TBAD Performance Analysis at Apache Point

April 9, 2014

Abstract

A transponder-based aircraft detector (TBAD) is mounted on the 3.5 m telescope at the Apache Point Observatory in southern New Mexico, Comparison of TBAD data with flight tracking logs from Flight Explorer reveals remarkably reliable performance in detecting aircraft passing close (within 12°) to the telescope boresight. In roughly three months of comparison (74 operating nights), the TBAD system alarmed for aircraft 108 times. Not all such aircraft were represented in the Flight Explorer database, while virtually every Flight Explorer track passing close to the telescope boresight resulted in TBAD requesting shutter closure. The only possible exception is fraught with unusual circumstances that mitigates its usefulness as a test. Thus we can say that in roughly one hundred passages of aircraft in field conditions over three months, we have no instances demonstrating failure of the TBAD system to identify and alarm when aircraft pass within about 12° of the telescope boresight direction.

1 Introduction

TBAD (the transponder-based aircraft detector) is an automated transponder detector designed to prevent accidental laser illumination of aircraft flying close to the boresight of a telescope projecting a laser skyward. TBAD is essentially a directionally-sensitive detector capable of discerning when a transponder is within about 12° of the antenna boresight. When the TBAD antenna is mounted on and co-aligned to a laser projection telescope, the protected zone is described by a cone ("beam") centered on the laser axis.

Unlike other illumination avoidance strategies, TBAD is not hampered by clouds, light levels, birds, bats, the Moon, Sun, or stars, meteors, or lightning. Because the Federal Aviation Administration (FAA) is intimately familiar with transponders and associated requirements, the performance of this system is much easier for the FAA to assess. The two notable failure modes of TBAD pertain to lack of transponder signals from an aircraft. This can happen for the following reasons.

1. The aircraft transponder is missing or not activated. This is legal in certain airspace below 10,000 ft MSL (mean sea level reference) or within 2000 ft AGL (above ground level).

2. The aircraft carries an operating transponder, but receives no interrogations from ground or airborne systems.

The first scenario is rarely encountered for observatories at high elevations. Observatory operations tend to transpire at night, and few airplanes tend to fly within 2,000 ft of mountainous terrain at night. The second scenario is even more rare over continental sites. Even over Hawaii in the middle of the night we find that transponders respond to more than two interrogations per second. Over the Apache Point Observatory (APO) in southern New Mexico, the rate is typically over 50 transmissions per second.

TBAD responds to any sufficiently strong transmission at 1090 MHz, which includes Mode-A, Mode-C, and Mode-S transponder signals, as well as some DME (distance-measuring equipment) transmissions.

This document summarizes a characterization campaign of TBAD at the Apache Point Observatory from 2013.12.15 to 2014.03.19. We are not able to compare every night during this period, because:

- the telescope dome is not open every night due to weather;
- the TBAD logging system (though not TBAD itself) had an outage for one week;
- flight track comparison data was not available 100% of the time.

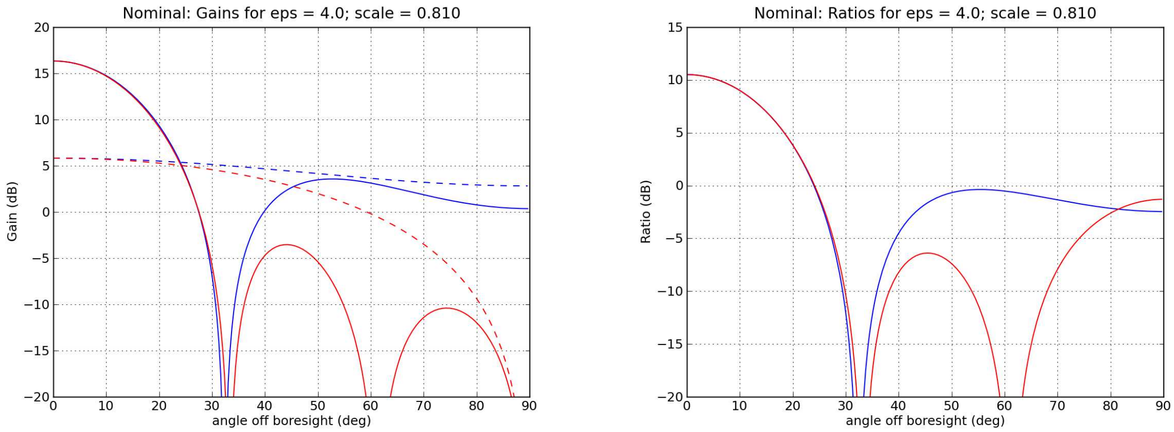


Figure 1: TBAD antenna response. At left, the two antenna feeds are represented as solid lines (directional) and dashed lines ("omni"). The two colors represent horizontal and vertical cuts through the beam pattern. Note that the omni pattern is always stronger than the directional pattern (sidelobes) outside of the central region. At right is the *ratio* between directional and omni feeds (0 dB is a ratio of 1; 10 dB is a ratio of 10). TBAD identifies a transmission as coming from "in the beam" if its directional/omni ratio is high.

Despite these influences, we had a total of 67 nights for which all elements were in place at once. What follows is an account of the results.

2 Concept and Brief History

TBAD was developed at UCSD, as described in Coles et al. (2012). In short, TBAD has two antenna feeds operating in a narrow band around 1090 MHz. The two antennas correspond to: a phased array of 7 patch antennas producing a "narrow" directional beam; plus a single patch antenna producing a broad (called "omni") beam. The central concept is that the *ratio* between directional and omni antenna feeds is a sensitive indicator of direction to the source, as illustrated in Fig. 1. Using the ratio as the primary basis for judgement eliminates variability due to transmitter power, distance, polarization, pulse shape etc. Besides triggering a shutter closure when the ratio indicates a transmission source near the antenna boresight, TBAD will also request closure if either antenna signal exceeds a set power level (termed saturation condition)—effectively mitigating close aircraft whose high angular speed may otherwise strain the response time of TBAD.

A TBAD prototype began operation at the Apache Point Observatory in December 2008. The W.M. Keck Observatory became interested in TBAD in February 2010 and borrowed the second-generation (improved) prototype for testing at the summit of Mauna Kea in the summer of 2010. The results encouraged them to purchase a third-generation system for installation on the Keck-II 10 m telescope, which was accomplished in April 2012. An extensive performance characterization campaign ensued, using a subscription to the Flight Explorer tracking service (a product of Sabre Inc.) to provide "truth" data on flight tracks. The chief problem was that the exceptionally low volume of air traffic over the Big Island during night operations resulted in only one "beam-crossing" airplane in the year that followed (TBAD reacted appropriately, with ample time, even though the laser was not operating at that time).

In January 2013, a three-day NASA volcanic shield mapping campaign presented a golden opportunity to collect multiple passes at high telescope elevations. We knew in advance the flight tracks to high precision, offering a chance to design tests that would maximize characterization of system performance. We also employed a spare third-generation TBAD system, operating outside on the summit of Mauna Kea for simultaneous testing. The outdoor unit could be steered more quickly, so that we could set up multiple pointings (or real-time continuous tracking) for each flyby, and also vary instrument settings to more fully characterize its performance. While this document does not detail the results of the NASA overflights, the short statement is that TBAD's performance was *flawless* on over 100 passes/pointings—some at rather large distances.

The external unit used in conjunction with the NASA overflight campaign was actually an upgrade of the original Apache Point TBAD unit. This unit was taken offline in late July 2012 in order to upgrade the first-generation detector to the third-generation standard.

3 Analysis Period

The upgraded TBAD was re-installed at APO in September 2013, but an inadvertent pinout change in cables resulted in incomplete data logging operation. This was remedied in December 2013, and at the same time the laser shutter interlock system was expanded to allow TBAD control of the laser shutter. Around the same time, the Keck Observatory subscription to Flight Explorer added a flight-logging zone centered on APO, so that we could begin accumulating "truth" data against which to compare the TBAD log information. We therefore begin the present analysis on 2013.12.15, when all of these pieces were simultaneously in place.

A brief outage of TBAD data logging due to failure of the logging computer knocks out 7.5 days from 2013.12.30 to 2014.01.06. It should be stressed that the TBAD system continued to operate normally during this computer outage. We just did not capture the log information (secondary to protection services). In principle, separate logs of interlock activity tell us when TBAD asserted a closed laser shutter (whether the laser is operating or not), and observatory records could elucidate telescope pointing during at those times for comparison with Flight Explorer logs. But we have no shortage of comparison nights, so it is not clear that the effort would add anything new. Also, some nights had partial or missing Flight Explorer logs, for unknown reasons. This, too, reduces slightly the number of comparison nights.

3.1 Coincidence with Spotters

TBAD was given control of the laser shutter as of mid December, 2013, but operates and collects data any time the telescope dome is open—independent of laser activity. By contrast, the APO laser system operates only about 2% of the on-sky time. During the comparison interval examined here, the APO laser system operated (with two human spotters) on 13 occasions, usually for about an hour at a time. Thus the overlap between spotters and TBAD during the evaluation period is not substantial. The only coincident activity happened when TBAD forced a 25 second shutter closure on 2014.01.09 at 00:57:57. This instance was due to saturation of the detector by a low-flying, nearby plane. The laser had finished a run at 00:57:30, and the next pulses were not emitted until 00:59:25. On this particular night, we had an unusual problem with a motor controller, and asked spotters to come inside the dome and listen for motor motion (during a cessation of laser firing). No notes exist to indicate whether the two-minute pause relates to waiting for an airplane to pass or to other activities.

Worth noting is the fact that APO laser operating times are communicated to the Albuquerque Center Air Traffic Control unit, which issues NOTAMs and also vectors aircraft away from Apache Point during laser activity. This reduces the likelihood of spotter sightings. It is a good layer of precaution that will be continued even if TBAD is the sole sentinel—further reducing risk of accidental illumination.

4 Data Sources and Description

In assessing the efficacy of TBAD, it is important to understand the available data streams and their limitations.

Before going further, it should be noted that the use of "in-beam" below refers to the $\sim 12^\circ$ half-angle beam of the TBAD directional antenna, otherwise called the protected zone. In this context, "in-beam" does not relate to the laser beam, which is seldom actually propagating.

