

Quantifying the Performance of Airborne Precision Spacing under Realistic Operating Conditions



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Benefits of APS



- “Throttle control” is delegated to the trailing aircraft, allowing it to manage fuel burn more efficiently than if directed from the ground
- Controller workload reduced
 - Fewer (i.e. no additional) speed commands issued from controllers to pilots
- Managing to a time interval allows more precise delivery to the runway threshold, especially in the presence of strong headwinds
 - Runway arrival rate with distance-based spacing varies with V_w :

$$RAR = \frac{V_a - V_w}{\Delta s}$$

As $V_w \uparrow$ then $V_g \downarrow$, $\Delta t \uparrow$, $RAR \downarrow$

$RAR \equiv$ Runway Arrival Rate, $V_a \equiv$ approach speed, $V_w \equiv$ (head) wind speed, $V_g \equiv$ ground speed, $\Delta s \equiv$ required spacing (nm)

- RAR with time-based spacing constant regardless of V_w :

$$RAR = \frac{\# \text{ aircraft}}{T} = \frac{1}{\Delta t_0}, \text{ constant regardless of } V_w.$$



Recent Research on APS



APS is an umbrella term covering several time-based spacing concepts, each more advanced than the previous

- Although similar to the FAA's Flight Deck Merging and Spacing (FDMS) concept, APS has been developed separately

1. Advanced Terminal Area Approach Spacing (ATAAS)

- Applies time-based techniques to a single arrival stream
- Human-in-the-loop (HITL) experiments demonstrated pilots could maintain one-second accuracy when the spacing command was coupled to an autothrottle vs. 4-5 seconds when manually controlled¹
- Flight trials with three research aircraft at ORD revealed the trailing aircraft achieved a time spacing of 0.8 ± 7.7 seconds within the required 90 seconds of spacing²

¹R. M. Oseguera-Lohr, G.W. Lohr, T. S. Abbott, and T. M. Eischeid, "Evaluation of Operational Procedures for Using a Time-Based Airborne Inter-Arrival Spacing Tool" Digital Avionics Systems Conference, Irvine, CA USA 2002.

²G. W. Lohr, R. M. Oseguera-Lohr, T. S. Abbott, and W. R. Capron, "Flight Evaluation of a Time-Based Airborne Inter-Arrival Spacing Tool", 5th USA/Europe Air Traffic Management Seminar, Budapest, Hungary, June 2003

Recent Research on APS, Continued



2. Airborne Spacing for Terminal Arrivals (ASTAR)

- Multiple arrival streams merged using time-based spacing, while simultaneously executing continuous descent arrivals
- Fast-time experiments revealed that gaps inserted into the arrival stream produced significant runway threshold errors¹
 - Runway threshold error: the difference in the assigned vs. achieved spacing by the trailing aircraft at the runway threshold*
- Another experiment revealed that artificial wind forecast errors of 5-15 knots increased the number of speed adjustments by the trailing aircraft by 3% over a perfect wind forecast scenario¹
- Other research showed that APS is less sensitive to wind forecast *direction* errors of up to 20 degrees than it is to wind forecast *speed* errors of 10 knots or larger²
- Further research revealed that wind forecast speed errors of 40 knots or larger have a significant detrimental effect on APS³

A 40 knot error can occur for two oppositely-directed merging streams of aircraft, each of which has a 20 knot speed forecast error

¹V. E. Houston and B. Barmore, "An Exploratory Study of Runway Arrival Procedures: Time-Based Arrival and Self-Spacing", 9th AIAA Air Traffic Integration and Operations Conference, Hilton Head, SC, September 2009.

²K. Krishnamurthy, B. Barmore, F. Bussink, L. Wetz, "Fast-Time Evaluations of Airborne Merging and Spacing in Terminal Arrival Operations", AIAA Guidance, Navigation, and Control Conference, San Francisco, CA, August 2005..

³B. Barmore, "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations." 25th Digital Avionics Systems Conference, Portland, OR : IEEE, October 2006..



A diagram showing a blue jet airplane flying from left to right. Concentric blue circles emanate from the front of the plane, representing sound waves. A blue arrow at the bottom points towards the center of the circles.



