



National Aeronautics and Space Administration

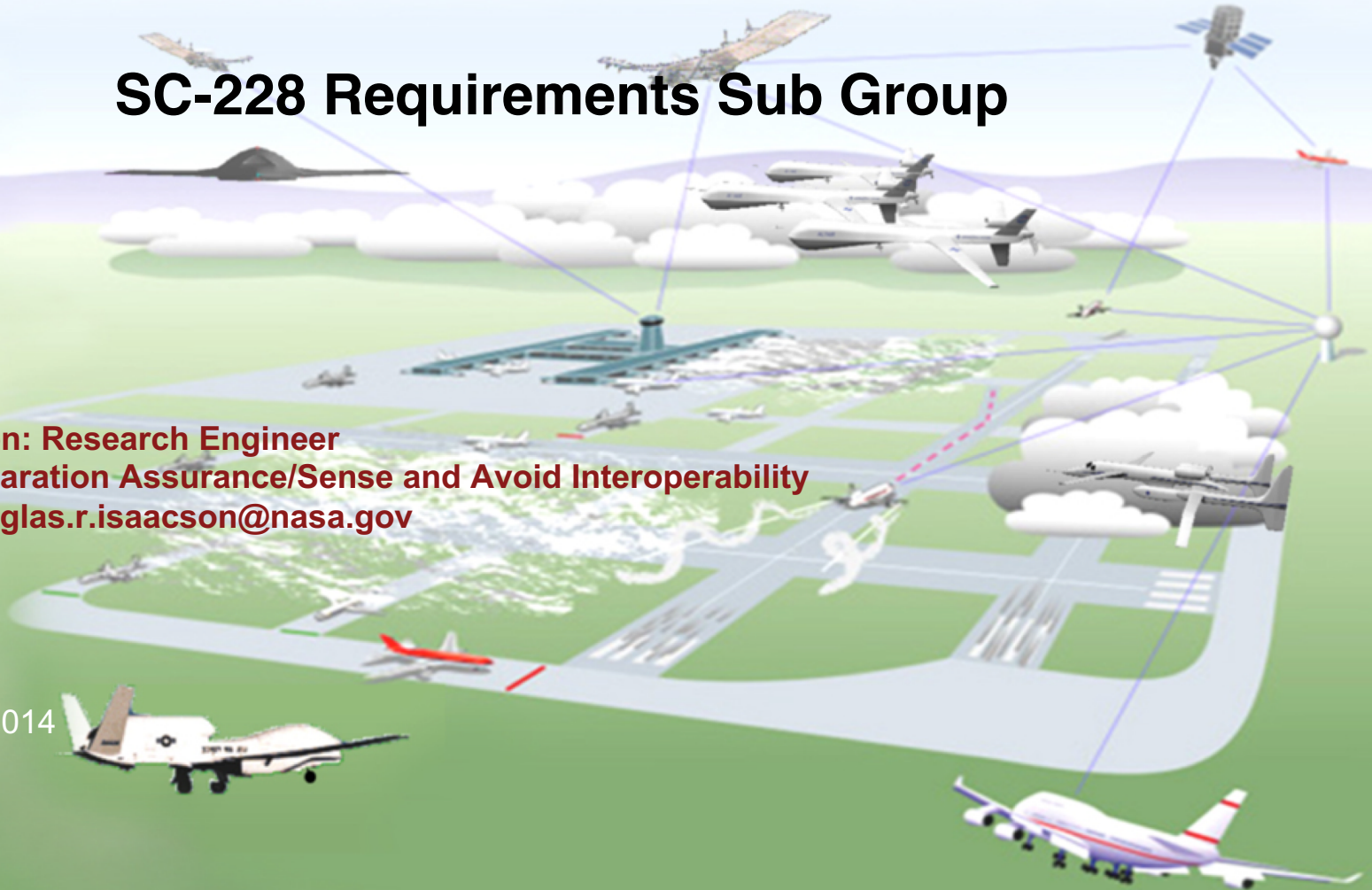


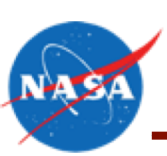
ACES Study of DAA-mitigated UAS Operations

SC-228 Requirements Sub Group

Doug Isaacson: Research Engineer
Separation Assurance/Sense and Avoid Interoperability
douglas.r.isaacson@nasa.gov

19 November 2014





ACES Review: What is ACES?



- Airspace Concept Evaluation System (ACES)... an agent-based, non-real-time, NAS-wide simulation capability
 - Fidelity of simulation tailored to needs via agent models (e.g. surveillance)
 - Aircraft movement can be recording playback or simulated
 - 4 DOF kinematic aircraft trajectory computation
 - Flight control agent for simulated traffic mimics action of pilot or autopilot
- As configured for DAA-mitigated UAS Studies
 - Simulated UAS aircraft movement with no uncertainty modeling
 - Basic, deterministic surveillance model
 - Standard Atmosphere, no winds
 - VFR aircraft movement playback from recording (filtered/smoothed tracks)
 - UAS traffic scenarios populated from 22 mission types
 - Non-UAS IFR traffic excluded from simulation to reduce run-time



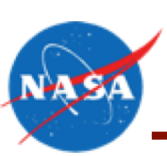
ACES Review: UAS Traffic Generation



- UAS Traffic generated from 22 mission types:

Air Taxi Remote Pilot (Mustang)	Weather Data Collection
Air Taxi Remote Pilot (Cirrus)	Wildlife Monitoring
Aerial Imaging and Mapping	Traffic Monitoring
Air Quality Monitoring	Spill Monitoring
Freight Forwarding	Maritime Patrol
Flood Inundation Mapping	HALE Transit (Comm. Relay)
Flood Stream Flow Monitoring	FAA NavAid Inspection
Law Enforcement	Damage Survey Assessment
Point Source Emission Monitoring	Airborne Pathogen Tracking
Strategic Fire Monitoring	News Gathering
Tactical Fire Monitoring	Border Patrol

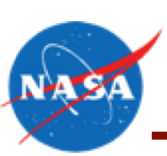
- Mission types, frequency and location generated in consultation with:
 - Likely/Potential UAS Operators
 - UAS Manufacturers
 - Air Traffic Authorities



ACES Review: VFR Traffic Playback



- VFR traffic derived from RADES data
 - Correlated tracks for non-cooperative traffic generated by Honeywell
 - Non-cooperative tracks assigned single altitude based on statistical distribution
 - Track smoothing employed to better represent realistic aircraft movement (truth)
- No uncertainty explicitly modeled, but tracks retain navigational 'error'
- No coordinated maneuvers for Self Separation or Collision Avoidance



ACES Review: Threat Evaluation Process



- In order to compute Loss of Well Clear (LoWC), current position and velocity of ownship and intruders are used to evaluate whether modTau, HMD, and ZTHR are penetrated.
- For self separation, a 'time-to-LoWC' approach is used for SST determination.
 - Time-to-LoWC is based on projections of ownship (UAS) and intruder states to avoid a "buffered" Well Clear definition.
 - To evaluate if a LoWC is predicted between a UAS and a given intruder, the following four-step process is used:
 - 1) Synthesize reference trajectories for the ownship and intruder starting from their current positions:
 - Our architecture can build ownship trajectory in three different ways,
 - i. Along intended flight plan
 - ii. Along Autopilot commanded target altitude, heading, and speed
 - iii. Along dead-reckoning (when intent is unavailable/undesirable)
 - Reference trajectory for the intruder is modeled using "dead-reckoning" extrapolation from best intruder state estimate (position/velocity)
 - Ownship and intruder trajectories are discretized at a prescribed interval (e.g. 1 sec)
 - 2) Create a series of time-synchronized state pairs for ownship and intruder using the reference trajectories out to a prescribed prediction horizon (aka 'look-ahead time')



ACES Review: Threat Evaluation Process (cont.)



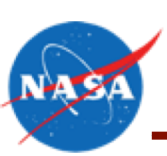
- 3) Compute modified tau, Horizontal Miss Distance (HMD) and vertical separation for each state-pair from ownship/intruder trajectories computed in 2)...
 - 4) Compare the computed modified tau, HMD and vertical separation from 3) to the “buffered” Well Clear definition for each state pair to determine if a LoWC is predicted along the current reference trajectories of the ownship and intruder
- If a (“buffered”) LoWC is predicted, the ‘time-to-LOWC’ is computed as the difference between the current time and the first state pair that penetrates the buffered Well Clear definition
 - If this time-to-LOWC is below the prescribed SST time-to-LoWC, e.g. 75 seconds, the SST has been crossed and action is deemed necessary



ACES Review: LoWC Avoidance Algorithm



- ACES employs Autoresolver adopted for DAA (AR-DAA):
 - Based upon mature Autoresolver algorithm derived from model of ATC separation practice
 - Discretizes maneuver option space according to parameterized values
 - Maneuver Degrees of Freedom: altitude, turnout angle, turnout duration
 - Additional constraints may apply to all resolutions (e.g. execution delay)
 - AR-DAA does not allow simultaneous vertical and horizontal maneuvers
 - Five-step process for selection of avoidance maneuver
 1. All allowable maneuvers are attempted and tested for LoWC , achieved separation, etc.
 2. All 'successful' maneuvers are scored according to a cost objective
 - Current objective: minimize deviation
 - Future objective: refined by HitL studies and SME feedback
 3. Successful resolutions are ranked according to heuristic preference and cost:
 - UAS Climbing/Descending: All vertical maneuvers ranked ahead of horizontal
 - UAS Level: All horizontal maneuvers ranked ahead of all vertical maneuvers
 - All successful maneuvers ranked (within preference) according to cost
 4. Highest ranking (successful) maneuver is selected.
 5. If no successful maneuvers are found, the attempt with max-min normalized separation is selected