4.1 TBAD Data Log

TBAD itself decodes the pulse patterns associated with Mode-A (squawk-ident) and Mode-C (altitude) transmissions. We therefore know the 4-digit code transmitted, and can generally work out whether it corresponds to an altitude or an identity code from context. But nothing in the signal itself indicates which flavor a particular transmission is. Mode-S transmissions have a characteristic pattern that, even though undeciphered, is identifiable as a Mode-S type transmission. DME signals have a characteristic two-pulse shape and timing, and so can also be distinguished.

The microcontroller in TBAD is responsible for deciding to shutter the laser based on transmission strengths and ratios. The decoded information is informational only, received and logged by a computer. The computer assigns a time stamp at millisecond resolution and better than one second accuracy relative to local GPS clocks at the observatory. Besides the decoded 4-digit pattern, the TBAD data indicates formatting pulses in the transmission and whether any of the conditions existed that would demand a shutter closure, as well as the state of the shutter. In addition, the logging computer extracts telescope pointing information for real-time reporting in the log. The logging software performs cursory interpretation of codes to help identify altitudes and other relevant information.

Below is a sample clip from a recent log file.

```
2014-03-18 03:13:48.248 o0573...PF.FD2  -----          -135.55  55.77 O
2014-03-18 03:13:48.253 o1624...PF.FD0  32000          -135.55  55.77 O
2014-03-18 03:13:48.328 o1624...PF.FD0  32000          -135.55  55.77 O
2014-03-18 03:13:48.349 o0100...PF..AC  ----- DME      -135.55  55.77 O
2014-03-18 03:13:48.382 o5537...PFXF01  ----- ModeS    -135.55  55.77 O
2014-03-18 03:13:48.436 o5537...PFXF01  ----- ModeS    -135.55  55.77 O
2014-03-18 03:13:48.726 o5777..BPFX.03  ----- ModeS    -135.55  55.77 O
2014-03-18 03:13:48.769 o5777..BPFX.03  ----- ModeS    -135.55  55.77 O
2014-03-18 03:13:48.776 o0573..BPF.FE6  -----          -135.55  55.77 O
2014-03-18 03:13:48.782 o1624..BPF.FE4  32000          -135.55  55.77 O
2014-03-18 03:13:48.788 o0573..BPF.FE6  -----          -135.55  55.77 O
2014-03-18 03:13:48.794 o1624..BPF.FE4  32000          -135.55  55.77 O
2014-03-18 03:13:48.800 o1624..BPF.FE4  32000          -135.55  55.77 O
2014-03-18 03:13:48.809 s1624..BPF.FE8  32000          -135.55  55.77 O
2014-03-18 03:13:48.813 s0573..BPF.FEA  -----          -135.55  55.77 O
```

Each entry begins with a date and time stamp, in UTC. Note that the entire sequence above lasts less than one second. This particular airplane is flying at 32,000 ft (corresponds to transponder code 1624), using squawk (identity) code 0573. We see one DME transmission and a cluster of four Mode-S transmissions (look like 5537 or 5557—not to be confused with squawk code of 0573). The telescope was at azimuth -135.55° and elevation 55.77°, with the dome open ("O"). The coded block of text after the time stamp is the actual TBAD data; the rest is added by the logging computer. This block indicates the shutter open ("o") in the beginning, but closed ("s") at the end. The next four digits represent the decoding result. The following three positions are used to indicate any shutter closure conditions: saturation of the broad or narrow TBAD antenna feeds (dots indicate none) or that the airplane is deemed to be in the protected "beam" zone ("B"). In this case, we see no closure conditions at first, but the airplane moves into the beam midway through. The TBAD unit at APO is configured (by an external knob selection) to close the shutter on the eighth "beam" alert in the last ten seconds—which in this case happens less than 0.1 s after the first "B" appears.

The main point of showing this log example is to show the virtues and limitations of the TBAD data stream. Key takeaway points are:

1. TBAD time stamps are good/reliable.
2. Airplane squawk code and altitude are known by virtue of TBAD's decoding.
3. Telescope pointing is known.
4. Data sampling is dense: many dozens of records per second, typically.
5. Airplane position or angle is *not* known from TBAD data.
6. Flight number, heading, speed, etc. are *not* known from TBAD data.
7. Aside from the "B" designation indicating a source within $\sim 12°$ of boresight, TBAD presents *no information* on *where* an airplane is on the sky.

4.2 Flight Explorer Data

Through the W.M. Keck Observatory's subscription to Flight Explorer (FE) services, we get records for airplanes passing through a 25 nmi radius cylinder centered on APO and capturing air traffic above 9,000 ft MSL. For each airplane in the region, we get a (crude, offset) time stamp, latitude and longitude, altitude, heading, speed, flight number, origin, and destination. An example entry appears below.

```
03/21/2014, 08:54:35, 1010, Aircraft entered area, JBU278, APO, SFO,
FLL, A320, 07:02, 11:37, 349, 563, 32.83530, −106.12970, 100

03/21/2014, 08:55:26, 1010, Aircraft entered area, JBU278, APO, SFO,
FLL, A320, 07:02, 11:37, 349, 563, 32.80640, −105.94830, 100
```

Here, we have Jet Blue flight 278: an Airbus 320 traveling from San Francisco to Ft. Lauderdale. It is cruising at flight level 349 (34,900 ft) at 563 knots and heading 100°. Two entries are included to illustrate a point. Although the time stamps differ by 51 seconds, converting the latitude and longitude differences into distances, the implied speed is 659 kt, which is unlikely. At the more characteristic 563 kt, as reported, the coordinate separation would be traveled in 59.7 s. So the time stamps really *should* be 60 s apart. For this flight, the six entries have time stamps separated by 60, 51, 70, 49, and 60 seconds, while the time steps calculated based on reported positions and speeds come to 59.8, 59.7, 56.1, 59.6, 60.1 seconds. So it appears that the *actual* cadence hews closely to one-minute samples. The reported times are unreliable. Moreover, there is an unknown overall delay averaging about 330 seconds for the records, and this delay varies from one flight to the next (and is in practice difficult to determine). A chief reason for the variability in time stamps is that they are generated by the client-side logging computer as entries arrive with unknown and variable latency from a variety of influences.

The take-away points for Flight Explorer data are:

1. The flight is easily and uniquely identified (unless blocked, as some are).
2. Excellent information is provided on position, speed, heading, and altitude.
3. **Time stamps are unreliable** and offset by an unknown amount.
4. Data are sparse: roughly one sample per minute.
5. The squawk code is *not* known for the flight.

4.3 Connecting TBAD and FE Data

Associating TBAD and FE data events is a non-trivial task. The *only* reliable connecting information is altitude. At least it's *something*. But consider that we do not always know for sure which TBAD records correspond to *actual* altitudes vs. squawk/identity codes that happen to map onto reasonable altitudes—which does happen. Also, there are plenty of instances in which multiple planes are in the area at any given time at the same altitude. After all, airplanes often hop into the smoothest altitude in the region. So altitude is not a unique identifier. The unknown time offset also creates difficulty in correctly pairing TBAD records with FE flights.

And not every transponder that TBAD sees has a corresponding airplane appearing in the FE database, since not all transponder-equipped airplanes are represented in Flight Explorer (see Section 7.2.3 on military aircraft). The reverse tends *not* to be true: FE flights generally have a corresponding TBAD set, provided that the telescope dome is open and that TBAD has a line-of-sight to the airplane.

Heavy traffic is especially hard to disentangle. The current analysis software can only match two simultaneous airplanes to FE flights. This handles most cases, but sometimes the software capacity is exceeded and we must "manually" verify that no beam threats went unanswered by TBAD.

4.4 Interlock Data

We separately log any changes to the interlock status. Thus we know (within roughly one second) the times when TBAD requests closure or releases the interlock shutter. This information is also present in the log of

TBAD activity, but in the event that the computer logging fails (as happened around the end of 2013), this separate record can help verify proper behavior of TBAD in the absence of logging.

5 Robustness: TBAD vs. Verification

The analysis to follow is imperfect for a number of reasons, but we should separate these shortcomings from the performance of TBAD itself. The verification process has various weaknesses:

- The logging computer may go offline, or suffer a full disk (as happened on 2013.12.30 due to a runaway video recording that had swelled to enormous size). Or the logging software (Python) could experience an error that causes it to crash.
- The Flight Explorer feed may be interrupted for reasons beyond our control or understanding.
- The software constructed to connect TBAD and FE records is imperfect. The connecting information is tenuous and easy for software to confuse. The association amounts to a pattern matching job for which computers are notoriously poor performers. The trickiest cases must be disambiguated by human intelligence (or more time invested in improving the pattern recognition software as a trade on time).

TBAD itself is not impacted by the problems above. It has no operating system, no storage medium, no external dependencies aside from power. TBAD is a self-contained electronics system with a microcontroller as its brains. Besides various knobs, switches, jumpers, and potentiometers used to manually set its behavior, it receives no input from the external world. It can detect faults in performance (such as a cable disconnect), and will shutter the laser under such conditions. Thus TBAD remains a stalwart sentinel on the sky despite hiccups in the verification analysis.

6 Example Analysis

We will later summarize the results across months of data. First, a few specific examples will clarify the nature of the TBAD/FE comparison and analysis.

