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Update on the Analysis of ACAS Performance on Global Hawk

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Summary

Initial results are presented from a Lincoln Laboratory study of ACAS performance on the Global Hawk UAV. The study has been applying the process outlined in the ICAO ACAS Manual which involves developing UAV airspace encounter models and running fast-time Monte Carlo simulations of encounters. ACAS performance was examined in conventional aircraft vs. conventional aircraft, conventional aircraft vs. non-ACAS Global Hawk, and conventional aircraft vs. ACAS-equipped Global Hawk cases. The existing ICAO and ACASA encounter models were modified to reflect Global Hawk flight characteristics. ACAS performance on Global Hawk was also assessed parametrically across reaction latencies from 0 - 20 s.

Global Hawk flight characteristics were shown to have a small but measurable negative impact on collision risk. Assuming no system failures or visual acquisition effects occur, performance with ACAS on Global Hawk is significantly better than without ACAS if response latencies (from the moment an RA is issued to the moment maneuvering begins) are less than 10 s. Performance drops off rapidly at latencies greater than 10 s. The needs for improved airspace models and a more in-depth study of the interaction between visual acquisition and ACAS are noted.

References:
1. FAA, "Certificate of Waiver or Authorization", FAA Form 7111-1, 13 August 2003.
2. Drumm, A., "TCAS on Unmanned Aerial Vehicles: Defining a Safety Analysis Plan", SCRSP WP A/4-145.
3. SCRSP, "ACAS Manual", 20 July 2004.
4. ICAO, Section 4.4 of Annex 10 – Aeronautical Telecommunications, Volume IV, 1998
5. Miquel, T. and K. Rigotti, "European Encounter Model" Parts 1 and 2, ACASA/WP1.1/186, December 4, 2001.
6. Kuchar, J., "Modifications to ACAS Safety Study Methods for Remotely Piloted Vehicles (RPVs)", SCRSP WG A IP/A/7-281, May 2004.
7. Kuchar, J., "Evaluation of Proposed Changes to the ACAS Modified Tau Calculation", ASP WG A/WP A10-03, May 2006.

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1. Introduction

1.1. The RQ-4A / RQ-4B Global Hawk is a high-altitude long-endurance unmanned aerial vehicle (UAV) currently being operated by the U. S. Air Force. As of February 2006, more than 8,700 flight-hours have been flown by Global Hawk aircraft. Current Global Hawk operations in the U. S. are based primarily at Edwards Air Force Base, CA, which provides an opportunity for Global Hawk to climb to Class A airspace while remaining in restricted airspace. The Air Force will begin operating Global Hawk out of Beale Air Force Base, CA, in 2006. Beale is within Class C airspace and so will not provide the same degree of segregation from civil air traffic.

1.2. Since 21 August 2003, Global Hawk has been operating under a National Certificate of Waiver or Authorization (COA) issued by the FAA. Two key excerpts from the Global Hawk COA (Special Provisions #2 and #9) are replicated below [1]:

> 2. The Department of the Air Force shall ensure a level of safety equal to or greater than that provided by a chase aircraft for all non-emergency operations outside of restricted or warning areas. This is accomplished by:
>
>   A. Filing and flying an IFR flight plan while in Class A, Class E above Class A, or oceanic controlled airspace.
>
>   B. Filing and flying an IFR flight plan with:
>   1) Primary radar or visual observation by military air or ground sites while operating within domestic airspace below Class A airspace.
>   or
>   2) Forward and side looking cameras and/or electronic detection equipment while operating within domestic airspace below Class A airspace.
>
>   Any operations in Class B Airspace require advance coordination and approval.
>
> 9. The Department of the Air Force, and/or its representative(s), is responsible at all times for collision avoidance with non-participating aircraft and the safety of persons or property on the surface during all phases of the [aircraft's] flight.

1.3. To date, compliance with the COA has been achieved using restricted airspace and/or the use of primary radar and visual observation below Class A airspace.

1.4. The Air Force is interested in the use of on-vehicle assets including ACAS and new sense-and-avoid technologies (e.g., electro-optical sensors) to reduce mid-air collision risk and improve the flexibility of access to civil airspace.