ACES Risk Ratio Study: Objectives



- 1) To estimate the achievable DAA self separation risk ratio under simplifying assumptions on pilot response and surveillance capabilities, and...
 - 2) To identify necessary capabilities improvements for assessing draft MOPS requirements in future studies.
- Provide sanity check on achievable DAA self separation risk ratio (SSRR)
 - Best case scenario for SSRR in some ways
 - No surveillance uncertainty: ownship senses intruder truth data
 - Simple pilot model includes ‘best-case’ assumptions among parameters
 - Threat detection logic is still being refined
 - Appropriate buffers for LoWC prediction and for resolution are TBD
 - Only HMD/DMOD buffer has been implemented for prediction
 - Assess ACES DAA-mitigated analysis capabilities
 - 1st Study with RTCA Well Clear Definition
 - Process check for data management and analysis tools
 - Do LoWC events with RTCA definition indicate need for new tools, processes, algorithms?
 - Identify key SSRR sensitivities within the limits of the existing capabilities
 - Gain insight into effective future analysis methodologies (e.g., sensitivity analyses)
 - Identify potential improvements in DAA Self Separation Algorithm and Alerting



ACES Risk Ratio Study: UAS Traffic Overview



- NAS-wide (<18,000 ft) analysis of a single day of recorded VFR traffic (1/5/2012)
- VFR traffic derived from RADES data and filtered to represent intruder truth
- UAS traffic: 14 mission types, 20,651 UAS flights, ~25,100* hrs of UAS flight

Mission Type	# Flights	# Flight Hours (<18,000ft AGL)
Air Taxi Remote Pilot (Cirrus)	8720	5891
Air Taxi Remote Pilot (Mustang)	3180	963
Aerial Imaging and Mapping	295	186
Air Quality Monitoring	1044	2386
Air Cargo	1317	1950
Flood Inundation Mapping	127	278
Flood Streamflow Monitoring	202	368
Law Enforcement	300	855
Point Source Emission Monitoring	432	642
Strategic Fire Monitoring	324	128
Tactical Fire Monitoring	2496	3367
Weather Data Collection	864	5958
Wildlife Monitoring	308	194
Traffic Monitoring	1043	1962



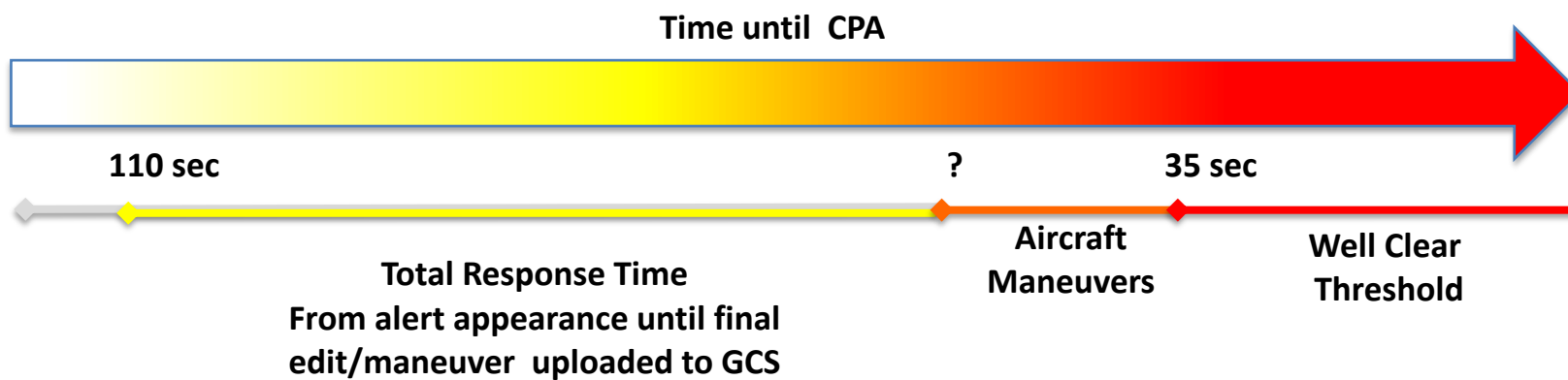
ACES Risk Ratio Study: Assumptions and Limitations



- Simple surveillance model ('ADS-B like')
 - No uncertainty
 - Surveillance Volume: 40nm range, unlimited altitude
- Non-UAS IFR aircraft excluded from simulation to save run time
 - No separation services simulated for IFR
 - Assumes independence of IFR services and aggregate SSRR metric
- Intruder intent unknown to ownship
 - RADES-derived intruder tracks with no intent knowledge
 - Intruder maneuvers and navigational variance retained
- Basic pilot response model
 - Deterministic pilot response time (input parameter)
 - Pilot response independent of encounter context
- CONUS NAS airspace... analysis limited to below 18,000 ft AGL



ACES Risk Ratio Study: Self-Separation Timeline





ACES Risk Ratio Study: Risk Ratio Computation



- Risk Ratio computed as the ratio of outcome frequency with and without a mitigation: e.g., $RR_{SS\&Cav} = \lambda_{NMACss\&Cav} / \lambda_{NMACunmitigated}$
- Risk Ratio estimated for ACES simulations by computing rate of LoWCs/FlightHour for a simulation scenario with and without DAA mitigation
- Only the Self Separation mitigation is considered in the ACES Risk Ratio Study
- $RR_{SS} = \lambda_{NMACss} / \lambda_{NMACunmitigated}$



ACES Risk Ratio Study: Experiment Matrix



- 2x2x2(x1 Day) Design
 - SST* (ttLoWC): 40s, 70s
 - Prediction HMD/DMOD : 4000 ft., 5000 ft.
 - HMD Resolution Buffer (% of Prediction HMD): 10%, 20%

Run Condition	SST ttLoWC (sec)	LoWC Prediction HMD/DMOD (incl. buffer) (ft.)	HMD Resolution Buffer (% of prediction HMD)
1	40s	4000 ft.	10%
2	70s	4000 ft.	10%
3	40s	5000 ft.	10%
4	70s	5000 ft.	10%
5	40s	4000 ft.	20%
6	70s	4000 ft.	20%
7	40s	5000 ft.	20%
8	70s	5000 ft.	20%

