

# Developing Sense & Avoid Requirements for Meeting an Equivalent Level of Safety

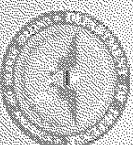
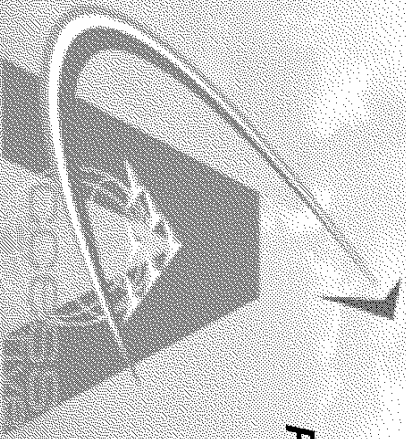
UVS Tech 2006

Salon-de-Provence, France

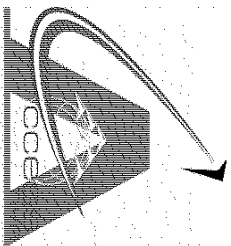
17-19 January 2006

Presenter: Russell Wolfe

Access 5 Technology IPT Lead  
Modern Technology Solutions, Inc

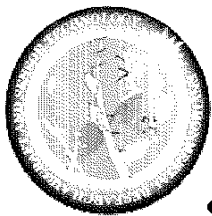


HALE UAS in the NAS

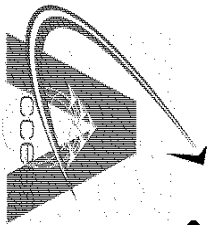


# UAS Collision Avoidance Initiatives

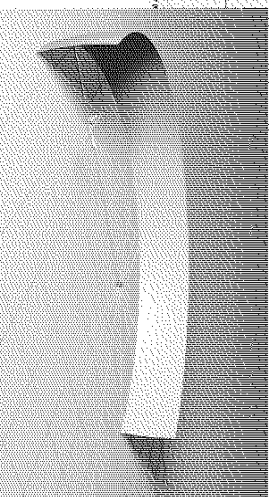
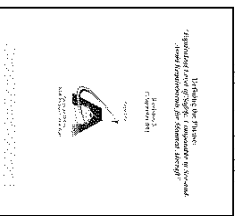
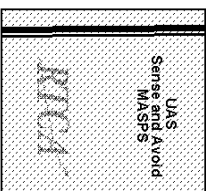
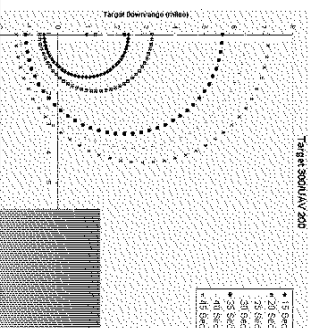
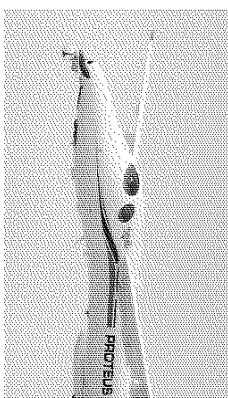
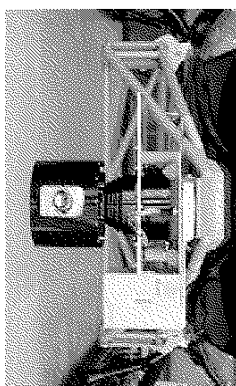
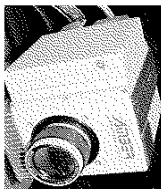
## NASA Dryden Flight Research Center

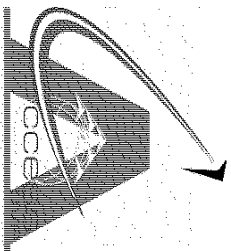


- ERAST: 1993 - 2003
  - Sensor Requirements
  - Sensor Concept Development
  - Flight Test Demonstrations
    - Cooperative
    - EO / IR
    - Radar



- ACCESS 5: 2004 - present
  - Requirements Development
  - Safety Analysis
  - Simulation Tools
  - Flight Test Demonstrations
  - Standards Development

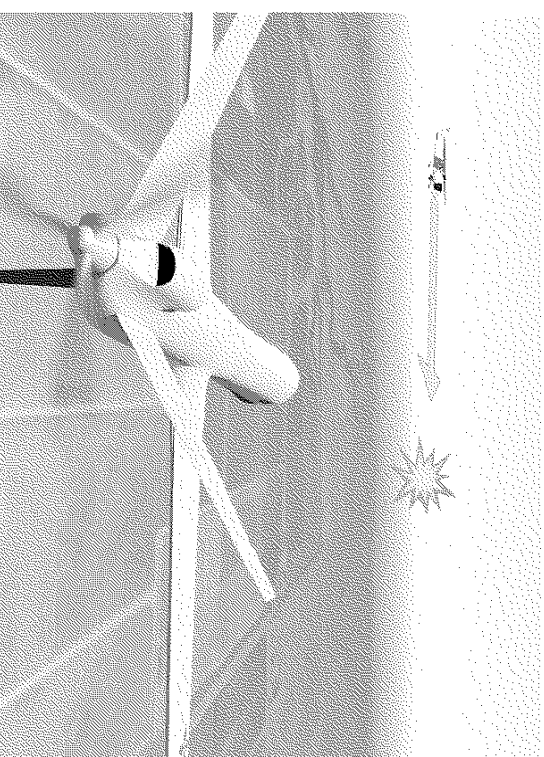


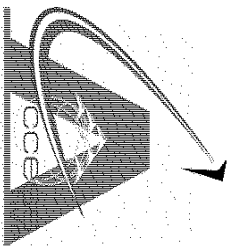


# ACCESS 5

## Collision Avoidance Work Package

- **Work Package Objectives:**
  - Define Equivalent Level of Safety (ELOS) for Sense and Avoid.
  - Develop collision avoidance (CA) requirements for Unmanned Aircraft Systems (UAS); validated through analysis, simulation, and flight demonstration.
  - Provide inputs to the FAA and RTCA Special Committee 203 “Unmanned Aircraft Systems”
- **Team Members:**
  - NASA Dryden & Langley
  - Northrop Grumman
  - Lockheed Martin (Ft. Worth)
  - MITRE

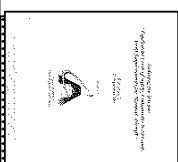




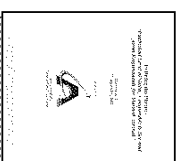
# ACCESS 5 Collision Avoidance Work Package

