TCAS Uncovered

In theory TCAS has been around since the late 1950's, in a practical sense from the FAA's initial focus in 1981 and then their mandate of 1993. The FAA wanted a new system that would help provide conflict resolution in the national airspace system. Even today when the airspace capacity is still determined by ATC workload the TCAS adds one last layer of safety into the system. The TCAS system actually gave legs to the Mode S transponder which due to lack of display options and any mandates never got a foothold in the market. The re-introduction of the Mode S transponder as part of this system has given the general aviation market further benefits and at little cost. The emergence of the Traffic Information Service (TIS) which provides even non-mandated type aircraft with ATC like traffic information in terminal areas was a huge safety benefit. This article will provide some additional insight into what happens "under the cover" of a typical TCAS II system.

What it is

TCAS is a predictive warning system that falls in the category of the Airborne Collision Avoidance System (ACAS) and is a proprietary part of that system. TCAS uses the Secondary Surveillance Radar (SSR) transponder returns it receives along with its own selective interrogations to determine presence of a possible conflict. In the beginning a massive undertaking took place just to come up with a software language and the proper computer modeling to prove out what the system should do and how it would do it. After several mid-air accidents the commitment was industry wide to get a system implemented. One of the core principals to evolve during system development was that *time* to the threat aircraft (intruder) was more important then distance. The system processor must constantly evaluate a specific volume of airspace and the geometry around it to solve any possible conflicts that may arise within it. The system must generate its own 1030 Mhz interrogations selectively in order to provide this level of safety. While the system provides alerting information on any SSR target the traffic avoidance alerts it provides to the pilot are possible only with other aircraft that provide Mode C and Mode S information. The Mode S transponder pseudo-randomly radiates (squitter) its unique Mode S address omni-directionally once per second so as to let its presence be known to other like equipped aircraft. Following receipt of a squitter, TCAS then sends a Mode S interrogation to that specific Mode S address contained in the message. The replies then received by TCAS are used to determine bearing, range and altitude. When transmitting the processor has the ability to control the effective radiated power by utilizing a scheme called *Whisper-Shout.* The Whisper-Shout method helps to manage the reach of the system. Intruder range is determined by the time delay between interrogation and the reply sequence and can also be further supplemented by the results of the Whisper-Shout routine. The aircraft is now an active interrogator in the system and as a result has increased 1030/1090 Mhz traffic. In order to limit the 1030/1090 Mhz traffic generated by TCAS, especially in high density areas a *TCAS Presence* message is broadcast. The TCAS is designed to limit its own transmissions when a specific traffic threshold is met, thus helping to minimize frequency traffic. The results of the *Whisper-Shout* routine will also allow certain aircraft to be de-selected as primary threats as the ranging and altitude data is gathered. Once an interrogation is recognized then the receiving aircraft logs in that data and can then start the tracking process. The constant interrogation, acquisition, tracking and predicting of the crossing geometries for all intruders keeps the system quite busy. Once established this bi-directional data-link between each TCAS II equipped aircraft is crucial to a successful resolution. TCAS does handle Mode A/C transponders differently. The TCAS does not interrogate Mode A however it does perform a *Mode C only all-call,* remember target altitude is critical. These replies are also tracked but not all are synchronous and so special algorithms are employed to provide the proper filtering.

The conflict resolution process starts with a Traffic Advisory (TA) which informative in nature, then informs the pilot to nearby traffic. This traffic advisory only later becomes a threat if conditions change. The next step is a Preventive Resolution Advisory (PRA). The PRA basically advises the pilot not to deviate from the present vertical flight profile he is on. This indicates to the crew that the situation is resolving itself as long as the crew maintains its current path. The Corrective Resolution Advisory (CRA) is the last step in conflict resolution. This command is given to advise the crew to take action vertically in order to avoid the developing threat. Vertical changes in ones flight path have been deemed the quickest resolution to a possible conflict. All this action must be done prior to the “Closest Point of Approach” (CPA) as computed by the processor. The CPA is that point ahead that the processor predicts will be an area of conflict with an intruder aircraft. With extremely high closure rates one can see that the element of time is crucial. Here is where the Mode S bi-directional data-link plays a huge role in that the commands issued to the pilot must be transmitted to the intruder aircraft so that complimentary maneuvers are assured. The Mode S air ground link can also be used to verify such things as the proper “N” number versus Mode S address assignment, this was a problem in the early days of the mandate. Reflecting back for a moment to earlier times with this system some of us may remember that TCAS reported many false targets or was missing target aircraft altogether. This created enough concern that in 1997 the FAA did a random sampling of some 548 Mode A/C transponders and found that 30% failed FAR Part 43 tests and a significant amount reported altitude errors. The Terra transponder actually required a modification as a result of these findings. All this data helped resolve some initial problems.