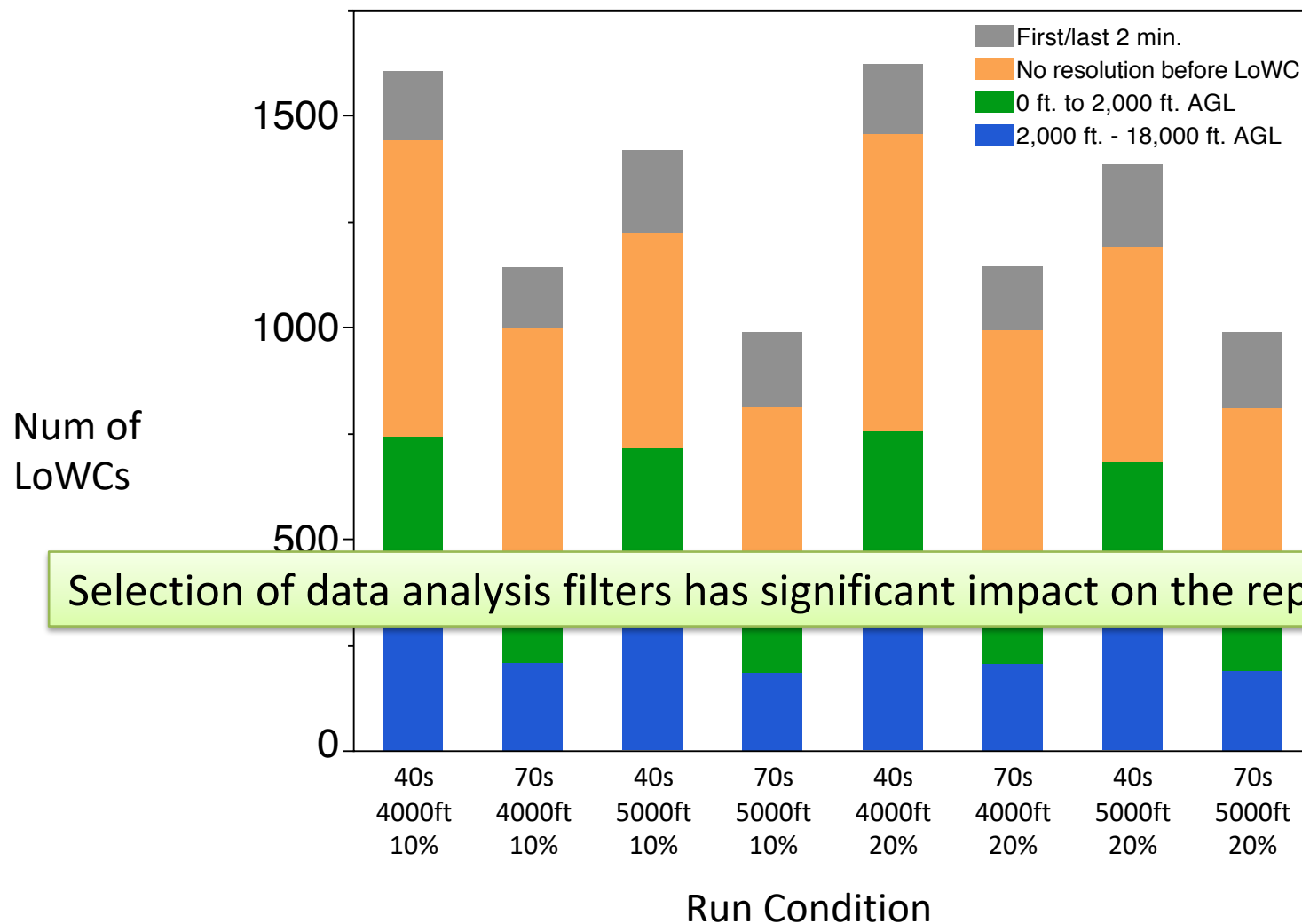


ACES Risk Ratio Study: Analysis Methodology



- Simulation and encounter data recorded to database for each run condition
- Aggregate metrics (LoWC rate, Risk Ratio) computed after filtering:
 - UAS flight time above 18,000 ft. AGL is not considered
 - UAS 'flight time' inside the terminal area is not considered
 - ACES simulates gate-to-gate and includes 'tracks' on airport surface and in TRACON
 - UAS flight considered to begin at departure fix crossing or first 'en route' track
 - UAS flight considered to end at arrival fix crossing or last 'en route' track
 - UAS flight in first or last 2 minutes of flight excluded from analysis
 - Optional analysis filters
 - Altitude stratification of LoWC events (e.g. exclude LoWCs below 2,000 ft. AGL)
 - Exclude LoWC events with no resolution attempt prior to LoWC
 - Exclude LoWC events with intruder maneuvering after ownship avoidance maneuver
- Diagnose unexpected findings to understand cause and identify any new capabilities needed for future studies

LoWC Classification by Run Condition





ACES Risk Ratio Study: Summary Results



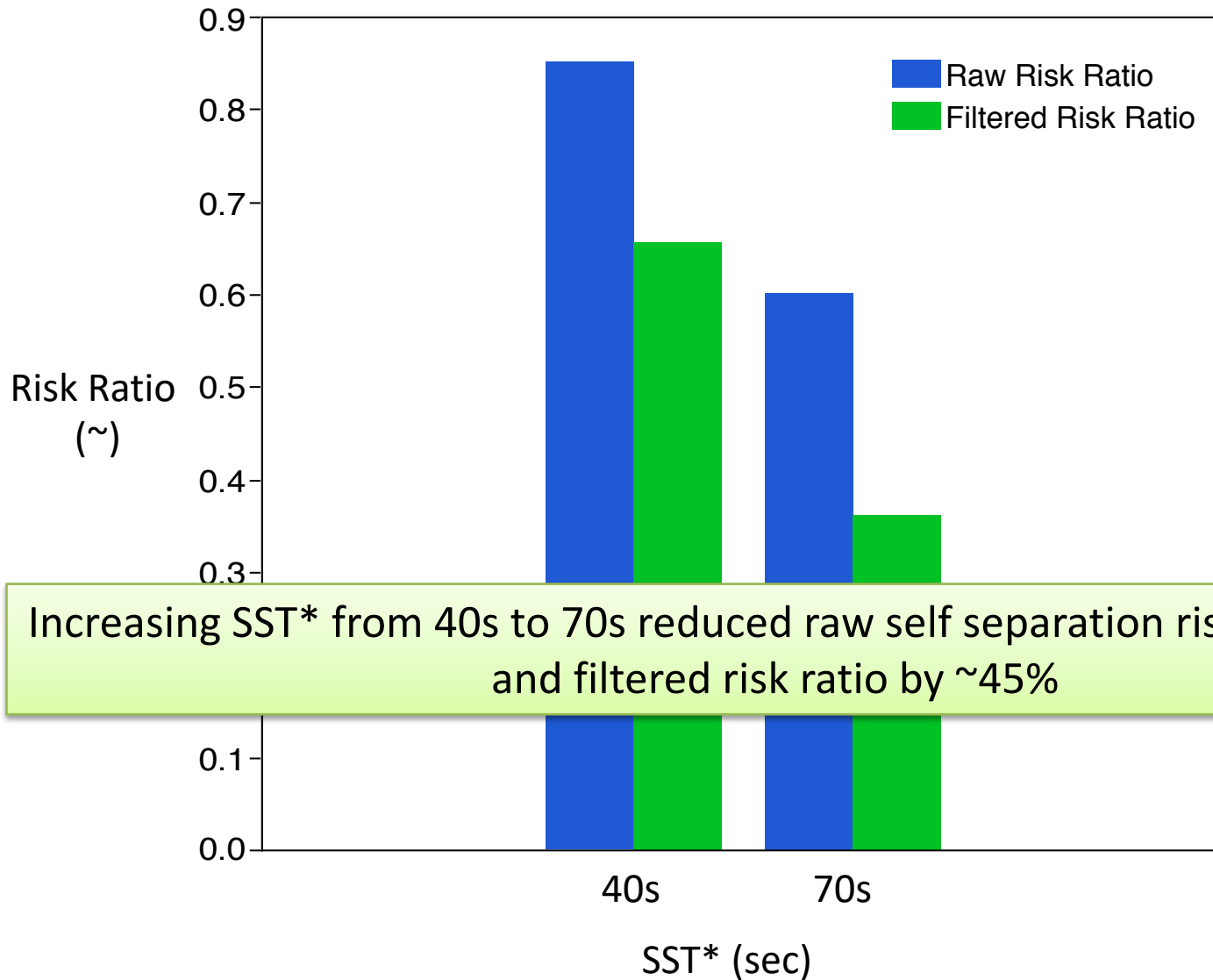
Run Condition (SST*/ Prediction HMD/ResBuffer)	# raw LoWCs	# filtered LoWCs	# Maneuvers	Raw Risk Ratio	Filtered Risk Ratio
Unmitigated	1771	1101	n/a	n/a	n/a
1 (40/4000/10%)	1604	742	1239	.91	.67
2 (70/4000/10%)	1140	422	1762	.64	.38
3 (40/5000/10%)	1411	742	1239	.91	.67
4 (70/5000/10%)	988	422	1762	.64	.38
5 (40/4000/20%)	1621	742	1239	.91	.67
6 (70/4000/20%)	1142	408	1791	.64	.37
7 (40/5000/20%)	1384	683	1688	.78	.62
8 (70/5000/20%)	989	379	2326	.56	.34

Neither raw nor filtered risk ratios include LoWCs in first/last 2 minutes of UAS or intruder flight.

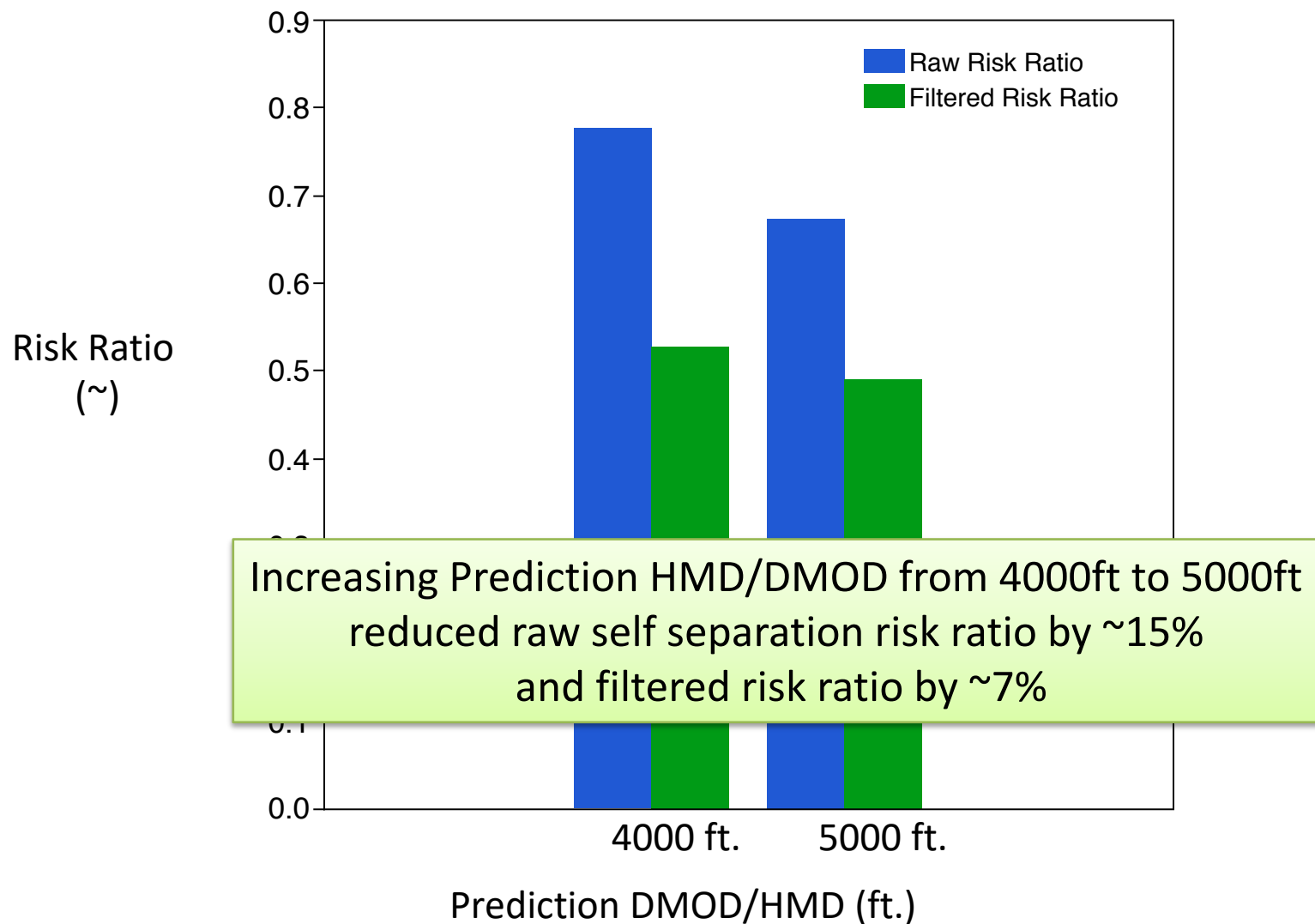
Filtered Risk Ratio also excludes LoWCs without an attempted resolution prior to LoWC.