6.1 Example Night

We start with an example from a moderately busy night early in the campaign. On 2013 December 16 UTC, the telescope dome opened a few minutes before 00:00:00 to quiet skies. During quiet periods, TBAD sends a keep-alive status message once per minute. This particular night saw 17 groups of aircraft transmission events separated by quiet periods (keep-alives). For each group, an attempt is made to identify squawk codes and altitudes, and to separate overlapping airplanes and correctly handle climbing or descending flights. The results are compared to the FE events that have temporal overlap, looking for altitude matches and using angle from boresight to resolve ambiguities. For 2013.12.16, we get the following reports.

```
Got 17 TBAD groups
 1. 00:20:52: Possible matches from 1 temporal candidates
  N707LM   at 33000 level 33000 with code 0566,  6.0 deg away  (alt) B
 2. 01:10:39: Possible matches from 1 temporal candidates
  AAL1093  at 32000 level 32000 with code 2330, 26.9 deg away  (alt)
 3. 01:40:53: Possible matches from 2 temporal candidates
  UAL632   at 38000 level 38000 with code 2454, 14.6 deg away  (alt)
 4. 01:48:39: Possible matches from 3 temporal candidates
  SWA427   at 40000 level 40000 with code 4041, 33.8 deg away  (alt)
 5. 02:05:39: Possible matches from 3 temporal candidates
  Clean separation: beg: 0.0/18.3/0.1; end: 0.0/52.8/0.0
  ASA763   at 38000 level 38000 with code 0721, 41.0 deg away  (alt)
  AAL949   at 32000 level 32000 with code 0557, 60.3 deg away  (alt)
 6. 02:25:45: Possible matches from 1 temporal candidates
```

```
  SWA2258  at 37000 level 37000 with code 7272, 31.2 deg away  (alt)
 7. 02:36:42: Possible matches from 2 temporal candidates
  UAL369   at 32000 level 32000 with code 2534, 57.0 deg away  (alt)
 8. 02:54:02: Possible matches from 1 temporal candidates
 BLOCKED_A at 39000 level 39000 with code 1356,  9.2 deg away  (alt) B
 9. 03:02:19: Possible matches from 3 temporal candidates
  DAL1080  at 36000 level 36100 with code 3177,  6.5 deg away  (ang) B
10. 03:46:48: Possible matches from 1 temporal candidates
  SWA233   at 35000 level 35000 with code 7370, 44.1 deg away  (alt)
11. 04:04:04: Possible matches from 3 temporal candidates
Clean separation: beg: 0.0/101.6/0.0; end: 0.2/89.4/0.0
  SWA4354  at 40000 level 40000 with code 2433,  1.6 deg away  (alt) B
  AAL2495  at 36000 level 36000 with code 2343, 38.4 deg away  (alt)
12. 04:12:52: Possible matches from 2 temporal candidates
 NO MATCH: Most popular codes/vals: '2370', 32000
  Excluded 1 codes/alts, totaling 10 TBAD events{12400: 10}
13. 04:17:43: Possible matches from 1 temporal candidates
  JBU578   at 35000 level 35000 with code 3240, 44.7 deg away  (alt)
14. 06:01:36: Possible matches from 1 temporal candidates
  AAL2497  at 38000 level 38000 with code 2233, 15.7 deg away  (alt)
15. 06:03:35: Possible matches from 1 temporal candidates
  AAL2497  at 38000 level 38000 with code 2233, 15.7 deg away  (alt)
16. 06:55:39: Possible matches from 1 temporal candidates
  AAL1001  at 34000 level 34000 with code 0573, 35.8 deg away  (alt)
17. 09:37:52: Possible matches from 1 temporal candidates
  AAL2366  at 39000 level 39000 with code 7231, 44.2 deg away  (alt)
```

For each TBAD group, a beginning time stamp is reported, along with a report of how many temporal matches exist in the FE database. Following this is a list (usually one entry) of matched flights, including: flight number; FE altitude average; TBAD altitude average; squawk code; closest approach to boresight, and whether altitude or angle was the primary means of identification. If the TBAD system detected the corresponding aircraft in the protected "beam" zone, a "B" is appended at the end of the line.

A few summaries are also provided. For instance, the block below indicates that: 18 airplanes were identified in the 17 groups (doubles in groups 5 and 11); 10 TBAD log events (out of tens of thousands) were excluded to ease the matching process; one TBAD plane (from group 12) had no (automated) match; no airplanes crossed close to the beam without triggering closure; and 4 airplanes did trigger beam closure.

```
17 groups; 18 identified; 10 excluded; 1 no-match; 0 missed; 4 in-beam
```

We can also separately look for FE flight tracks that crossed close to the telescope boresight and ask whether the shutter closed around that time (within FE time offset uncertainty). This bypasses attempts to match TBAD and FE records, asking a simpler question. In the list below, all the paths passing within 12° did cause the shutter to close. The last line indicates any flight tracks that TBAD likely could have seen yet went unidentified in the groups. Note that the flight in question has a time and altitude that likely corresponds to the missing identification in group 12 above. Sometimes the pattern matching gets thrown off by extraneous information that a human would quickly ignore.

```
Shutter closed for   SWA4354 ( 1.6 deg) at 04:06:16 due to ..B
Shutter closed for   DAL1080 ( 6.5 deg) at 03:02:54 due to ..B
Shutter closed for    N707LM ( 6.0 deg) at 00:21:37 due to ..B
DID NOT detect shutter closure for UAL632 (14.5 deg) at 01:42:18
Shutter closed for BLOCKED_A ( 9.3 deg) at 02:54:13 due to ..B

MISSED    AAL1507 at 04:14:59 level at 31924, PCA 48.4 deg (PA 180.5)
```

But the most revealing way to look at results is by way of a graphical view as would be seen by the TBAD antenna (Fig. 2). The TBAD antenna moves during the night as the telescope tracks different points

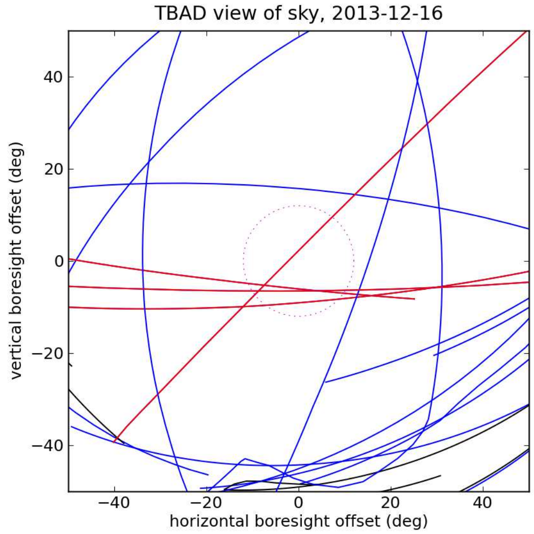


Figure 2: Flight tracks as seen by the (moving) TBAD antenna during the night of 2013.12.16 UTC. Blue tracks indicate identified planes; black tracks are unidentified (by the limited analysis software), and red tracks are associated with shutter closure requests. A circle in the center demarcates a 12° radius circle. Any path crossing through this circle should be colored red, indicating that this path caused TBAD to request shutter closure.

on the sky—sometimes moving quickly as the telescope slews. The view in Fig. 2 is what a long-exposure camera attached to the front of the telescope would see throughout the night. In this case, we plot flight tracks as perceived by TBAD. Note that all tracks crossing through the central region (dotted 12° radius circle in center) are red, which is the adopted convention for indicating that TBAD successfully detected these airplanes as threats.

6.2 More Graphical Examples

We are now in a better position to look at some instructive examples, which will help in understanding the summary table presented later. The Appendix contains corresponding views for all nights used in this analysis.

Fig. 3 shows a fairly typical night for TBAD, in which 12 groups were seen. Out of these, 9 flights were identified. Two planes crossed through the protected zone, and one came close, at 14.9° but did not trigger TBAD.

On the extreme end, some nights are very busy, as was the case on 2014.02.17 (Fig. 4). On this night, TBAD saw 29 groups of transponder transmissions. Out of these, 29 flights were identified, and 3 had no FE matches. Six flights passed through the protected beam and triggered the shutter.

Fig. 5 shows one of several instances of a gross matching failure that must be sorted out manually. In this case, the part of the code that asks: "did the shutter close around the time that a track passed close to boresight?" produces the following result.

```
Shutter closed for  UAL1015 ( 3.3 deg) at 01:51:25 due to ..B
Shutter closed for   AWE470 (13.3 deg) at 03:06:42 due to ..B
Shutter closed for  SKW6220 ( 4.0 deg) at 03:42:15 due to ..B
Shutter closed for   UAL388 (13.7 deg) at 03:43:45 due to ..B
Shutter closed for  AAL1507 ( 8.2 deg) at 03:54:41 due to ..B
Shutter closed for   AAL275 ( 6.1 deg) at 05:41:05 due to ..B
```

So it appears that the six closest tracks triggered the shutter (borne out by a more thorough investigation). The black line in Fig. 5 17° below the center belongs to SWA1428 at 03:09 in the midst of 7 FE planes

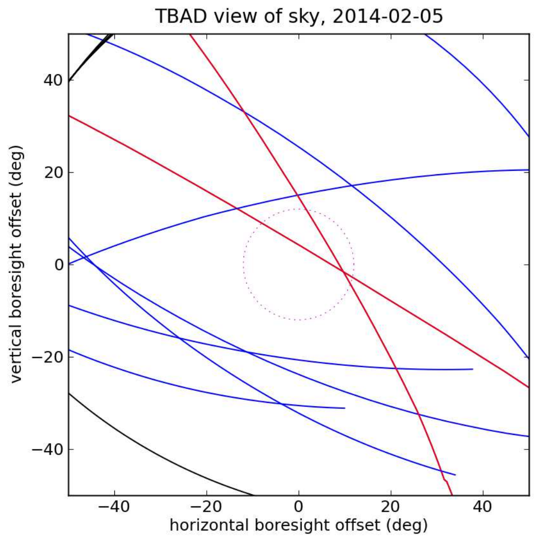


Figure 3: A typical night: two planes crossed through the protected beam zone and were flagged as shutter-closure events. Most of the other flights were identified properly by TBAD (blue tracks) even if they did not pose a threat and therefore did not trigger shutter closure.

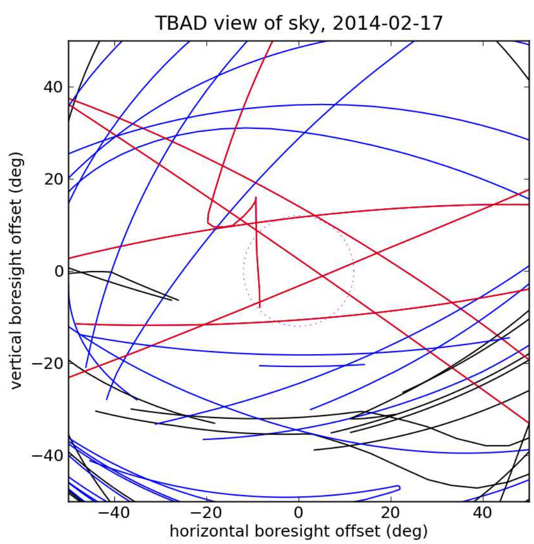


Figure 4: A crowded sky: six planes crossed within the protected zone and caused TBAD to request shutter closure. The odd tracks are a result of the telescope slewing during airplane passage. The odd track near the center terminates because it disappears into the distance and hits the edge of the FE cylinder (the telescope was at 20° elevation at the time, so the end of this track is low on the horizon).