## 5 Major Task Areas

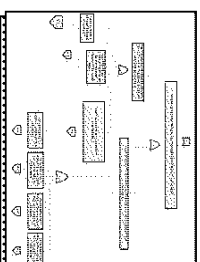
- CA Task 1:  
**Define ELOS for See & Avoid**



- CA Task 2:  
**Develop CA Requirements**



- CA Task 3:  
**Perform CA Safety Analysis**

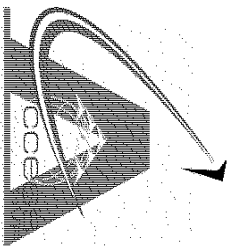


- CA Task 4:  
**Develop CA Simulation Tool**



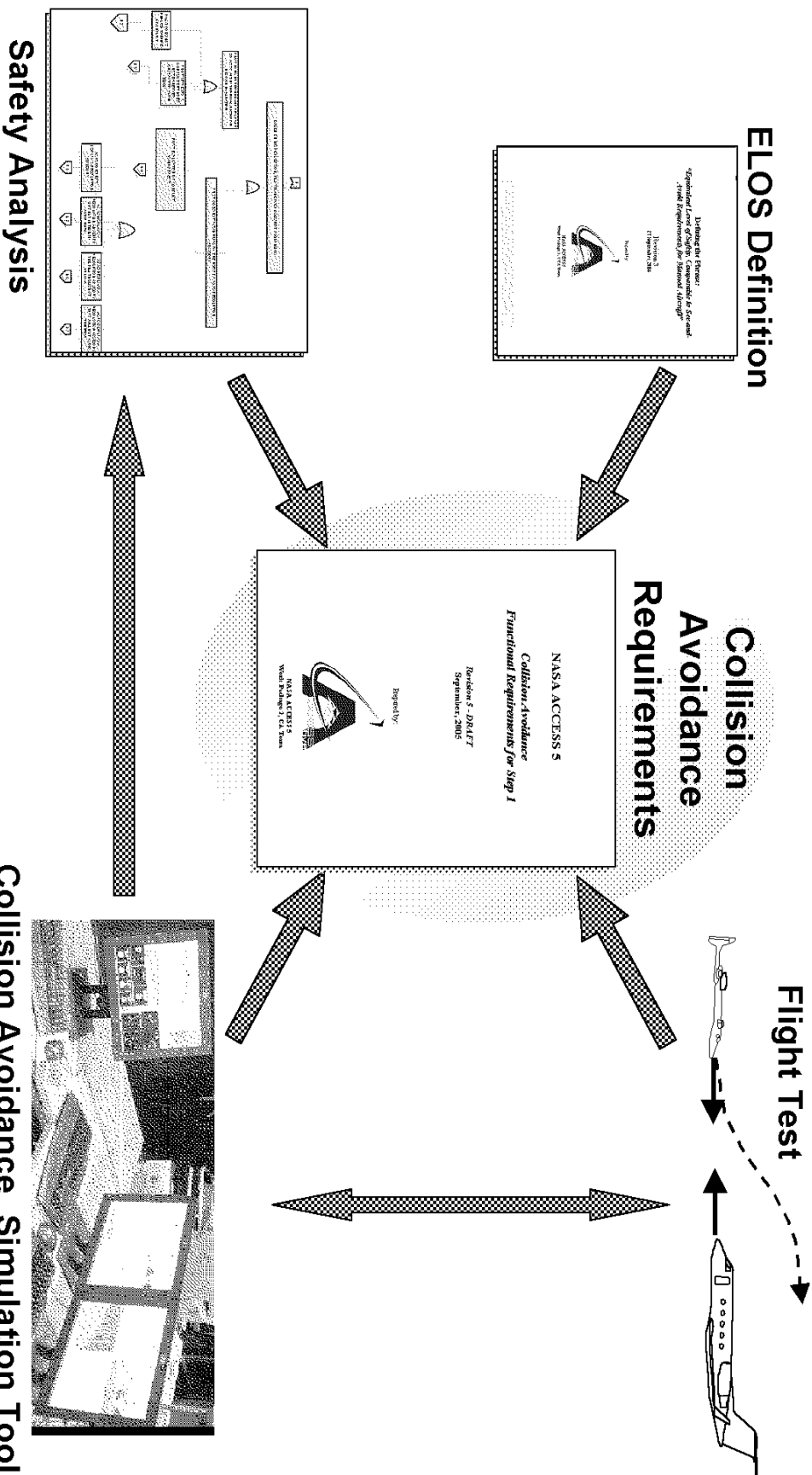
- CA Task 5:  
**Perform CA Flight Test**