Increasing SST* from 40s to 70s increases number of total maneuvers by ~32-42%

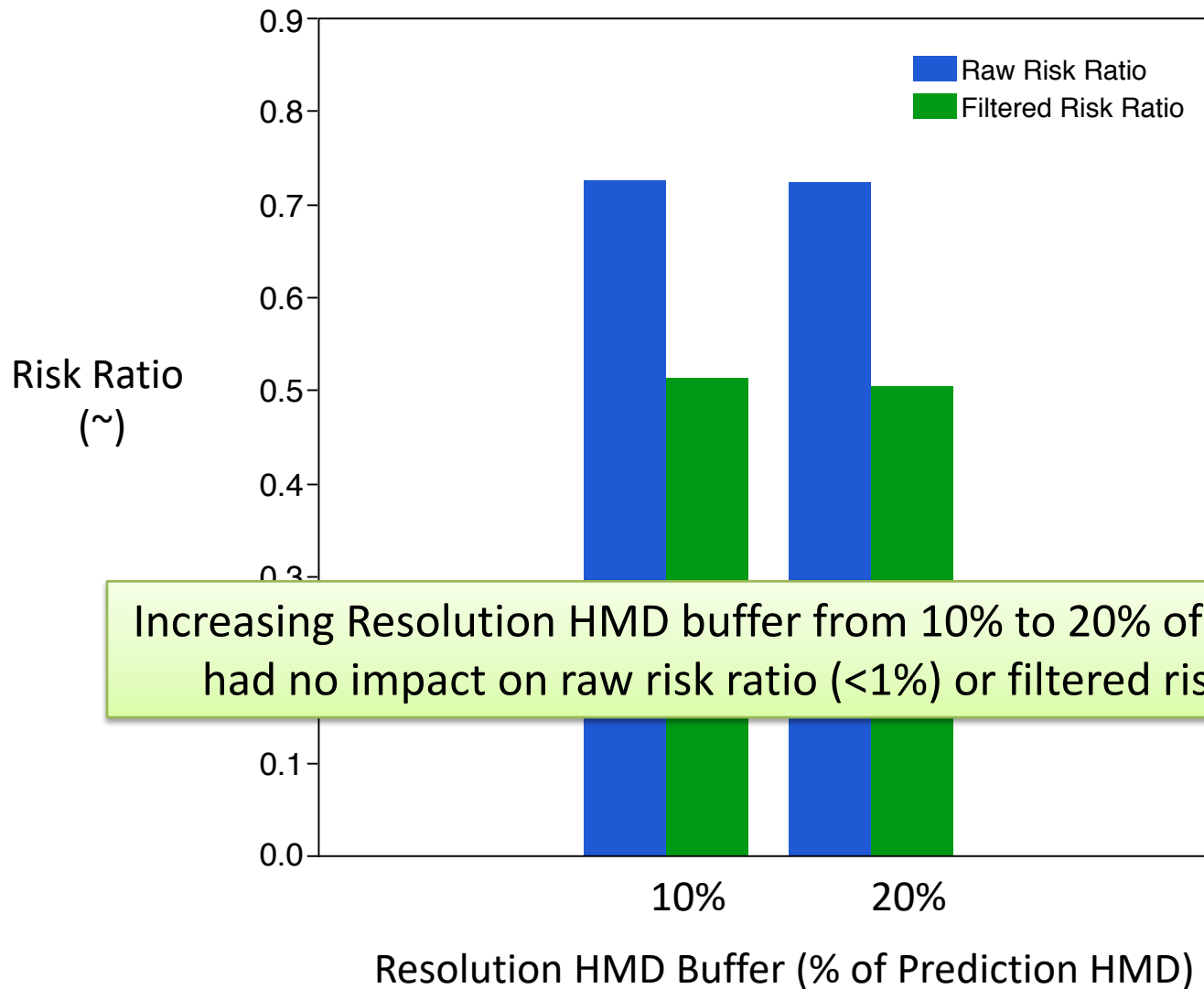
Effect of SST* (ttLoWC) on Risk Ratio



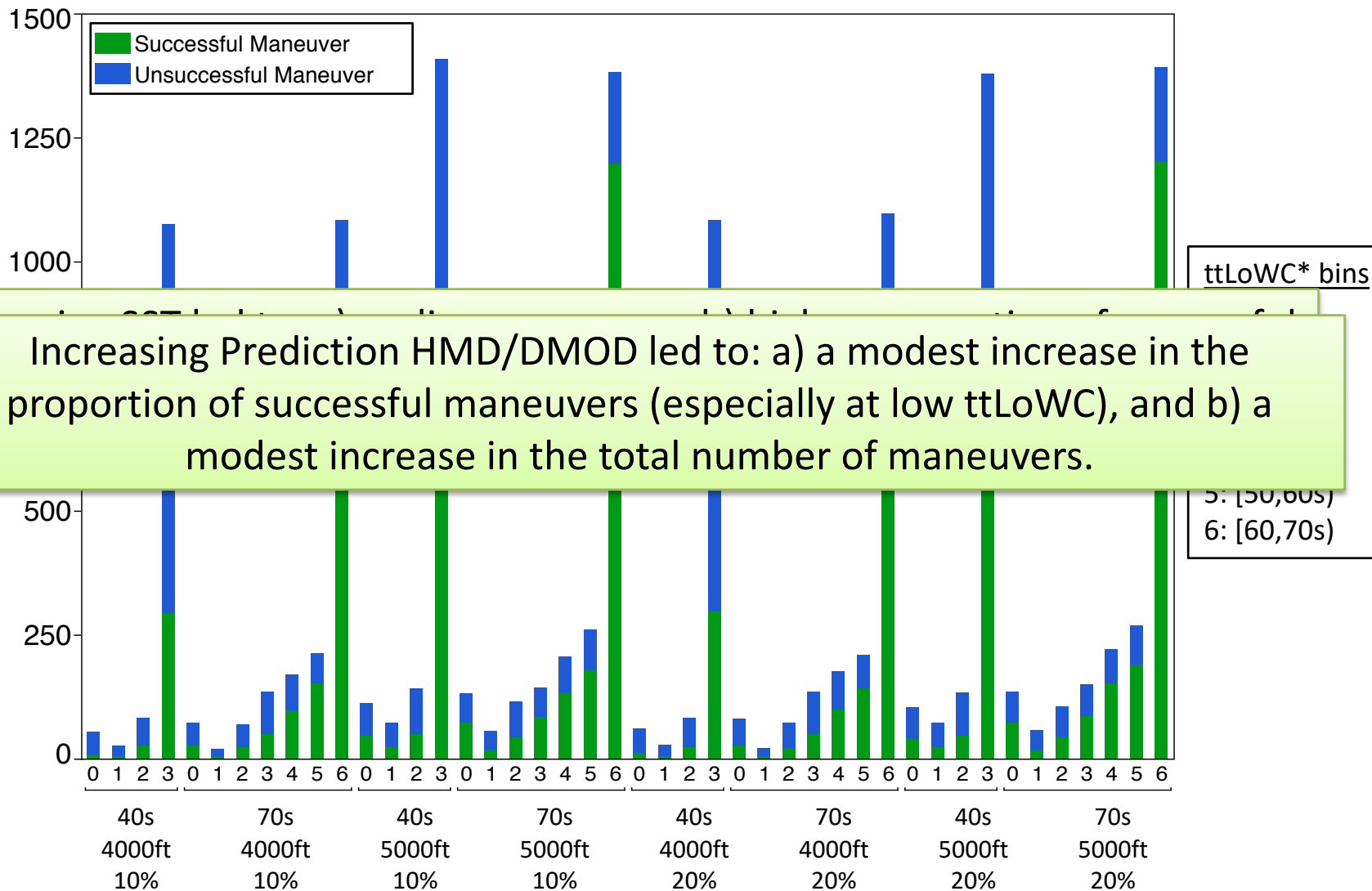
Effect of Prediction DMOD/HMD on Risk Ratio



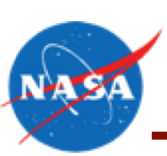
Effect of Resolution HMD Buffer on Risk Ratio



Effect of SST*, HMD/DMOD & Resolution HMD Buffer on Maneuver Statistics



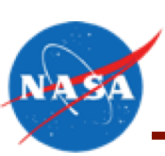
Run Condition, C (SST, HMD/DMOD, Res. HMD Buffer)



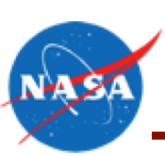
ACES Risk Ratio Study: Takeaways



- Increasing SST* demonstrated greatest Risk Ratio reduction : Highlights importance of pilot response modeling to DAA risk ratio estimation
- Increasing prediction HMD/DMOD showed modest risk ratio reduction: poor risk ratios for no buffer case (4000 ft prediction HMD/DMOD)... points to importance of prediction buffers
 - No buffers used for modified Tau or $Z_{\text{THRESHOLD}}$
 - Modeling $Z_{\text{THRESHOLD}}$ is not straightforward (e.g., pilot response to alerting in level vs. non-level encounters)
- Resolution HMD buffer had negligible impact on Risk Ratio (may need larger buffers)
- Difficult to assess achievable risk ratio with current limitations
 - Best filtered SS risk ratio achieved for (70s SST*, 5000 ft. HMD, 20% resolution buffer)
 - 0.34 Risk Ratio @ 1 maneuver per 8.9 flight hours
 - Risk Ratio expected to improve with improved pilot response model and refined buffers
 - Does not include collision avoidance mitigation
 - Does not include mitigation of SS maneuvers after LoWC in reducing P(NMAC)
 - No modeling of vertical alerts and pilot response to vertical alerts
- While (current and planned) capabilities and analysis tools appear well suited for future needs, simulation time and analysis time are considerable... timely development and integration of pilot response model and validation methods (e.g. metrics) will dictate amount of data that can be collected



Questions?



