Formation Flight Feasibility Study

Outline

- Motivation and goals
- High-level architecture
- Key tradeoffs and relationships
- Component descriptions
- Procedures
- Program plan
- Business case
- Conclusions

Results

- There is a business case for implementing formation flight in the long range widebody cargo aircraft market
  - The business case is close for medium range
  - There is probably not a case for short range
- There is a likely market in long-range aircraft large enough to cover development costs
- Fuel benefits from formation flight range from 5% to 20% for 2 to 5 aircraft formations
- Critical needs:
  - Detailed market and cost study
  - Flight tests

Motivation

- **Why formation flight?**
  - Flying at a given spot in the wake of another aircraft can decrease induced drag
- **Why now?**
  - New advances in software and GPS have enabled position-keeping
    - NASA AFF program
  - World air cargo traffic growing on average 6.4% per year in the next 20 years
    - Asian market growing at 10.3%
  - Fuel prices increasing (44% over the past year)
    - Demand for technology to lower fuel costs
    - Fuel costs normally 12-18% of total airline costs

System Goal

To enable existing commercial cargo aircraft to fly in formation, in order to achieve cost savings, increase range, and increase airspace capacity.

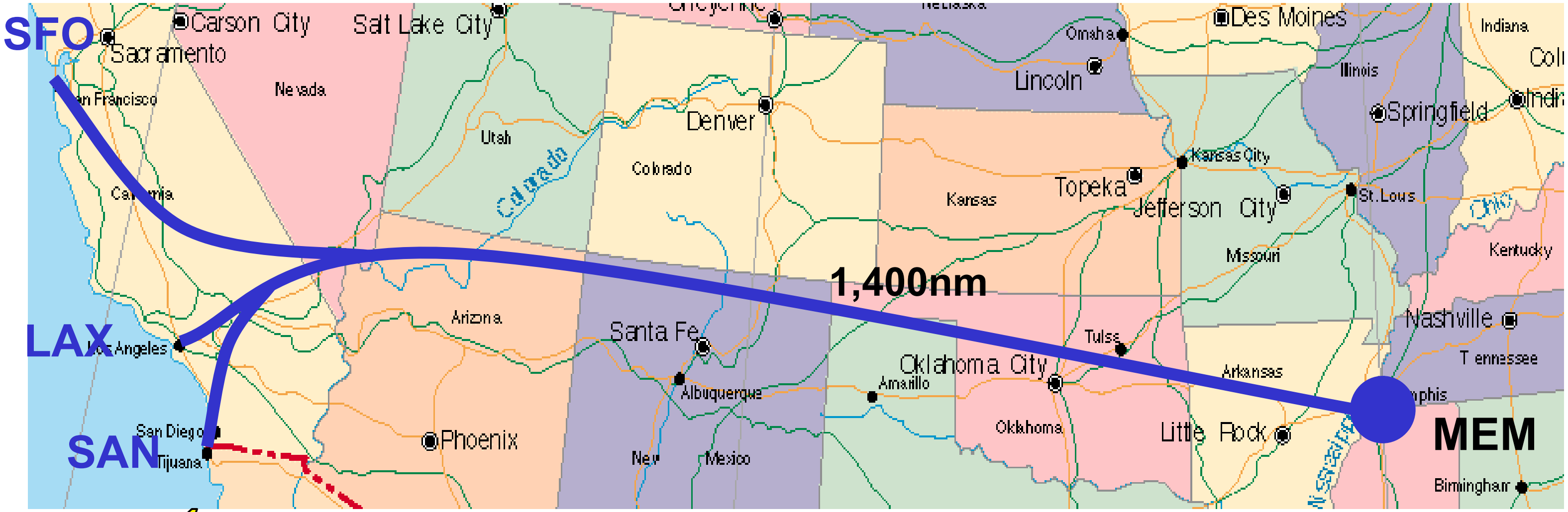
Includes:

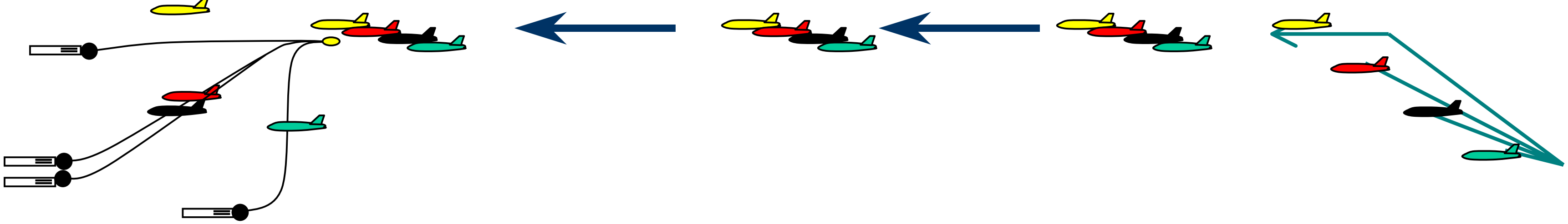
-A set of physical components

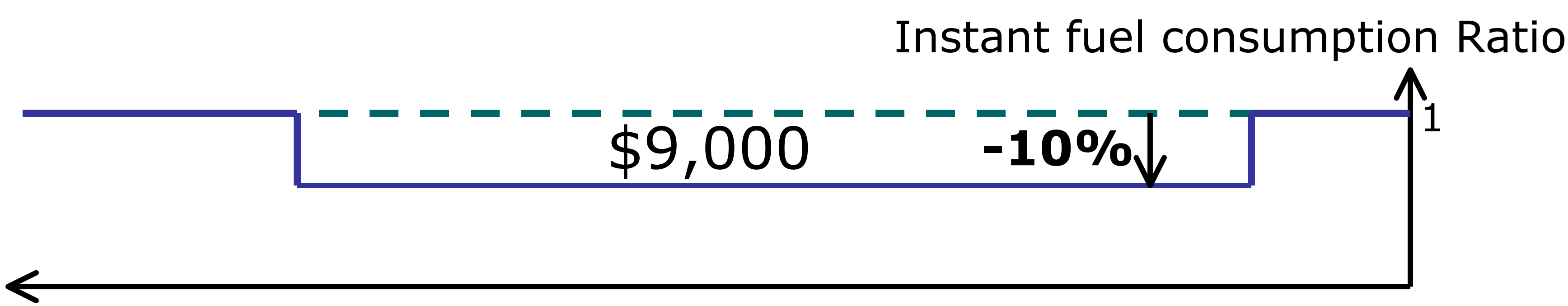
-Procedures within the air transportation system

