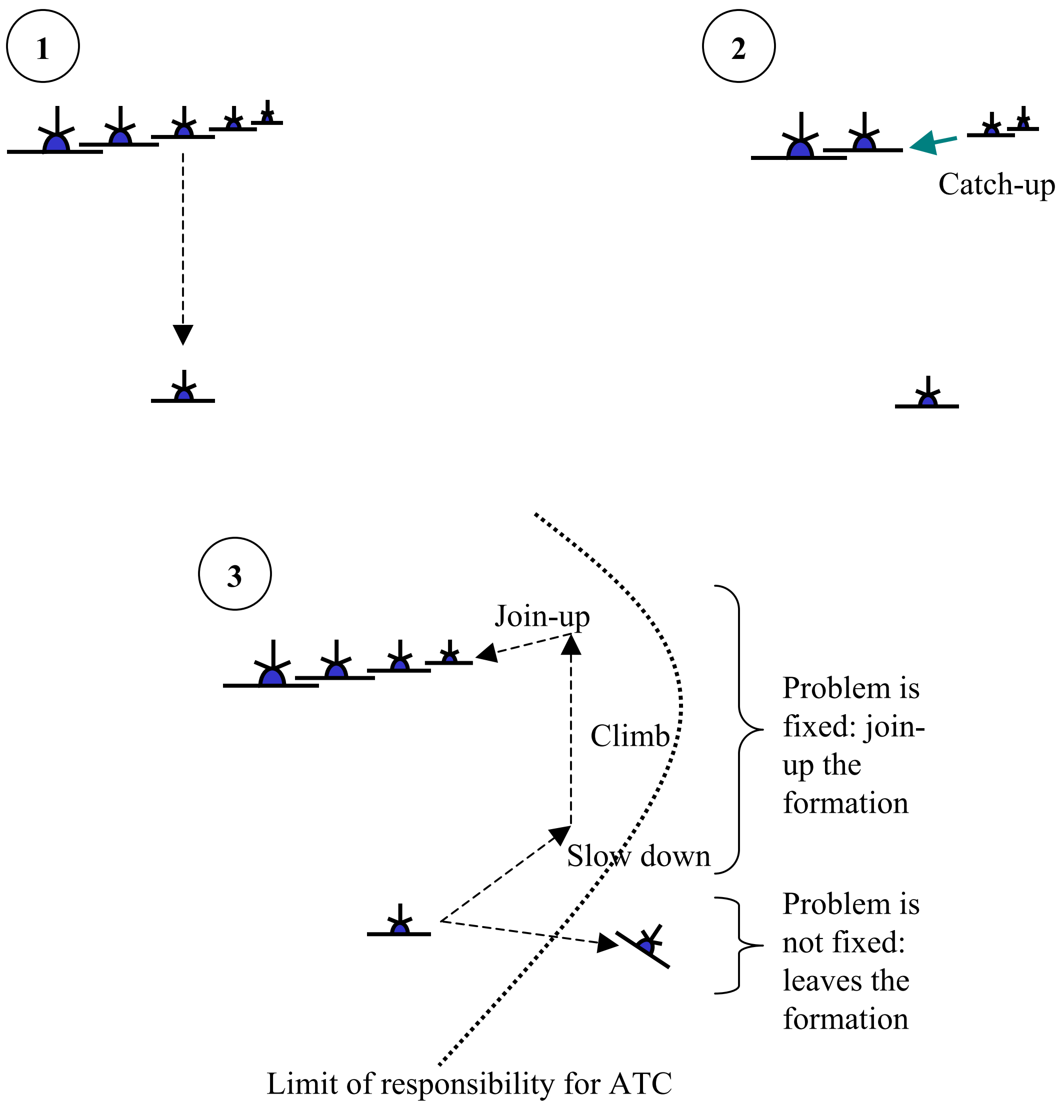
Break-away Procedures



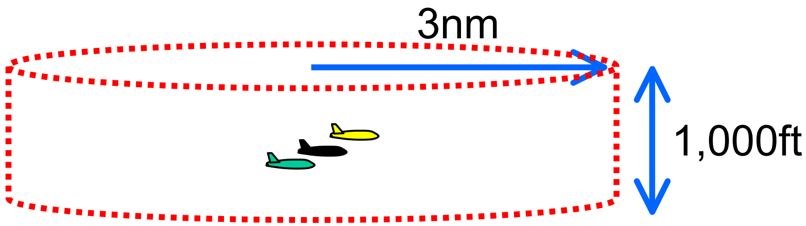