1.5. Issues related to the use of ACAS on UAVs have been raised at several prior SICASP and SCRSP meetings [2]. These issues and a process for performing safety studies of ACAS on UAVs have since been documented in the ACAS Manual [3]. The key concerns with the use of ACAS on UAVs revolve around the potential for latencies in the communication, command, and control loop, the inability to visually corroborate TCAS information, and the inability to detect uncooperative threats.

1.6. Since 2003, MIT Lincoln Laboratory has been conducting a safety study of ACAS on Global Hawk under Air Force funding. The objective has been to follow the safety analysis process identified in the ACAS Manual to obtain quantitative data with which to judge the potential risks and benefits from ACAS equipage.

1.7. Work to date has focused on the development of UAV-specific airspace encounter models and Monte Carlo simulation of encounters between conventional aircraft and Global Hawk with and without ACAS equipage. The Lincoln Laboratory Collision Avoidance System Safety Assessment Tool (CASSATT) was used to perform these analyses.

2. Global Hawk Airspace Encounter Models

2.1. CASSATT has the capability to run two-aircraft encounters generated from either the ICAO standard encounter model [4] or the ACAS Analysis (ACASA) program's European encounter model [5]. Both models were also modified by Lincoln Laboratory to better represent potential Global Hawk characteristics in encounter situations where ACAS may issue RAs. When running Global Hawk simulations, one aircraft was given Global Hawk flight characteristics and constraints. The second aircraft followed conventional flight characteristics as defined by the encounter model being used.

2.2. Encounter model modification involved two aspects: enforcing flight performance constraints, and modifying the likelihood of the various vertical profiles that might occur during an encounter based on expected Global Hawk mission profile characteristics.

2.3. Global Hawk performance data were obtained from the U. S. Air Force, and the appropriate constraints were imposed on airspeed, vertical rate, bank angle, and pitch rate (load factor). The encounter model probability tables for the Global Hawk aircraft were then modified so that random selection of parameter values met those performance constraints. Figure 1 shows an example of Global Hawk's maximum climb rate vs. altitude. Above FL 200, Global Hawk cannot achieve the nominal 2500 ft/min climb rate for an increase climb RA, and above FL 300 Global Hawk cannot achieve the nominal 1500 ft/min climb rate for an initial climb RA. In this initial study, ACAS climb inhibits were not used in the simulations.

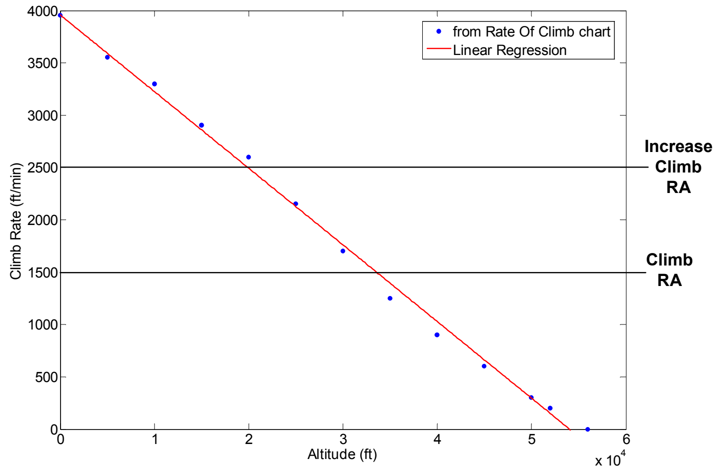


Figure 1: Global Hawk Maximum Climb Rate vs. Altitude

2.4. Figure 2 shows an example of the nominal Global Hawk altitude vs. speed profile, the modeled minimum and maximum limits on airspeed in each ACASA model altitude layer, and the maximum vertical acceleration possible based on Global Hawk's 2 °/s pitch rate limit. As Figure 2 shows, depending on its airspeed, Global Hawk may not be able to achieve the desired 0.25 g vertical acceleration to respond to ACAS. Regardless of airspeed, however, Global Hawk can always achieve at least 0.18 g, and if flying its nominal airspeed profile it can always achieve more than 0.25 g.

