Detect & **A**vo**id** **A**lerting **L**ogic for **U**nmanned **S**ystems[1]

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[1] The DAIDALUS logo was designed by M. Malekpour.

See and Avoid

Michael Huerta, Administrator, Federal Aviation Administration:[2]

> *A bedrock principle of aviation is see and avoid. And if you don't have a pilot on board the aircraft, you need something that will substitute for that, which will sense other aircraft, and we can ensure appropriate levels of safety.*

[2] http://www.pbs.org/newshour/bb/drone-industry-grows-faster-flick-joystick-regulation-lag.

Detect and Avoid[3]

Detect and Avoid (DAA) was defined by the FAA sponsored SAA for UAS (First) Workshop Final Report published in October 9, 2009 as the combination of UAS Self-Separation (SS) plus Collision Avoidance (CA) as a means of compliance with 14CFR Part 91, §91.111 and §91.113.

[3] Formerly called Sense and Avoid.

14CFR Part 91

- 91.111 (a) No person may operate an aircraft **so close to another aircraft as to create a collision hazard.**
- 91.113 (b) General. When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, **vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft**. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and **may not pass over, under, or ahead of it unless well clear**.

Requirements for DAA Concept

Concept shall . . .

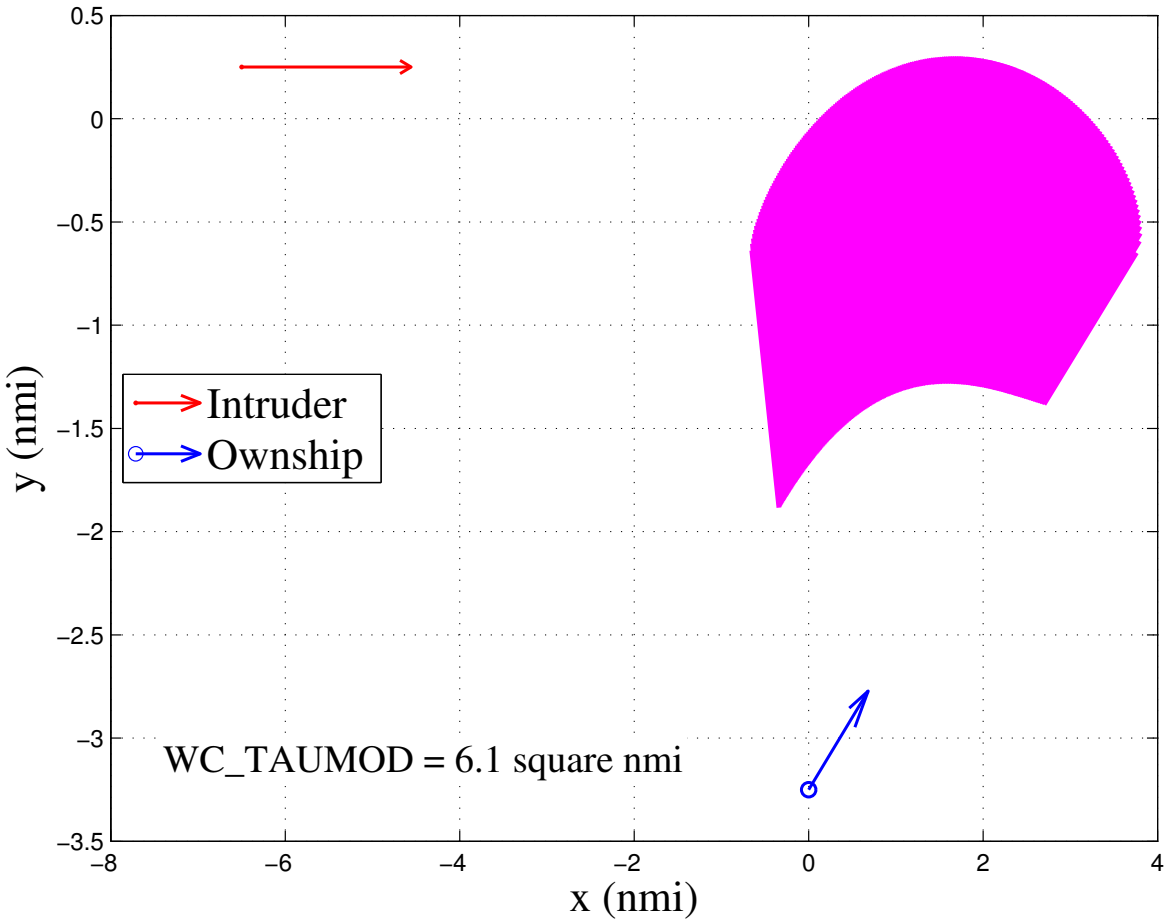
- provide a geometric means to determine well-clear status,
- enable self-separation capabilities,
- avoid undue concern for traffic aircraft,
- interoperate with existing collision avoidance systems, e.g., TCAS.

