A Transponder-Based Aircraft Detector for SLR

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Abstract

A transponder-based aircraft detector (TBAD) has been developed for aircraft detection in the context of laser propagation, and deployed on a number of astronomical telescopes. The Federal Aviation Administration (FAA) in the United States has approved TBAD as a single-tier safety device for three telescopes at two locations, and these numbers are expected to grow. This paper outlines the concept, highlights results, and presents a status update for the technology.

1 Introduction

Propagating a laser beam through the atmosphere requires attention to aircraft safety. Different countries have different requirements, and in practice these requirements are satisfied in a variety of ways. In the astronomical community, where lasers are used to create artificial guide stars for use in adaptive optics systems, the default solution has been to use aircraft spotters able to terminate laser propagation. In the satellite laser ranging (SLR) community, active radar systems are more common.

Detecting airplanes optically or via infrared imaging is prone to false detections from the Sun, Moon, stars, birds, insects, bats, meteors, satellites, lightning, and clouds. Clouds can also obscure an airplane from view. Human spotters are better at coping with many of these confusions, but still may not see through clouds—and also are susceptible to wandering attention, reduced acuity in harsh conditions, and may interfere with planned observations if sick, late, or otherwise absent. Radar systems avoid most of these drawbacks, but operate in a $1/r^4$ signal strength regime—familiar to SLR operations. It is difficult to detect distant aircraft using radar, commonly encountered when working at low elevation angles. Radar systems are generally not permitted at astronomical telescopes due to their impact on sensitive electronics. At some SLR sites, co-located very long baseline interferometry (VLBI) antennas can have difficulty coping with local radar blasts.

2 Concept

TBAD listens to radio frequency (RF) transponder transmissions from aircraft at 1090 MHz. The basic concept is described in Coles et al. (2012). Transponder signals are strong, broadcast omnidirectionally, and detection scales as $1/r^2$. TBAD does not interrogate airplanes (does not request transmission), but rather relies on the constant stream of interrogations coming from ground facilities and other aircraft. In a busy airspace, an airplane sometimes responds several hundred times per second to interrogations. Over remote Mauna Kea, a more typical rate is 10 Hz.

The key to TBAD is a directionally-sensitive array composed of seven narrow-band patch antennas. By evaluating the *ratio* of the array output to that of a single patch antenna, TBAD is able to ascertain if the source of transmission is within $\sim 15^\circ$ of the boresight direction—independent of transmitter power, polarization, distance, etc. Various thresholds control how far TBAD is allowed to look (has no trouble with 100 km or greater, if desired). Figure 1 illustrates the difference in beam patterns between the array and a single patch.

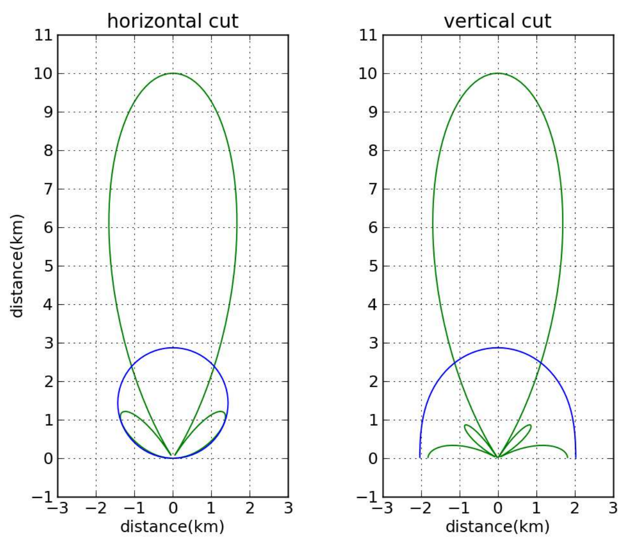

Figure 1: Beam patterns from the TBAD antenna, set to an arbitrary distance scale. Only in the forward direction is the directional signal (green) stronger than the single-patch broad signal (blue). By setting a threshold on the ratio between these two, TBAD unambiguously identifies sources in the forward direction.

The transmissions from aircraft at 1090 MHz can take several forms. The most common are Mode-A and Mode-C, which communicate the temporarily assigned "squawk" identification and an encoded altitude, respectively. These use a 15-pulse-position format, whereby each pulse position either does or does not contain RF power (required to be 70–500 W at the transmitter, depending on airplane type). The first and last "framing" pulses are always present, while the middle pulse (X-bit) is never used in practice. The other 12 pulses provide 4096 possibilities, generally represented as a 4-digit octal number. About one third of these codes map to altitudes (for Mode-C) covering -1200 ft to 126,700 ft in 100 ft increments, following a Gray Code sequence. Figure 2 provides an example transmission. The other common form is Mode-S, which is a multi-purpose format of either 56 or 112 bits of information in a flexible coding scheme that can be used to communicate permanent aircraft identity as well as altitude, latitude, longitude, velocity and heading, text fields (often flight number) and other useful information. Finally, some distance measuring equipment (DME) signals occupy the 1090 Mhz band, and are seen as two broad pulses by TBAD.