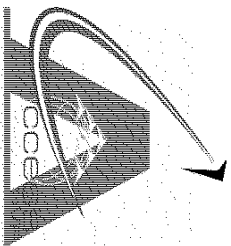




# Collision Avoidance Work Package

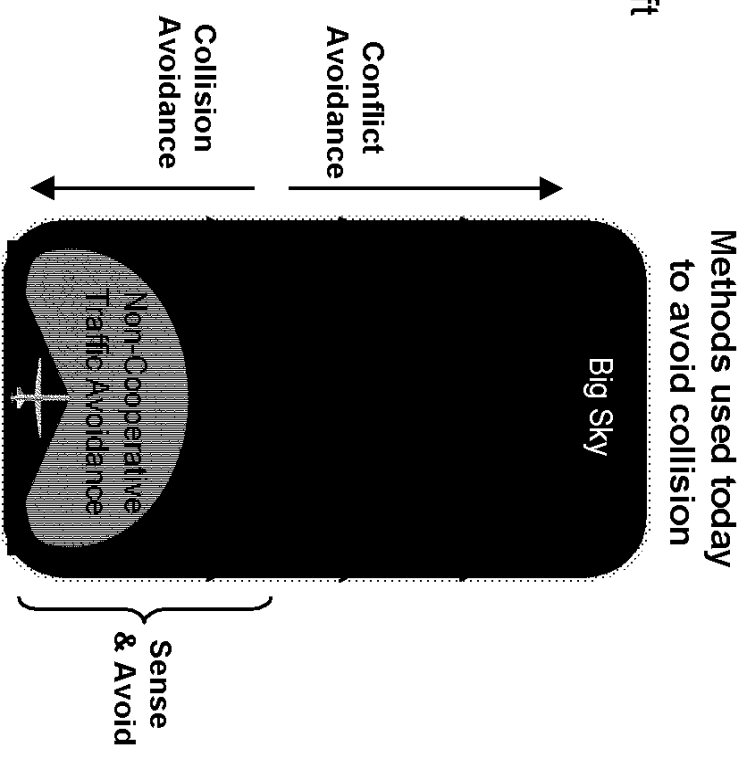
## Task Relationships



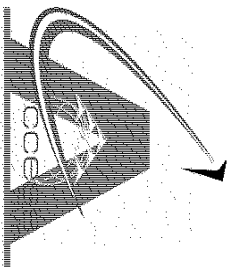


## Task 1: ELOS Definition Document

- Objective: To present a recommended approach for defining an equivalent level of safety, as it pertains to see and avoid.
- Deliverable Content:
  - Current regulatory / operational environment
    - 14 CFR 91.113(b), Right of Way Rules
    - 14 CFR 91.111, Operating near other aircraft
  - Basis for having to meet an Equivalent Level of Safety
    - 14 CFR 21.21(b), Certification Procedures
    - FAA Order 8110.4C, Equivalent Level of Safety Findings
  - Potential Approaches & Methodologies for defining ELOS
    - 1) Statistical Approach
    - 2) Performance / Rule Based Approach
  - Recommended Definition and Measures of Performance for Sense and Avoid ELOS



- Status: Delivered to FAA on 23 Nov 2004

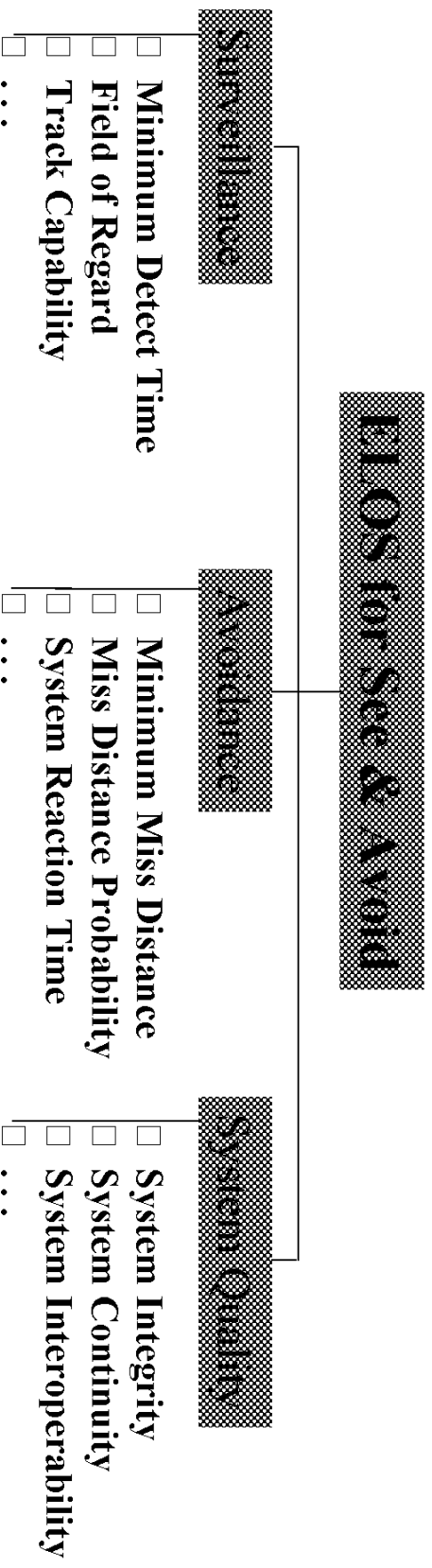


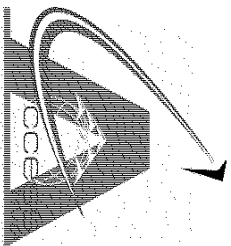
# Task 1: ELOS Definition Document

## Definition and Measures of Performance

- Definition: “Equivalent level of safety to manned aircraft see-and-avoid” is the capability to provide situational awareness with adequate time to detect conflicting traffic and the ability to take the appropriate action necessary to avoid collisions.”

- Measures of Performance:

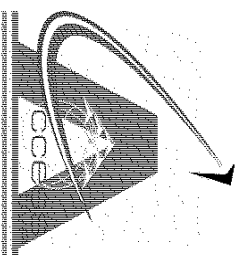




## ***Task 2: Develop Collision Avoidance Reqmts***

- **Objective:** To develop the collision avoidance operational, functional, and performance requirements for HALE UAS.
- **Deliverable Content:**
  - Notional CA Subsystem Description
    - Subsystem Architecture
    - Interfaces
  - Operational Requirements
  - Functional Analysis
    - List of Collision Avoidance Functions
    - Functional Flow Block Diagram
    - Functional Requirements
  - Performance Requirements
    - Design Guidelines
    - Performance Trade-offs
  - Verification Method (Analysis, Inspection, Simulation/Modeling, Demo, Test)
- **Status:** Intend to release Revision 6.0 in February 2006  
(All previous revisions have included FAA input and review)