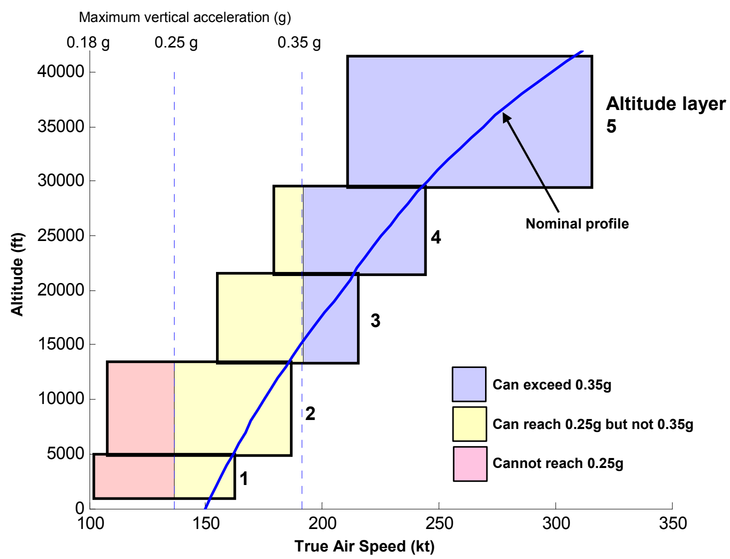
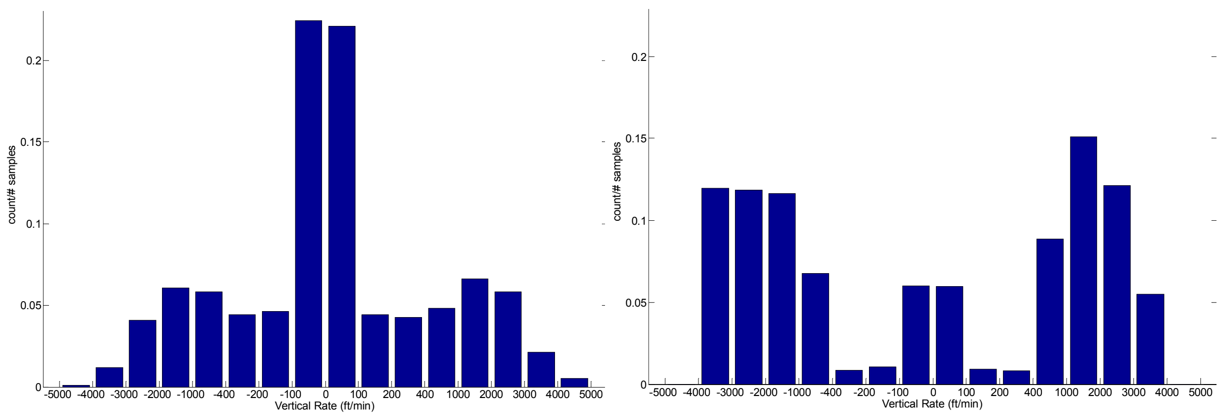


Figure 2: Global Hawk Altitude, Speed, and Vertical Acceleration Limits

2.5. Vertical profile probabilities were also modified to reflect the mission profile of Global Hawk, which rapidly climbs to and descends from cruising flight levels that are above conventional air traffic. Should an encounter with Global Hawk occur, it is therefore expected to be more likely that Global Hawk would be following a climb or descent profile than in level cruise. Vertical profile probabilities were modified based on a technique previously presented to SCRSP [6]. The method begins by prescribing a probability to each possible Global Hawk vertical profile during an encounter. As an initial engineering estimate, it was assumed, for any given encounter, that Global Hawk would be in a steady climb 40% of the time, in a steady descent 40% of the time, in a level profile 14% of the time, and in some other profile (e.g., start of climb or end of descent) for the remaining 6% of the time. Next, the probability of the vertical profile of the conventional aircraft in the encounter pair was computed using conditional probabilities derived from the existing encounter model tables [6]. The result was a shift in the vertical profile probabilities to produce a larger proportion of encounters in which Global Hawk was climbing or descending, while maintaining the same mix of profiles for the conventional aircraft as exist in the current encounter models. Figure 3 shows an example set of initial vertical rates selected by the ACASA encounter model compared to the initial vertical rates selected for a Global Hawk aircraft.



Conventional Aircraft Global Hawk

Figure 3: Example Initial Vertical Rate Histograms (ACASA Encounter Model)

2.6. The result of this modeling activity was the development of four encounter models for evaluating ACAS on Global Hawk. The existing ICAO and ACASA models allowed for an examination of ACAS performance assuming that Global Hawk's mission profile did not alter the distribution of vertical profiles in encounters. ICAO and ACASA models modified to reflect the Global Hawk mission profile allowed for an examination of the effect of that profile on ACAS performance.