-Development and implementation plan

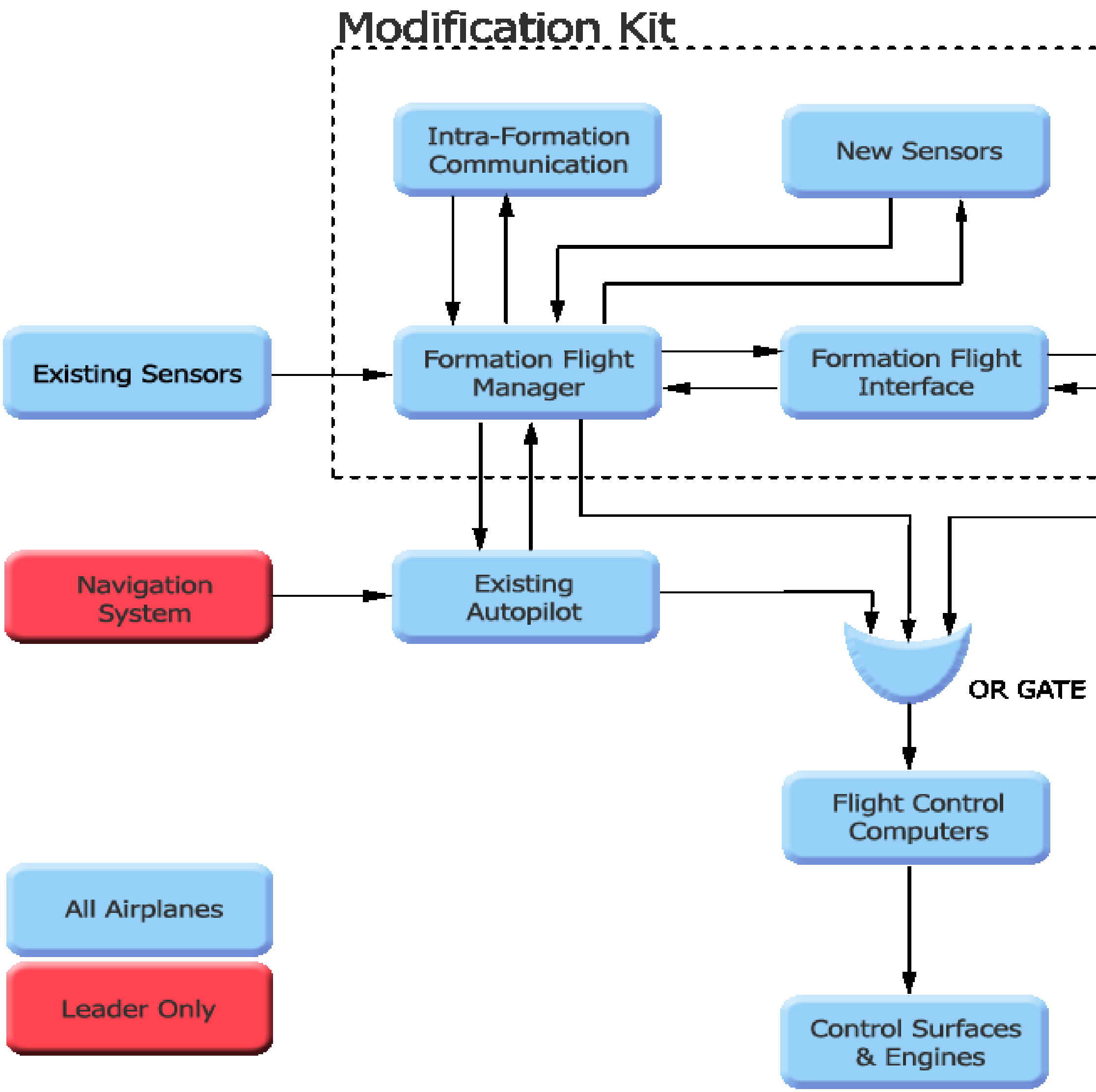
Mission Overview: Example







System High-Level Architecture



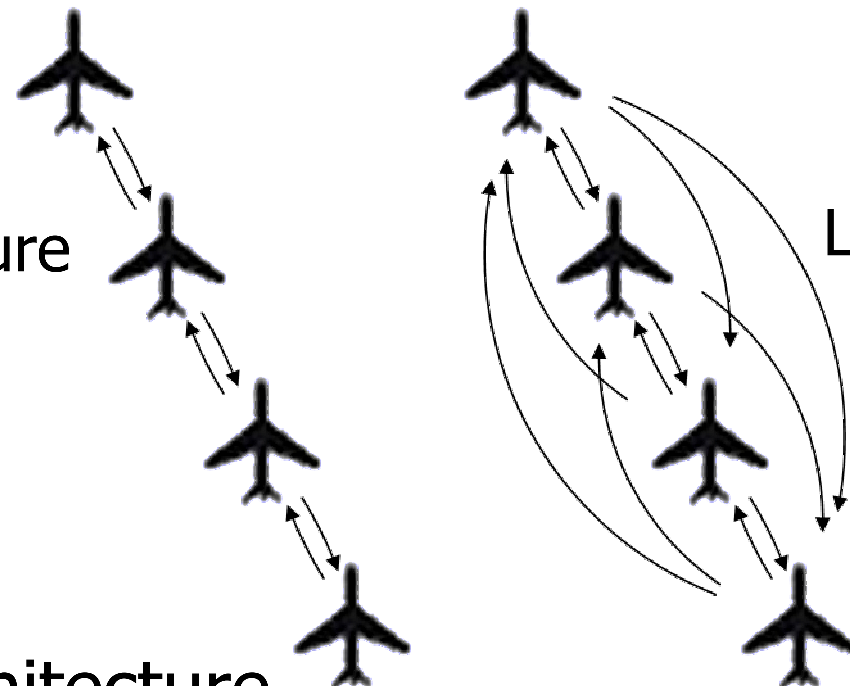
Key Tradeoffs

Variable	Advantages	Drawbacks
↑ precision	↓ drag	↑ cost
↑ system integration level	↑ precision	↑ cost ,↑ risk ↑ development time
↑ new technologies	↑ precision	↑ risk, ↑ cost
↑ no. of aircraft in formation	↓ drag ↓ congestion	↑ ATC separation ↓ string stability ↑ controller workload
↑ types and no. of aircraft certified to fly in formation	↑ operational flexibility	↑ size of test matrix ↑ mapping matrix ↑ time to certify
↑ ATC separation buffer	↑ safety	↑ congestion