Each trailing AC given flight ID of the leader and minimum time spacing behind leader

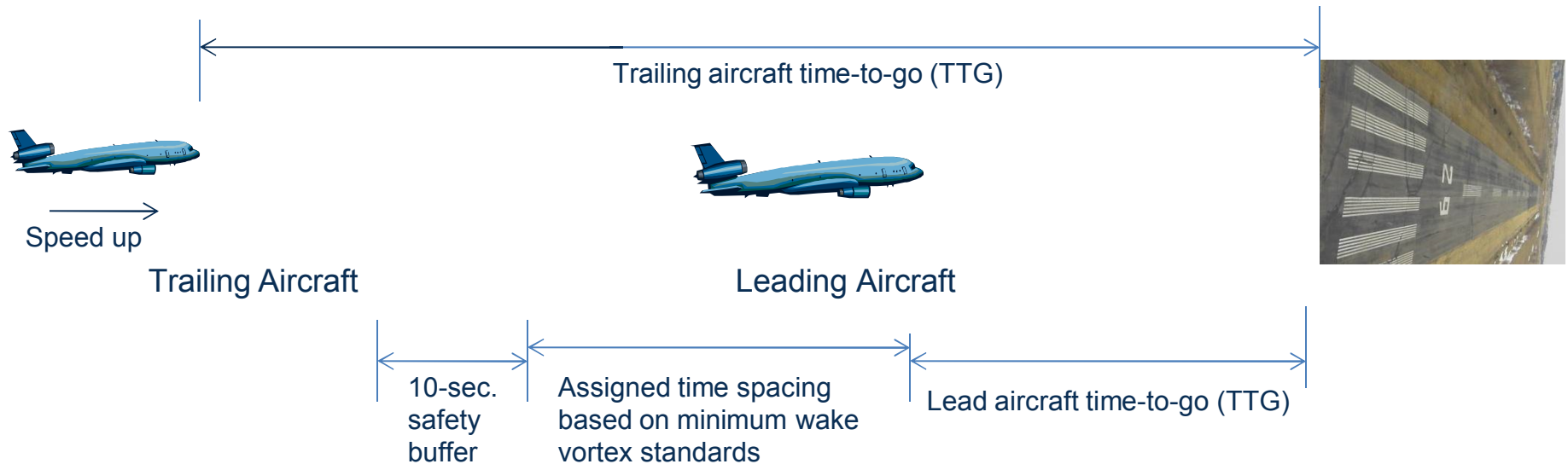
1. If either leading or trailing aircraft deviates from spacing, controller notified and aircraft fly published approach routes.
2. If trailing aircraft violates time spacing by twenty seconds or more, controller notified and trailing aircraft flies slowest safe speed until spacing re-established.
3. For system outage (i.e. GPS unavailable), pilots fly published approaches, controllers contacted, and current-day procedures invoked.



APS Concept of Operation, ctd.



- Minimum time spacing derived from published wake-vortex distance spacing
- 10 second “safety buffer” added to time spacings to account for natural variabilities in performance
- On-board avionics computes the speed adjustments required to maintain spacing