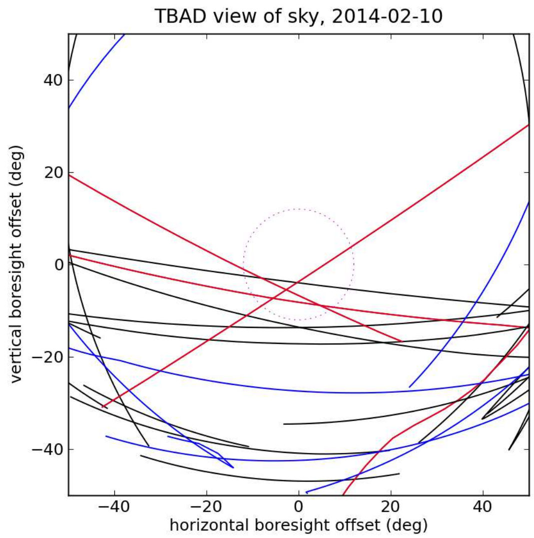


Figure 5: Too many planes at once confuse the matching software (black lines are unidentified tracks), but this can be sorted out manually.

that overlap with that TBAD group. That group was too crowded for the limited-intelligence software to disentangle.

7 Summary Results

In 90 nights of TBAD monitoring, the telescope dome opened on 74 of the nights, accumulating 47,028 minutes of on-sky operation (36% open time). During this time, TBAD requested shutter closure 108 times for a total closure time of 3453 seconds, representing a 0.12% closure time from TBAD. This is an important fact, because when we ask the question: "did TBAD close the shutter around the time the FE data indicates that a track went close to boresight?" the chances of this happening randomly or coincidentally are *very* low.

In Table 1, we see the results of this approximately three-month campaign. Nights correspond to UTC dates, and only nights when the dome was open and the TBAD log was active are presented. For each night, the telescope open time (in minutes) is given, as is the number of distinct flight groups detected by TBAD (sometimes multiple planes within a group between quiet periods). Next is the number of planes for which TBAD requested shutter closure due to a beam-crossing threat. Following this is the number of flight paths crossing within 12° of boresight as indicated by combining Flight Explorer data with telescope pointing information within the TBAD log. Sometimes, this is shown as a range. When this is so, the smaller number represents the number of airplanes within 12.0° of boresight. The larger number includes airplanes farther than this that still managed to trigger a "beam" closure (see Appendix for case-by-case visualization). The edge of the TBAD zone is not precipitously steep (see Fig. 8). The next column indicates TBAD closure due to saturation of the omni or directional antennas, indicating a nearby airplane whose angular speed may be high—triggering a preventive closure. Comments are blank when no shutter events are present, "OK" when there is no mismatch between what TBAD did and what FE indicates should be done. In many cases, TBAD sees something at odds with the 12° criterion from FE, earning a comment as to why. Special cases (dates marked by asterisk) receive additional explanatory attention in Section 7.1. Graphical representations of every night in Table 1 having FE coverage can also be found in the Appendix.

Table 1: Nightly Activity Performance Summary

UTC date	open time	groups	# B	# FE cross	# other	comments
13.12.15	825	6	0	0	0	—
13.12.16	780	17	4	4	0	OK
13.12.17	654	16	1	0	0	'B' for VFR at 10100 ft
13.12.18	754	15	2	1	0	'B' for VFR at 10300 ft
13.12.19	390	7	1	0	0	'B' for '0264' at 10700 ft
13.12.20	459	11	1	0–1	1	SWA571 13.6° away; 'O' for VFR at 11100
13.12.24*	807	25	2	3	0	AWE491 too distant and low on horizon
13.12.25	815	9	1	1	0	OK
13.12.26	531	10	1	1	0	OK
13.12.27*	744	19	2	2–3	0	SWA4209 11.8° away did not trigger 'B'
13.12.28	830	15	1	1	0	OK
13.12.29	619	13	2	2	0	OK
13.12.30	262[1]	9	3	2–3	0	UAL1033 18.3° away
14.01.07*	630	5	3	2–3	0	AAL180 twice due to slew; RSP756 15.4° away
14.01.08*	306	5	2	1–2	0	miss N93WB at 10.5°?; SWA1257 trips twice
14.01.09	844	29	1	1	1	'O' for VFR at 10600
14.01.10	385	3	0	0	0	—
14.01.11*	705	13	2	0–1	0	'2713' at 40000; SWA1257 at 12.7°
14.01.12	797	21	2	1–2	0	UAL1204 at 16.3°
14.01.13	424	20	1	1	0	DAL1115 on edge at 12.2°
14.01.14*	719	13	3	2	0	'1302' at 11800 ft
14.01.15	724	11	2	1–2	0	SWA1713 at 14.0°
14.01.16	719	11	1	1	0	NKS971 caught during slew
14.01.17	816	19	1	1	0	OK
14.01.18	777	15	1	1	1	'O' for VFR at 10300
14.01.19	775	14	1	1	0	OK
14.01.20	753	13	1	1	0	OK
14.01.21	770	7	1	1	0	OK
14.01.22	627	6	1	0–1	1	'O' for VFR at 10400 ft; AAL2497 at 13.7°
14.01.23	273	5	1	1	0	OK
14.01.24	157	2	0	0	0	—
14.01.25	733	20	5	—	0	FE data missing; 5 "in-beam"
14.01.26	814	10	1	0–1	0	SWA2513 at 13.5°
14.01.27	545	13	0	0	0	—
14.01.28	776	14	0	—	0	partial FE data loss
14.01.29	792	11	0	—	0	no FE data
14.01.30*	846	25	3	1–2	1	'O' for VFR at 10400 ft; '3551' at 32000 ft
14.01.31*	566	22	2	1	0	'B' for VFR at 10,800 ft
14.02.03	570	11	1	1	0	OK
14.02.05	511	12	2	2	0	OK
14.02.08	748	10	2	2	0	OK
14.02.09	717	7	1	0–1	0	AAL2495 at 13.8°
14.02.10	777	14	6	4–6	0	AWE470 at 13.3°; UAL388 at 13.7°
14.02.11	615	14	1	1	0	OK
14.02.12	801	31	0	—	0	missing FE data
14.02.13	799	8	0	—	0	no FE data
14.02.14	718	4	1	—	0	no FE data
14.02.15	754	14	1	0	0	'B' for VFR at 10300 ft
14.02.16	704	13	2	2	0	OK
14.02.17	709	29	6	6	0	OK

[1] TBAD log failed partway into night.

UTC date	open time	groups	# B	# FE cross	# other	comments
14.02.18	611	5	3	3	0	OK
14.02.19	613	12	4	3–4	0	EJA939 at 14.5°
14.02.20*	169	2	1	0	0	'0746' at 33000 ft
14.02.21	729	7	0	0	0	—
14.02.22	702	5	0	0	0	—
14.02.23	684	13	1	1	0	OK
14.02.24	252	4	0	—	0	no FE data
14.02.25	752	4	0	0	0	—
14.02.27	599	1	0	0	0	—
14.02.28	352	8	0	0	0	—
14.03.01	775	11	1	0–1	0	AAL2461 at 14.0°
14.03.03	515	12	1	1	0	OK
14.03.04	666	6	1	1	0	OK
14.03.05	183	0	0	0	0	—
14.03.06	717	2	1	1	0	OK
14.03.07	292	4	0	0	0	—
14.03.08	573	22	2	1–2	0	SWA230 at 16.7°
14.03.10	729	13	1	0–1	0	DAL1242 at 12.7°
14.03.11	763	10	0	0	0	—
14.03.12	400	10	0	0	0	—
14.03.13	673	13	2	2	0	OK
14.03.17	696	8	1	1	0	OK
14.03.18*	752	9	4	0	0	FE data loss; 'B' for VFR at 12500 ft
14.03.19	663	4	1	—	0	no FE data; '3260' at 37,000 ft
totals	47028	851	103	67–85	5	

7.1 Anomalies

Some added notes are presented in chronological order for various anomalies noted in Table 1 by asterisks.

7.1.1 2013.12.24

FE tracks showed three airplanes crossing close to boresight: SWA372 passing within 8.1°, SKW6261 passing within 7.9°, and AWE491 passing within 9.5°. TBAD saw and triggered on the first two, but only saw DME transmissions from the last one (which tend to be stronger than the transponder signals). This circumstance was slightly unusual. The telescope was slewing to its end-of-night position (facing ENE at azimuth 76° and elevation 20°). When the airplane was first picked up, the telescope was already at 20° elevation, but facing south and turning eastward. The airplane, meanwhile, was to the SSE (azimuth around 145°) and heading west at a distance of 26 miles and only 10° above the horizon. The telescope and airplane, moving in opposite directions, quickly crossed paths while the airplane was still very far away. Although TBAD is in principle *capable* of detecting and protecting to this distance, it is not presently tuned to do so. Laser operations at APO are typically performed at elevations higher than 25°, and never below 18°. Thus protecting an airplane 10° off the horizon is not a requirement and we can safely disregard this instance.

7.1.2 2013.12.27

Three airplanes came close to the boresight on this night: SWA233 passed 1.8° from center, SWA4209 passed within 11.8°, and SKW5529 passed 12.6° away. TBAD saw all three airplanes, but only triggered a "beam" closure for the first and last. This is a good opportunity to note that the nominal 12° cone angle is not sharply defined (Fig. 8), so that we will exercise forgiveness in the range from 11–15°. We see plenty of other examples of variable performance in this zone, but this is not a key concern. In the particular case of SWA4209, the signal did "tickle" the "in-beam" criterion four times in short succession, but fell short of the settable 8-event threshold for which the APO TBAD unit is configured.

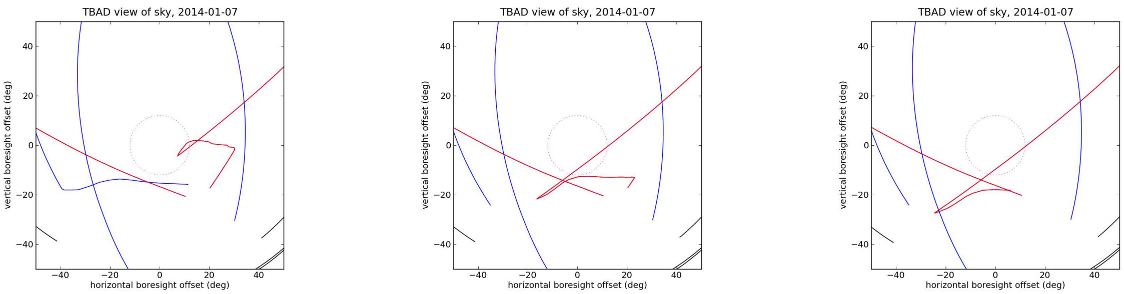


Figure 6: Effect of Flight Explorer time offset variability on tracks during telescope slews. On 2014.01.07, flight AAL180 was tracking through the TBAD protected field around the same time that the telescope initiated a slew. The shape of the resulting track as seen by the antenna depends on the unknown time delay in Flight Explorer data. Here we have, from left to right, 4.5, 5.5, and 6.5 minute delays assumed for the FE data. We do know that the beam condition was triggered in two groups, so that the middle panel is most consistent.