Backup Slides



Backup Slides: UAS Mission Performance Requirements



Sl. No.	UAS Mission Name	Aircraft	FDS flight count in year 1	FDS flight count in year 26	Cruise altitude	Cruise speed (KTAS)	Flight duration
1	Aerial Imaging and Mapping	MK47	30	295	3,000 ft. AGL	44 to 51	~40 mins.
2	Air Quality Monitoring	RQ7B	10	1,044	4,000 to 5,000 ft. AGL	74 to 89	1 to 4 hrs.
3	Airborne Pathogen Tracking	RQ7B	108	1,308	3,000 to 10,000 ft. AGL	72 to 97	1 to 4 hrs.
4	Border Patrol	MQ-9	102	867	5,000 to 15,000 ft. AGL	129 to 173	2 to 7 hrs.
5	Cargo Delivery	PA34, AT43	597	645	626 to 25,000 ft. MSL	146 to 308	20 to 200 mins.
6	Communication and Broadcast Relay	HALE	12,516	24,291	60,000 to 65,000 ft. MSL	70	170 to 590 hrs.
7	FAA Waypoint Inspection	BE20, C560, CL60, LJ45	16	26	226 to 30,000 ft. MSL	295 to 448	4 to 6 hrs.
8	Flood Inundation Mapping	MK47	99	127	4,000 ft. AGL	46 to 51	1 to 4 hrs.
9	Law Enforcement	MK47	300	300	3,000 ft. AGL	44 to 51	3 to 8 hrs.
10	Maritime Patrol	RQ4A	112	1,512	5,000 to 35,000 ft. AGL	151 to 343	4.5 to 14 hrs.
11	On-demand Air Taxi: Remote Pilot Cirrus SR22	SR22	5,175	8,720	6,000 to 11,000 ft. MSL	153 to 166	20 to 45 mins.
12	On-demand Air Taxi: Remote Pilot Cessna Mustang	C510	1,658	3,180	10,000 to 33,000 ft. MSL	156 to 340	20 to 45 mins.
13	On-demand Air Taxi: Auto. Cessna Mustang	C510	1,994	3,792	10,000 to 33,000 ft. MSL	156 to 340	20 to 45 mins.
14	On-demand Air Taxi: Auto. Cirrus SR22	SR22	6,407	10,508	6,000 to 11,000 ft. MSL	153 to 166	20 to 45 mins.
15	Point Source Emission Monitoring	RQ7B	30	432	3,000 ft. AGL	72 to 80	40 to 300 mins.
16	Spill Monitoring	RQ7B	55	880	3,000 to 13,000 ft. AGL	72 to 93	40 to 260 mins.
17	Strategic Wildfire Monitoring	MQ-9	74	324	31,000 ft. MSL	209	~20 hrs.
18	Streamflow Monitoring	MK47	20	202	4,000 ft. AGL	46 to 51	1 to 4 hrs.
19	Tactical Wildfire Monitoring: Max. Fire Counts	SCNE	1,044	10,432	3,000 ft. AGL	72 to 81	1 to 1.5 hrs.
20	Tactical Wildfire Monitoring: Median Fire Counts	SCNE	243	2,496	3,000 ft. AGL	72 to 75	1 to 1.5 hrs.
21	Tactical Wildfire Monitoring: Min. Fire Counts	SCNE	64	640	3,000 ft. AGL	72 to 75	1 to 1.5 hrs.
22	Traffic Monitoring	RQ7B	491	1,043	1,169 to 7,660 ft. MSL	58 to 84	up to 2 hrs.
23	Weather Data Collection	RQ4A	560	2,401	5,000 ft. to 35,000 ft. AGL	151 to 343	1.5 to 13 hrs.
24	Wildlife Monitoring	MK47	31	308	3,000 ft. AGL	44 to 51	~40 mins.
25	News Gathering			Underway			
26	Damage/Survey Assessment			Underway			



Backup Slides: VFR Annual Operations (OpsNet)