3. Overview of Results

3.1. A more complete Lincoln Laboratory report on the ACAS on Global Hawk study is being developed for the Summer of 2006. This section provides a brief overview of the main findings from that analysis.

3.2. Results are presented first for four different conditions: (1) conventional aircraft in the existing airspace models in ACAS vs. unequipped encounters, (2) conventional aircraft in the existing airspace models in ACAS vs. ACAS encounters, (3) Global Hawk (without ACAS) vs. conventional aircraft (with ACAS) in the modified encounter models, and (4) Global Hawk (with ACAS) vs. conventional aircraft (with ACAS) in the modified encounter models. Cases (1) and (2) serve as baselines for comparison and reflect existing Lincoln Laboratory results from other ACAS analyses (i.e., for CP112E).

Results are presented in terms of the relative risk of Near Mid-Air Collision (NMAC), where an NMAC is defined as a situation in which two aircraft are within 100 ft vertically and 500 ft horizontally. This relative risk is termed the risk ratio, computed as p(NMAC) with TCAS equipage allocated as described above for conditions (1)-(4) divided by p(NMAC) without TCAS installed on any aircraft.

3.3. All ACAS-equipped aircraft (including Global Hawk) were assumed to use the standard 5 s response latency to initial RAs and 2.5 s latency to increase RAs or reversal RAs. Pitch rate, airspeed, bank angle, and vertical rate constraints were imposed on the Global Hawk aircraft. Other reaction latencies were also studied for Global Hawk. For each condition, a total of 310,000 encounter runs were performed in each altitude layer with the ICAO encounter model, and 200,000 runs were performed in each layer with the ACASA model.