Landing configurations

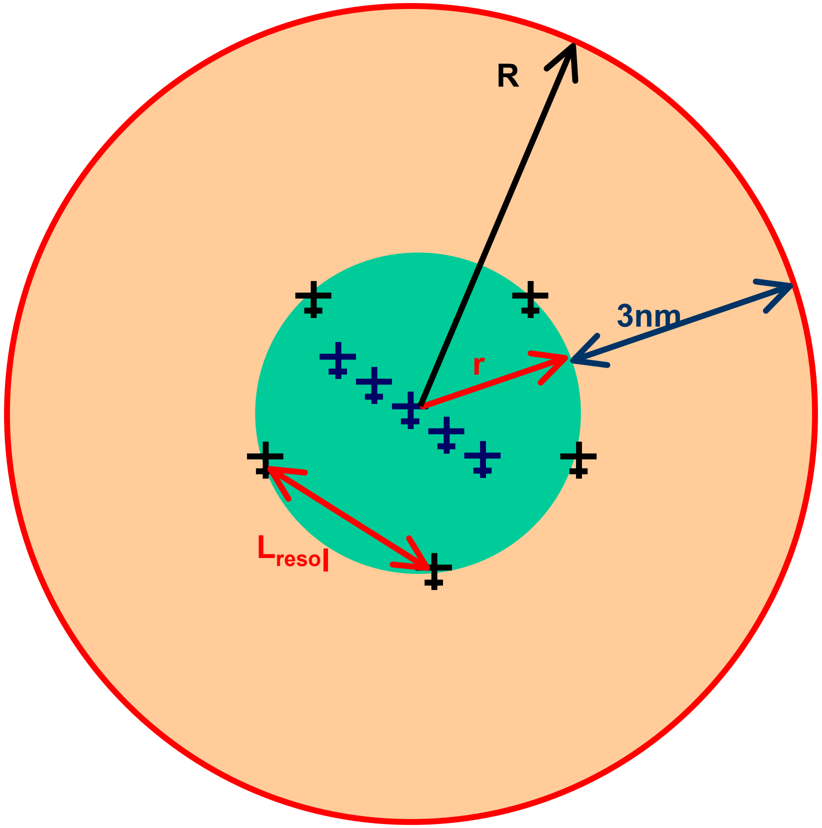


Unexpected break-away Procedures