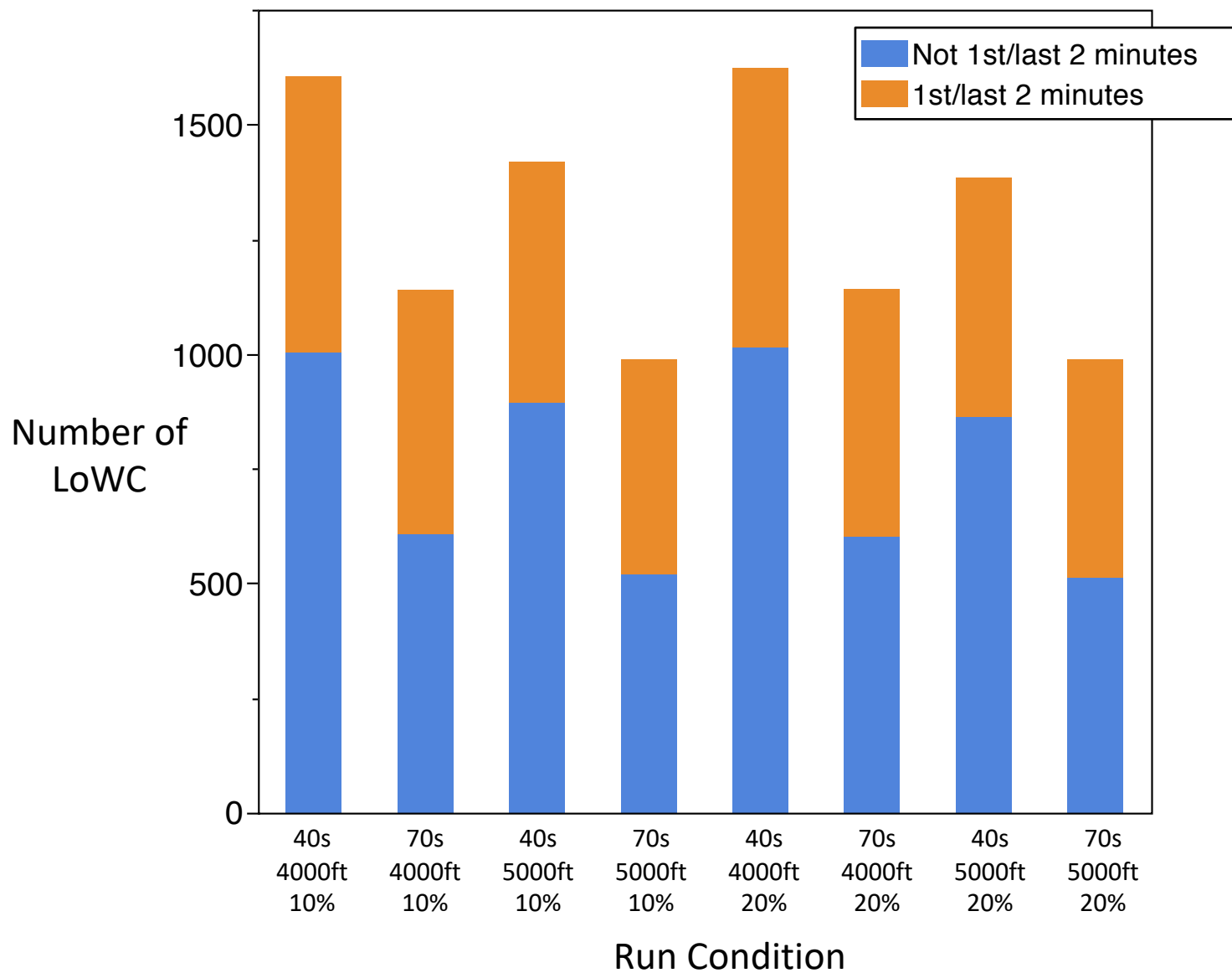


From 01/1989 To 09/2014

Calendar Year	VFR Itinerant					Itinerant					Local			
	Air Carrier	Air Taxi	General Aviation	Military	Total	Air Carrier	Air Taxi	General Aviation	Military	Total	Civil	Military	Total	Total Operations
1989	106,260	52,457	102,199	12,432	273,348	2,459,580	992,694	738,142	72,819	4,263,235	88,354	13,831	102,185	4,365,420
1990	492,036	1,537,378	12,145,764	445,974	14,621,152	12,962,103	9,095,491	23,259,659	1,448,843	46,766,096	17,352,919	1,387,276	18,740,195	65,506,291
1991	503,696	1,609,827	11,822,938	470,120	14,406,581	12,343,024	9,056,308	22,009,223	1,352,724	44,761,279	16,396,388	1,263,968	17,660,356	62,421,635
1992	527,762	1,730,304	11,981,597	549,938	14,789,601	12,485,720	9,558,104	21,894,055	1,490,627	45,428,506	16,197,114	1,393,060	17,590,174	63,018,680
1993	639,289	1,967,969	11,770,267	555,704	14,933,229	12,718,488	9,951,421	21,172,322	1,408,916	45,251,147	15,419,615	1,275,720	16,695,335	61,946,482
1994	510,370	1,811,624	11,912,739	492,815	14,727,548	13,382,593	10,201,783	21,039,756	1,319,558	45,943,690	15,253,876	1,255,006	16,508,882	62,452,572
1995	567,925	2,176,257	14,093,162	597,160	17,434,504	13,661,471	10,249,803	20,795,685	1,324,175	46,031,134	14,783,956	1,259,216	16,043,172	62,074,306
1996	532,587	2,111,863	14,061,129	581,920	17,287,499	13,925,740	10,130,056	20,798,237	1,312,549	46,166,582	14,402,957	1,247,886	15,650,843	61,817,425
1997	490,972	2,059,467	14,906,539	579,541	18,036,519	14,318,820	10,083,129	21,922,663	1,286,910	47,611,522	15,545,903	1,283,522	16,829,425	64,440,947
1998	491,707	2,057,191	15,087,019	609,135	18,245,052	14,272,318	10,297,124	22,472,826	1,398,366	48,440,634	16,311,991	1,459,109	17,771,100	66,211,734
1999	469,957	2,083,594	15,555,737	639,757	18,749,045	14,826,796	10,561,572	23,146,537	1,442,387	49,977,292	17,186,449	1,508,499	18,694,948	68,672,240
2000	430,271	2,035,725	14,734,828	559,264	17,760,088	15,130,733	10,819,571	22,269,071	1,422,028	49,641,403	16,621,631	1,419,080	18,040,711	67,682,114
2001	800,292	2,008,725	13,993,462	519,906	17,322,385	14,177,655	10,836,776	21,274,300	1,507,820	47,796,551	16,220,728	1,447,706	17,668,434	65,464,985
2002	866,550	2,042,834	14,192,271	553,918	17,655,573	13,309,745	11,160,855	21,386,443	1,554,228	47,411,271	16,063,361	1,520,585	17,583,946	64,995,217
2003	885,792	2,054,778	13,349,594	539,916	16,830,080	12,667,389	11,601,690	20,152,454	1,532,263	45,953,796	15,152,056	1,492,834	16,644,890	62,598,686
2004	1,116,901	2,289,771	13,036,940	570,722	17,014,334	13,140,372	12,395,387	19,726,898	1,471,943	46,734,600	14,849,783	1,457,885	16,307,668	63,042,268
2005	607,327	2,153,236	12,667,630	491,749	15,919,942	13,467,204	12,437,123	19,151,192	1,389,814	46,445,333	14,774,016	1,445,191	16,219,207	62,664,540
2006	125,084	1,986,380	12,479,234	493,165	15,083,863	13,356,029	11,848,397	18,811,006	1,360,726	45,376,158	14,479,620	1,419,181	15,898,801	61,274,959
2007	78,673	1,902,496	12,131,646	491,201	14,604,016	13,687,788	11,581,071	18,335,008	1,296,229	44,900,096	14,560,618	1,377,542	15,938,160	60,838,256
2008	58,124	1,875,450	11,309,353	447,668	13,690,595	13,544,809	10,604,907	17,013,618	1,275,590	42,438,924	13,589,686	1,228,865	14,818,551	57,257,475
2009	24,270	1,684,398	10,295,247	426,622	12,430,537	12,732,804	9,412,534	15,283,655	1,308,053	38,737,046	12,229,985	1,272,041	13,502,026	52,239,072
2010	18,762	1,729,677	9,918,605	451,395	12,118,439	12,722,700	9,436,641	14,846,037	1,319,936	38,325,314	11,629,445	1,323,870	12,953,315	51,278,629
2011	15,975	1,719,394	9,710,720	432,566	11,878,655	12,861,792	9,177,953	14,475,524	1,306,753	37,822,022	11,481,565	1,294,867	12,776,432	50,598,454
2012	15,356	1,803,099	9,699,141	460,252	11,977,848	12,818,415	8,903,614	14,398,052	1,320,069	37,440,150	11,556,479	1,267,679	12,824,158	50,264,308
2013	19,234	1,860,676	9,476,044	441,147	11,797,101	12,845,544	8,796,539	14,125,183	1,245,620	37,012,886	11,730,379	1,272,093	13,002,472	50,015,358
2014	14,069	1,546,304	7,163,651	356,435	9,080,459	9,817,135	6,349,894	10,647,720	996,989	27,811,738	8,942,940	964,490	9,907,430	37,719,168
Total:	10,409,241	47,890,874	307,597,456	12,770,422	378,667,993	333,636,767	255,540,437	481,145,266	34,165,935	1,104,488,405	362,821,814	33,551,002	396,372,816	1,500,861,221

