Guide to TBAD Output

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Contents

1 Introduction

TBAD (the Transponder-Based Aircraft Detector) receives 1090 MHz transmissions from aircraft, and decodes the transmitted pulse patterns into data sequences, sending the result out via serial RS-232. A secondary stage (a Python program, typically) reads the serial output from TBAD and offers a layer of interpretation for more human-readable log-file output along with time stamps.

This document explores the data types and formats, and offers tips for interpretation.

2 Transmission Types

Possible signals at 1090 MHz are:

- Mode-A transmissions: up to 15 pulses in rigid format lasting 20.75 μs; represented as four octal (base-8, 3-bit, 0–7) numbers, labeled A, B, C, and D, plus three formatting bits/pulses called F1, X, and F2; 4096 possible combinations; conveys identity (squawk) code temporarily assigned by air traffic control (ATC); only distinguishable from Mode-C if no altitude mapping for particular code (see next item)

- Mode-C transmission: same pulse format as Mode-A, but encodes pressure altitude;. a Gray-code maps roughly a third (1280/4096) of the 4-digit octal codes into altitudes from -1200 ft to 126,700 ft in increments of 100 ft; indistinguishable from Mode-A except in context

- Mode-S transmissions: unique, static preamble followed by 56-bit packet including format type, data payload, and 24-bit parity; data payload may convey aircraft permanent ID, altitude, or temporarily assigned (squawk) identity for correlation to Mode-A transmissions; sometimes aircraft ID is superimposed on parity, and sometimes ground interrogator ID is superimposed on parity

- ADS-B transmissions: also called “extended squitter” carrying 112-bit packets that may include latitude, longitude, altitude, velocity, text, and other useful information; these tend to be spontaneously transmitted by aircraft roughly once per second; still rare in 2015, these signals should become ubiquitous by 2020

- DME, or distance-measuring equipment: not all DME transmissions are at 1090 MHz, but some 1090 MHz activity comes from these signals; consist of two broad, Gaussian-shaped pulses 12 μs apart; sections below will discuss TBAD’s interpretation of these events

- Static discharge and other disturbances: broadband emissions can put energy in the 1090 MHz band, but generally will not mimic aircraft temporal signatures; most common are single pulses of variable duration; many TBAD installations see elevated levels of these false signals when someone is physically present and working in the local environment, possibly creating static discharge in dry climates; sections below will discuss TBAD’s interpretation of these events

Mode-A/C/S transmissions may all be interrogated (requested) by ground stations or other aircraft as part of a traffic collision avoidance system (TCAS). The interrogator knows whether a Mode-A or Mode-C transmission was requested, so has an easier time differentiating the two. Interpretation of TBAD data must rely on other contexts to differentiate.

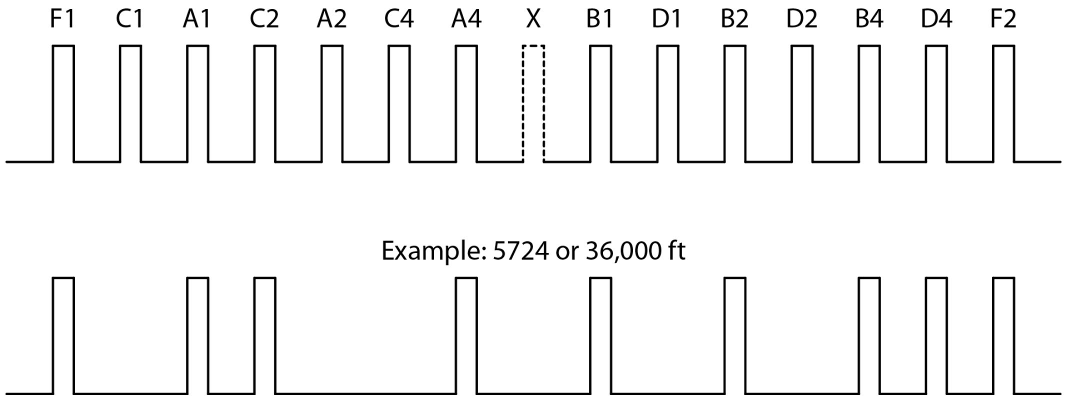

Figure 1: Mode-A/C pulse format. Pulses are 0.45 µs in duration, separated by 1.45 µs. The sequence is bracketed by framing pulses F1 and F2. The X format bit in the middle is not used in practice. The remaining 12 pulses define the 4-digit octal (ABCD) code.