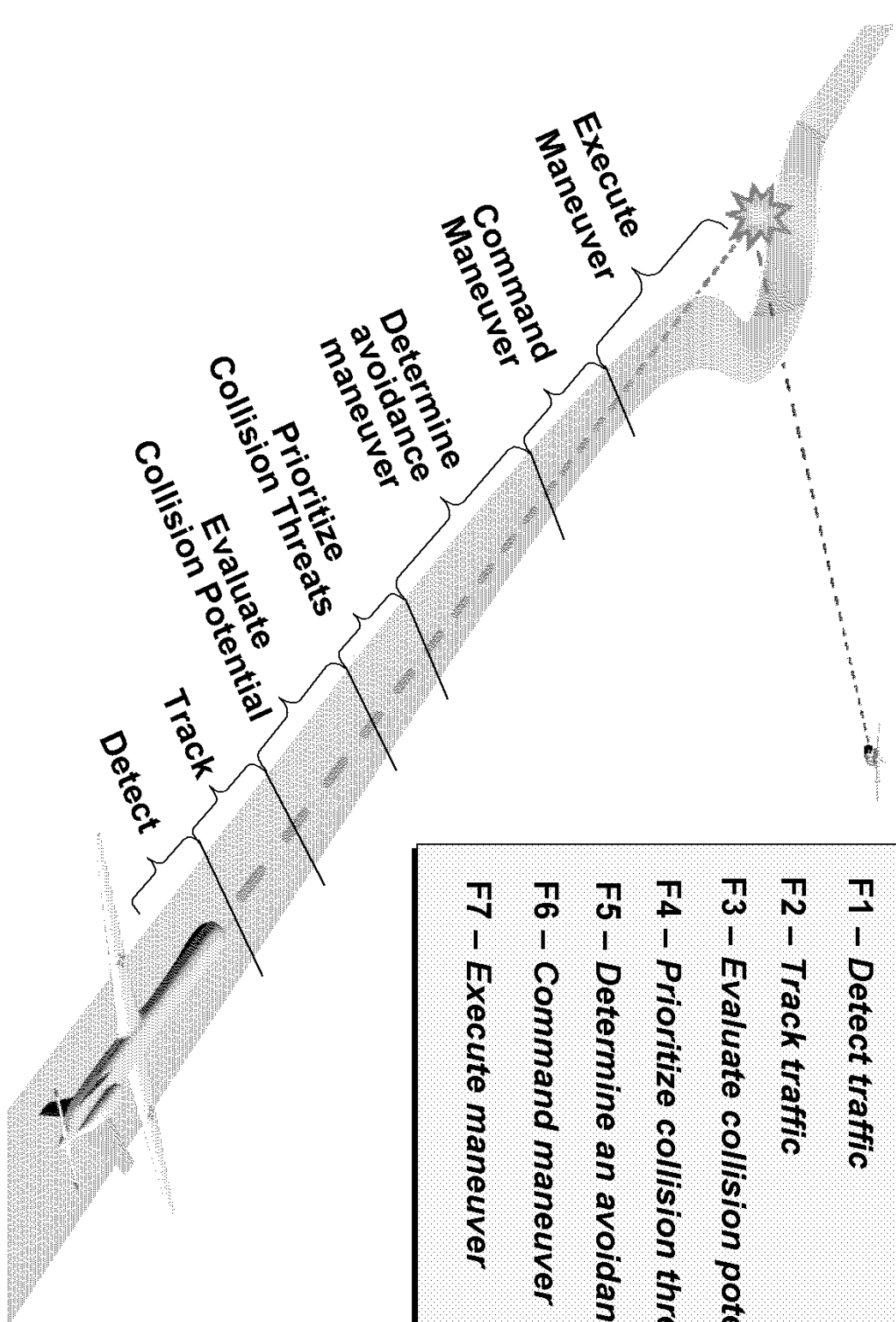


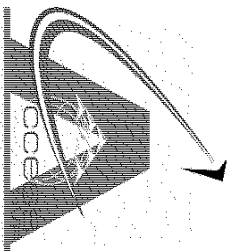


# Task 2: Develop Collision Avoidance Reqmts

## Collision Avoidance Functions

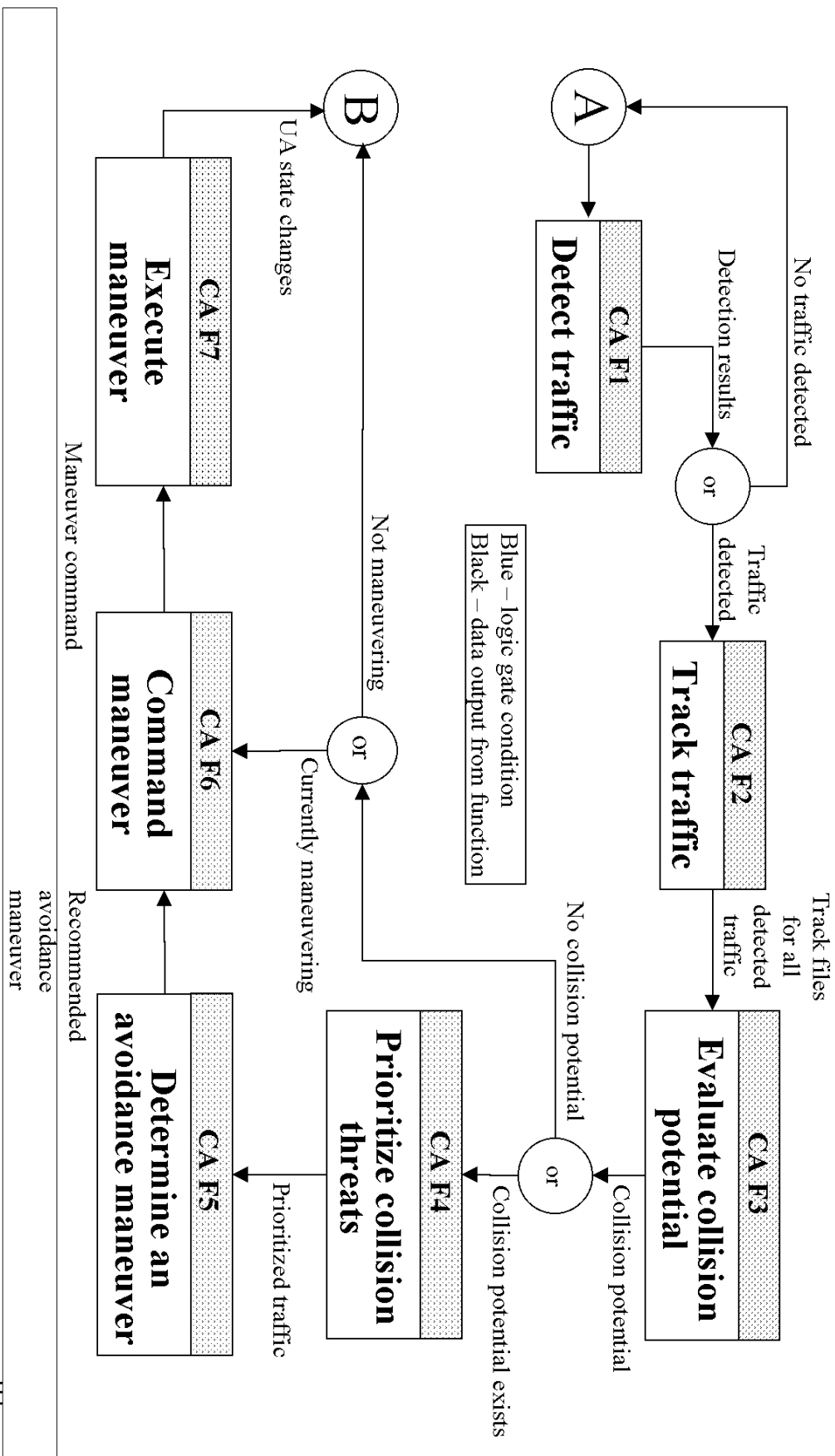
- F1 – Detect traffic
- F2 – Track traffic
- F3 – Evaluate collision potential
- F4 – Prioritize collision threats
- F5 – Determine an avoidance maneuver
- F6 – Command maneuver
- F7 – Execute maneuver