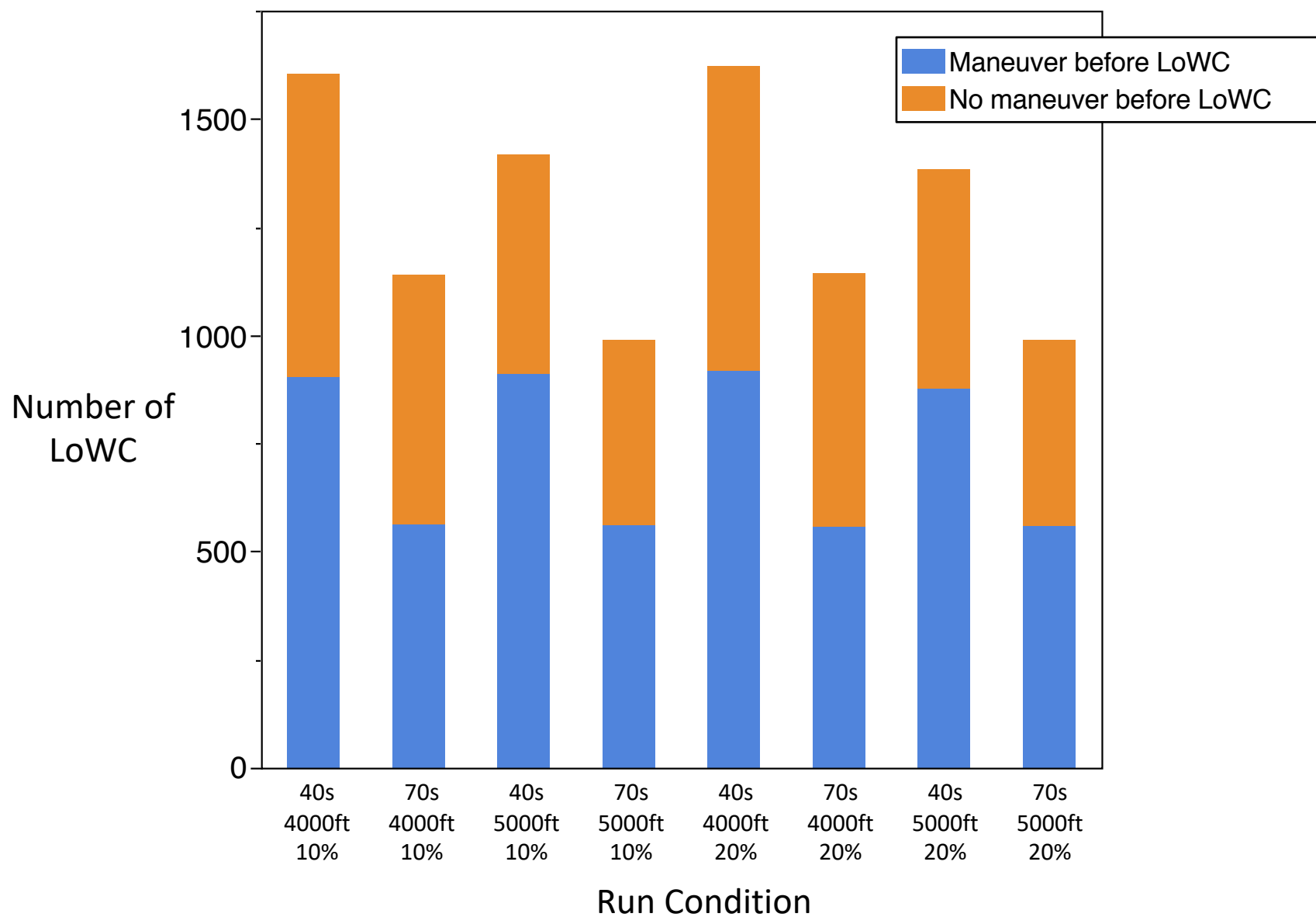


Backup Slides: 1st 2 minute filter by run condition



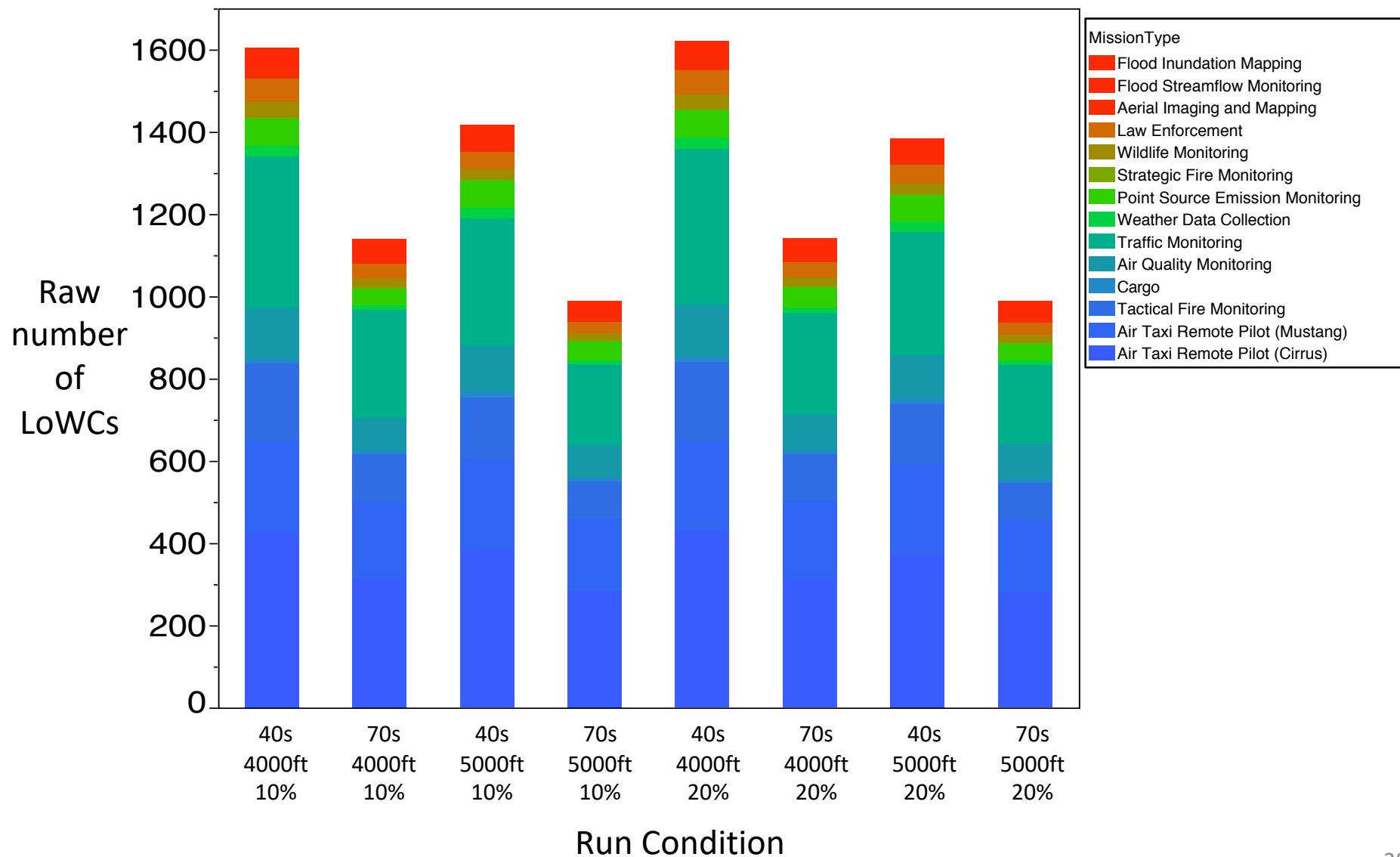


Backup Slides: noRes filter by run condition



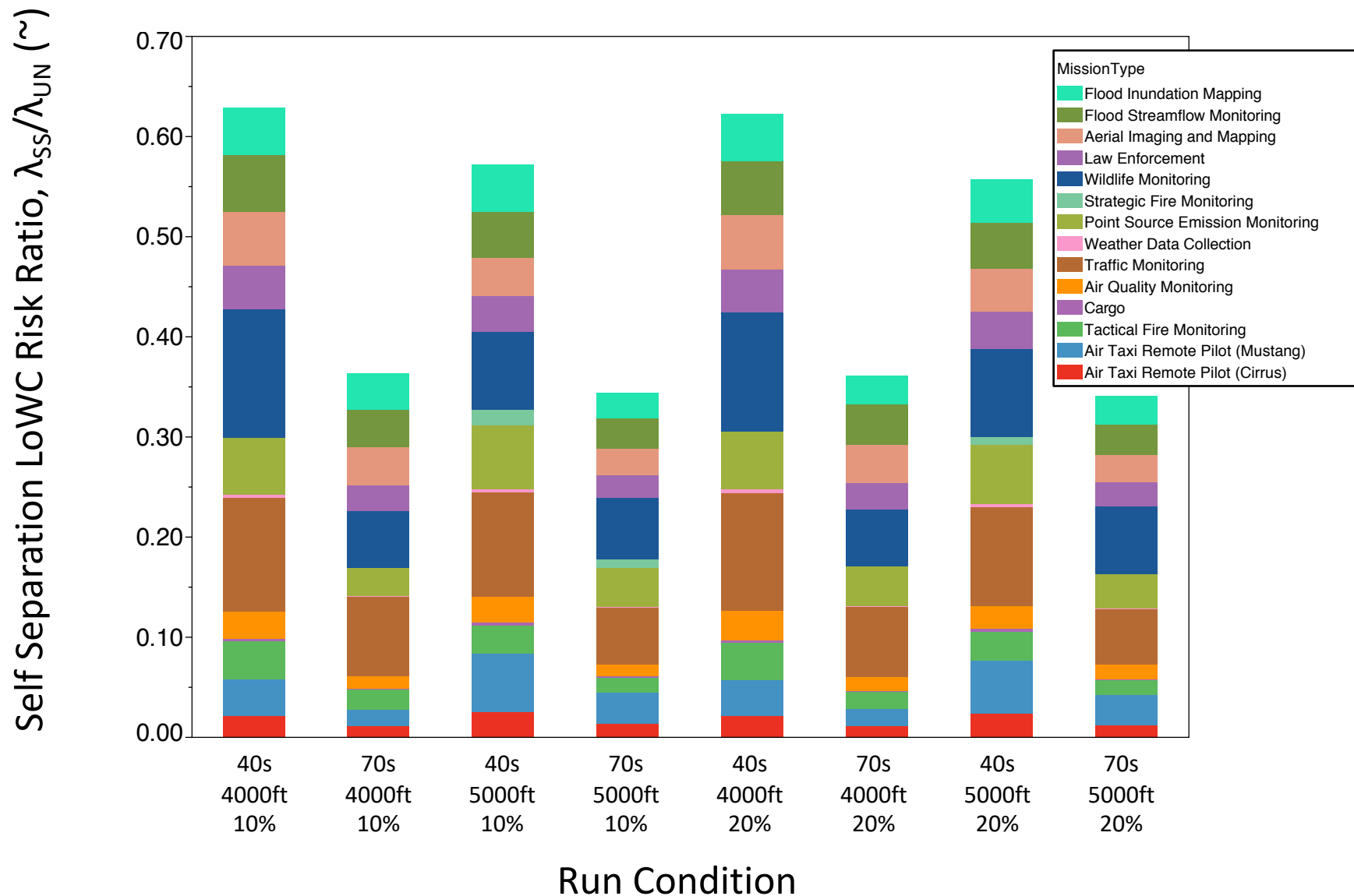


Backup Slides: LoWCs by Mission Type and Run Condition



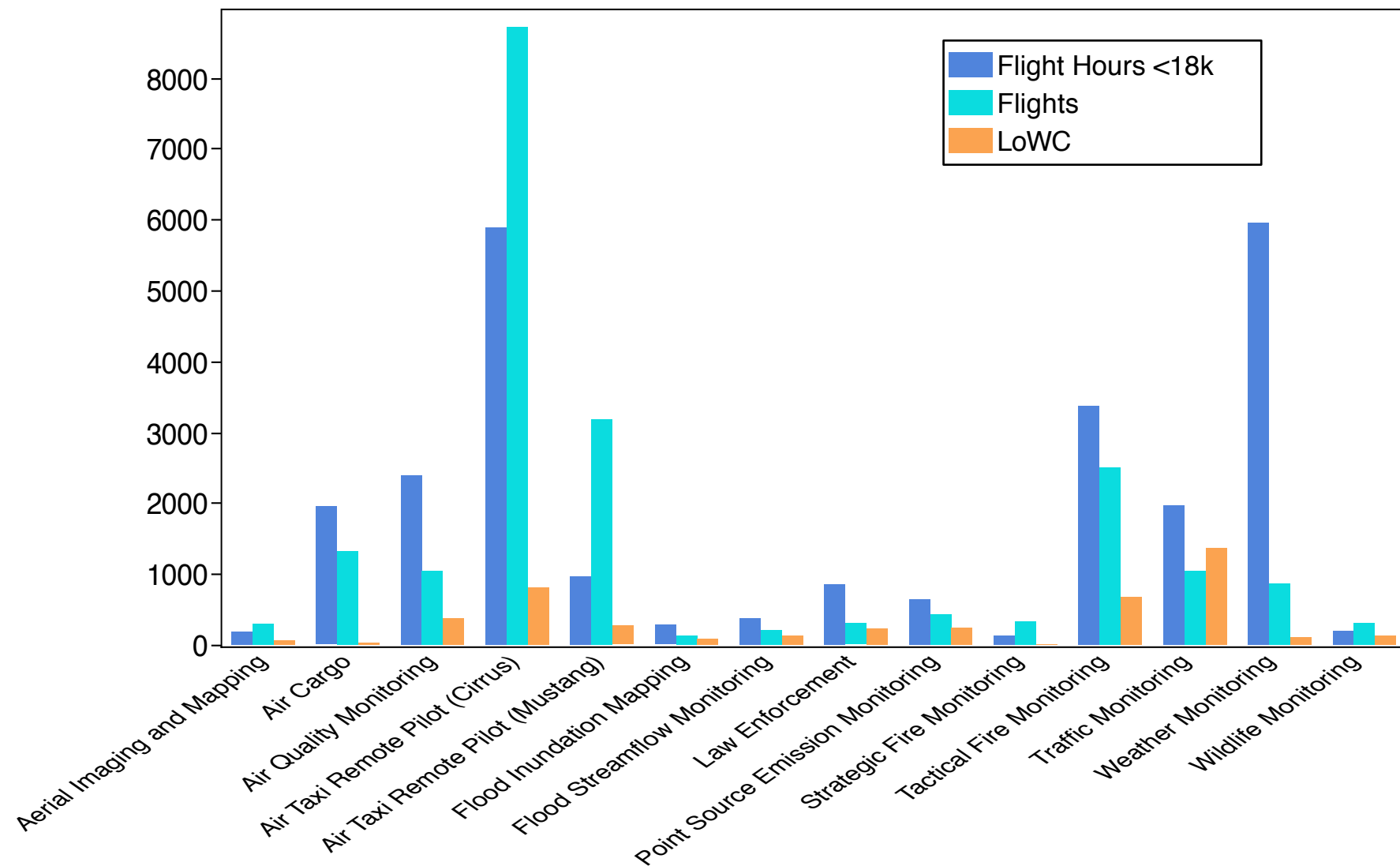