7.1.3 2014.01.07

This is an interesting case because the telescope slewed to a different spot on the sky just after AAL180 had crossed through the protected zone (triggering a shutter close request). The slew direction resulted in the antenna sweeping past the airplane again, triggering a second closure request. Note that for time-critical events of this nature, variable delay in the FE time stamps lead to uncertainty about the exact path of the airplane relative to the antenna, as seen in Fig. 6.

7.1.4 2014.01.08

A couple of noteworthy events occurred on this night. First, the telescope dome opened at 23:04:40 on 2014.01.07. At 23:54:13, an aircraft squawking ident '6566' at 41,000 ft tripped the "in beam" condition, resulting in a shutter closure of 26 seconds. The only airplane indicated in the last hour of the (UTC) day on 2014.01.07 is at 12,000 ft, not 41,000 ft. A second, minor issue occurred for flight SWA1257, passing 15.7° from the boresight at around 03:09:15. This airplane twice tickled the edge of the beam, resulting in two shutter closure requests separated by 5 s. But the disturbing anomaly of this night was around 00:40:00. FE reports N93WB traveling from Houston to nearby Alamogordo, descending from 15,000 ft to 14,100 ft. Four records appear in the FE log with timestamps: 00:39:17, 00:40:38, 00:41:56, and 00:47:17, and altitudes (15,000, 14,400, 14,100, and 14,100). Note that the last time stamp is well separated from the previous three. The speeds inferred from FE-reported positions and time stamps come out to (213, 663, and 56 kt), which is clearly unphysical. Using the positions together with the reported speeds (184, 181, 176, 176 knots), one finds that the time intervals *should* be 95, 294, and 103 seconds, rather than the reported 81, 78, and 321. Also, the positions indicate an irregular (zig-zag) path, with FE-reported headings of 287, 300, 284, 287. While this is possible, it's yet another anomalous aspect of this record set.

Meanwhile, TBAD recorded 1500 transponder events from a VFR (Visual Flight Rules) plane initially at 12,900 ft at 00:38:38, descending to 11,200 ft by 00:41:38. Is this the same plane, later in its descent, after dropping flight following from air traffic control? Perhaps for this non-commercial flight, the Flight Explorer time stamps are considerably in error? The descent rate observed by TBAD is a fairly steady 600 feet per minute (fpm).

The FE records indicate descent rates for the three intervals between entries of 440 fpm, 230 fpm, and 0 fpm if the time stamps are taken literally. Using the adjusted time stamps based on reported positions and speeds, the descent rates become 380 fpm and 60 fpm, followed by 0 fpm for the last interval. It is possible that the airplane arrested its descent as it terminated flight following (e.g., cleared for descent to 14,000 ft), later picking up the pace for a 600 fpm descent.

If we extrapolate theTBAD descent of 600 fpm back to when the plane would have been at 14,100 ft, we find that this would have been at 00:36:38, corresponding to a Flight Explorer time of 00:42:08 following the usual 330 s offset. This is not terribly far (12 seconds) from the third record in the FE log, which is the first part that makes any sense. But it gets worse again.

The FE-reported positions have the airplane making a pass within 0.72 miles (horizontally) of the telescope, at an azimuth of 349° and an elevation of 52°, and still at 14,100 ft. The problem with this scenario is that the dome/telescope were at the parking position of 76° azimuth and 20° elevation from 23:16:00 until 01:04:00. The narrow slit of the dome at that azimuth would not permit line-of-sight to the point of closest approach, and the later stages of the flight would be even less visible as the airplane disappeared behind the telescope to the west. Maybe the TBAD VFR plane was not at all the N93WB airplane reported by Flight Explorer. If they are the same—as seems likely due to coincidence in time, approximate flight path, and descending intermediate altitude profile—then telescope pointing demands that the altitudes reported in the FE log be wrong, since the TBAD altitudes are considerably lower than those reported in the FE log (a disagreement never seen in other flights). If the TBAD and FE airplanes are truly different, then N93WB was operating illegally without a transponder at 15,000 ft.

Given the large list of anomalies in this flight: FE time stamp irregularities; inferred whiplash speed changes; zig-zag flight path; altitude anomalies; a coincident descending VFR plane with mismatched altitudes; we must wonder if the FE data are at all accurate. We cannot trust that this plane truly flew within 10.5° of the TBAD boresight at all (while over 14,000 ft). Perhaps this non-commercial flight suffered inaccurate reporting. In any case, the irregularities are too numerous to conclusively demonstrate fault with TBAD. In some ways, it would be more settling to have a clear-cut failure case without all the oddities. But this is not such an event.

7.1.5 2014.01.11

TBAD closed twice for beam events, but the matching software found no FE associations. The first was an airplane squawking 2713 at 40,000 ft, closing the shutter at 01:40:59 for 34 seconds. The FE log has no traffic near this altitude around this time. The second instance is a plane squawking 7244 at 35,000 ft, closing the shutter at 02:57:42 for 19 s. This appears to be SWA1257 crossing 12.7° from boresight. Just a few minutes before, TBAD watched an airplane at 28,000 ft squawking 4324 that did not appear in the FE logs.

7.1.6 2014.01.14

At 01:07:41, the shutter was requested closed for 28 seconds, due to an airplane "in-beam" at 11,800 ft squawking 1302. Flight Explorer indicates an airplane destined for Alamogordo, descending from 18,800 to 11,200 ft. Flight Explorer shows the airplane level at 12,000 ft from 01:12:26 to 01:16:38, only dipping to 11,200 ft in the last record at 01:17:57. The implication is a ten-minute delay of the FE data. This could be another case of unreliable time delays in the FE database. In any case, TBAD saw and triggered on the airplane even if it is not clear it needed to do so based on FE.

7.1.7 2014.01.30

The shutter was requested closed four times this night, although Flight Explorer only knows about two. First, N96RX triggered the "in beam" from 17.8° away at 00:41:09. Then a VFR plane (unknown to FE) descending through 10,400 ft triggered omni (and directional) saturation resulting in a 29 s shutter closure at 01:27:48. Next, UAL1490 generated a 36 s shutter closure request at 05:04:38, passing 6.1° from the boresight. Finally, an airplane squawking '3551' flying at 32,000 ft triggered the shutter for 33 seconds at 12:16:28. No records appear in the FE log between 10:49 and 12:35.

7.1.8 2014.01.31

A VFR airplane climbing through 10,800 ft and appearing "in-beam" triggered the TBAD shutter for 15 s at 01:08:15.

7.1.9 2014.02.20

At 12:31:34, an airplane squawking '0746' at 33,000 ft entered the TBAD "beam," resulting in a 42 s shutter closure request. No records appear in the FE log between 10:35 and 13:33.

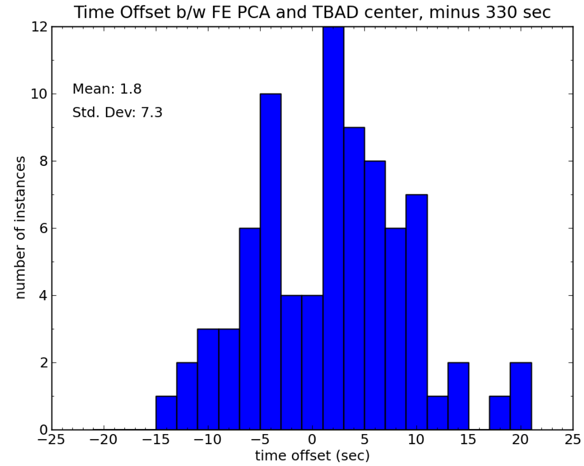


Figure 7: Variable time offsets for 81 "in-beam" TBAD events with corresponding FE data. In practice, the mean offset appears to be about 332 s, with variability confined to ±20 s, roughly.

7.1.10 2014.03.18

Early in the night (00:14:34), with the telescope at 10° elevation and 76° azimuth, a VFR plane descending through 12,500 ft twice triggered shutter closure, with a 12 s gap between events (the first closure lasted 12.5 s and the second 41.7 s). At 03:13:48, TBAD triggered an in-beam event for an airplane squawking 0573 at 32,000 ft, resulting in a 36 s shutter closure. Shortly after, at 03:14:51, another (38 s) shutter closure was requested for a beam event relating to squawk code 6211 at 34,000 ft. Finally, the shutter closed a final time at 04:37:55 for a beam event associated with squawk 2426 at 36,000 ft. The FE log was quiet from 00:39 to 04:44, which looks like missing FE data and can potentially explain the last three failed FE identifications.

7.2 Analysis Byproducts

Having identified numerous associations between TBAD and Flight Explorer, we can explore a few of the overall characteristics.

7.2.1 FE Time Delays

First, when TBAD triggers due to an "in-beam" condition, we get accurate timing information from the TBAD data. Establishing a "center" of the shutter-closure event (after accounting for the programmed 10 s hold-off at the end), we can compare this to the time of closest approach, as gleaned from the FE stream. Using a 330 s offset as the default between FE and TBAD, we can plot the residuals, as shown in Fig. 7. We see that the FE time uncertainty is relatively well confined for most cases. Although we have pointed out gross offsets in the sections detailing anomalies above (2014.01.08; 2014.01.14). It appears that when FE timestamps are bad, they can be *very* bad, and well away from the cluster shown in Fig. 7.