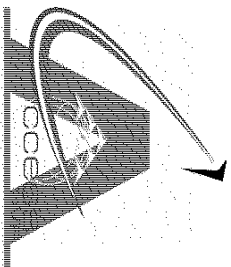




# Task 2: Develop Collision Avoidance Reqmts

## Functional Flow Block Diagram

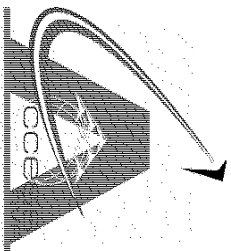




## **Task 2: Develop Collision Avoidance Reqmts**

### *Function 1: Detect Traffic Requirements (Example)*

- **F1: Detect Traffic - The UAS shall detect traffic within its surveillance volume.**
  - **F1.1: Minimum Detect Time** - The CAS shall detect traffic with sufficient time remaining for successful performance of all required collision avoidance functions.
  - **F1.2: Detection Range** - The CAS shall detect cooperative traffic at a range of at least xx nautical miles. (see *Table F1.2*)
  - **F1.3: Azimuth Field of Regard** - The CAS shall detect cooperative traffic within an azimuth FOR of at least +/-110° referenced from the flight path of the UA.
  - **F1.4: Elevation Field of Regard** - The CAS shall detect cooperative traffic within an elevation FOR of at least +/-15° referenced from the flight path of the UA.
  - **F1.5: Detection Probability** - The CAS shall detect cooperative traffic in the surveillance volume at a rate that supports the track probability guideline (see *F2.3*).
  - **F1.6: Detection Rate** - The average CAS detection rate shall be equal to or greater than xx hertz. (see *Table F1.6*)
  - **F1.7: Detection Accuracy** - The CAS shall detect cooperative traffic with an accuracy of TBD ft for range determinations, and TBD ft for altitude determinations
  - **F1.8: False Detection/Nuisance** - False detections shall account for less than TBD% of all detected traffic.



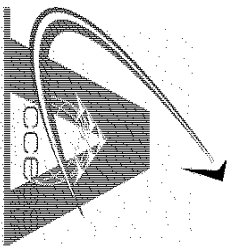
## ***Task 3: Perform Safety Analysis***

- Objective: To develop a method for evaluating the safety of collision avoidance for UAS.

- Establish equivalent level of safety to manned aircraft using event/fault trees and logic risk ratios

$$\text{Risk Ratio} = \frac{P(\text{collision UAS})}{P(\text{collision manned AC})} \leq 1$$

- Accomplishments:
  - Developed visual acquisition model based on Lincoln Lab's SEE1 model
  - Developed surveillance error models for GPS/ADS-B
  - Performed multiple assessments using results from the CA simulation tool for the primary event tree probabilities.
  - Supported requirements development in the areas of Surveillance, Effectiveness, Detection Accuracies, Detection times, Reaction times, Maneuver times, etc.
- Status: Currently finalizing final report and lessons learned

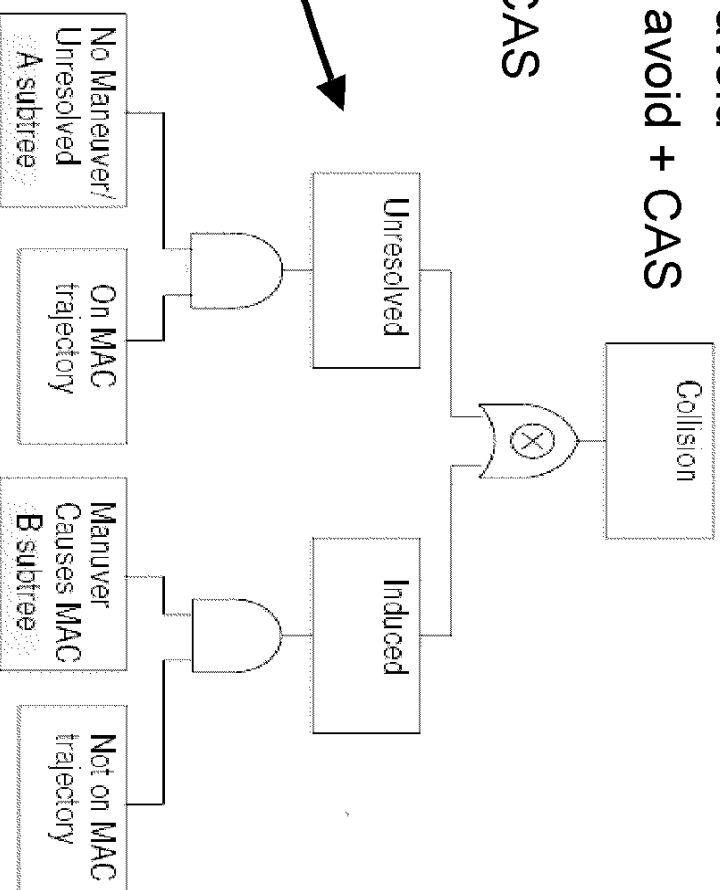


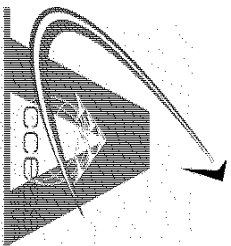
## Task 3: Perform Safety Analysis

### Generic Event/Fault Tree for Collision Probability Estimation

- Generic Event/Fault Tree established to provide a consistent basis for comparison:
  - 1. Manned aircraft using see & avoid
  - 2. Manned aircraft using see & avoid + CAS
  - 3. UAS with Sense & Avoid
  - 4. UAS with Sense & Avoid + CAS

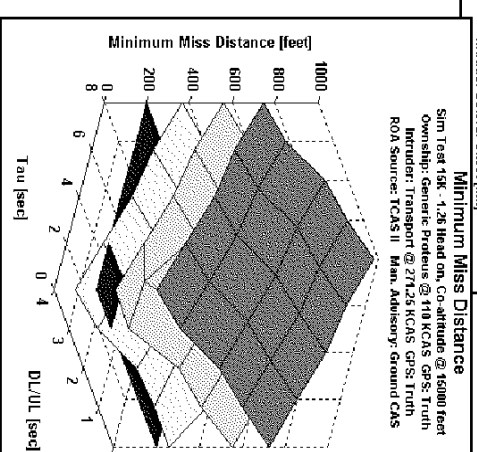
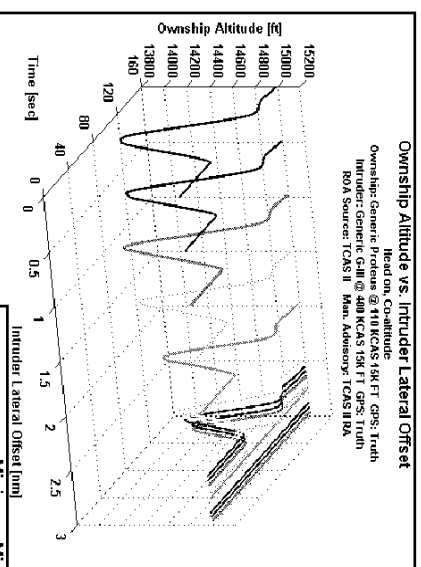
**Simplified Fault Tree**  (actual tree is several pages long)