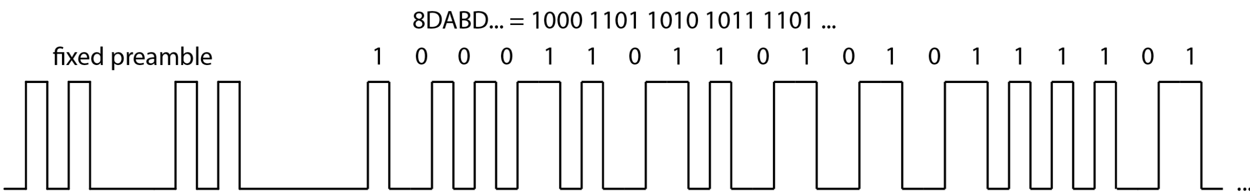

Figure 2: Mode-S and ADS-B format. This example is the first part of a DF-17 code (the first five bits equate to 17). After the preamble, transitions are guaranteed just after each data value position (indicated with ones and zeros). Sampling at the positions of the labels yields the sequence values. Pulses are always 0.5 or 1.0 µs long.

2.1 Pulse Formats

Before covering how TBAD data capture works, we'll glance at the pulse formats used by transponders. Figure 1 shows the pulse format used for Mode-A and Mode-C. The example shows what the pulse pattern would look like for Mode-A code 5724, which maps to Mode-C altitude of 36,000 ft. Figure 2 shows the beginning of a Mode-S format (actually ADS-B in this instance, but both use the same scheme).

3 TBAD's Simple Scheme

TBAD data capture is not sophisticated. It is based on a comparator sensing the radio-frequency (RF) power level relative to some threshold and generating a logic-level data stream for the microcontroller to interpret. Most of the time, no signals are present and the microcontroller waits for a leading edge of a pulse. It spends the next $\sim 6\,\mu$s evaluating the input pattern, looking for additional leading-edges (new pulses) and at one point sampling to see if the signal is high or low (above or below threshold). Figure 3 illustrates TBAD's schedule for sampling/testing the to classes of transmission formats.

If TBAD sees a pattern that matches the preamble for Mode-S and ADS-B "extended squitter"

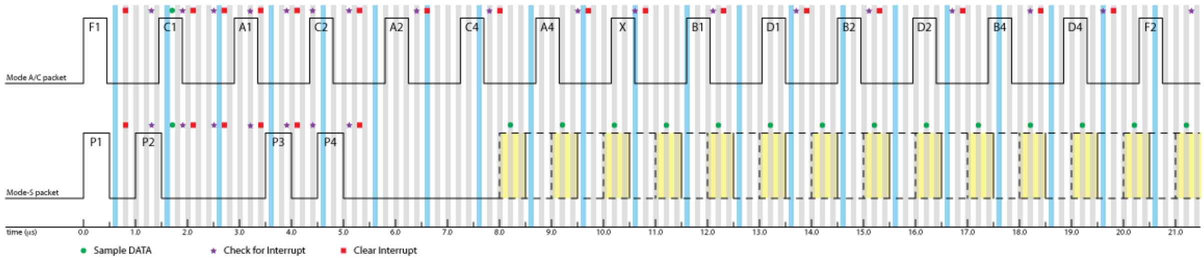

Figure 3: TBAD acquisition scheme for the two primary data types. Mode-A/C follows the top scheme, also depicted in Figure 1. Mode-S and ADS-B signals obey the second pattern, consisting of a fixed preamble followed by a data packet where solid lines are guaranteed transitions, dashed lines are possible transitions, and the level at yellow segments determines the bit value (see also Figure 2). A combination of edge-sensing (via interrupts) and sampling is used to differentiate a Mode-S preamble from Mode-A/C transmissions. Edges (interrupts) drive the remainder of Mode-A/C acquisition, while Mode-S/ADS-B relies on sampling alone. Vertical bands delineate the underlying 100 ns machine instruction period.

transmissions, it begins sampling the ensuing packet at 1.0 μs intervals. Otherwise it assumes Mode-A/C and resumes an interrupt-driven rising-edge-finding exercise to identify pulses. Some care is taken so that if a Mode-S/ADS-B signal failed the preamble check, the interrupt sampling of the data packet will fall into identifiable patterns and possibly still identify the nature of the transmission, even if not properly decoded.

One key insight: the first edge TBAD senses is associated with the first framing pulse or the start of the preamble. TBAD will call it F1 (in the Mode-A/C context) no matter what it actually is. If it's a DME pulse, the first threshold-crossing is interpreted as F1. A single static discharge pulse is interpreted as F1. **All default TBAD decodes have F1**, by construction (Mode-S/ADS-B exempt, but only a valid preamble triggers this decode path).