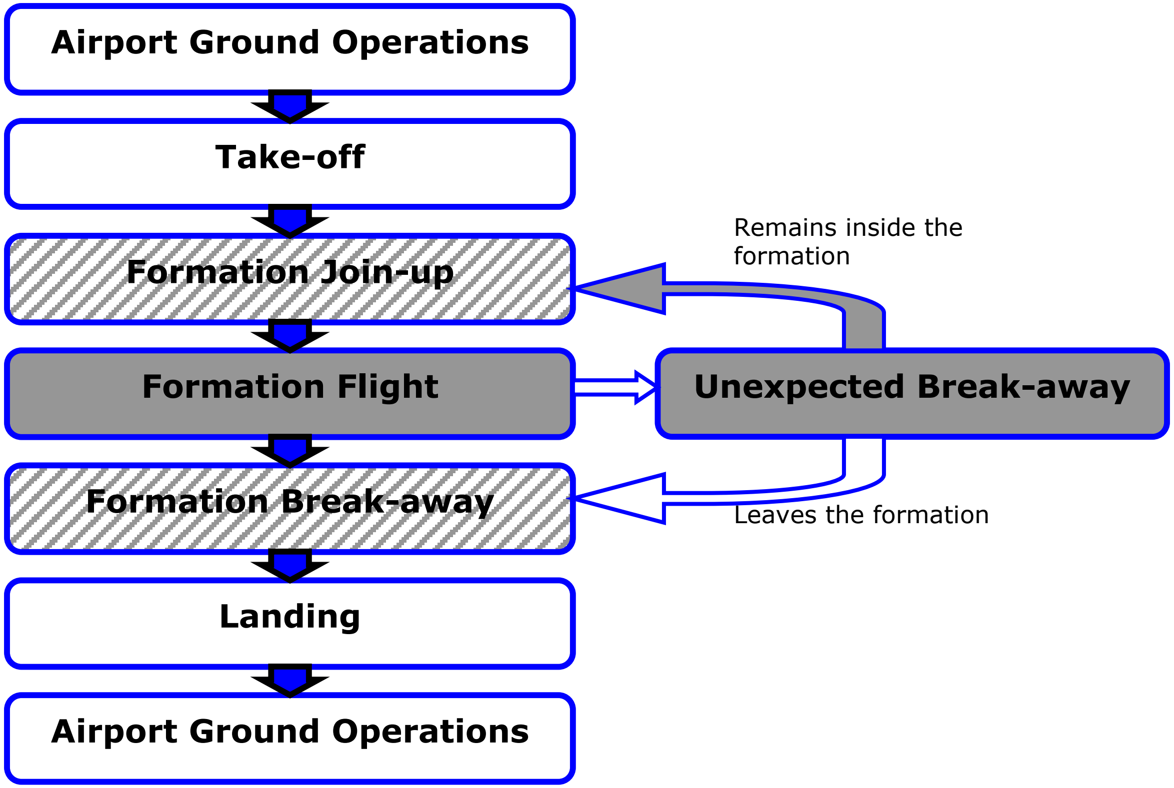
Minimum Separation Criteria



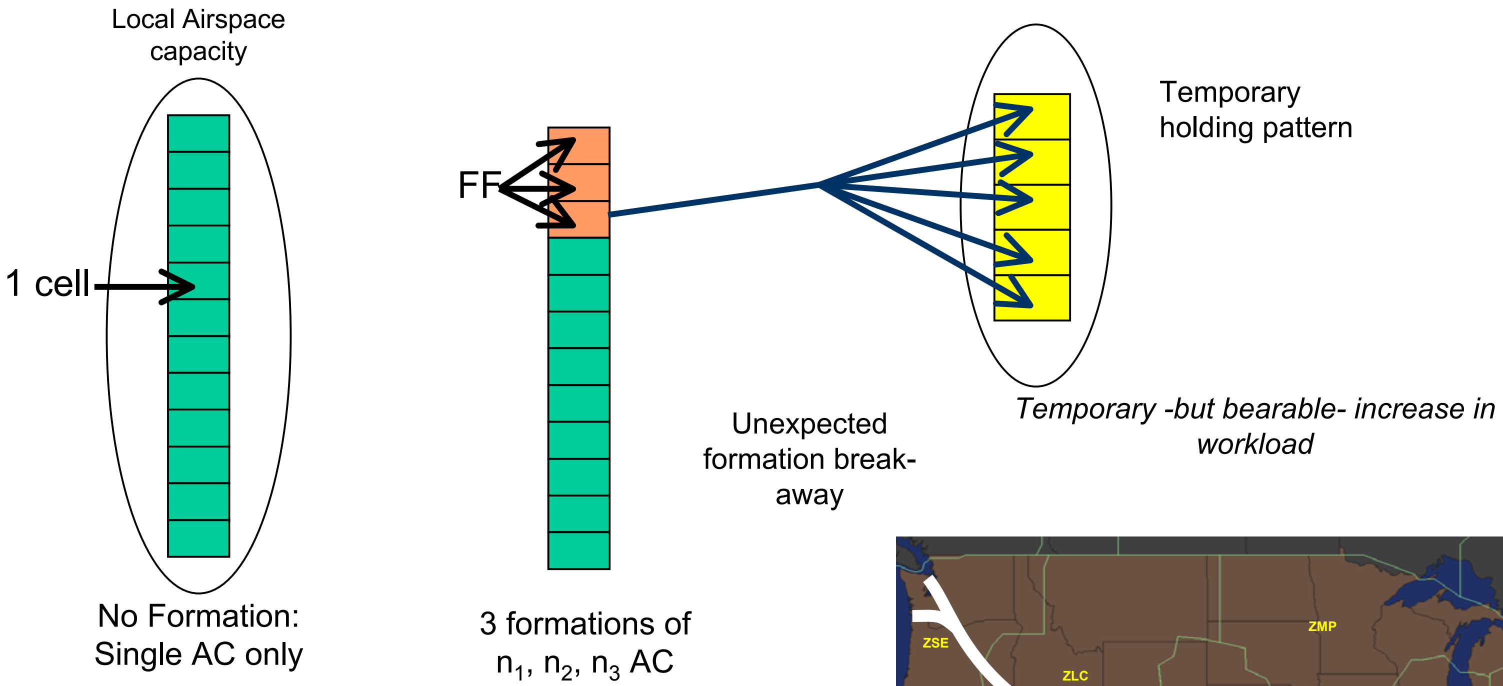