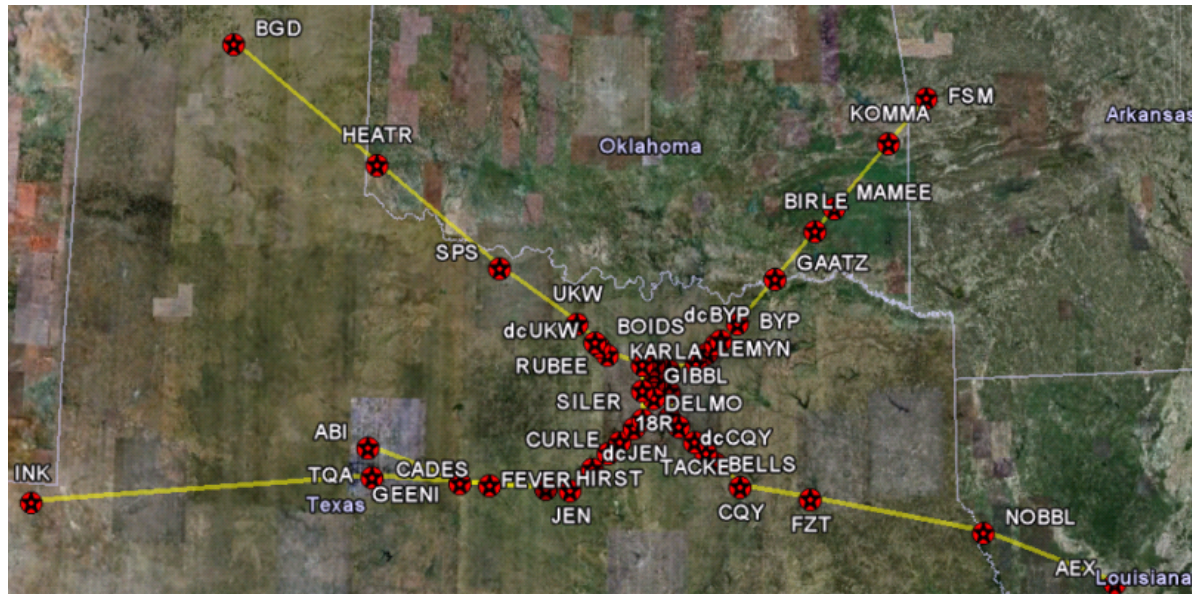
Experimental Design



- Research questions:

1. What is the impact of realistic winds on APS?
 - Expected: performance varies with forecast error
2. What is the impact of limited ADS-B range on APS?
 - Expected: limited range negatively impacts performance
3. What is the impact of a “Scheduled Time of Arrival” (STA) mitigation algorithm?
 - Expected: mitigation increases performance at limited ADS-B range

- Study Area: DFW airport, four approaches



Experimental Design, ctd.

- Use seven “realistic” weather days with “realistic” weather forecasts (discussed later)
- Fifty flights simulated, from just before TOD to exiting runway.
- Vary ADS-B range from 25 nm to unlimited
- Turn “STA Mitigation” algorithm on and off
- Aircraft in arrival stream are randomly ordered for each of the seven landing sequences
- For each of the landing sequences, aircraft start time just before TOD is randomized from ideal (± 40 secs, uniform)
 - Models “realistic” delivery of aircraft from enroute airspace
 - Produces spacing inaccuracy at start from which APS must recover

Wind-Wind Forecast Error Combinations	ADS-B Range	STA Migration	Landing Sequence
None	25 nm	Enabled	1
January 7, 2009, 6PM local	40 nm	Disabled	2
January 11, 2009, 6 PM local	90 nm		3
March 2, 2009, 6 PM local	Unlimited		4
March 6, 2009, 6 PM local			5
May 17, 2009, 7 PM local			6
June 23, 2009, 7 PM local			7
June 25, 2009, 7 PM local			



“Realistic” Weather Days

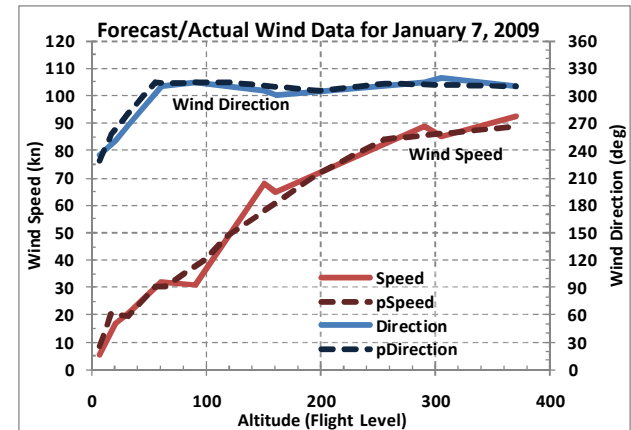
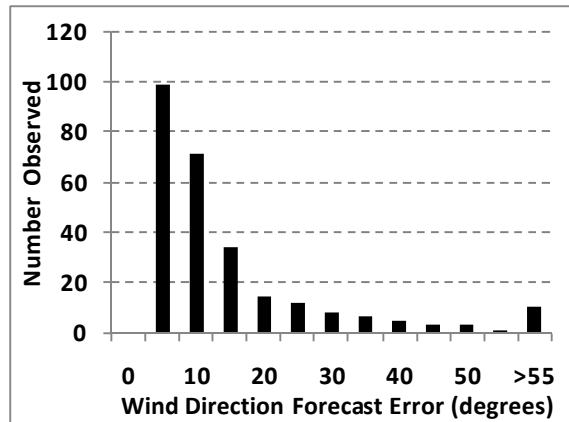
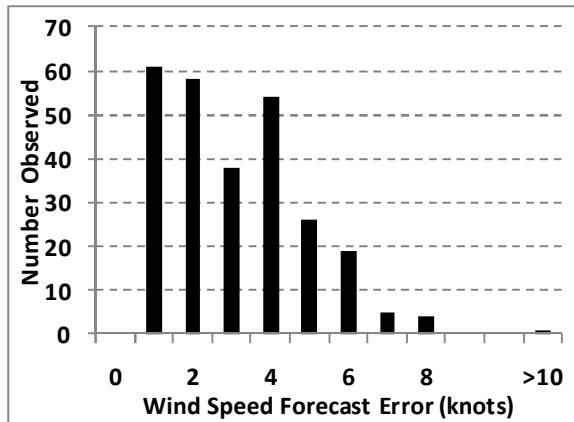