4 TBAD Output Teaser

Below is an example sequence obtained by the Apache Point Observatory installation of TBAD, illustrating some variety of signals. At this point, it is meant provide a visual impression and motivate further investigation.

```
2015-06-18 04:06:54.394 o7325...HF.FCC  -----          126.98  35.88 0
2015-06-18 04:06:54.403 o5724...HF.FCD  36000          126.98  35.88 0
2015-06-18 04:06:54.423 o0110...HF..A5   2300 DME      126.98  35.88 0
2015-06-18 04:06:54.430 o5724...HF.FCD  36000          126.98  35.88 0
2015-06-18 04:06:54.449 o7325...HF.FCC  -----          126.98  35.88 0
2015-06-18 04:06:54.459 o5724...HF.FCD  36000          126.98  35.88 0
2015-06-18 04:06:54.478 o7325...HF.FCC  -----          126.98  35.88 0
2015-06-18 04:06:54.503 o7325...HF.FCC  -----          126.98  35.88 0
2015-06-18 04:06:54.622 o0110...HF..A5   2300 DME      126.98  35.89 0
2015-06-18 04:06:54.675 o7325...HF.FCC  -----          126.98  35.89 0
```

```
2015-06-18 04:06:54.824 o5724...HF.FCD  36000          126.98  35.89 0
2015-06-18 04:06:54.868 o8DABD20458B981DA90A60596E7AB...HF..45 DF-17 126.98 35.89
   DF-17: PPass, ID ABD204, Alt 36000, Lat=32.78064, Lon=-105.66535   31.5/91
2015-06-18 04:06:54.884 o7325...HF.FCC  -----          126.98  35.89 0
2015-06-18 04:06:54.895 o5DABD204CA225D...HF..1A DF-11 126.98  35.89 0
   DF-11: PPass, ID ABD204
2015-06-18 04:06:54.901 o7325...HF.FCC  -----          126.98  35.89 0
2015-06-18 04:06:54.906 o5DABD204CA225F...HF..1C DF-11 126.98  35.89 0
   DF-11: PngID, ID ABD204, interrog: 000002
2015-06-18 04:06:54.914 o5724...HF.FCD  36000          126.98  35.89 0
2015-06-18 04:06:54.914 o7325...HF.FCC  -----          126.98  35.89 0
```

This document aims to build familiarity with such sequences. An "expert" quickly notes that this is likely a commercial flight at 36,000 ft using temporarily-assigned (squawk) ID of 7325. It is using a DME device, has Mode-S transmissions, and is equipped with ADS-B. The permanent airframe number is ABD204, and it is being interrogated by at least two sources: one identified as ground station 2. The latitude/longitude are broadcast in the long code, and it is currently deemed to be 31.5° from telescope boresight, to the right at position angle 91° (measured east from north). The telescope azimuth, elevation, and dome status are the last entries on the line. Now we can dig in a bit further.

5 Mode-A/C Codes

The bulk of transponder chatter at present is in the form of Mode-A and Mode-C (identity and altitude). Because they use the same pulse format and timing, TBAD and its interpretive Python logging program is unable to distinguish one from the other, in many cases. If only they had decided to use the otherwise never-used X pulse to differentiate. The only sure differentiation is if the 4-digit octal code (ABCD) does not map to an altitude. Then it is for sure a Mode-A (identity) transmission. For the 1280 possible codes (out of 4096) that *do* map to an altitude, many will not make sense in context: half of the codes map to altitudes above the 60,000 ft Class-A airspace ceiling, and even planes over 45,000 ft are rare. So only about 10% of the 4096 possible transmissions map to *reasonable* altitudes. While the ability to differentiate Mode-A from Mode-C is incomplete, it is not at all hopeless.

What follows are examples from a series of different airplane passes at Apache Point, in each case showing only one Mode-A and one Mode-C entry in the Python log. No special selection has been exercised: these are consecutive occurrences.

```
2015-07-27 09:04:46.083 o7242...HF.FCA 104700         37.14  57.72 0
2015-07-27 09:04:46.084 o5124...HF.FC7  35000         37.14  57.72 0

2015-07-27 09:10:01.249 o5224...HF.FC8  37000         30.00  80.00 0
2015-07-27 09:10:01.251 o7366...HF.FD1  84600         30.00  80.00 0

2015-07-27 09:45:25.666 o1720...HF.FC5  28000         37.61  61.60 0
2015-07-27 09:45:25.674 o0261...HF.FC4  -----         37.61  61.60 0
```

```
2015-07-27 10:48:02.496 o2610...HF.FC4  13300         -31.49  42.20 O
2015-07-27 10:48:02.513 o0264...HF.FC7  60900         -31.49  42.20 O

2015-07-27 11:01:43.265 o0266...HF.FC9  64600         -69.51  40.13 O
2015-07-27 11:01:43.270 o4730...HF.FC9   4100         -69.51  40.13 O

2015-07-28 06:31:35.460 o5124...HF.FC7  35000          59.34  55.12 O
2015-07-28 06:31:35.460 o0737...HF.FCC  -----          59.34  55.12 O

2015-07-28 06:34:32.662 o5234...HF.FC9  37100          23.02  55.38 O
2015-07-28 06:34:32.662 o1303...HF.FC2  -----          23.02  55.38 O
```