Backup Slides: Filtered Risk Ratio Contribution by Mission



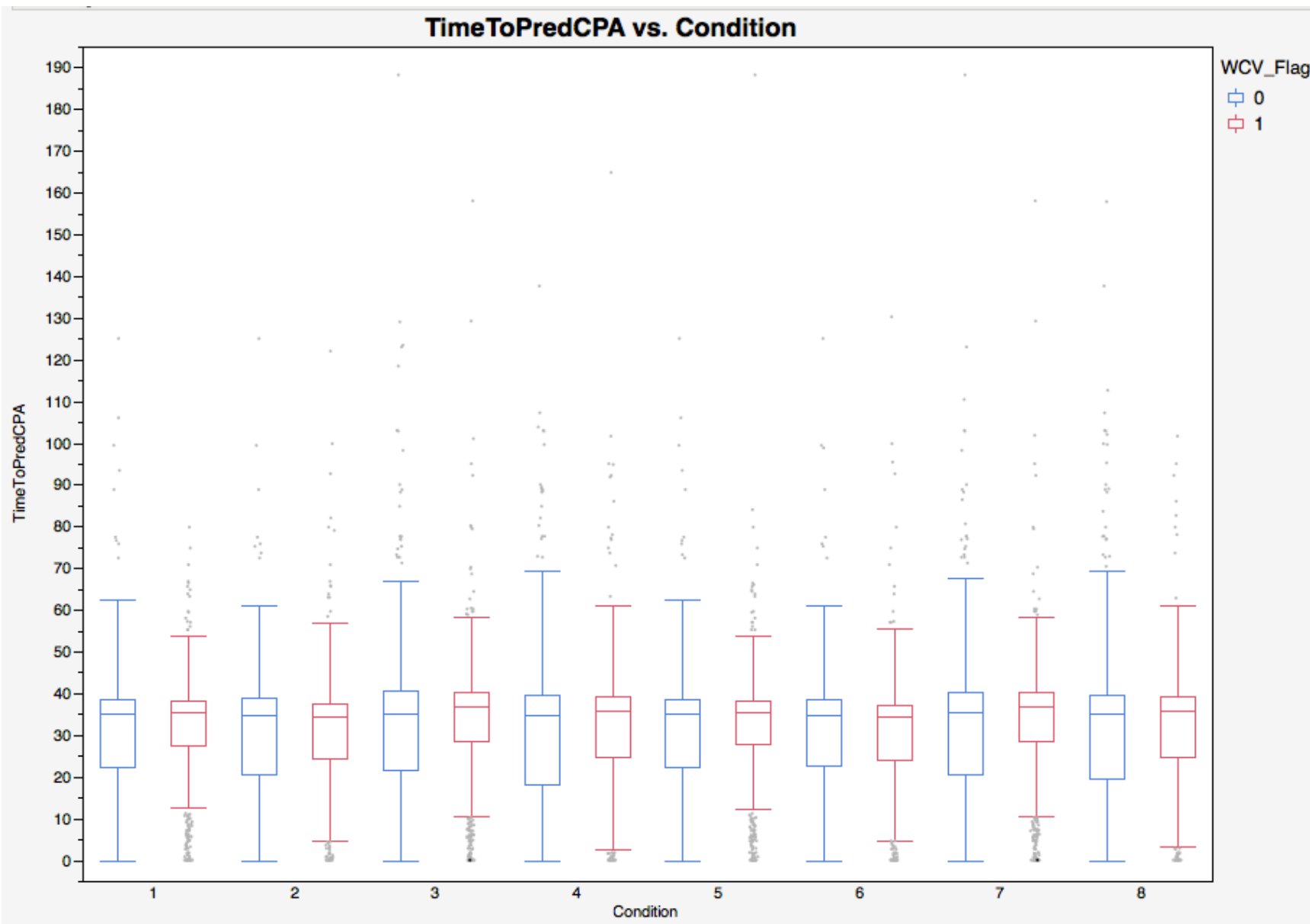


Backup Slides: Flights, Hours, LoWCs by Mission

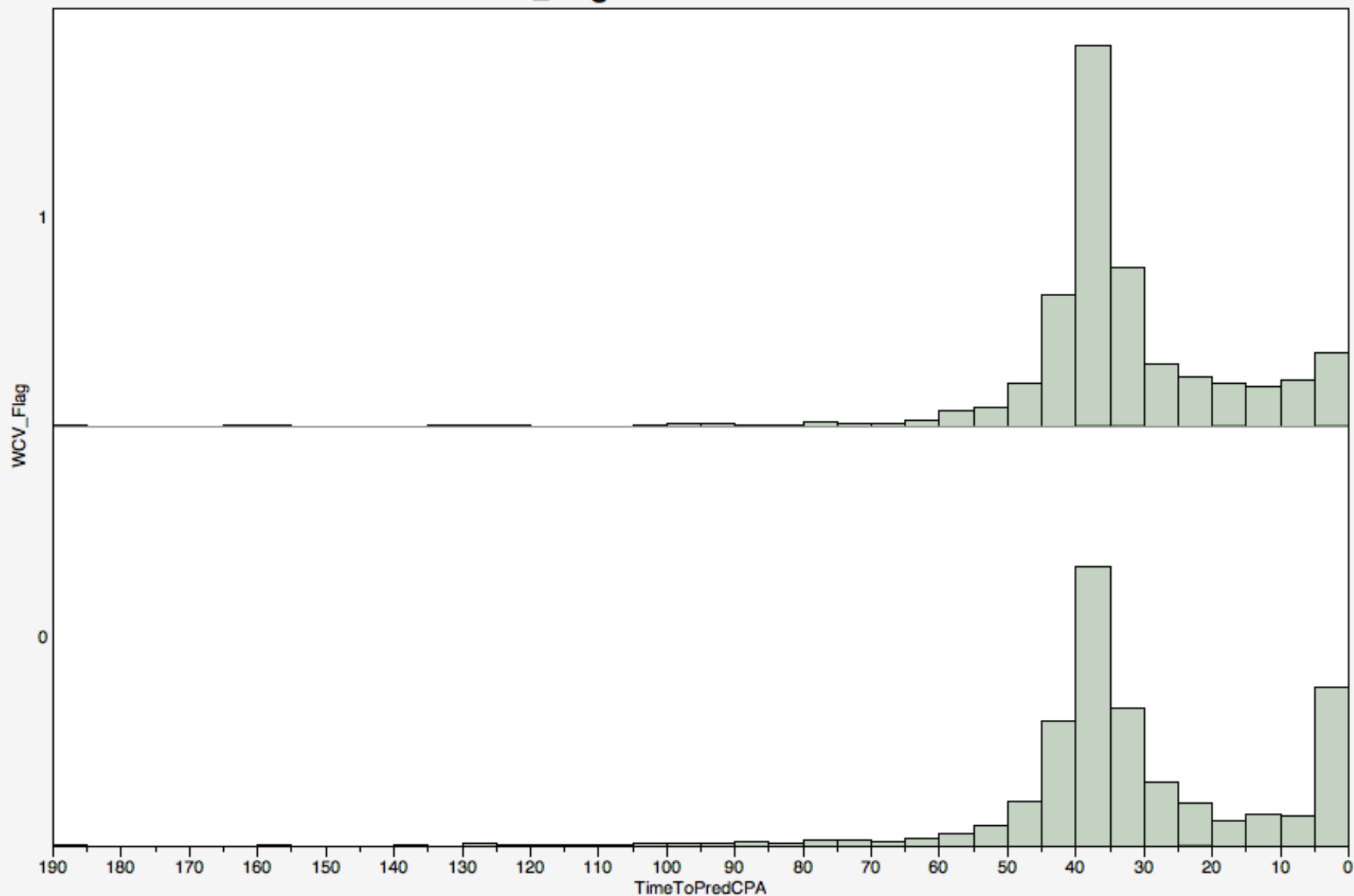




Backup Slides: Time to PredCPA @ Z_alert by Condition



WCV_Flag vs. TimeToPredCPA





ACES Risk Ratio Study: Self-Separation Timeline