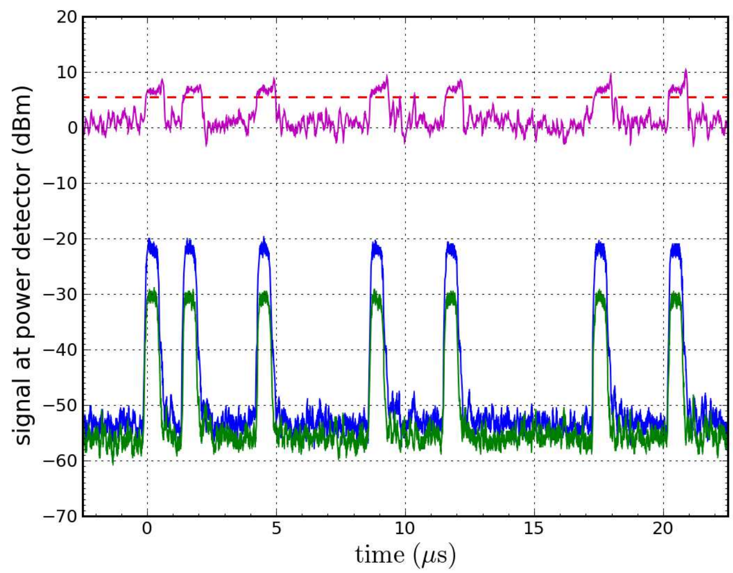

Figure 2: Example Mode-C code, showing the directional antenna signal in blue (taller pulses), the broad-beam signal in green (shorter), and at top the ratio (difference in log space). The red dashed line indicates a 5 dB ratio threshold for considering the source to be in the protected beam zone—in this case satisfied. The first and last pulses are framing pulses, and the ones in between convey the octal code 4530, which may translate to 3400 ft of altitude.

As an accompanying device to TBAD, a transponder simulator, called TSIM, produces RF pulses mimicking those from aircraft as a means of testing TBAD response. One may either inject the TSIM signals directly into the TBAD RF inputs via coaxial cables for bench testing, or via free-space transmission into the directional antenna. In remote locations where air traffic is sparse, TSIM provides a useful check that the TBAD system is still responsive, and offers a calibration baseline against which to gauge consistent behavior.

TBAD is packaged in discrete units as pictured in Figure 3. The antenna assembly hosts both the narrow and broad beam feeds. The weather-tolerant discriminator box—responsible for assessing ratios and signal strengths relative to tunable thresholds—sits near the antenna plate, which itself must have a clear sky view and point in the direction of laser transmission. The decoder unit can be located much farther away (indoors) and provides serial communication to a computer for the sake of monitoring.

3 Performance

Various tests of TBAD performance have been conducted at a number of locations. These include the busy skies of Southern California, the Apache Point Observatory, Palomar Observatory, Mauna

Figure 3: The complete TBAD system. Clockwise spiral from top: antenna assembly; TSIM (gray) atop the TBAD decoder unit (blue, rack-mount); TSIM transmit antenna; AC power cords; short SMA cables for connecting antenna to discriminator box; test cable connecting decoder box to discriminator box (can be up to 50 meters long); discriminator box (installed near antenna); spare boards for discriminator, decoder, TSIM.

Kea in Hawaii, Cerro Pachon in Chile, and (briefly) the Monument Peak SLR station in California. This latter test established that TBAD is not adversely affected by a 9.4 GHz radar system operating $\sim$ 10 m away. TBAD characterization efforts range from long-term campaigns at observatories to intense tests involving airplanes following pre-arranged flight paths—sometimes chartered and arranged by the TBAD users to maximize testing efficacy. The short of it is that TBAD has not yet failed to request shutter closure in time to protect any aircraft crossing the protected zone. Charter operations arranged by the W. M. Keck Observatory (WMKO; Mauna Kea) showed compliance with the recent functional standards for laser protection created by the SAE G-10T committee, known as AS-6029A. Comparison to flight-track logs from Flight Explorer at WMKO and at the Apache Point Observatory (APO) in southern New Mexico have not revealed any beam-crossing airplanes not reported (and protected) by TBAD. Indeed, TBAD picks up planes not available to tracking services, such as military and general aviation aircraft. Anecdotally, at UCSD, TBAD has never failed to react to visually sighted air traffic at any altitude, be they helicopters, small recreational planes, arrivals to San Diego passing overhead at 8,000 ft, departures hugging the Mexican border, or high-flyers at 30,000–45,000 ft. Even though aircraft are not required to operate transponders below 10,000 ft, in practice the vast majority do. The key exceptions may be crop dusters and vintage aircraft.