Collision Avoidance Logic

When the goal is to avoid any collision with intruder aircraft then the system must be predictive. This principal has two basic concepts: the system sensitivity level and the warning time available. The level of sensitivity is a function of altitude and helps define protection levels. The warning time is based on the time to the Closest Point of Approach (CPA) which is that point of conflict. The TCAS must achieve a good balance between sensitivity and time within that protected volume of airspace so as to minimize any unnecessary alarms. All the above being said, in collision avoidance, time-to-go to the CPA, and not distance-to-go to the CPA is the most important concept. With a system designed to ensure collision avoidance between any two aircraft, with closure rates of up to 1200 knots and vertical rates as high as 10,000 fpm one can see how critical time can be. To deconflict with any intruder aircraft the TCAS processor must be constantly aware of the airspace geometry it is transitioning through and the traffic content within it. This volume of airspace and associated trigger thresholds change with altitude. As mentioned earlier the processor deals in *time* not distance as it tries to deconflict with any known intruder. The CPA is that critical spot within the concerned volume of airspace the TCAS must constantly be evaluating for conflicts with intruder crossing geometries. Several actions can be taken; change in course (slow), a change in speed or a change in altitude (quickest). The processor knows some aircraft specifics based on its installation configuration and can modify its commands accordingly. While tracking intruder aircraft the computer evaluates the slant range, bearing and altitude of each, then computes the closure rates of each within the surveilled range. All this is done to determine the time in seconds to the CPA along with the horizontal miss distance to the CPA. The intruders vertical speed is simply obtained by measuring the time to cross successive altitude increments. Altitude increments are based on the encoder/ADC resolution (100ft/25ft). TCAS can simultaneously track up to 30 aircraft, in a nominal range of 14 NM for Mode A/C targets and 30 NM for Mode S targets. This information is passed along to the collision avoidance logic in the computer to determine the requirement for TAs or RAs.

A recent improvement implemented by change 7.0 includes an adjustment to vertical speed commands so that rates of climb and descent are modified for more practical closure rates on assigned altitudes. One benefit of this is it should minimize vertical profile bumps (overshooting) during a climb or descent profile.

Directional Antenna

The directional antenna although passive is a critical component to the system. The system is defined by its accuracy and here is where the directional antenna plays a very important role. Important to the pilot is what quadrant is the intruder aircraft in and what is its bearing and altitude. All of these of course are time critical and serve to aid in the visual acquisition process. Let’s explore this *angle of arrival* as it is termed and see how it can be determined. The angle could be measured using the typical four quadrant sine/cosine vector vs. amplitude arrangement but the monopulse technique employed here and trying to resolve bearing ambiguity then present problems. The angle can be measured by comparison between amplitude and phase of the monopulse or finally by the *Phase Interferometer Method*. It was determined that measuring signal amplitude was somewhat less reliable due to stresses on the antenna which ultimately could influence received signal strength. The phase interferometer measurement is a process used for measuring very short pulses and their phase relationships. The size of the antenna including height also plays a big part in its accuracy and yet a low profile type is employed for obvious reasons. The antenna radiation pattern is controlled through an electronic beam steering network in the processor in which any one quadrant can be selectively activated and the phase to each element controlled. When using the scheme of direct phase interferometer (also used in optics) the phase matching of the antenna system was found to be critical and therefore must be controlled to maintain system accuracy. This could be compensated for by allowing the processor to self-calibrate itself to the antenna after installation and then subsequently while in flight. The calibration must be done from the antenna multiplexer in the processor out to the antenna as well as inboard of the multiplexer. Utilization of the electronic beam steering technique allows only one quadrant or sector of the antenna array to transmit interrogations. This selective quadrant transmission results in the transponders in the non-selected quadrants around the aircraft to be suppressed due to large side lobes (P2). Thus the radiation pattern is controlled. The antenna angle of arrival can now be further resolved by concentrating in this one quadrant. If multiple elements are employed in each quadrant of the antenna then resolution is certainly improved. The angle ambiguity can be further resolved by performing directional interrogations in the remaining quadrants. The concept employed by the TCAS then is to control the signal phasing to all elements in the antenna resulting in control of the radiation pattern around the aircraft. This technique then allows for directing a lot of processing power to just a small section of airspace at any one time. The third generation or TCAS III system antenna will consist of a pair (top/bottom) of eight-element, 10.5 inch diameter, electronically steerable circular arrays which continuously scan the space surrounding the aircraft.

The Future

TCAS will remain very important as we transition into the ADS-B type of national airspace system. In the future we will further enhance our system by linking actual GPS position information into the TCAS. This will result in improved location accuracy and further develop the Free-Flight concept. Further utilization of the Mode S Data Link will also likely occur. Currently we can downlink RA reports to Mode S ground sites and during an RA, every eight seconds TCAS generates a spontaneous message that contains information on the current advisory. This real-time air to ground link will bear more fruit as the ADS-B system takes over in the years to come.

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