7.2.2 TBAD Beam Edge

Another worthwhile evaluation is the fraction of the time events passing a given angle from the boresight triggered the shutter. We have seen that the record inside 12° is nearly perfect, but we have also seen stragglers beyond this that sometimes do, sometimes don't trigger the TBAD shutter alarm. Fig. 8 displays TBAD's track record for closing the shutter as a function of angular offset. Inside 10°, TBAD catches all identified traffic. Then we see a tapering of efficacy toward larger angles. The source of variation is likely on account of variations in pulse shape sensed by the detector, since TBAD looks only at the first $\sim$ 50 ns of each pulse as a way to mitigate multipath-induced false alarms. Cases near the nominal edge (perhaps 14°) have a 50% chance of the pulse shape triggering a beam alarm, while pulse overshoots and undershoots can

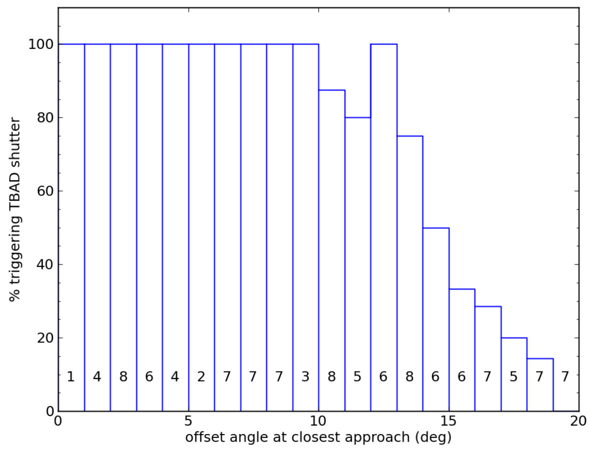


Figure 8: Fidelity of "in-beam" determination as a function of the angle of closest approach for 81 TBAD shutter events out of a total of 114 within 20°. Numbers along the bottom represent the total number of FE tracks observed in each bin.

alter performance. For instance, a transponder at 12° would ordinarily result in a beam trigger. But if the pulses detected by the directional antenna have a sluggish rise (undershoot), or the broad (omni) antenna sees an overshoot, the ratio of direc/broad—which is the basis for judgement of being in the beam—may not achieve the steady-state value within the tight 50 ns window. Conversely, a transponder 16° away might happen to produce pulses that overshoot in the directional channel and/or undershoot in the omni channel, resulting in an "in-beam" characterization that may not be accurate in the steady state (pulses are 450 ns long). Technical details aside, the main point of Fig. 8 is that TBAD performance is reliable in the central region.

7.2.3 Military Aircraft

Like VFR airplanes, military flights are not represented in the Flight Explorer data feed. Apache Point is located near Holloman Air Force Base outside of Alamogordo. We have noticed that squawk codes recorded by TBAD with no corresponding flights in the FE database tend to cluster in the range from 0260–0276. This clustering is apparent in Fig. 9. Out of a total of 216 unidentified squawk codes, 86 are in the suspected military cluster, and 37 are in the VFR spike.

One way to explore whether the suspected military cluster is a different population from the other groups is to look at the other primary piece of information provided by TBAD: altitude. Fig. 10 confirms that the suspected military planes are distributed differently from either commercial or VFR flights. While also showing an affinity for the valley floor (where the Air Force Base is located), most of the activity takes place between 20,000–25,000 ft. It is also worth noting that the military-identified codes tend to cluster temporally as well. The 86 instances noted here happened on just 22 nights. For instance, on 2014.01.09, a cluster of 12 military codes (separated by quiescent moments) were seen over the course of 65 minutes at around 23,000 ft. Another two were spotted near the end of the night, at elevation 3900 (on the ground).

Only one of these military-identified codes passed through the TBAD beam, on 2013.12.19. But the main point is that TBAD is equally sensitive to military aircraft, which are required to operate transponders over domestic airspace unless on combat missions. Flight Explorer, meanwhile, does not track these operations.

7.2.4 Multiple Simultaneous Aircraft

During the evaluation period, there were no instances of two airplanes producing shutter closure conditions simultaneously. An airplane traveling at 500 kt at 35,000 ft will spend 13 s crossing the ±12° beam when the telescope is at 80° elevation, becoming 30 s at 25° elevation. Having seen approximately 110 events (let's

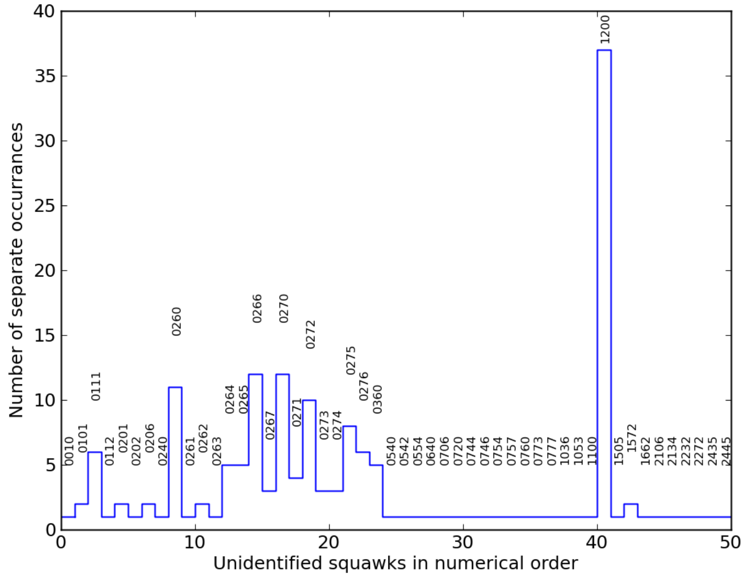


Figure 9: Squawk codes associated with TBAD detections not identified in the Flight Explorer data feed, by frequency. The plot continues to higher codes to the right, but without further structure of interest. The large spike is from VFR planes squawking '1200' by default. The suspected military cluster occupies squawk codes from 0260 to 0276.

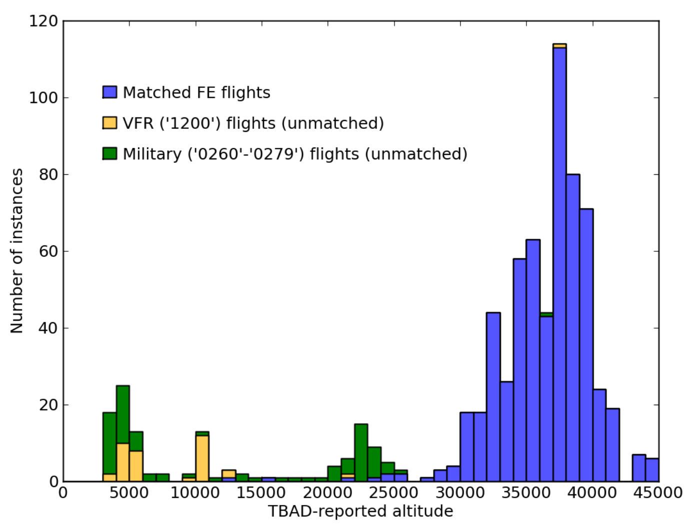


Figure 10: Histogram of altitudes by three populations: flights for which matches were found between TBAD and Flight Explorer (607 in number); VFR airplanes (37 in number), and suspected military aircraft (86 in number). VFR airplanes cluster around the valley floor and 10,000 ft—above the mountains. Identified (mostly commercial) flights are primarily found between 30,000–40,000 ft, as expected. The suspected military planes appear distinct: clustered around the valley floor and 20,000–25,000 ft.

say 20 s each) over a span of 47,028 minutes, the probability of any overlap is about 8%. And indeed, it did not happen in this trial. Two instances came close: on 2014.02.10, UAL388 and SKW6220 were separated by 65 s, and on 2014.03.18, two airplanes with no FE match/data were separated by 37 s.

Fundamentally, there is no reason why TBAD cannot respond to two or more threats at once. This is commonplace when testing in the busy skies over San Diego. In some sense, the threshold for action is lowered, since multiple airplanes contribute to the number of in-beam signals, thus reaching the minimum count for shutter action sooner.

7.3 Summary Analysis and Conclusions

TBAD tends to see and respond to events not showing up in Flight Explorer. Excluding the instances of missing FE data, we have 101 TBAD shutter events, compared to 85 that are explicable by FE data. Thus TBAD is catching airplanes not being tracked by Flight Explorer.

On the flip side, there are three instances of FE data suggesting that TBAD might be expected to trigger, when it did not. The first is on 2013.12.24 (9.5° off boresight), but this airplane was low on the horizon and very far away. The APO TBAD unit is not configured to protect this far/low. The next instance is on 2013.12.27, when SWA4209 passed within 11.8° of boresight without resulting in a shutter closure. This airplane did emit four transmissions that were characterized as "in-beam," which is four short of the current TBAD setting at APO for how many "in-beam" events are required to generate a shutter closure. Being so close to the (fuzzy) edge of the sensitive zone (Fig. 8) is perhaps reason enough to dismiss this one as no concern. Finally, on 2014.01.08, a descending airplane is reported by FE with strange jumps in the time stamps and altitudes that do not match what TBAD observed in a VFR airplane around the same time. While this is the most troubling of the TBAD "misses," it is fraught with uncertainty due to Flight Explorer irregularities.