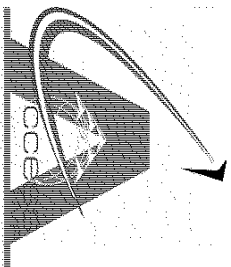




# Task 4: Develop CA Simulation Tool

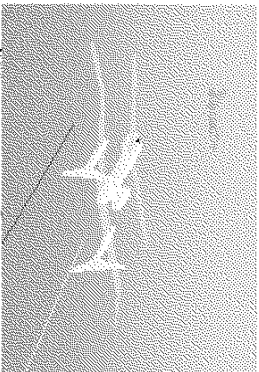
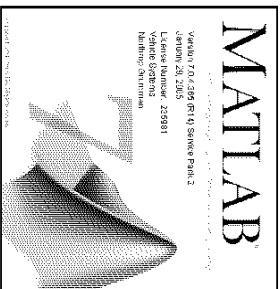
- **Objective:** To assess the validity of the proposed CA Functional Requirements via Simulation as well as support the CA Flight Test activities.
  - Allows characterization of:
    - Ownship Vehicle Dynamics
    - CA Equipment and Software
    - Encounter Scenarios
- **Accomplishments:**
  - Duplicated Tech Demo Scenarios
    - Flight Test Risk Reduction
    - Improve Probability of Obtaining Useful Data
  - Validated Against the System Integration Lab (SIL)
    - Flight Test Risk Reduction
    - CCA Component Models
  - Sensitivity Analyses performed
- **Status:** Currently analyzing flight test data and validating the CA simulation tool.