The comparison campaign at APO lasted about three months and involved 108 shutter closure requests from TBAD in 783 hours of on-sky operation. The closures totaled 3453 seconds, constituting 0.12% closure time. TBAD noted approximately 900 separate flights in this period, issued 108 shutter requests, and did not fail to close for any flight track that Flight Explorer clearly indicated went through the protected region of the TBAD field of view (about 70 instances). Additional closure events appear to stem from real aircraft that are either military (characteristic squawk codes) or low-flying planes that are not tracked by Flight Explorer. The full report is available at `aircraft-avoid.com`.

4 Status

As of this writing (March 2015), eleven TBAD systems have been built and are in various states of deployment on a number of telescopes. Thus far, all units have been built as part of a development effort at the University of California at San Diego (UCSD). Future units will be built by Aircraft Avoidance Systems, LLC.: a company formed by the same individuals. Table 1 details the current state of TBAD deployment. Unit numbers track the hardware revision number as improvements have been made (but no difference in core functionality). In addition to spare units, some of the users have spare circuit boards for an easy swap should an installed unit suffer a problem.

Table 1: Status of TBAD Units as of Feb. 1, 2015

Unit	Telescope	Location	Built	Delivered	Installed	FAA-approved
3.1	Apache Point 3.5 m	Sunsopt, NM, USA	Y	Y	Y	Y
3.2	Keck II 10 m	Mauna Kea, HI, USA	Y	Y	Y	Y
4.1	Keck I 10 m	Mauna Kea, HI USA	Y	Y	Y	Y
4.2	Subaru 8.2 m	Mauna Kea, HI USA	Y	Y	?	N
4.3	Gemini N 8.1 m	Mauna Kea, HI USA	Y	Y	Y	N
4.4	Gemini S 8.1 m	Cerro Pachon, Chile	Y	Y	Y	N
4.5	UCSD Test Unit	San Diego, CA, USA	Y	Y	N/A	N/A
4.6	WMKO Spare Unit	Mauna Kea, HI USA	Y	Y	spare	(Y)
4.7	Gemini Spare Unit	Mauna Kea, HI USA	Y	Y	spare	(N)
5.1	Large Binocular 8.4 m	Mt. Graham, AZ, USA	Y	Y	Y	N
5.2	Large Binocular 8.4 m	Mt. Graham, AZ, USA	Y	Y	Y	N

As of this writing, three installations have received Letters of No Objection from the FAA to operate with TBAD as the sole aircraft detection scheme. Others are just getting started on the process, but in general prospects look favorable.

In late 2014, a new capability was added to TBAD: it can now decode Mode-S and ADS-B transmissions from aircraft. These transmissions provide a wealth of additional information about the flight including permanent aircraft identification code, latitude, longitude, altitude, temporary squawk identity code, velocity, heading, and textual information like the flight number. By 2020, airplanes will be required to carry ADS-B transponders in the United States as part of the next-generation air navigation system. By decoding these signals, TBAD's ability to self-diagnose efficacy is greatly enhanced. Combined with accurate knowledge of antenna/telescope pointing, a position report from the airplane allows calculation of off-axis angle, so that one may study the degree to which TBAD correctly responds to aircraft near boresight while ignoring those further away.

5 SLR Suitability

While TBAD has not yet been used in an SLR context, it may be an attractive and relatively low cost ($\sim 35,000$ USD) substitute for radar, spotters, or lack thereof. The main differences between SLR and astronomical applications pertain to aperture and site elevation.

Thus far, TBAD has been able to mount either in front of the (large) secondary mirror of large telescopes, or on the top ring structure around the periphery of the aperture. For telescopes smaller than the 4-meter class, these may not be options. NASA is planning to test TBAD on the MOBLAS-7 installation at Greenbelt, mounting the antenna plate directly on the telescope—likely in a hinged arrangement for easy stowing when not in use. While the antenna does have some slots to reduce wind loading, the antenna may still impact tracking performance in windy conditions. MOBLAS-7 uses a wide enough beam divergence that the wind shake is likely not a limiting factor.

Lower elevation sites admit a greater likelihood for aircraft operating without transponders. As mentioned above, extensive testing in San Diego (near sea level) has not yet revealed any low aircraft operating without transponders, representing a sample of roughly 100 visually sighted aircraft confirmed to transmit at 1090 MHz. Visual sightings at a half-dozen other locations at various elevations tell a similar story. Perhaps the most incisive test will come from the MOBLAS-7 campaign, operating TBAD in parallel with the existing radar system and camera system. Likely scoring hundreds of detections in a matter of months, we should develop an idea about the frequency of airplanes confirmed by radar and camera that do not appear to carry a transponder. Based on previous experiences, we do not expect many silent flyers over Greenbelt.

References

[1] Coles, W. A., Murphy, T. W., Melser, J. F., Tu, J. K., White, G. A., Kassabian, K. H., Bales, K., & Baumgartner, B., "A Radio System for Avoiding Illuminating Aircraft with a Laser Beam," *Publications of the Astronomical Society of the Pacific*, **124**, 42–50, (2012) (arXiv:0910.5685)