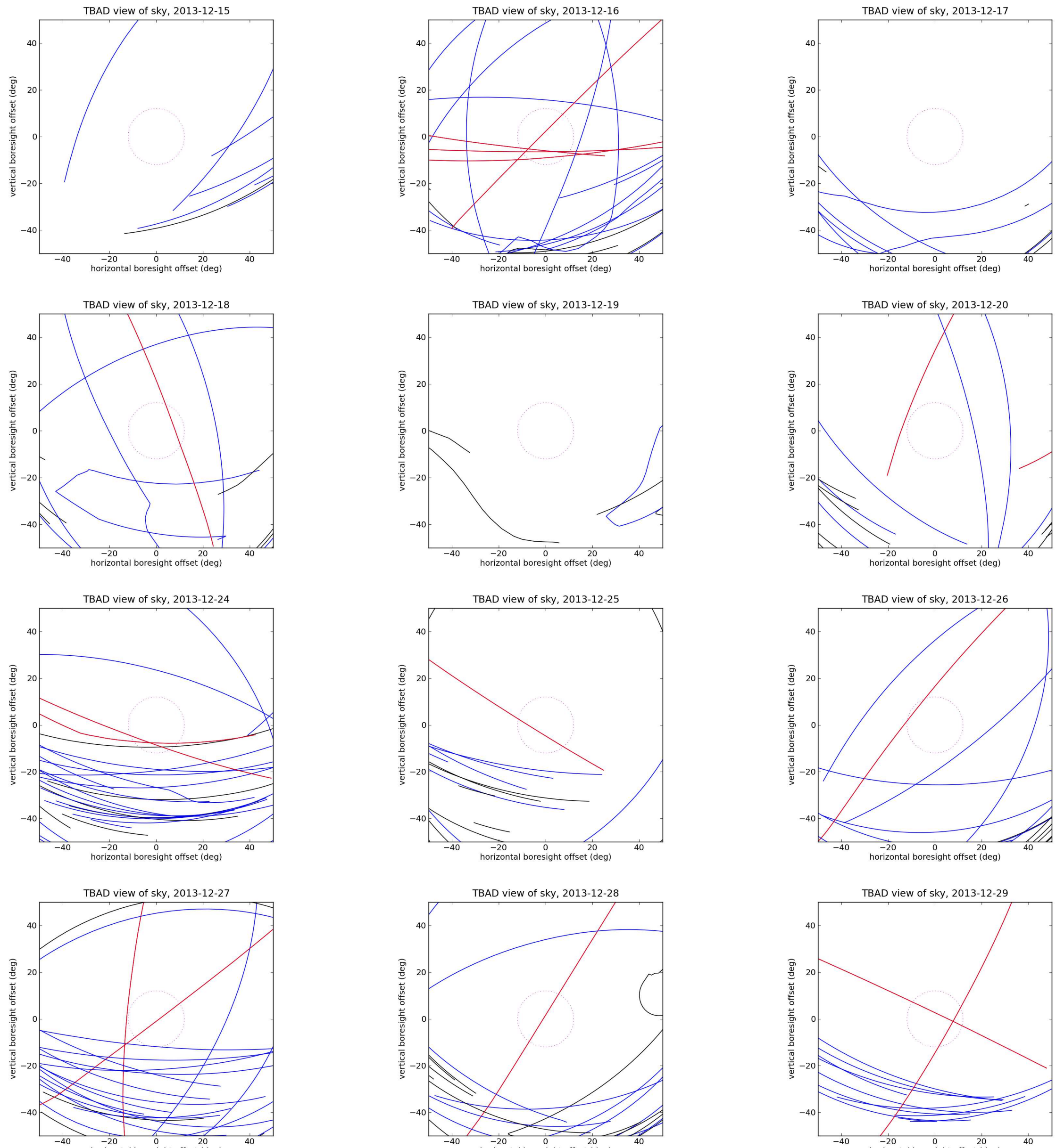
We are therefore able to say that TBAD:

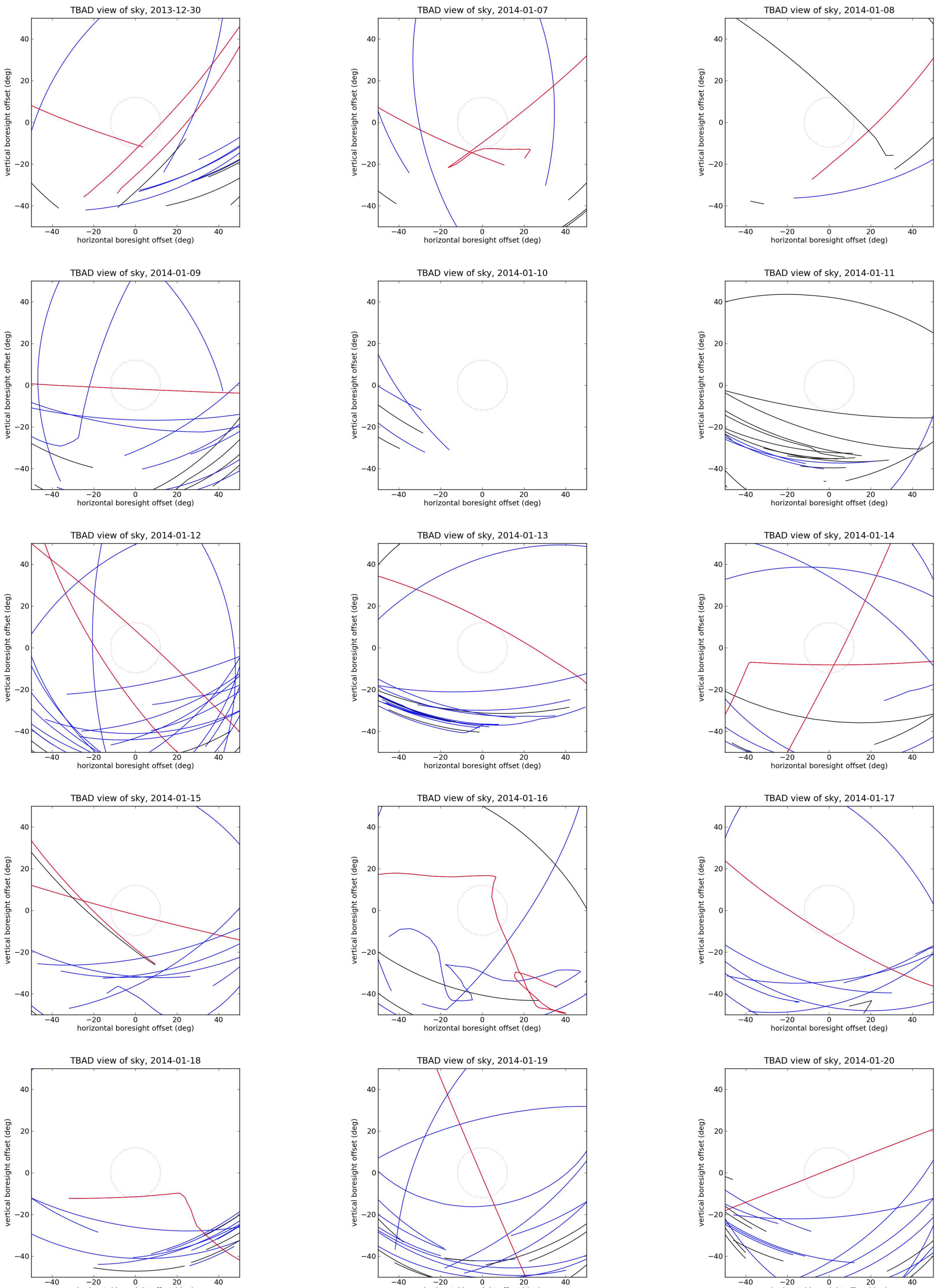
- did not miss any known commercial aircraft during normal night-time operations flying within 11.8° of boresight;
- responded to approximately 16—often lower-flying—aircraft not present in FE data;
- produced surprises only for two aircraft; one too low and distant to generate concern, and one a descending non-commercial flight whose FE data shows considerable irregularity.

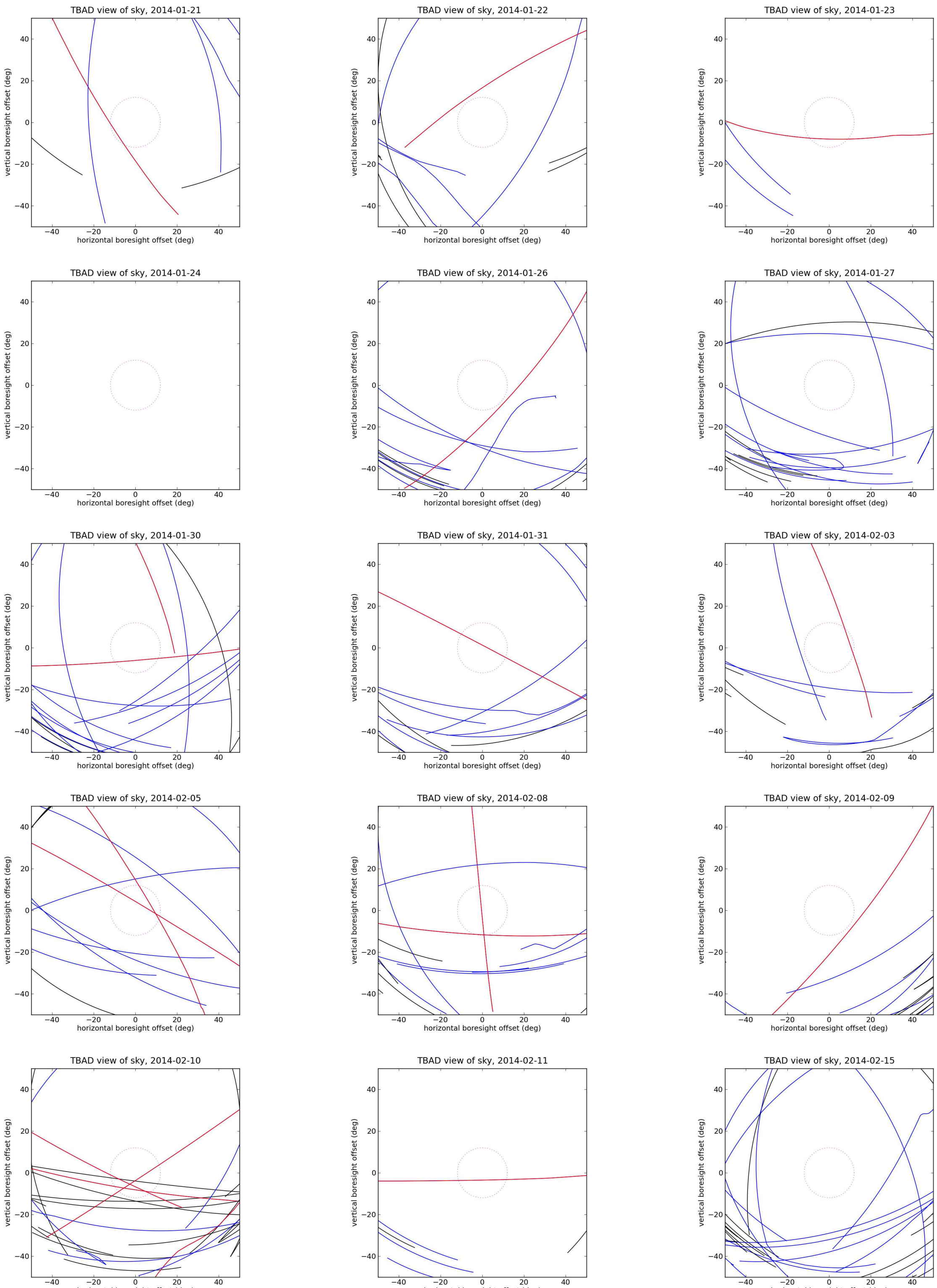
The shutter was closed for legitimate aircraft activity for a total of 3453 s. In addition to this, nuisance closures accounted for another 2400 s of shutter-closed requests. These false closures are associated with human activity in the dome at the beginning and end of some nights, or during mid-night instrument changes—likely from static discharge. Such conditions will not impact laser observations, but even so the failure is in the safe direction (shutter requested closed). Remarkably, despite discerning an average of 12 groupings of transponder activity each night, TBAD closes the shutter only 1.5 times per night, and in this record we find no instances of false alarms that correspond to known aircraft nowhere near the TBAD boresight. Thus the false-alarm record is flawless, and we have no smoking-gun indications that the unit ever failed to react to an airplane. Therefore, as far as these analyses are concerned, we have no evidence that TBAD's performance is anything but perfect.