Formation Flight Manager

- Functions
  - Produce heading, velocity, altitude commands to existing autopilot
    - Alternative: Entirely new autopilot generating control surface deflections
  - Interface with pilot
  - Channels required information to communications link
- High-level control strategy: Centralized leader-follower
  - Leader
    - Issues commands to follower aircraft to optimize formation trajectory
    - Provides timely information for anticipation of maneuvers
  - Follower
    - Generation of control commands to reach leader-specified positions
  - Refinements
    - Performance-seeking control

Inter-Aircraft Communications



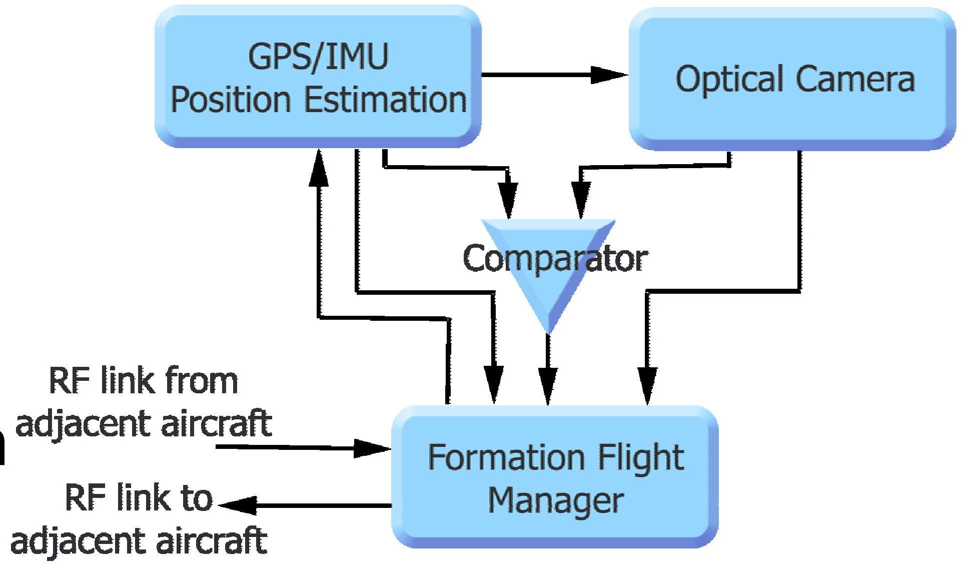
- Physical architecture
  - All aircraft communicate only with adjacent aircraft via radio link
- Logical architecture
  - All aircraft have information about all other aircraft

Pilot Interface

- Flight Display on ND 1 & 2:
  - 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
- CDU pages dedicated to formation flight:
  - Status and route of the formation, updated automatically from the leader
  - Status of the formation software characteristics and the associated alarms

Position and Velocity Sensing

- Primary system
  - Coupled carrier-phase differential GPS and IMU
- Backup system
  - Optical Camera
    - Aimed using GPS/IMU data
  - Constantly compared with GPS/IMU output to check validity of position data
  - Takes over when GPS/IMU fails for safe breakaway from formation