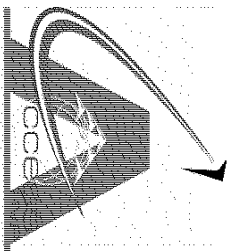
# Task 4: Develop CA Simulation Tool

## Simulation Features



```
1 % Script to generate aircraft geometry. Run in MATLAB or Simulink.
2 %
3 % Note: Use a MATLAB license that supports Simulink. Make sure
4 % that you have a compatible MATLAB license.
5 %
6 % Run this script in the MATLAB Command Window.
7 %
8 %
9 %
10 %
11 %
12 %
13 %
14 %
15 %
16 %
17 %
18 %
19 %
20 %
21 %
22 %
23 %
24 %
25 %
26 %
27 %
28 %
29 %
30 %
31 %
32 %
33 %
34 %
35 %
36 %
37 %
38 %
39 %
40 %
41 %
42 %
43 %
44 %
45 %
46 %
47 %
48 %
49 %
50 %
51 %
52 %
53 %
54 %
55 %
56 %
57 %
58 %
59 %
60 %
61 %
62 %
63 %
64 %
65 %
66 %
67 %
68 %
69 %
70 %
71 %
72 %
73 %
74 %
75 %
76 %
77 %
78 %
79 %
80 %
81 %
82 %
83 %
84 %
85 %
86 %
87 %
88 %
89 %
90 %
91 %
92 %
93 %
94 %
95 %
96 %
97 %
98 %
99 %
100 %
101 %
102 %
103 %
104 %
105 %
106 %
107 %
108 %
109 %
110 %
111 %
112 %
113 %
114 %
115 %
116 %
117 %
118 %
119 %
120 %
121 %
122 %
123 %
124 %
125 %
126 %
127 %
128 %
129 %
130 %
131 %
132 %
133 %
134 %
135 %
136 %
137 %
138 %
139 %
140 %
141 %
142 %
143 %
144 %
145 %
146 %
147 %
148 %
149 %
150 %
151 %
152 %
153 %
154 %
155 %
156 %
157 %
158 %
159 %
160 %
161 %
162 %
163 %
164 %
165 %
166 %
167 %
168 %
169 %
170 %
171 %
172 %
173 %
174 %
175 %
176 %
177 %
178 %
179 %
180 %
181 %
182 %
183 %
184 %
185 %
186 %
187 %
188 %
189 %
190 %
191 %
192 %
193 %
194 %
195 %
196 %
197 %
198 %
199 %
200 %
201 %
202 %
203 %
204 %
205 %
206 %
207 %
208 %
209 %
210 %
211 %
212 %
213 %
214 %
215 %
216 %
217 %
218 %
219 %
220 %
221 %
222 %
223 %
224 %
225 %
226 %
227 %
228 %
229 %
230 %
231 %
232 %
233 %
234 %
235 %
236 %
237 %
238 %
239 %
240 %
241 %
242 %
243 %
244 %
245 %
246 %
247 %
248 %
249 %
250 %
251 %
252 %
253 %
254 %
255 %
256 %
257 %
258 %
259 %
260 %
261 %
262 %
263 %
264 %
265 %
266 %
267 %
268 %
269 %
270 %
271 %
272 %
273 %
274 %
275 %
276 %
277 %
278 %
279 %
280 %
281 %
282 %
283 %
284 %
285 %
286 %
287 %
288 %
289 %
290 %
291 %
292 %
293 %
294 %
295 %
296 %
297 %
298 %
299 %
300 %
301 %
302 %
303 %
304 %
305 %
306 %
307 %
308 %
309 %
310 %
311 %
312 %
313 %
314 %
315 %
316 %
317 %
318 %
319 %
320 %
321 %
322 %
323 %
324 %
325 %
326 %
327 %
328 %
329 %
330 %
331 %
332 %
333 %
334 %
335 %
336 %
337 %
338 %
339 %
340 %
341 %
342 %
343 %
344 %
345 %
346 %
347 %
348 %
349 %
350 %
351 %
352 %
353 %
354 %
355 %
356 %
357 %
358 %
359 %
360 %
361 %
362 %
363 %
364 %
365 %
366 %
367 %
368 %
369 %
370 %
371 %
372 %
373 %
374 %
375 %
376 %
377 %
378 %
379 %
380 %
381 %
382 %
383 %
384 %
385 %
386 %
387 %
388 %
389 %
390 %
391 %
392 %
393 %
394 %
395 %
396 %
397 %
398 %
399 %
400 %
401 %
402 %
403 %
404 %
405 %
406 %
407 %
408 %
409 %
410 %
411 %
412 %
413 %
414 %
415 %
416 %
417 %
418 %
419 %
420 %
421 %
422 %
423 %
424 %
425 %
426 %
427 %
428 %
429 %
430 %
431 %
432 %
433 %
434 %
435 %
436 %
437 %
438 %
439 %
440 %
441 %
442 %
443 %
444 %
445 %
446 %
447 %
448 %
449 %
450 %
451 %
452 %
453 %
454 %
455 %
456 %
457 %
458 %
459 %
460 %
461 %
462 %
463 %
464 %
465 %
466 %
467 %
468 %
469 %
470 %
471 %
472 %
473 %
474 %
475 %
476 %
477 %
478 %
479 %
480 %
481 %
482 %
483 %
484 %
485 %
486 %
487 %
488 %
489 %
490 %
491 %
492 %
493 %
494 %
495 %
496 %
497 %
498 %
499 %
500 %
501 %
502 %
503 %
504 %
505 %
506 %
507 %
508 %
509 %
510 %
511 %
512 %
513 %
514 %
515 %
516 %
517 %
518 %
519 %
520 %
521 %
522 %
523 %
524 %
525 %
526 %
527 %
528 %
529 %
530 %
531 %
532 %
533 %
534 %
535 %
536 %
537 %
538 %
539 %
540 %
541 %
542 %
543 %
544 %
545 %
546 %
547 %
548 %
549 %
550 %
551 %
552 %
553 %
554 %
555 %
556 %
557 %
558 %
559 %
560 %
561 %
562 %
563 %
564 %
565 %
566 %
567 %
568 %
569 %
570 %
571 %
572 %
573 %
574 %
575 %
576 %
577 %
578 %
579 %
580 %
581 %
582 %
583 %
584 %
585 %
586 %
587 %
588 %
589 %
590 %
591 %
592 %
593 %
594 %
595 %
596 %
597 %
598 %
599 %
600 %
601 %
602 %
603 %
604 %
605 %
606 %
607 %
608 %
609 %
610 %
611 %
612 %
613 %
614 %
615 %
616 %
617 %
618 %
619 %
620 %
621 %
622 %
623 %
624 %
625 %
626 %
627 %
628 %
629 %
630 %
631 %
632 %
633 %
634 %
635 %
636 %
637 %
638 %
639 %
640 %
641 %
642 %
643 %
644 %
645 %
646 %
647 %
648 %
649 %
650 %
651 %
652 %
653 %
654 %
655 %
656 %
657 %
658 %
659 %
660 %
661 %
662 %
663 %
664 %
665 %
666 %
667 %
668 %
669 %
670 %
671 %
672 %
673 %
674 %
675 %
676 %
677 %
678 %
679 %
680 %
681 %
682 %
683 %
684 %
685 %
686 %
687 %
688 %
689 %
690 %
691 %
692 %
693 %
694 %
695 %
696 %
697 %
698 %
699 %
700 %
701 %
702 %
703 %
704 %
705 %
706 %
707 %
708 %
709 %
710 %
711 %
712 %
713 %
714 %
715 %
716 %
717 %
718 %
719 %
720 %
721 %
722 %
723 %
724 %
725 %
726 %
727 %
728 %
729 %
730 %
731 %
732 %
733 %
734 %
735 %
736 %
737 %
738 %
739 %
740 %
741 %
742 %
743 %
744 %
745 %
746 %
747 %
748 %
749 %
750 %
751 %
752 %
753 %
754 %
755 %
756 %
757 %
758 %
759 %
760 %
761 %
762 %
763 %
764 %
765 %
766 %
767 %
768 %
769 %
770 %
771 %
772 %
773 %
774 %
775 %
776 %
777 %
778 %
779 %
780 %
781 %
782 %
783 %
784 %
785 %
786 %
787 %
788 %
789 %
790 %
791 %
792 %
793 %
794 %
795 %
796 %
797 %
798 %
799 %
800 %
801 %
802 %
803 %
804 %
805 %
806 %
807 %
808 %
809 %
810 %
811 %
812 %
813 %
814 %
815 %
816 %
817 %
818 %
819 %
820 %
821 %
822 %
823 %
824 %
825 %
826 %
827 %
828 %
829 %
830 %
831 %
832 %
833 %
834 %
835 %
836 %
837 %
838 %
839 %
840 %
841 %
842 %
843 %
844 %
845 %
846 %
847 %
848 %
849 %
850 %
851 %
852 %
853 %
854 %
855 %
856 %
857 %
858 %
859 %
860 %
861 %
862 %
863 %
864 %
865 %
866 %
867 %
868 %
869 %
870 %
871 %
872 %
873 %
874 %
875 %
876 %
877 %
878 %
879 %
880 %
881 %
882 %
883 %
884 %
885 %
886 %
887 %
888 %
889 %
890 %
891 %
892 %
893 %
894 %
895 %
896 %
897 %
898 %
899 %
900 %
901 %
902 %
903 %
904 %
905 %
906 %
907 %
908 %
909 %
910 %
911 %
912 %
913 %
914 %
915 %
916 %
917 %
918 %
919 %
920 %
921 %
922 %
923 %
924 %
925 %
926 %
927 %
928 %
929 %
930 %
931 %
932 %
933 %
934 %
935 %
936 %
937 %
938 %
939 %
940 %
941 %
942 %
943 %
944 %
945 %
946 %
947 %
948 %
949 %
950 %
951 %
952 %
953 %
954 %
955 %
956 %
957 %
958 %
959 %
960 %
961 %
962 %
963 %
964 %
965 %
966 %
967 %
968 %
969 %
970 %
971 %
972 %
973 %
974 %
975 %
976 %
977 %
978 %
979 %
980 %
981 %
982 %
983 %
984 %
985 %
986 %
987 %
988 %
989 %
990 %
991 %
992 %
993 %
994 %
995 %
996 %
997 %
998 %
999 %
1000 %
```