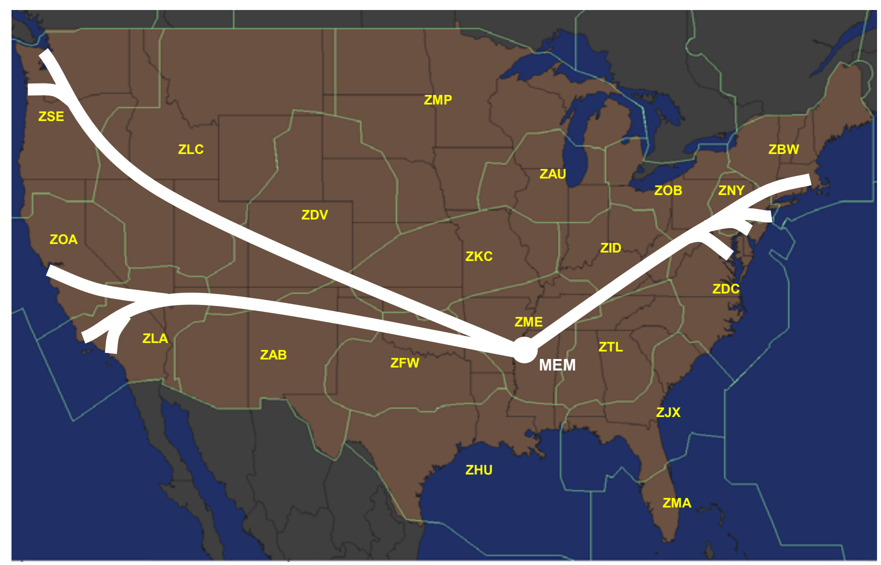
n	2	3	4	5	6
r	.50	.58	.70	.85	1.0
R	**3.50**	**3.58**	**3.70**	**3.85**	**4.0**