3.4. Figure 4 shows the risk ratio results for the European ACASA encounter model.

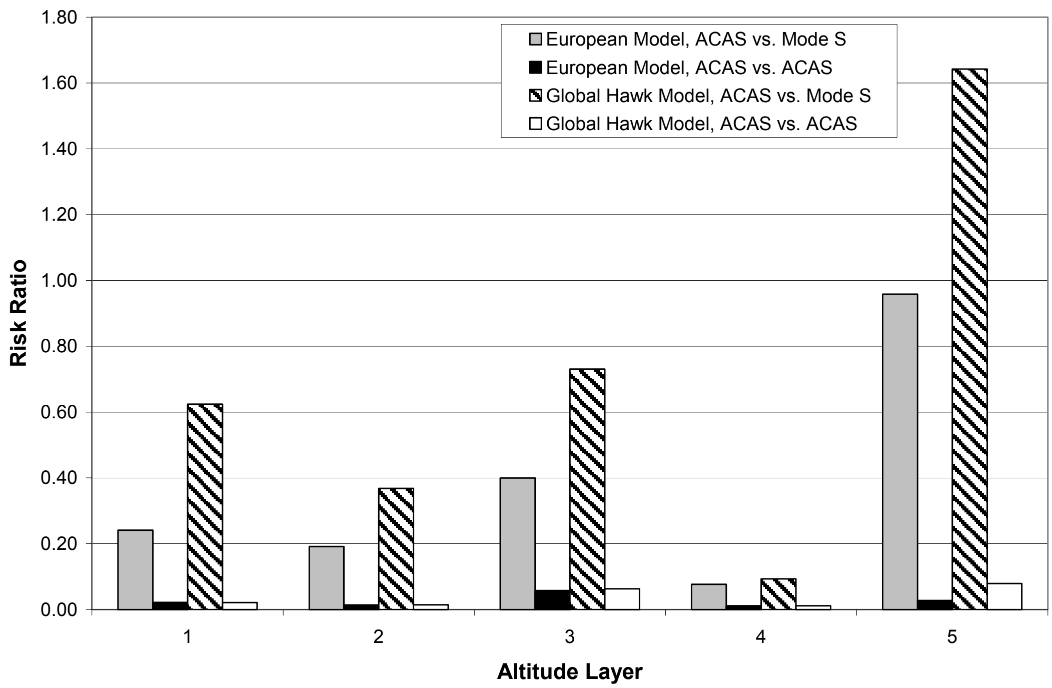


Figure 4: European ACASA Model Risk Ratio Results

The solid gray bars show risk ratio for the existing encounter model (and conventional aircraft) in ACAS vs. unequipped encounters (condition 1). Performance for conventional aircraft in ACAS vs. ACAS encounters is shown using solid black bars (condition 2). Global Hawk performance is shown using the black-and-white striped bars (for non-ACAS Global Hawk vs. ACAS conventional aircraft) and white bars (for ACAS-equipped Global Hawk vs. ACAS conventional aircraft), representing conditions 3 and 4. Risk ratios for Global Hawk are generally larger than for a conventional aircraft with comparable equipage. As discussed above, most Global Hawk encounters involved a climbing or descending UAV, potentially with pitch rate and vertical rate limits, and these types of encounters are generally more difficult for ACAS to resolve successfully.

ACAS equipage provides a clear safety benefit relative to the unequipped (Mode S) condition for both conventional aircraft and Global Hawk under the no-failure assumptions that were used. Results using the ICAO encounter model were generally comparable.

3.5. The relatively large risk ratio for non-ACAS equipage in altitude layer 5 is due to improper RAs issued on the ACAS aircraft because of the current critical interval calculation. This is a known vulnerability in ACAS when faced with a climbing or descending non-ACAS intruder on a nearly parallel track [7]. These problem encounters are especially prominent in altitude layer 5 of the Lincoln Laboratory implementation of the ACASA encounter model. Note that equipping both aircraft with ACAS abates most of this critical interval risk if both aircraft respond properly to their RAs.

3.6. Further analysis into the incremental effects of Global Hawk's pitch rate constraint and climb rate limits were also performed when Global Hawk was ACAS-equipped. The pitch rate constraint was found to have a small but measurable effect on risk ratios at low altitude. At altitudes below 5000 ft, Global Hawk's relatively slow airspeed and pitch rate limit reduced its ability to achieve the desired 0.25 g or 0.35 g accelerations to comply with initial or strengthened / reversed RAs, respectively. In the ICAO model, risk ratios in altitude layer 1 increased from approximately 0.040 to 0.055 when including the pitch rate constraint. In the ACASA model, risk ratios in layer 1 increased from approximately 0.018 to 0.021. Risk ratios at other altitude layers were not measurably impacted by the pitch rate constraint.

3.7. The impact of Global Hawk's climb rate limit on risk ratio was small. With the ICAO model, risk ratio in the highest altitude layer (6) increased from approximately 0.013 to 0.017. With the ACASA model, risk ratio increased from 0.078 to 0.079 in the highest altitude layer (5) when comparing performance without vs. with the climb rate limit.

3.8. The effects of response latency on Global Hawk risk ratios were also examined for each altitude layer. Figure 5 shows risk ratio with ACAS on Global Hawk normalized against the risk ratio without ACAS on Global Hawk in each layer ('Mode S only') as a function of response latency. Values at a latency of 5 s reflect the standard ACAS response assumptions for manned aircraft [4]. Risk ratios increase with increasing latency, and ACAS performance becomes worse than non-ACAS performance at latencies above approximately 15 s.

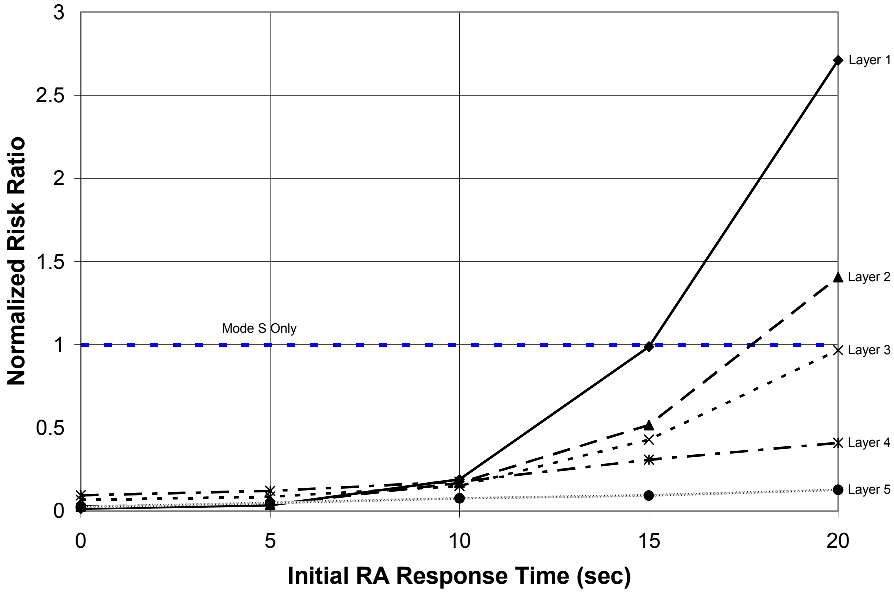


Figure 5: Response Latency Effects (ACASA Modified Model)