Appendix: TBAD Sky View Plots

To help interpret the events of each night, the following collection of plots shows the TBAD sky view for all nights listed in Table 1 for which FE data exists. Conventions follow that of Fig. 2. Occasionally, black lines are seen intruding on the inner zone. In many cases, this is a result of confused software in associating FE and TBAD data. The only exceptions are on 2013.12.24 (dome closure likely culprit) and 2014.01.08 (suspect timestamps in FE log corrupted). The worst offense would be a blue (identified) line crossing through the middle, which would correspond to TBAD saying, "yes, I see you and know you're there, but don't consider you a threat." The closest we come to this is on 2013.12.27, when an identified plane passed 11.8° from boresight.




TBAD view of sky, 2013-12-30
TBAD view of sky, 2014-01-07
TBAD view of sky, 2014-01-08
TBAD view of sky, 2014-01-09
TBAD view of sky, 2014-01-10
TBAD view of sky, 2014-01-11
TBAD view of sky, 2014-01-12
TBAD view of sky, 2014-01-13
TBAD view of sky, 2014-01-14
TBAD view of sky, 2014-01-15
TBAD view of sky, 2014-01-16
TBAD view of sky, 2014-01-17
TBAD view of sky, 2014-01-18
TBAD view of sky, 2014-01-19
TBAD view of sky, 2014-01-20
vertical boresight offset (deg)
horizontal boresight offset (deg)
−40
−20
0
20
40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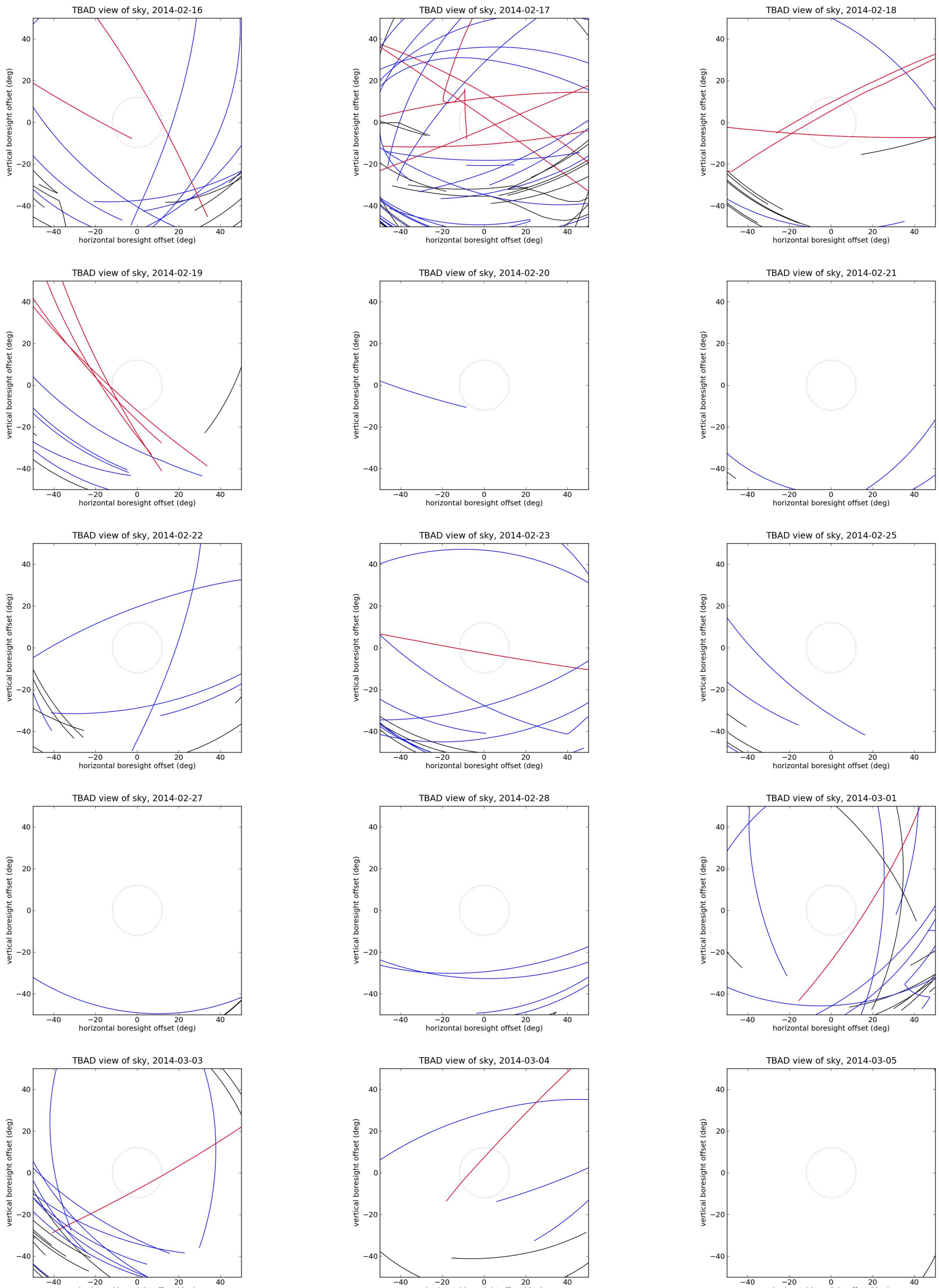
vertical boresight offset (deg)
horizontal boresight offset (deg)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TBAD view of sky, 2014-02-28
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TBAD view of sky, 2014-03-03
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vertical boresight offset (deg)
horizontal boresight offset (deg)
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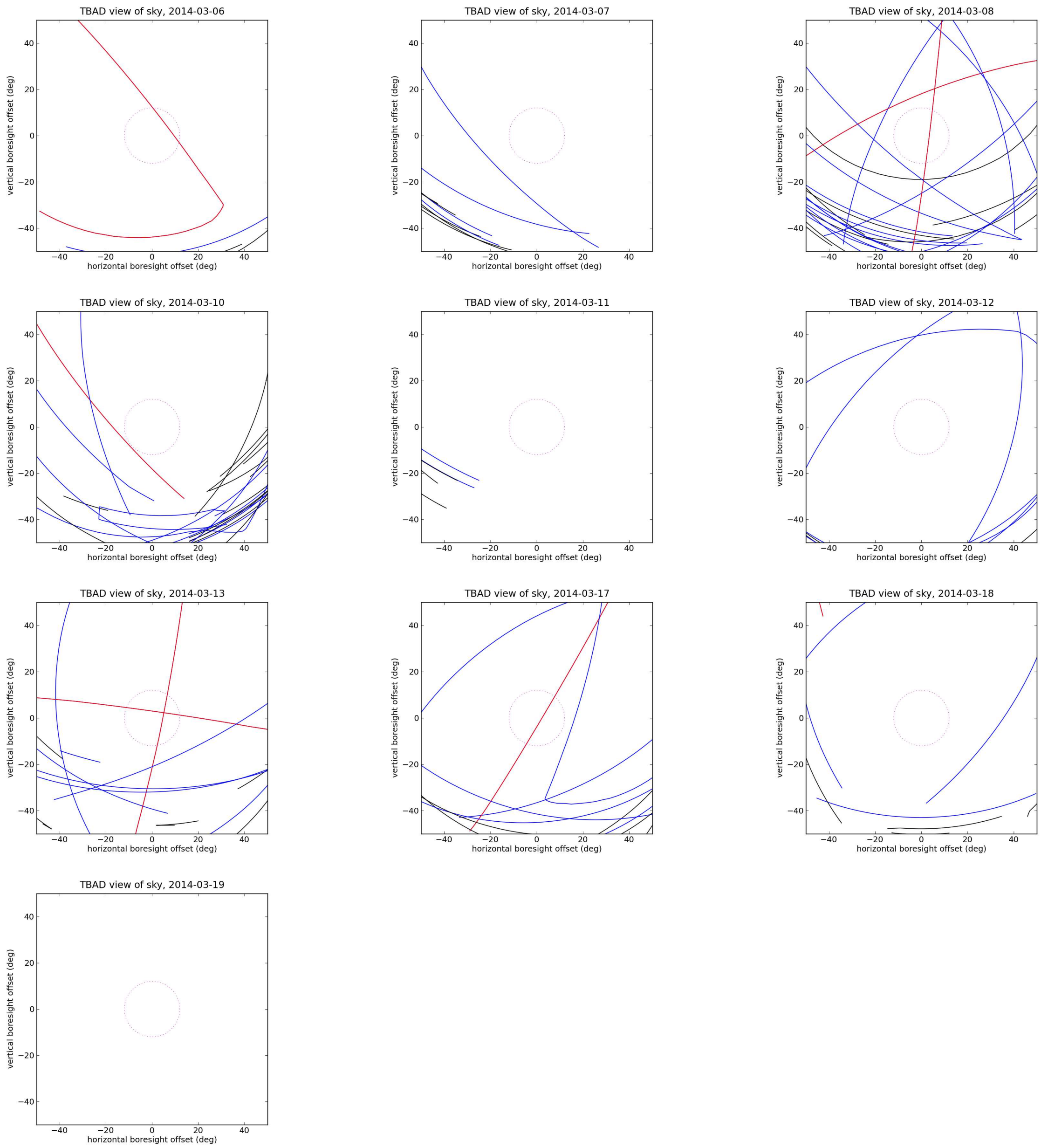
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TBAD view of sky, 2014-03-12
TBAD view of sky, 2014-03-13
TBAD view of sky, 2014-03-17
TBAD view of sky, 2014-03-18
TBAD view of sky, 2014-03-19
vertical boresight offset (deg)
horizontal boresight offset (deg)
−40
−20
0
20
40

References

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`)