Modeling Delivery Accuracy for Metering Operations to Support RNAV Arrivals

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Overview

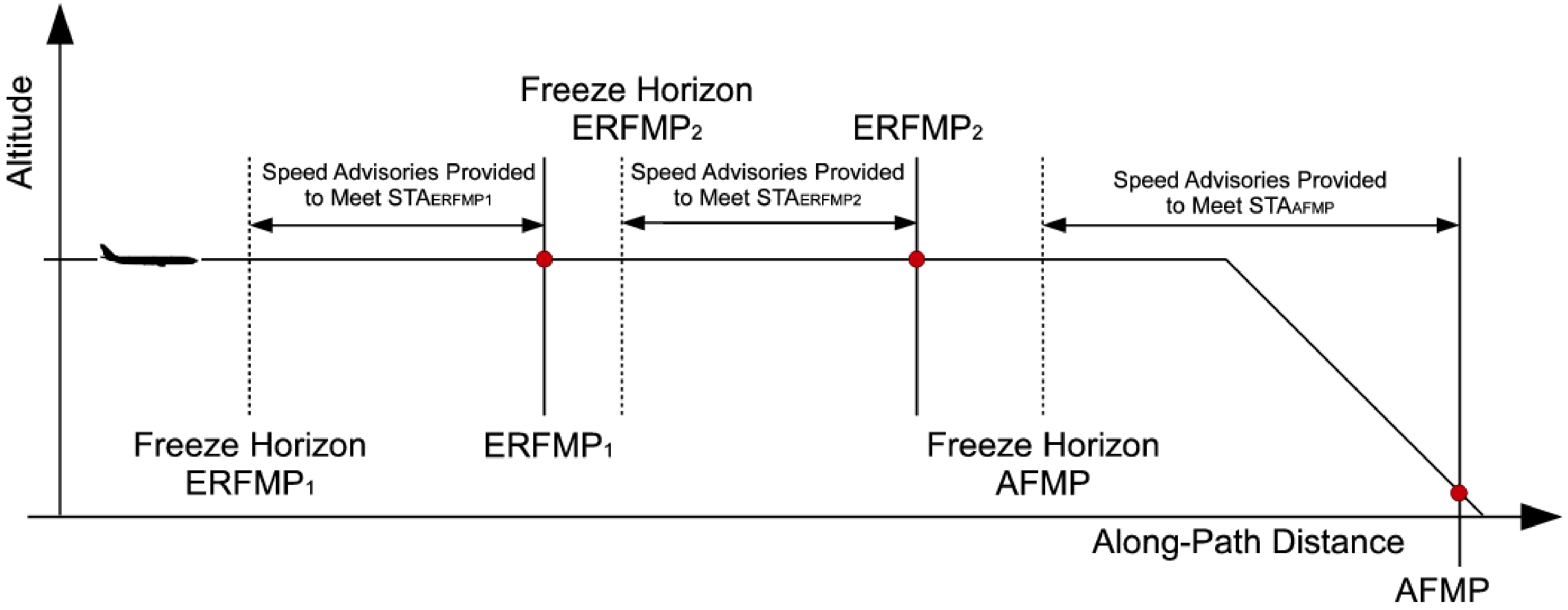
- The accuracy with which aircraft are delivered to their Scheduled Times of Arrival (STAs) affects the performance of metering operations in the terminal area.
- A top-down, parametric analysis is constructed from first principles, which constrains the delivery accuracy in two ways for the GIM-S operation
- Results are useable for requirements derivation, and to guide local adaptations

ARRIVAL MANAGEMENT

Arrival Management Overview

- **Schedule**
  - Develops sequence and schedule of aircraft to the runway
  - STAs for each aircraft to multiple meter points inside and outside of the TRACON
- **Management to schedule**
  - Controllers deliver aircraft to their STAs at Constraint Satisfaction Points (CSPs)
  - Automation tools aid with the delivery, e.g. Ground-based Interval Management – Spacing (GIM-S)
- **Management to relative spacing interval**
  - Relative spacing interval between aircraft is managed, compatible with the schedule
  - Interval Management operations involve airborne management of the spacing interval

GIM-S Initial Ground System



- Schedule to En-Route Flow Management Point (ERFMP) and Arrival Flow Management Point (AFMP)
- Speed advisories based on ETAs are calculated and provided to the controller to help manage aircraft to their STAs