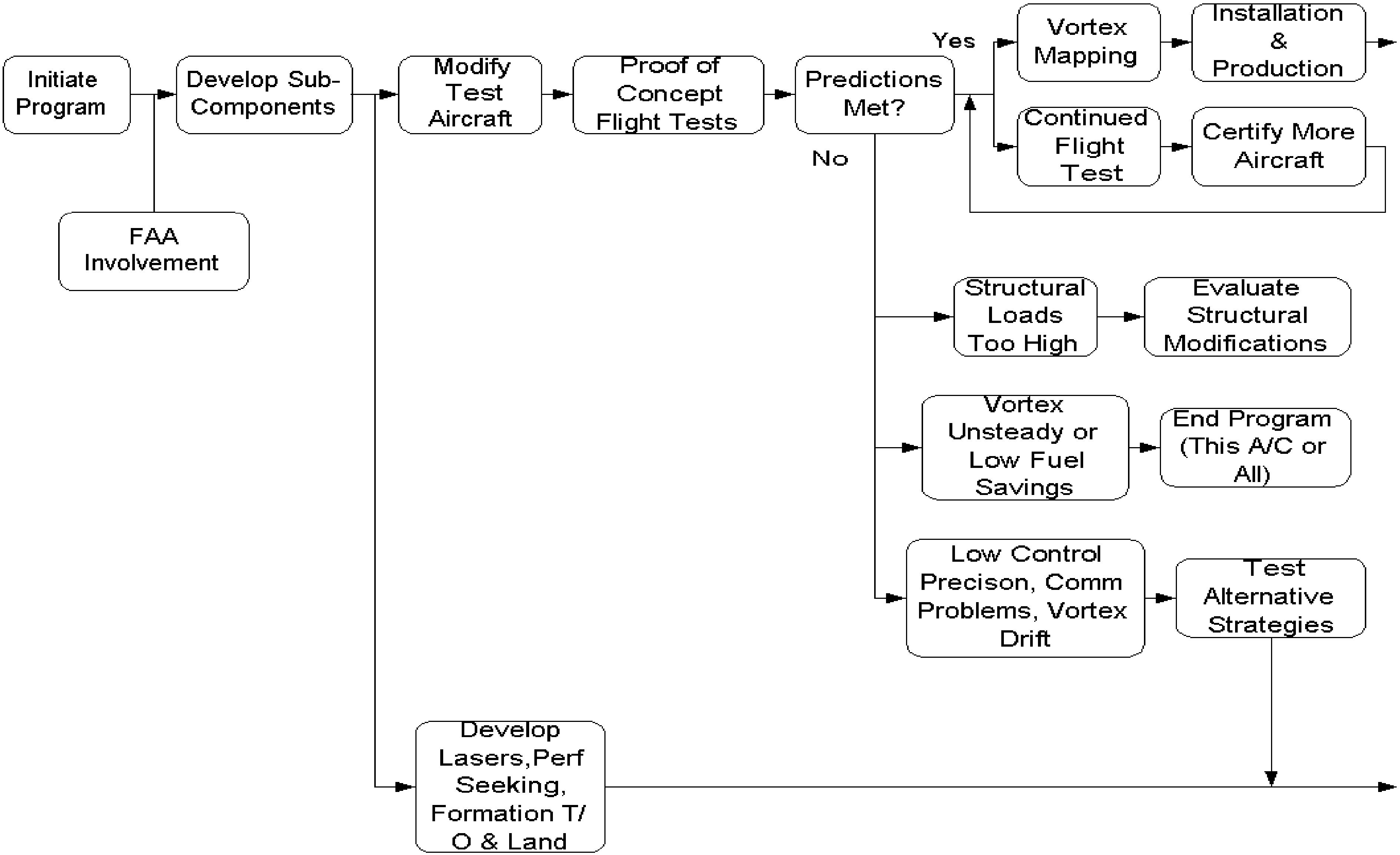
Procedures

- Formation shape: rotating echelon or staggered chevron
- Procedures driven by fuel consumption, delays, and safety
- Take-off and landing procedures
  - When possible, by pairs, with different ROC to avoid holding pattern and save fuel
  - Different airports: join-up by timing & turning, landing easily handled
- Join-up procedures
  - Joining aircraft arrive from behind
- Break-away procedures
  - Separate aircraft horizontally and vertically
- Unexpected break-away procedures
  - Partial (can catch-up and join-up again)
  - Leaves the formation permanently (ATC Clearance)

ATC

- Add relevant formation data to flight strip (join-up, break-away locations)
- Increase in minimum separation criteria (1nm)
- ATC talks with one pilot only
- Safety inside the formation is the pilots' responsibility
- "EFOPS" for formations using extended range routes
- NAS capacity enhancement, decrease in workload
  - 1 formation = 1 cell
- Handling unexpected break-aways:
  - Temporary overload
  - Identify emergency procedures (holding patterns)