- 28 weather (wx) days considered, down-selected to 7 using a *k-Medoids* clustering algorithm ($k = 7$ produced maximum variability between clusters)

Wind-Wind Forecast Error Combinations	Wind Direction			Wind Strength	Wind Inflections
	Headwind	Crosswind	Tailwind		
January 07	Low			High	Minimal
January 11	Low			High	Minimal
March 02		Medium		High	Moderate
March 06	High			Medium	Large
May 17			Medium	Medium	Moderate
June 23		Low		Low	Large
June 25		Medium		Low	Moderate

“Realistic” Wind Forecasts

- “Truth” winds from University of Wyoming sounding data for the seven days selected
- “Forecast” winds from Rapid Update Cycle (RUC)-20 wind grids centered on the study area (DFW)



*Speed, direction = true speed and direction
pSpeed, pDirection = forecast speed and direction*

Wind speed and direction forecast errors used in this experiment are (generally) small because the forecast “lookahead time” is 1 hour, sufficient for travel time from TOD to runway threshold.

Traffic Manager (TMX)



- Developed by National Aerospace Laboratory of the Netherlands
 - Updated by both the National Institute of Aerospace and NASA Langley Research Center (LaRC)
- 6 degree of freedom aircraft model with auto-flight functions and a pilot model
- Can handle up to 1,000 aircraft at a given time
- BADA used to model 200 different aircraft types
- Aircraft state provided in three ways:
 - “True” state generated by trajectory model
 - “Perceived” state, after sensor errors introduced
 - “ADS-B” state, which is perceived state transmitted at ADS-B update rate and attenuated by ADS-B range limitations
- Both true and forecast wind fields are recognized by the model
- ASTAR speed guidance module added by LaRC



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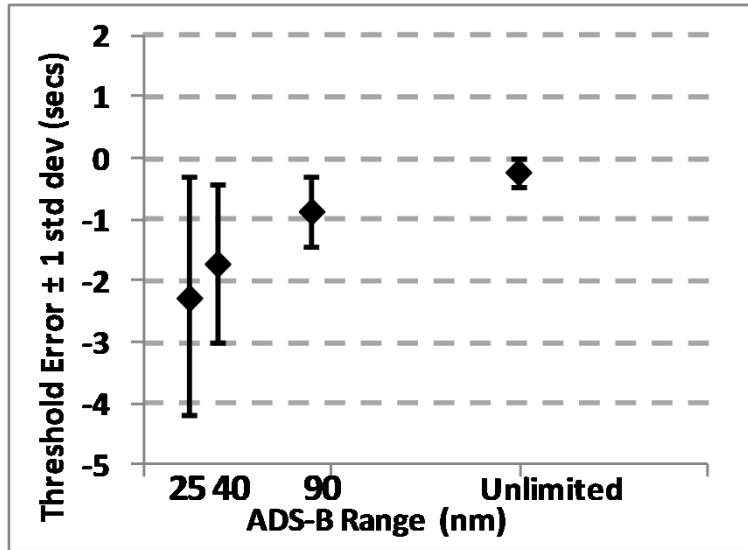
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Threshold Error Metric