PROBLEM DESCRIPTION

Problem Statement

- How accurately must aircraft be delivered to their assigned STAs at the ERFMP and AFMP in order to remain on their RNAV arrival routes?
  - Purpose to enable aircraft to conduct OPDs in medium- to high-density traffic prior to TRACON entry
- Builds on prior work by Ren & Clarke [6, 7], Shresta & Mayer [8], and Thipphavong & Mulfinger [9]
- Basic analysis reveals relationship between delivery accuracy and delay allocation

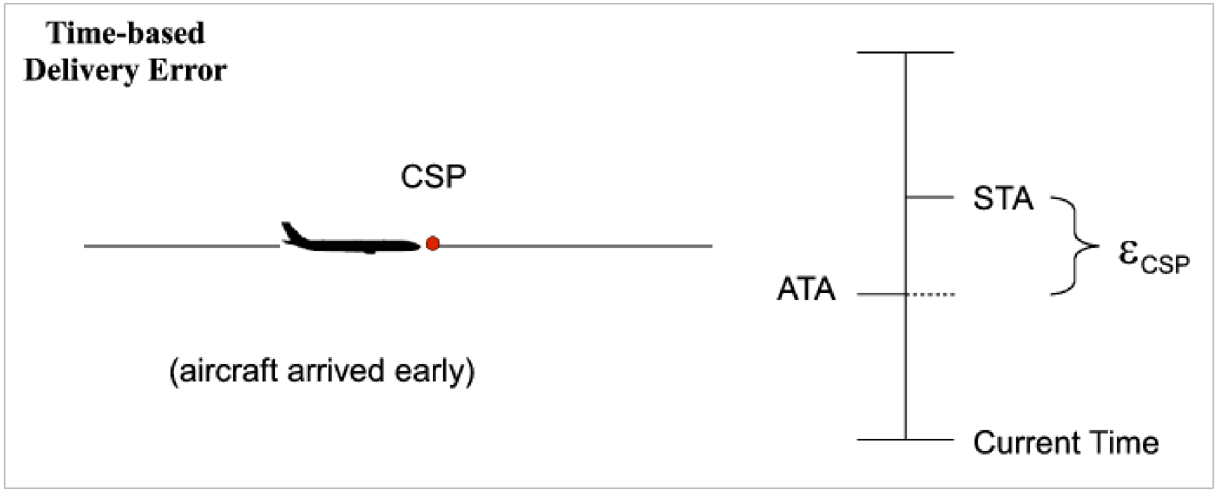
Definition of Delivery Error

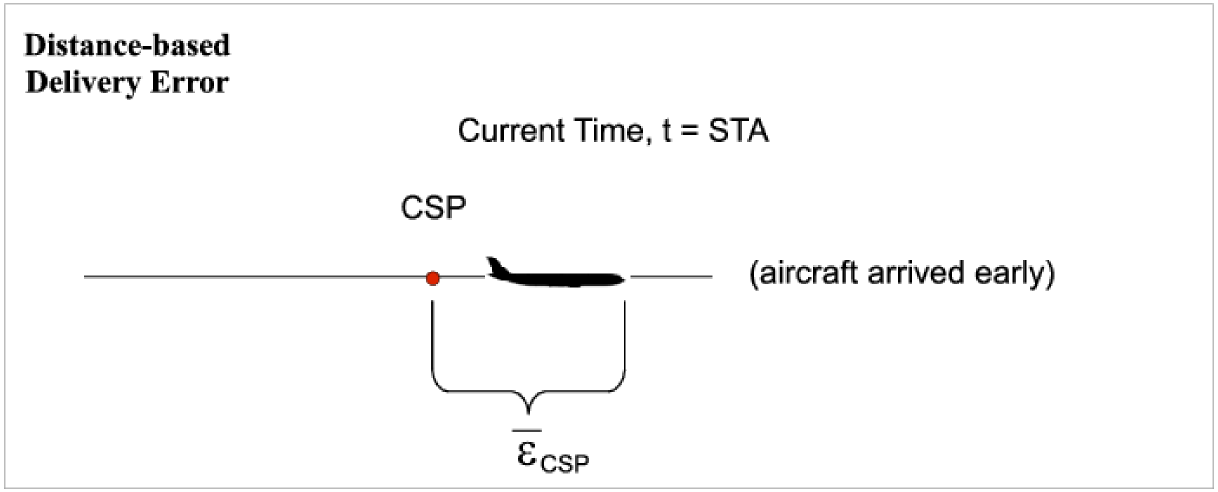
- Delivery error (at a Meter Point) is the difference between the *actual* arrival time of an aircraft and the frozen (accepted) STA determined by GIM-S