Safety Responsibilities

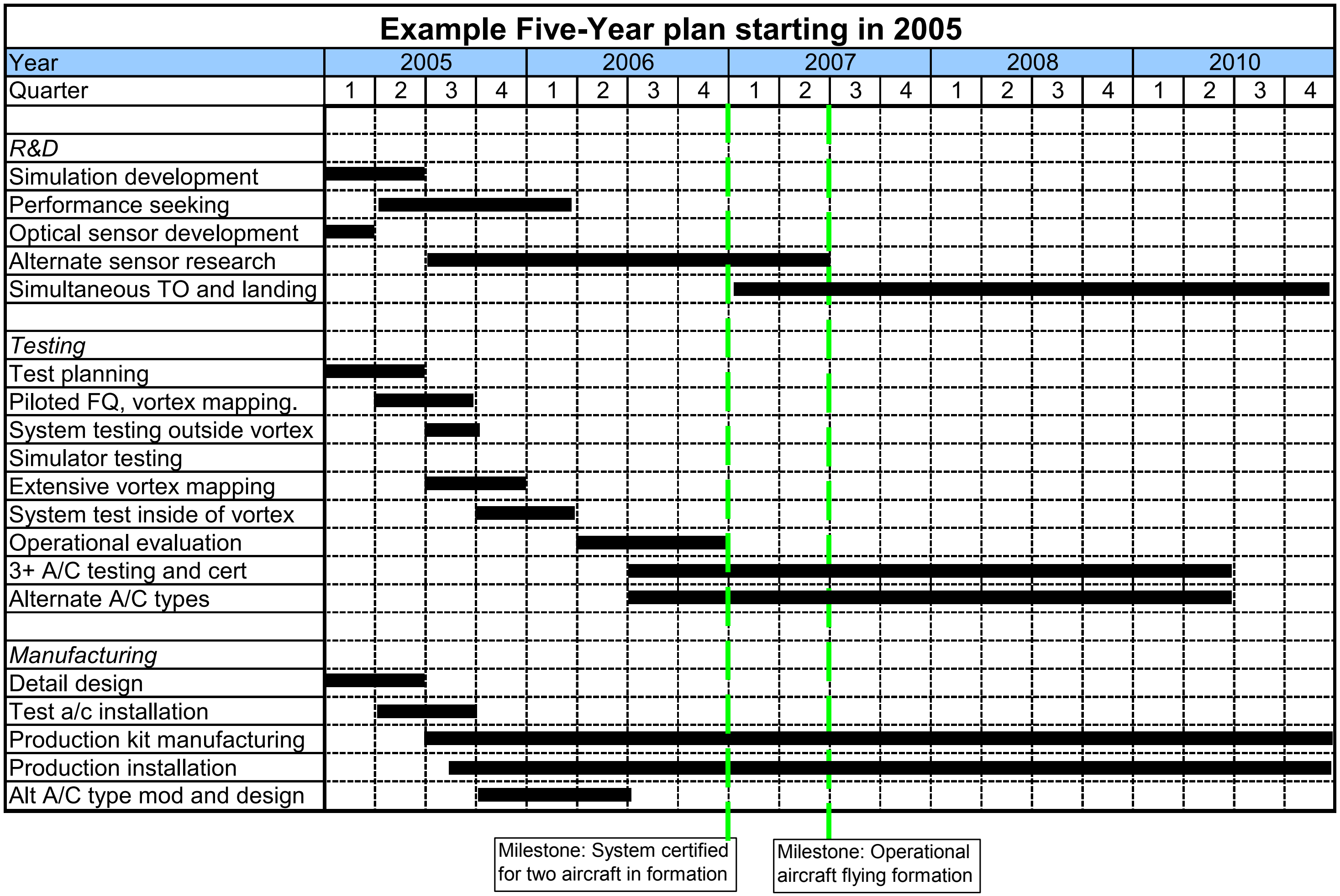


NAS Capacity & ATC Workload





Development Timeline



Hazard Analysis

Event	Consequence	Severity	Probability	Mitigation Strategy
Leader's communication system fails	No aircraft know where to go	Low	Moderate	Another aircraft is prepared to become leader when it stops hearing from leader
Two aircraft think they're leaders	Possible collision	High	Moderate	Make sure this can't happen
Non-leader transmit failure	Leader doesn't know where all aircraft are, possible collision	High	Moderate	When communication stops, break up
Non-leader receive failure	Aircraft doesn't know where to go (it leaves the formation)	Low	Moderate	When communication stops, break up
Position sensor failure	Leader gets wrong data, possible collision	High	Low	Make sure prob is low with redundancy in position sensors
Leader has an engine failure	Leader loses thrust, slows down, possible collision	High	Moderate	Enough spacing, all aircraft can act as leaders, breakup planning
Non-leader has an engine failure	Same as above (unless if it's the last aircraft)	High	Moderate	Enough spacing to handle this event, communication of warnings to other aircraft
Common mode engine failure (e.g. formation flies through ash)	Possible collision	High	Low	Make breakup plan robust to common problems

Hazard Analysis 2

Event	Consequence	Severity	Probability	Mitigation Strategy
Common mode communication failure(e.g. static electricity)'	Possible collision	High	Low	Breakup must not require communication
Pilot misinterprets display and takes over when he shouldn't	Possible collision	High	Moderate	Make display & warnings clear as possible
Pilot misinterprets display and doesn't take over	Possible collision	High	Moderate	Make display & warnings clear as possible
Software error in leader's position software	Possible collision	High	Low	Good software planning & testing
Icing, one aircraft more than another	Aircraft have different aerodynamic loads and go at diff speeds	Moderate	Low	Don't fly in icing conditions
Aircraft control system failure	Aircraft cannot take desired position or leave the formation, possible collision	High	Moderate	Aircraft remove themselves from formation when anything fails
Some other aircraft system failure	Any of a number of things, including a possible collision	Moderate	Moderate	Aircraft remove themselves from formation when anything fails
Common-mode control system failure	All aircraft lose control and have very high probability of collision	High	Low	Breakup strategy is robust to common errors

Certification Plan

- Software to DO-178B (Level A/B/C)
- Minimize intrusion/changes into existing avionics
- Certifiability
  - Early FAA consultation critical
  - Testable
  - Predictable
  - Redundant