Development Plan



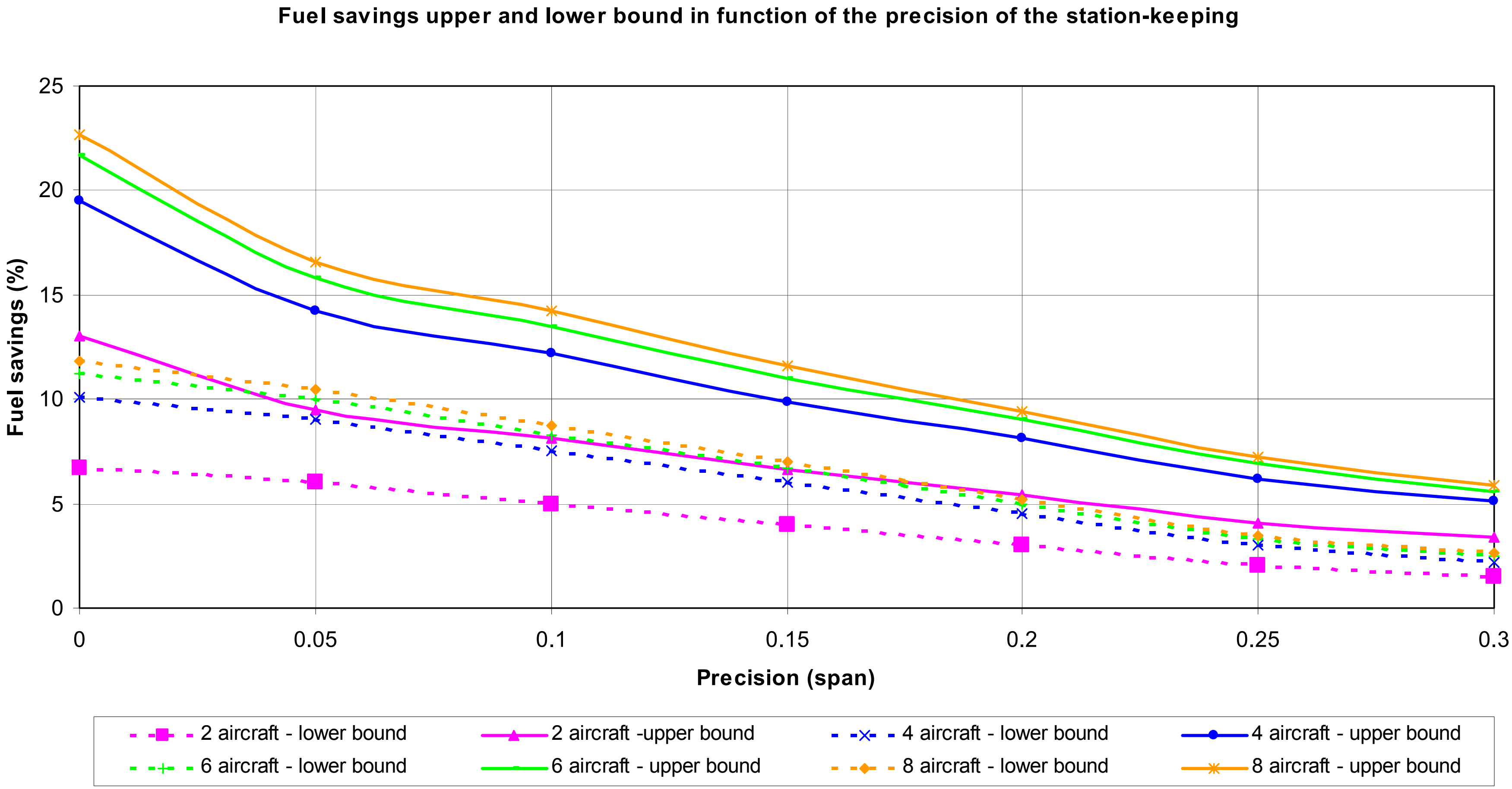
Safety Analysis

Event	Consequence	Severity	Probability
Communication failure	Visual system takes over, formation breaks up, lose some benefits until comm is restored	Low	Moderate
Visual system failure	Formation breaks up due to lack of backup system, lose benefits	Low	Moderate
Dual comm & visual system failure	Formation breaks up, safety hazard due to lack of knowledge of other positions	High	Low
Single aircraft system failure (engines, controls, whatever)	Aircraft leaves the formation until problem is fixed, lose benefits	Low	Moderate
Common mode aircraft system failure	Formation breaks up, lose benefits	Low	Low
Pilot misinterprets display and takes over when he shouldn't	Formation breaks up unnecessarily and loses benefits	Low	Moderate
Pilot misinterprets display and doesn't take over	Possible collision	High	Low