$$\varepsilon_{CSP} = ATA_{CSP} - STA_{CSP}$$

- Late arrival is positive, early is negative
- In this analysis, ε is assumed relatively small, modeled as Gaussian error w/ std. dev. ≡ σ_{DA}

Depiction of Delivery Error





Spacing Definitions (adapted from DO-328)

Spacing Interval: The Spacing Interval is the true horizontal along-path spacing between aircraft. The Spacing Interval is understood to apply to true aircraft positions.

- For distance-based spacing, the Spacing Interval is defined as the true along-path distance between the lead and trail aircraft.
- For time-based spacing, the Spacing Interval is defined to be the time elapsed since the lead aircraft was at the trail aircraft's current (true) position.

Approach – Impose 2 Constraints

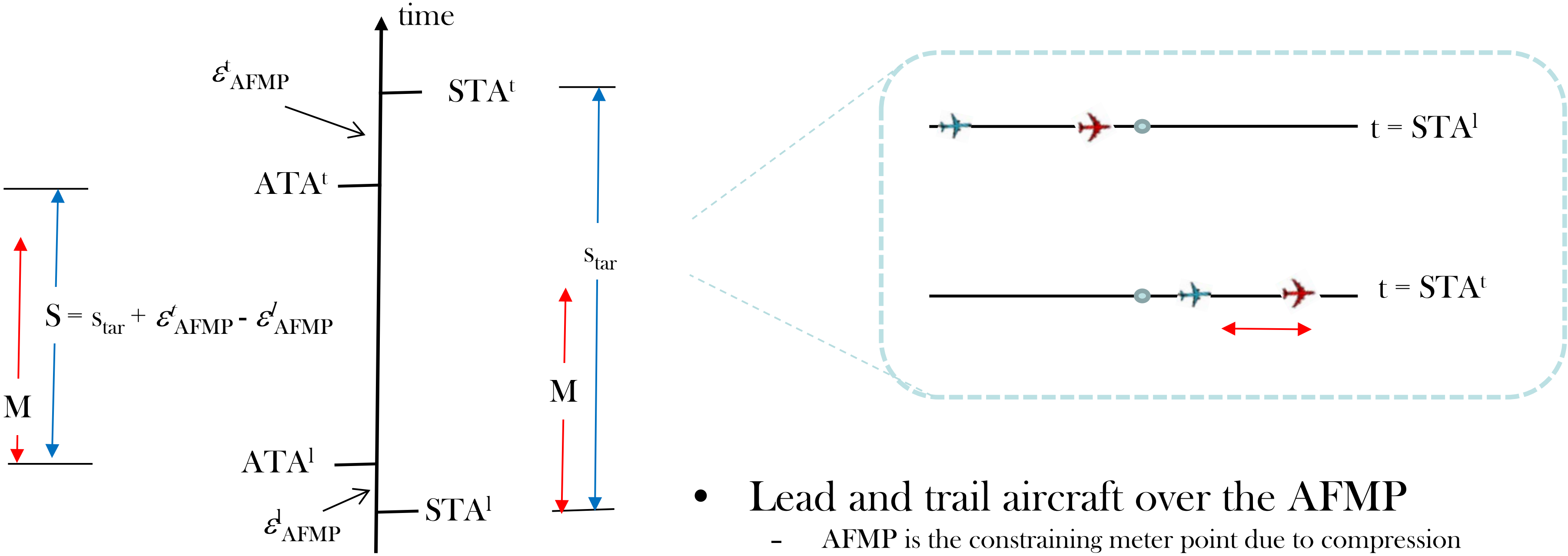
1. Successive aircraft are conflict-free (above the separation minimum) at each meter point (with a given probability); and

2. Each aircraft can fly the trajectory constrained by the STAs without the need for path length adjustments with a given probability (maximum schedule change due to speed adjustments).