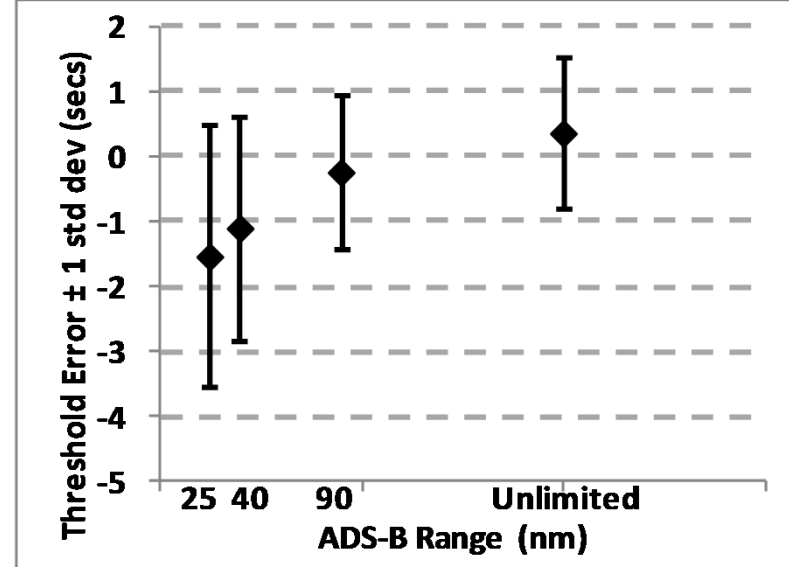


- Main metric computed from simulation output is the threshold error metric, which is the assigned time spacing at the runway threshold minus the actual spacing achieved
 - This metric represents the goal of APS
 - Negative numbers indicate a loss of spacing; positive indicate spacing is larger than assigned
 - Because of the 10-second safety buffer, the magnitude of the negative spacing must be significantly greater than 10 seconds before safety issues arise

Threshold Error Metric, Perfect and Forecasted Winds



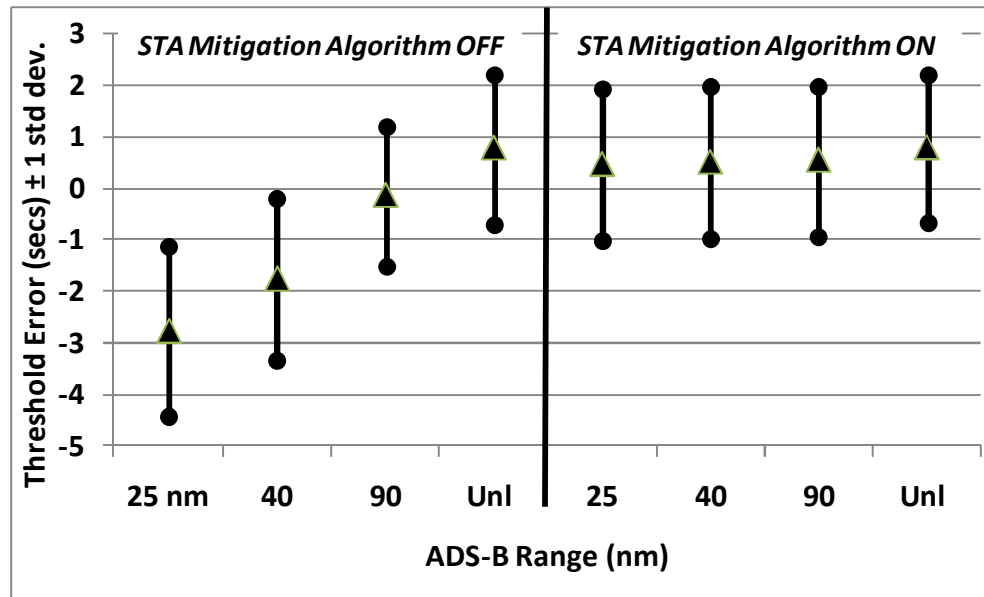
Threshold error for a perfect wind forecast scenario. Threshold error decreases as ADS-B range increases, but in all cases it is within the 10 second safety buffer.



Realistic wind forecast errors increase the variance of the threshold error metric, but the overall results are within the 10-second safety buffer.

Effect of realistic wind forecast is to increase the variance of the threshold error metric at high ADS-B ranges, but there is no discernible effect at low ADS-B range.