Well Clear

- Two aircraft are well clear if appropriate *distance* and *time* variables determined by their states remain outside a set of predefined threshold values.
- A well-clear violation occurs when:
  - horizontal range is less than DMOD **or** (distance at time of CPA is less than HMD **and** modified tau is less than TAUMOD) **and**
  - relative altitude is less than ZTHR **or** time to co-altitude is less than TCOA.
- Concrete values for threshold values is matter of on-going research. Current values by poposed by the Sense and Avoid Science Research Panel (SARP): HMD = DMOD = 4000 ft, TAUMOD = 35 s, ZTHR = 450 ft, and TCOA = 0 s.

Well-Clear Violation Volume

Top View of an Example Encounter



Well-Clear Properties

- Inclusion: For an appropriate choice of threshold values, the well-clear violation volume is larger than the TCAS volume.
- Symmetry: In a pair-wise situation, both aircraft make the same determination about their well-clear status.
- Local Convexity: In a non-maneuvering trajectory, there is at most one time interval where the aircraft are in well-clear violation.

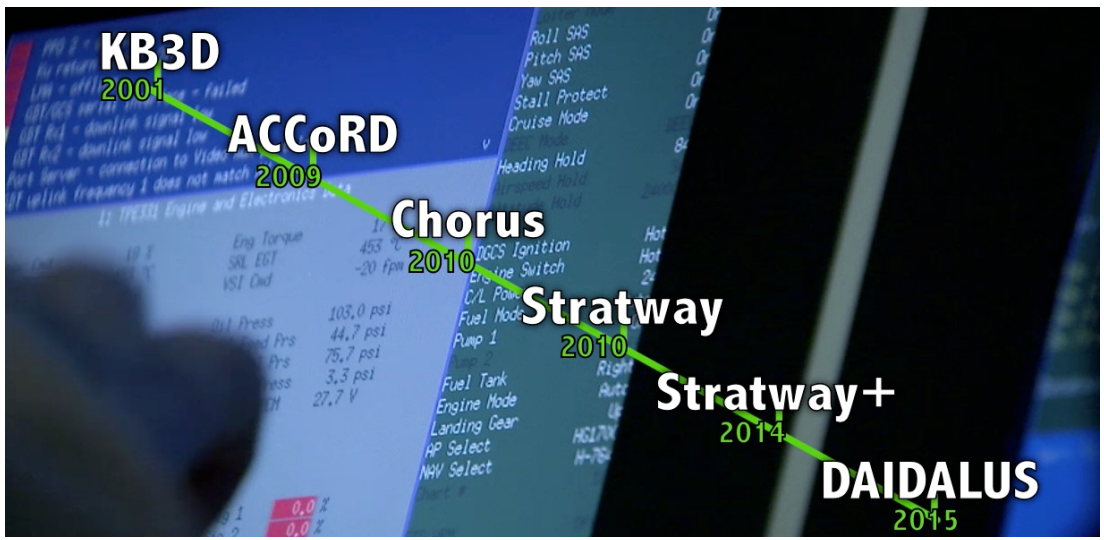
These properties were ...

- proposed by the FM group at NASA LaRC and formally verified in the Prototype Verification System (PVS) for a family of well-clear concepts,
- considered to be *necessary conditions* by SARP for any well-clear definition, and
- helped to discard 2 of 3 proposed definitions of the well-clear violation volume.