Separation infringement at a point

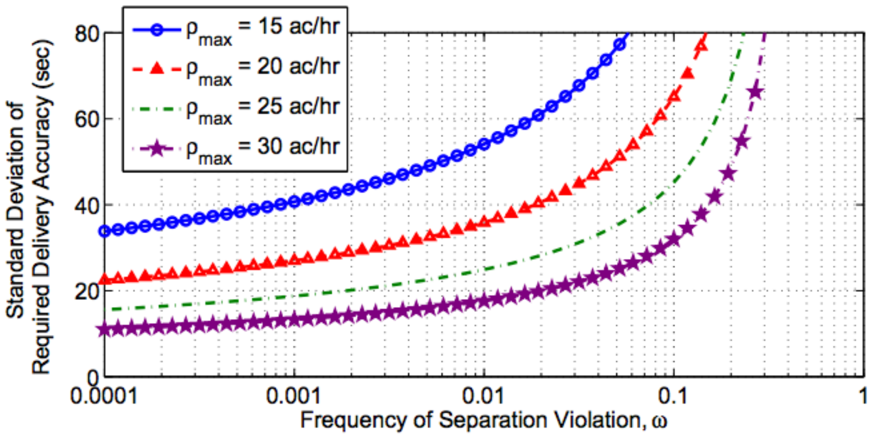
CONSTRAINT 1

Constraint 1 – Modeling



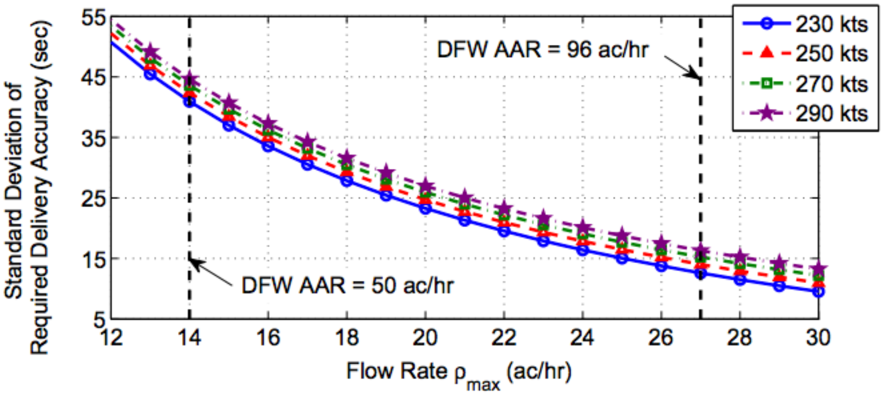
- Lead and trail aircraft over the AFMP
  - AFMP is the constraining meter point due to compression
- M is the separation minimum, converted to time by groundspeed
- s_{tar} is the average inter-aircraft spacing, in time
- S is the actual spacing, in time
- Constrain $Pr(S < M) < \omega$