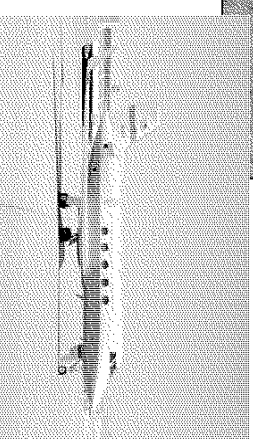
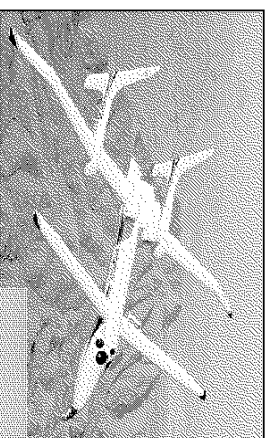
- MATLAB™/Simulink® Simulation Environment
- Multi-Vehicle Simulation (4 Aircraft Max)
- Generic Aircraft Models Represent Any Fixed Wing Aircraft
  - Each Aircraft = 1 Parameter File
  - Scripts Trim & Initialize Aircraft to Any Encounter Geometry
- Modular Components
  - Blocks Can be Copied and/or Swapped Out for Software Upgrades (e.g. CA Sensors, Maneuver Advisory)
- Capable of Batch Runs for Parametric Variation Studies
  - Uses Microsoft Excel Input Dataset
  - Multiple Plot Outputs Available
- PC Portable (< 37 MB)
- Can Run in Both Fast Sim-Time & Soft Real-Time



## ***Task 5: Perform CA Flight Test***

- **Objective:** To collect cooperative collision avoidance data to validate the CA simulation tool

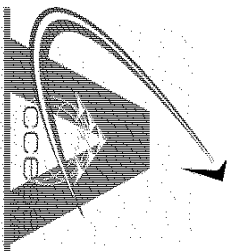
OPV - Proteus



Intruder – Gulfstream III

- **Accomplishments:**
  - Developed Interface Control Document
  - Developed System Integration Lab (SIL)
  - Developed CA algorithms
  - Developed CA software and human interface tool
  - Procured CA sensors and integrated them onto Proteus platform
  - Developed CA scenarios and test cards
  - Post-processed flight data and prepared for data analysis effort
- **Status:** Successfully completed over 50 collision scenarios during the last two weeks of September 2005.





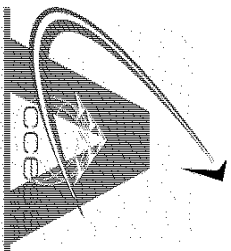
# Task 5: Perform CA Flight Test

## Test Scenarios

- Test scenarios included multiple collision geometries:
  - Co heading, Intruder overtaking
  - Low aspect, co-altitude
  - Co heading, Intruder climbing
  - Abeam, co-altitude
  - Head-on, co-altitude
  - Head-on, descending

Scenario #	HOST		INTRUDER		PICTORIAL
	Climb Rate (fpm)	$\Delta\psi$ (degrees)	Climb Rate (fpm)		
1	0	0	0		
2	0	10	0		
3	0	0	500		
4	0	-90	0		
5	0	180	0		
6	-500	180	0		

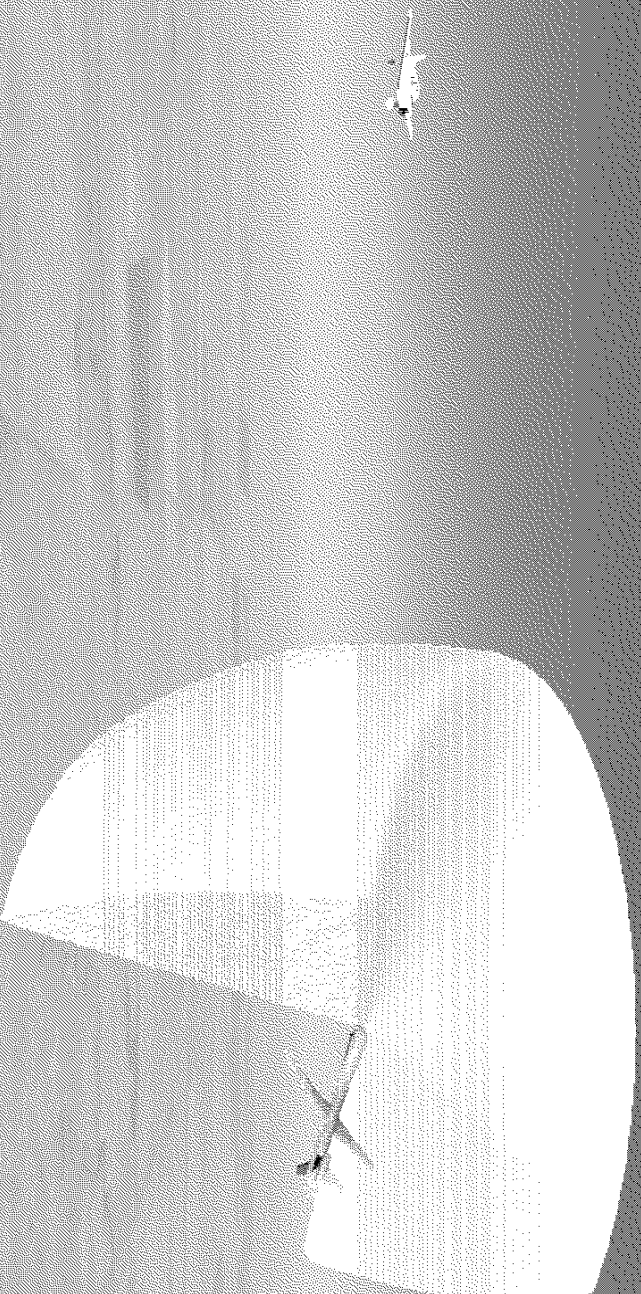
Scenario	Configuration						
	Buffer	TGC & AGA		TRT			
1. Co-Heading, Co-Alt, Intruder Overtaking	6	4	2	0	4	0	0
2. Low Aspect, Co-Alt	0	0	0	0	2	0	2
3. Co-Heading, Intruder Climbing							
4. Abeam, Co-Alt	1	1	1	2	1	1	1
5. Head-On, Co-Alt	1	1	1	2	1	1	1
6. Head-On, Descending	1	1	1	2	1	1	1
Link Delay							



## ***Next Steps***

- Document the results and lessons learned from the Safety Analysis and Flight Test Activities
- Complete validating the CA Simulation tool
- Derive practical values/ranges for the TBDs in the performance requirements
  - Utilize the validated CA Simulation tool
  - Utilize the safety analysis results
- Begin Non-cooperative Collision Avoidance Activities
  - Derive unique Non-cooperative performance requirements
  - Perform Trade Studies and Concept Assessments
  - Conduct Non-cooperative Simulation Runs and Flight Demos
- Support RTCA SC-203 on developing the Sense & Avoid Minimum Aviation System Performance Standards (MASPS)

# QUESTIONS ?



**Russell Wolfe**

**Modern Technology Solutions, Inc.**

**Russell.C.Wolfe@mtsi-va.com**

**(703) 212-8870 x126**