DAIDALUS

Detect and **A**v**o**i**d** **A**lerting **L**ogic for **U**nmanned **S**ystems

- DAIDALUS is an implementation in Java, C++, and PVS, developed by the FM group at NASA LaRC, of SARP's DAA concept.
- DAIDALUS provides algorithms for
  - Checking and predicting loss of well clear (1×1)
  - Computing alert level (1×1)
  - Computing conflict and recovery bands (1×n)



What's in a Name?

- DAIDALUS is a reference to the craftsman of Greek mythology, *Daedalus*, the father of Icarus.
- Daedalus made wings for himself and for Icarus and warned Icarus not to fly too high, because the heat of the sun would melt the wax, nor too low, because the sea foam would soak the feathers.

[4]

[4] Image taken from `http://en.wikipedia.org/wiki/Daedalus`.

Well-Clear Algorithms: Time To Violation

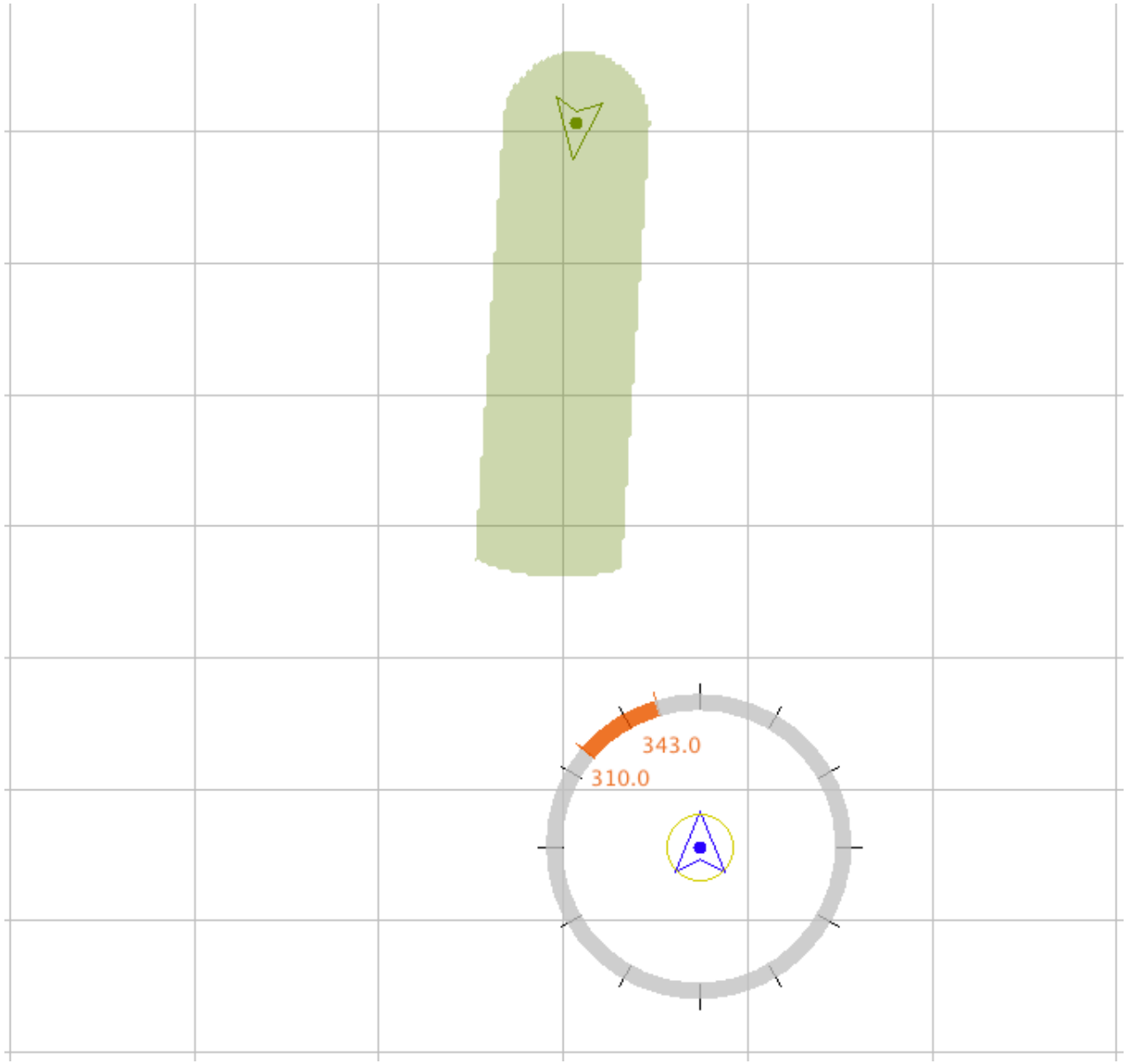
- Given ownship and intruder state information and a lookahead time, return the time interval of well-clear violation assuming non-maneuvering trajectories.
- Return the empty interval when aircraft are not predicted to be in well-clear violation within the lookahead time.
- Return an interval that contains 0 (current time) when aircraft are currently in well-clear violation.