The format of each line is: date, time (UTC), TBAD serial code (verbatim), altitude translation, comment (blank for all above), telescope azimuth ($180 - az_{\mathrm{conv}}$ for APO), telescope elevation angle, dome status (O means open).

Of the seven examples above, three display clear differentiation between Mode-A and Mode-C, as indicated by the altitude translation field lacking a numerical code. The other groups have two numbers in each altitude field, but only one is feasible in each case. Do the alternate numbers make contextual sense? In this case, yes. Airliners (first two and last two) tend to cruise between 32,000 ft and 40,000 ft. Also, they tend to be on the thousand, as three of these are—the fourth being 100 ft off (not that unusual).

The three events in the middle are military operations from Holloman Air Force Base, which characteristically use squawk IDs around 0250–0270, perform operations between 25,000–30,000 ft, and start from the base on the valley floor around 4,000 ft. Note that the Apache Point telescope uses an unusual azimuth convention, $180 - azim_{\mathrm{conventional}}$, so that the instance seeing the airplane on the valley floor did indeed have the telescope pointing toward the west, where the valley lies.

Two cases of normal Mode-A reports trigger the Python program to fill in the optional comment field, missing in all instances above.

```
2015-07-27 09:52:25.766 o1200...HF.FBE  ----- VFR      14.83  62.10 O
2015-07-02 11:34:19.063 s0000...HF.FBF  ----- zeros    104.00  20.02 O
```

Airplanes following visual flight rules (VFR)—often not in contact with ATC—are requested to use the reserved code 1200 to signal their status. Sometimes, military airplanes transmit just zeros (0000). A glitch (Sec. 6.4), or single pulse, also implicitly has zeros for the data fields, but will not have the final framing pulse, F2, present (both framing pulses and lack of the X-bit are seen here as the 'F.F' pattern in the TBAD serial transmission, as covered below).

5.1 Data Format and Flags

Study the format of the TBAD serial transmissions in the examples above. The first character is shutter status ('o' for open, 's' for shut), followed by the four-digit ABCD code (payload). The next three fields may be occupied by 'O', 'D', or 'B', respectively if that particular transmission achieved OS (omni saturation), DS (directional saturation), or BT (in beam) conditions—populated with periods otherwise. These are closure-inducing conditions and are so-flagged in the TBAD data. Example combinations:

`...` no closure-inducing conditions

`O..` "omni" antenna saturation (OS): just one will close shutter

`.D.` directional antenna saturation (DS): just one will close shutter

`..B` deemed to be in the $\sim 15^\circ$ half-angle protected zone; shutter closes after pre-set number

`.DB` saturating directional, but also in the protected zone

`ODB` all at once!

The next letter indicates how many beam events are required for shutter closure, and upper case also indicates nominal power and current draw. The next three fields indicate the presence or absence (`'.'`) of the first framing pulse (F1), the X-bit, and the final framing pulse (F2)—see Figure. 1. Valid Mode-A/C transmissions will show `F.F`. The last two characters are a hexadecimal checksum (simple sum) of all ASCII characters up to that point in the transmission.

All of the examples in Section 5 are free of closure flags, all have valid `F.F` formatting, and all but one happened while the shutter was open.

6 Compromised Codes

When signals are strong and free from interference, the decoding scheme works very robustly, and depending on air traffic density in the area, this can mean virtually all transmissions. However, some things happen beyond TBAD's control, and are worth understanding.

6.1 DME

This is not a compromised code, per se, but it is a good first example of how TBAD casts most signals into a Mode-A/C context even if that is not the true nature of the signal. The first of the two DME pulses rises above the detection threshold and sets TBAD in motion, associating that edge with the first framing pulse, F1. In looking for a possible preamble, TBAD makes one sample (as opposed to edge-sense) 1.6 μs after the initial edge detection. For the several-microsecond-wide DME pulses, the signal will generally still be high and as a result this bit will usually be set—interpreted as C1 (thus $C = 1$). About 12 μs after the initial pulse edge, the second edge is sensed, which usually will fall into B1, but sometimes D1. Thus the DME code will usually look like 0110, but sometimes 0011. The Python program flags these two codes as DME.