3.9. The latency performance results also suggest that an autonomous RA response (with essentially 0 latency) may hold promise for further reductions in collision risk. No failure modes have been considered in this analysis, however, so additional study is certainly required.

4. Visual Acquisition Issues

4.1. The interactions between visual acquisition and ACAS RAs have not been precisely quantified. In prior studies, when using fault tree models to estimate collision risk, assumptions were made regarding the probability of visual acquisition in ACAS encounters, but extensive data were not available on which to base those assumptions. The degree to which visual acquisition compensates for system failures (e.g., inaccurate altitude measurement, unexpected intruder maneuvers, or uncooperative aircraft in the avoidance path) also needs further study. How often visual acquisition might induce an improper response and cause a collision is also not known. We therefore have limited understanding of both the frequency with which visual acquisition may come into play and the impact that visual acquisition would have in changing the outcome.

4.2. The ability to perform visual acquisition (weather permitting) to see and avoid other air traffic is a clear requirement in current regulations. ACAS does not perform a see and avoid function, so file-and-fly UAV access to civil airspace will not be enabled solely by equipping with ACAS. Additionally, there is a strong argument that the ability to visually acquire aircraft is an integral part of ACAS operation. ACAS and visual acquisition can interact through the use of the traffic display, TAs, and when responding to RAs. The main argument is that although ACAS can still be used in instrument conditions, in visual conditions it is critical that the ability to see and avoid exists in close conjunction with ACAS information.

4.3. For these reasons, it is expected that ACAS cannot be accepted for use on UAVs until either a thorough safety analysis demonstrates that the lack of visual acquisition on the UAV does not present a significant risk when using ACAS, or other technologies have been developed, demonstrated, and accepted as surrogates for visual acquisition.

5. Summary

5.1. If no system failures occur, response latencies are less than 10 s, all pilots respond to their RAs, and visual acquisition is not considered, the simulation results suggest that equipping Global Hawk with ACAS would provide a significant reduction in collision risk relative to equipping Global Hawk with only a Mode S transponder. However, there is currently uncertainty with regard to the potential frequency and impact of system failures, latencies, and visual acquisition or other compensation against the lack of an onboard pilot, and so equipping with ACAS cannot be recommended at this time.

5.2. Latency analysis implies that the use of ACAS may be possible in some phases of flight but not in others. For example, operations close to the departure / arrival airport that are conducted using line-of-sight links may have sufficient robustness and low-latency characteristics to allow for use of ACAS. Flight beyond line of sight may not provide enough robustness for low-latency ACAS operation. Lincoln Laboratory is currently working with the U. S. Air Force to develop flight tests using Global Hawk to obtain statistics on latency, dropout rates, and ACAS data accuracy for line of sight and beyond line of sight operations.

5.3. ACAS performance is sensitive to the geometry of an encounter, and little is currently known about the potential characteristics of close encounters between Global Hawk and conventional aircraft. An initial engineering estimate of Global Hawk profiles was made in this study. Further study can establish the vulnerabilities or capabilities of ACAS in specific encounter geometries so that exposure to risks can be better assessed. The use of new encounter models such as the Eurocontrol ACAS Safety Analysis Post-RVSM Project (ASARP) model and an updated U. S. encounter model would provide better fidelity in representing the characteristics of encounters in the current environment. The potential for problem encounters due to an interaction between Global Hawk's flight profile and the existing ACAS critical interval calculation also warrants additional study.

5.4. In keeping with the recommendations from the ACAS Manual [3], analysis of the effects of visual acquisition is a critical part of the safety study of ACAS on UAVs. The Lincoln Laboratory effort is expected to place more emphasis on visual acquisition issues in the near future.

5.5. The ASP is invited to comment on the Global Hawk ACAS safety study and provide feedback on the key areas requiring improved modeling or further analysis.