Well-Clear Algorithms: Conflict Bands

- Given ownship and traffic state information and a lookahead time, compute ranges of *track*, *ground speed*, *vertical speed*, and *altitude* that lead to well-clear violation within lookahead time...
- ...assuming a kinematic trajectory for the ownship and non-maneuvering trajectories for the traffic aircraft.

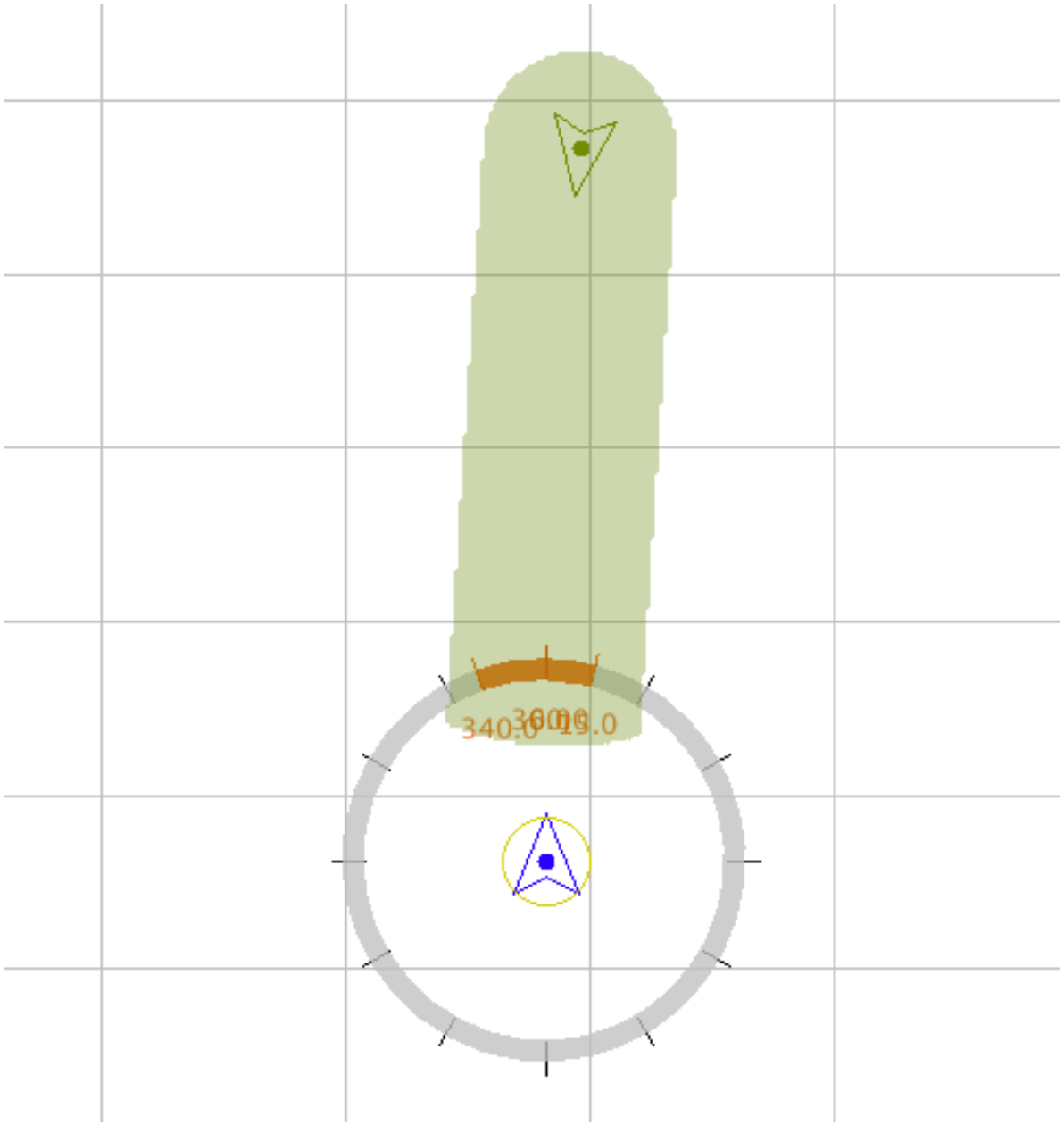
Preventive Bands

Bands outside current trajectory of the aircraft:



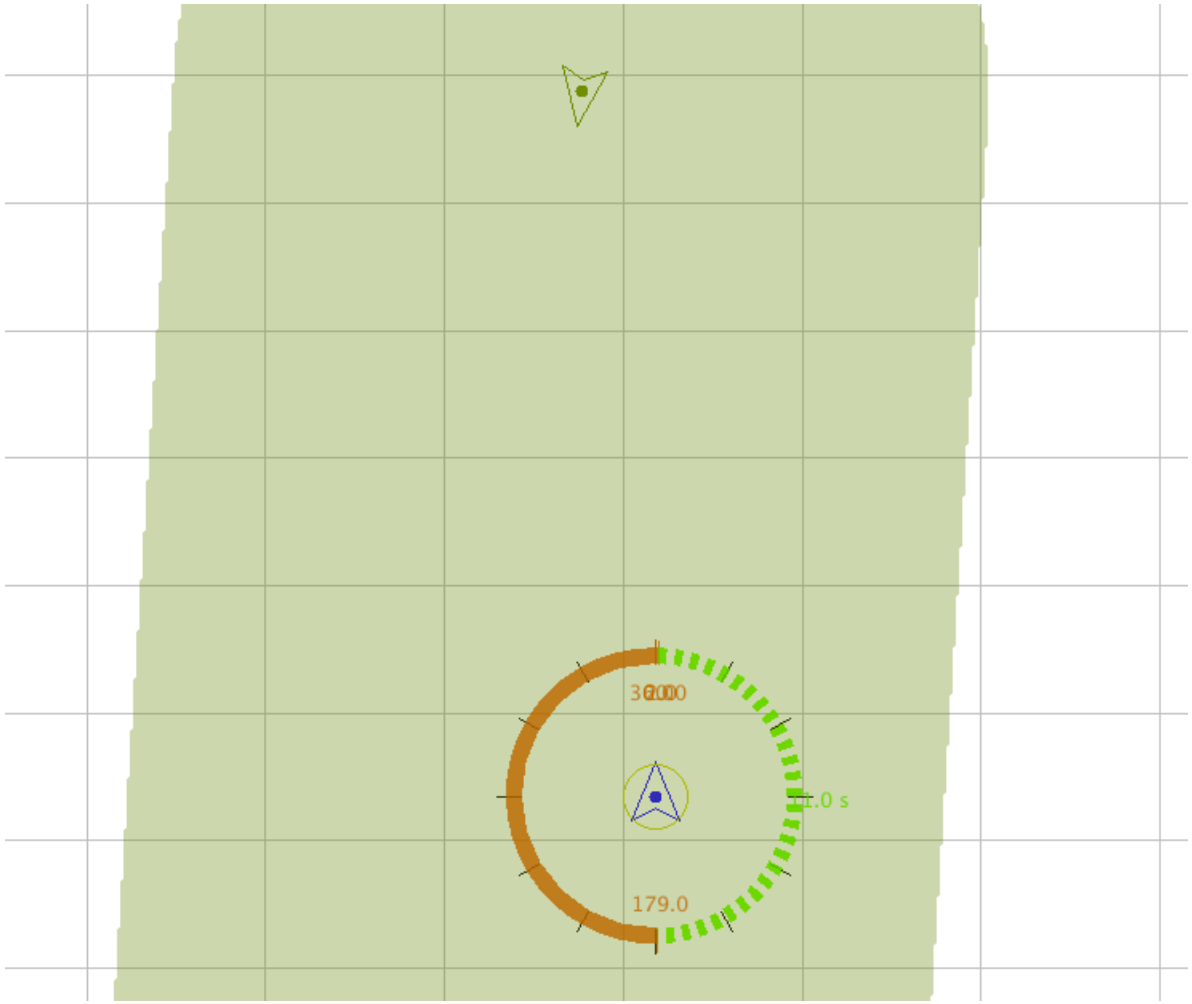
Corrective Bands

Bands in current trajectory of the aircraft:



Recovery Bands

Aircraft are (about to be) in well-clear violation:



Well-Clear Algorithms: Alerting Logic

- Given ownship and intruder state information, return an alert level (numerical value) indicating severity of potential loss of well clear.
- Two alerting schemas are supported (matter of on-going research):
  - Thresholds-based.
  - Bands-based.

Research Outcomes

- Mathematical definition (in PVS) of a family of well-clear concepts.
- Formally verified algorithms (in PVS) for maintaining well-clear and recovering from well-clear losses.
- Software implementations (in Java and C++) of SARP's well-clear concept released under NASA's Open Source Agreement.

DAIDALUS has been tested in flight experiments conducted under NASA's UAS in the NAS Project.

Unexpected Outcomes

- DAIDALUS is being considered for inclusion as DAA reference implementation in the appendix of RTCA Special Committee 228 Minimum Operational Performance Standards (MOPS) for Unmanned Aircraft Systems. Ref. Don Walker (FAA).
- DAIDALUS is being considered by FAA Tech Center for flight test study to determine the minimum pilot interface requirements for DAA. Ref. Kevin Williams (FAA).
- Mathematical framework was used in the development of SAA concept by General Atomics Aeronautical Systems (GA-ASI). Ref. Brandon Suarez (GA).

On-Going Work

- Validation of software implementation against formal models:
  - Test cases are automatically generated.
  - Software outputs are checked against outputs of executable formal models for different degrees of accuracy.
- Validation of software implementation against performance metrics.
  - What is a stressing case?

References (I)

- C. Muñoz, A. Narkawicz, G. Hagen, J. Upchurch, A. Dutle and M. Consiglio, *Detect & Avoid Alerting Logic for Unmanned Systems (DAIDALUS)*, submitted 2015.
- J. Upchurch, C. Muñoz, A. Narkawicz, M. Consiglio, and J. Chamberlain, and M. Consiglio, *Characterizing the Effects of a Vertical Time Threshold for a Class of Well-Clear Definitions*, submitted, 2015.
- J. Upchurch, C. Muñoz, A. Narkawicz, J. Chamberlain, and M. Consiglio, *Analysis of Well-Clear Boundary Models for the Integration of UAS in the NAS*, Technical Memorandum, NASA/TM-2014-218280, June 2014.
- C. Muñoz, A. Narkawicz, J. Chamberlain, M. Consiglio, and J. Upchurch, *A Family of Well-Clear Boundary Models for the Integration of UAS in the NAS*, Proceedings of the 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA-2014-2412, Atlanta, Georgia, 2014.

References (II)

- A. Narkawicz, C. Muñoz, J. Upchurch, J. Chamberlain, and M. Consiglio, *A Well-Clear Volume Based on Time to Entry Point*, Technical Memorandum, NASA/TM-2014-218155, January 2014
- C. Muñoz, A. Narkawicz, and J. Chamberlain, *A TCAS-II Resolution Advisory Algorithm*, Proceedings of the AIAA Guidance, Navigation, and Control Conference (GNC), AIAA-2013-4622, Boston, Massachusetts, August 2013.
- M. Consiglio, J. Chamberlain, C. Muñoz, and K. Hoffer, *Concept of integration for UAS operations in the NAS*, Proceedings of the 28th International Congress of the Aeronautical Sciences (ICAS 2012), 2012.

Software Releases Under NASA's Open Source Agreement

- ACCoRD $\subseteq$ Bands $\subseteq$ Chorus $\subseteq$ Stratway: `http://shemesh.larc.nasa.gov/fm/fm-at-codes.html`.
- Well-Clear: `http://github.com/nasa/WellClear`.
- DAIDALUS $\subseteq$ Stratway $\cup$ Well-Clear.