Constraint 1 -- Parametric results



- ρ_{max} is the maximum flow rate over all AFMPs for a given facility

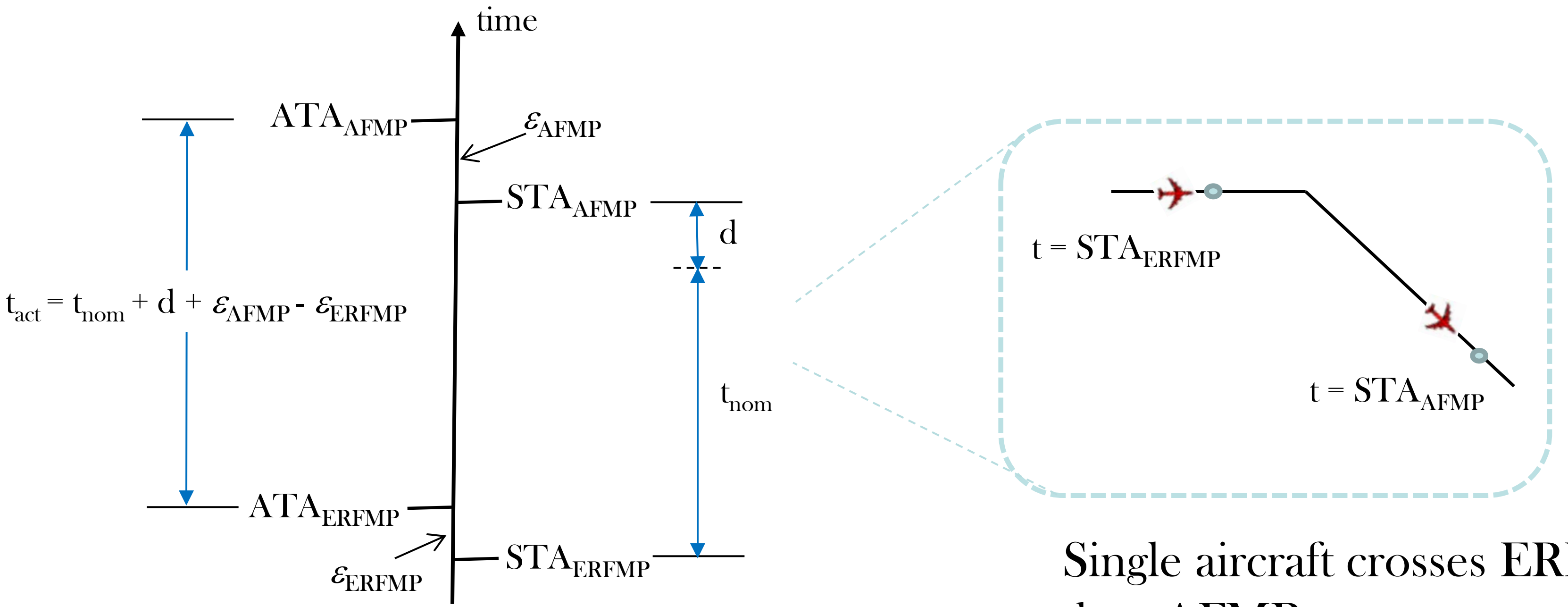
- DFW example assumes an 80% directional bias in traffic over two of four AFMPs



Feasibility of staying on RNAV arrival path

CONSTRAINT 2

Constraint 2 – Modeling



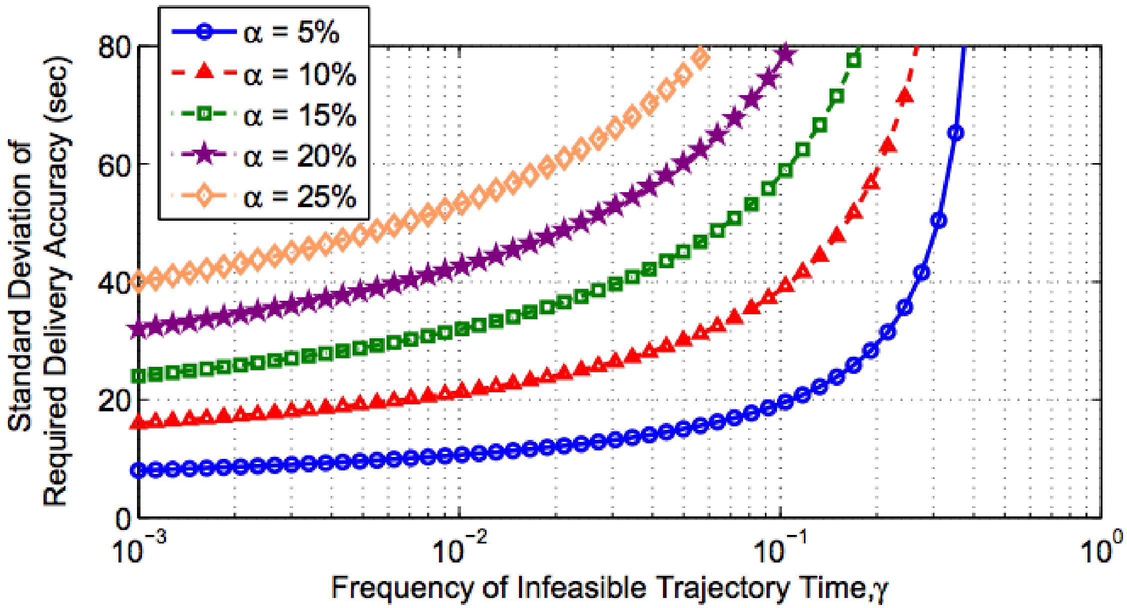
Single aircraft crosses ERFMP, then AFMP