Program Risk Analysis

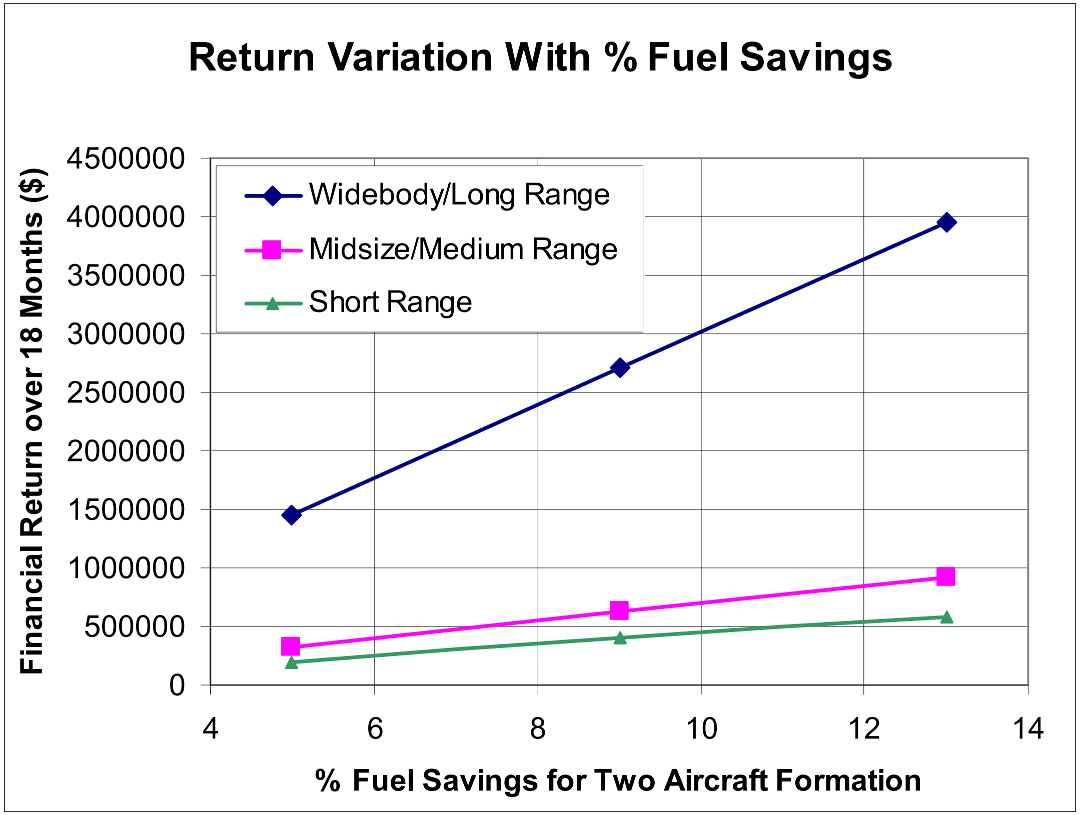
Risk	Risk Level	Mitigation Strategy
Vortices drift or position hold controllers do not get predicted benefits	Medium	Parallel development of performance seeking control. Extensive vortex mapping early in the program
Required precision not realized	Low	Alternate control strategies and sensing developed in parallel
Static or fatigue loading exceeded in vortex	Low	Testing scheduled early in program
FAA does not approve	Medium	FAA brought into program early

Fuel Benefit vs. Precision



Variation of Return with Performance

- The benefit to the cargo airline or developing company is a strong function of the chosen market and achievable precision of formation flight