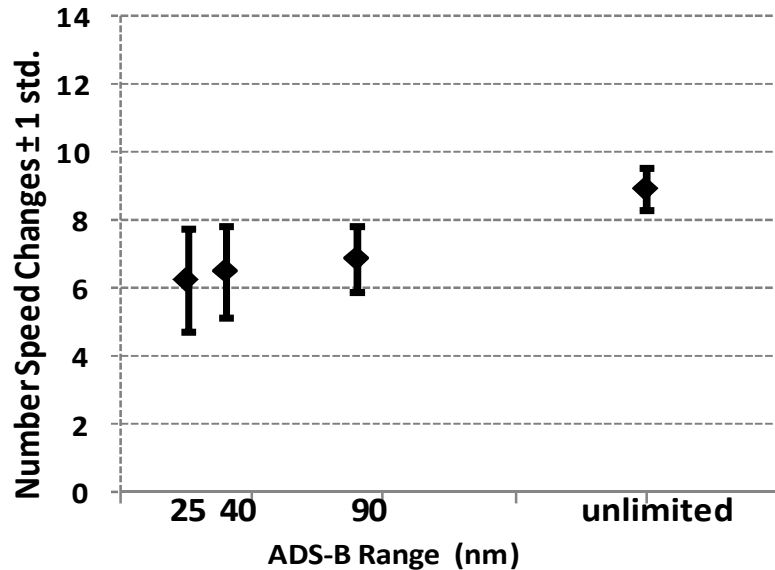
Results—STA Mitigation Algorithm



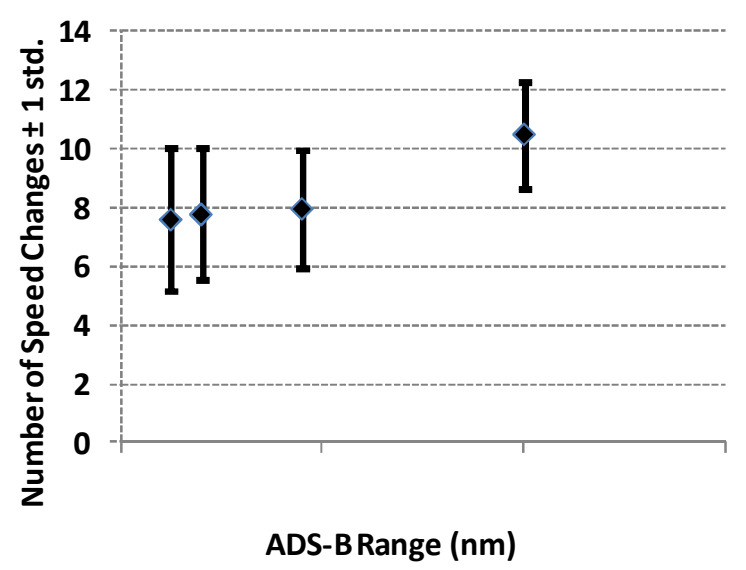
- Scheduled Time of Arrival (STA) mitigation algorithm estimates the lead aircraft's current position when ADS-B signal unavailable.
- Estimate is based upon back-computing the probable location of the lead aircraft given its scheduled time of arrival.
- Hypothesis is that the STA mitigation algorithm will improve APS performance when the ADS-B range is low.

Results confirm the hypothesis: *STA mitigation algorithm significantly improves APS performance at ADS-B range of 25 and 40 nm.*

Results—Speed Changes (Workload Proxy)



Speed changes with perfect wind forecast are within reason: 6-10 speed changes per flight, during its 30 minute descent from TOD.

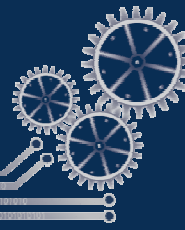


With realistic winds, the variance of the number of speed changes increases, as does the mean (slightly).

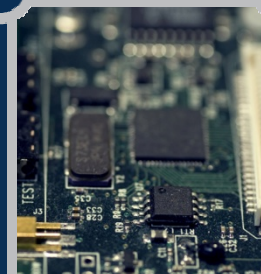
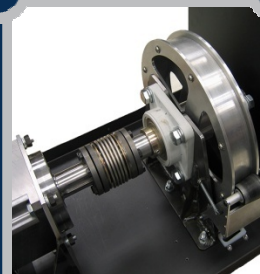
Number of speed changes is a proxy for controller workload that is offloaded to pilots. *Workload between perfect and realistic wind forecasts increases by 33% for low ADS-B ranges, by about 10% for unlimited ADS-B range; variance in this metric increases significantly with the realistic forecast.*

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