Letting Δ represent the maximum amount by which the trajectory time can be adjusted by speed alone, we constrain:

$$\Pr(|t_{act} - t_{nom}| > \Delta) < \gamma$$

Delay, d, is applied by the scheduler between the meter points

Constraint 2 – parametric results



- 1400 second nominal trajectory time between meter points
- Percentage of nominal that can be adjusted by speed alone is **α**
  - i.e. $\Delta = \alpha \cdot 1400$ seconds
- Delay allocation is set to $\Delta/2$

NUMERICAL EXAMPLE

Analysis of PHX EAGUL5 arrival

- Possible trajectory-time change (Δ) is determined using MITRE trajectory modeler – two cases shown:
  - 270 knot IAS speed constraint throughout procecure
  - No speed constraints
- Choose an adaption and maximum amount of delay that can be applied
- Determine σ_{DA} as based on Constraint 2
- Determine maximum flow rate over the AFMP that can be supported with said value of σ_{DA}, per Constraint 1 analysis

Trajectory Times, Delay, Delivery Accuracy, and Flow Rate

Distance to AFMP (nmi)	t_{slow} 270-kt IAS 0.74 Mach	t_{nom} 270-kt IAS 0.78 Mach	t_{fast} 270-kt IAS 0.82 Mach	Max Deviation Δ (sec)	$d_{max} =$ 0.50Δ (sec)	Delivery Accuracy σ (sec)	$d_{max} =$ 0.25Δ (sec)	Delivery Accuracy σ (sec)	$d_{max} =$ 0 (sec)	Delivery Accuracy σ (sec)
100	942.0	933.0	927.0	6.0	3.0	0.7	1.5	1.0	0.0	1.4
200	1793.5	1740.5	1695.0	45.5	22.8	5.2	11.4	7.8	0.0	10.4
300	2645.0	2548.0	2463.0	85.0	42.5	9.7	21.3	14.6	0.0	19.5
400	3496.0	3355.5	3231.0	124.5	62.3	14.2	31.1	21.4	0.0	28.5

TABLE II
TRAJECTORY TIMES AND REQUIRED DELIVERY ACCURACY (NO SPEED CONSTRAINTS)

Distance to AFMP (nmi)	t_{slow} 250-kt IAS 0.74 Mach	t_{nom} 270-kt IAS 0.78 Mach	t_{fast} 300-kt IAS 0.82 Mach	Max Deviation Δ (sec)	$d_{max} =$ 0.50Δ (sec)	Delivery Accuracy σ (sec)	$d_{max} =$ 0.25Δ (sec)	Delivery Accuracy σ (sec)	$d_{max} =$ 0 (sec)	Delivery Accuracy σ (sec)
100	1002.5	933.0	852.5	69.5	34.8	7.5	17.4	11.2	0.0	14.9
200	1854.5	1740.5	1621.0	114.0	57.0	12.3	28.5	18.4	0.0	24.5
300	2706.0	2548.0	2389.5	158.0	79.0	17.0	39.5	25.5	0.0	34.0
400	3557.5	3355.5	3157.5	198.0	99.0	21.3	49.5	31.9	0.0	42.6

- Green indicates where σ_{DA} > 15 seconds
- Imposing speed constraints on GIM-S operation greatly limits performance
- Without speed constraints, using a 200 nmi freeze horizon, and allocating 30 seconds to delay, we get a requirement of σ_{DA}=19.2 seconds
- Maximum flow rate over an AFMP that can be supported with this accuracy is 24.6 ac/hr

CONCLUSION

Conclusions and Next Steps

- **Tradeoff between delay, delivery accuracy, and arrival rates is described through simple relationships**
- **Sensitivity analyses are planned or ongoing**
  - Distribution of scheduled inter-aircraft spacing at a point
  - Delay distribution
  - Delivery accuracy distribution
  - Delivery error at AFMP conditional on delivery error at ERFMP
- **Extension of the analysis to Interval Management Operations**
  - Interplay between absolute and relative spacing

Thank you for listening…

QUESTIONS?