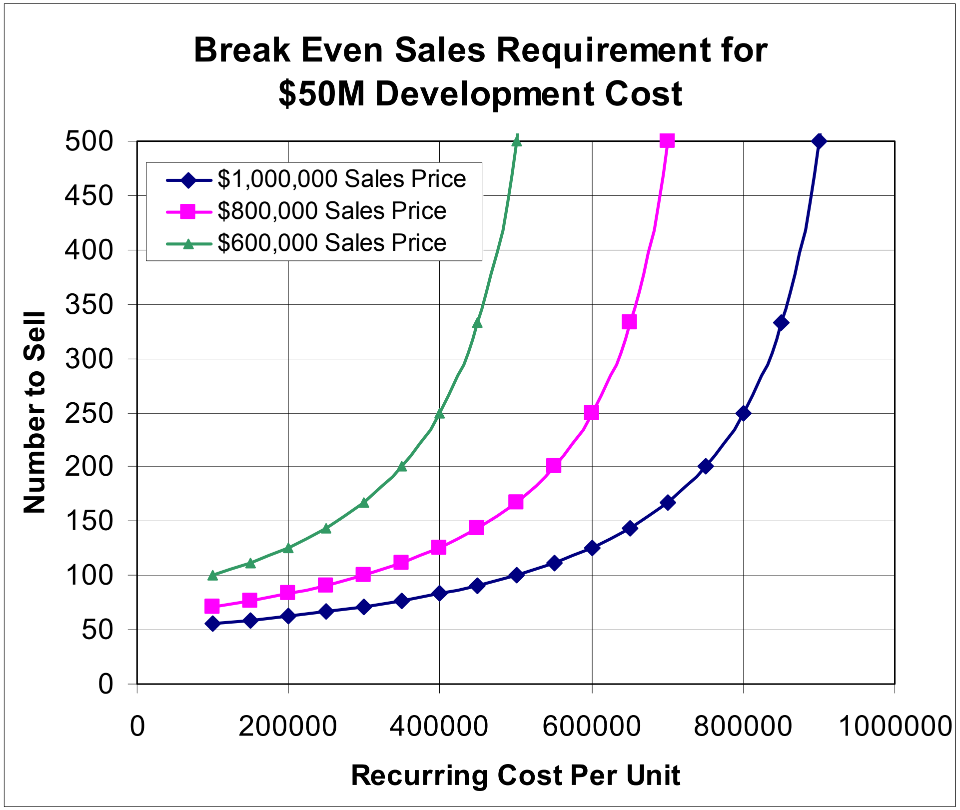
Business Case (Airline Side)

- UPS Daily flight schedule (incomplete international data)
- Grouping by origin/destination with <1hr flight time change (domestic), <3hr flight time change (Int'l)
- Fuel cost: $1/gal
- Fuel Savings: 9-15% based on mean value of fuel savings for 2 to 5 aircraft in formation

Flight Distance:	<500 nm	500-1000 nm	1000-2500 nm	>2500 nm
Percentage of Flights:	45%	28%	22%	6%
Savings/Flight	-	$350-$582	$400-$1411	$2170-$3180
18 month Savings/Plane	-	$315,000-$523,800	$360,000-$1,269,900	$1,953,000-$2,862,000

Business Case (Developer Side)

- Development Cost Estimate:
  - Compare to similar programs
  - **$50,000,000** (ceiling based upon complexity)
- Recurring Cost Estimate:
  - Sum estimated component costs
  - **$400,000/unit**
- Refit during C/D check to eliminate fleet downtime



Market Estimation

- 83-250 installations for break-even (depending upon sales price).
- Total Market Estimate:
  - Boeing: currently 690 Medium/Widebody freighters in service, approximately 400 Widebodies
- Developer would need to install kits on 21-63% of all Widebodies to break even
- Airline Widebody Fleet Estimate:
  - FedEx: 174 (DC-10/MD-10/MD-11/A330)
  - Atlas: 39 (747)

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Value of Formation Flight

- For air cargo airlines:
  - Cargo carriers save money
  - Reduced prices capture market share, increase profit
  - Increased range reaches additional markets, more profit
- For the air transportation system:
  - Reduces air traffic en-route
  - Will lead to autonomous formation take-off and landing to reduce airport congestion
- For the environment:
  - Reduces aircraft emissions and global warming
- For the military:
  - Could lead to autonomous refueling
  - Enhances the mission capabilities of the current fleet

Open Questions

- What are the true, realizable induced drag savings of formation flight for large transport aircraft?
  - Size, location, strength, stability of wing vortices
- How well will the proposed control approach work?
  - Will use of the existing autopilot be adequate?
  - Will performance seeking or other advanced algorithms improve this?
- Structural fatigue: Modifications required?
- More detailed market analysis
- Will the FAA certify a formation flight system? If so, what will be the cost?

Conclusions

- A formation flight system concept is:
  - A viable idea with a sizable and growing potential market
  - An enabling technology for new markets
- Technology for realization of benefits exists, but needs flight testing and certification
- Many questions about true performance benefits must be answered in order to reduce program risk

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