6.2 Weak Signal

Airplanes come and go. They start far (weak), get close (strong), and then "go dark" again. TBAD is threshold-based, so airplanes on the edge of the sensitivity limit may display erratic signal behavior. In an isolated environment with little air traffic, the resulting pattern of odd transmissions is easy to identify on the leading and trailing edges of a pass. Some pulses will be missing. If the first framing pulse (F1) is sub-threshold, it will be mis-identified and the final framing pulse

(F2) will not be there. Moreover, the chances of an X-bit/pulse showing up (never present in legitimate Mode-A/C transmissions) increase if the framing is off. Any transmission either having an X-bit/pulse or missing the F2 is flagged by the Python program as ODD.

If F1 and F2 are intact (register above threshold), then the signal will not be flagged as ODD, but may have non-sensical data fields, missing bits here and there. Often it is possible, once you know what the ultimate code becomes, to identify the poor cousins missing some teeth. For instance, if a code were meant to be 3742, a single missing tooth could look like 1742, 2742, 3342, 3542, 3642, 3702, or 3740. There are naturally even more combinations with two missing bits. Some of these will translate to altitudes, often patently absurd.

Weak DME signals may miss the C1 bit sample and thus look like 0100 or 0001.

6.3 Signal Collisions

One of the main purposes of the transponder system (or "secondary radar") is to prevent collisions of airplanes. But no one is terribly concerned about collisions of transmissions, and it happens all the time. And it's not so easy to control, as it depends on geometry. The Mode-A/C transmissions last about 21 μs, which corresponds to about 6 km or 4 mi in light travel. Let's imagine a scenario of two airplanes slightly farther apart than this along a north-south line emitting signals at the same time. Observers situated to the east/west will experience signal collision, while observers to the north or south of both aircraft will find signals that are free of each other.

In busy skies, signal collisions are common. It will be slightly worse for the longer Mode-S/ADS-B packets, since their temporal exposure is greater. TBAD can easily produce a nonsense decode result. The likelihood for the otherwise unused X-bit increases, so some will have an obvious flag (ODD in Python interpreting program). The only other identifiable characteristic will be a tendency to have more bits set, so that 7, 6, 5, 3 are more likely.

Fortunately, the constantly changing geometry between interrogator, aircraft, and TBAD means that signal collision scenarios are short-lived.

6.4 Extraneous Signals

TBAD can respond to non-aircraft signals at 1090 MHz. At its core, it's just reporting threshold-crossing transmissions at this frequency. TBAD reacts differently depending on the nature of the signal.

Short, single pulses are called "glitches" by the Python program, and are characterized by only the F1 pulse and nothing else (0000, no X, no F2). Unless some closure condition (Beam, Saturation) is associated with the glitch, TBAD does not bother reporting it, in order to avoid clogging the serial transmission bandwidth and fill up the Python log file. If a closure condition is present/reported, TBAD will create a serial transmission, which the Python program will log and report as a glitch based on its (complete lack of) data content.

Single pulses longer than $\sim 1.5\,\mu$s will also trip the C1 sample and will show F1 and 0010 and nothing else. These are flagged as "pulse" by the Python program.

Double pulses, where the second pulse happens within $\sim 20\,\mu$s of the first are sometimes seen and believed to be spurious (no F2). Rev 6 of TBAD has a dipswitch to be able to ignore such "single-bit" transmissions, even if tripping a saturation or beam condition.

It should also be mentioned in this context that if TBAD is inundated with some external transmission such that the average signal level creates a high background, TBAD will detect this situation and establish a closure condition. This is via the "DC" threshold and a duty-cycle setting on TBAD. A warning message is issued in these situations, so that the nature of the condition is understood.

7 Mode-S and ADS-B

For TBAD units equipped to decode Mode-S and ADS-B signals, the results can be rich and interesting. The TBAD serial transmission is the same as in the default (Mode-A/C) case, except that instead of four octal numbers ABCD, Mode-S transmissions contain 14 hexadecimal digits (0–9, A–F) and ADS-B transmissions contain 28 hex digits. All other fields carry the same meaning. There will never be an X-bit or F2 in these codes, since TBAD knows from the preamble not to use that context.

We will examine a particular flight on 2015.06.18 seen from Apache Point; selected for its nearly perfect passage through the telescope boresight. We will just highlight unique codes that tell us something new. Other flights will complete the sampling after.

This flight was first sensed by TBAD at 04:06:39 via DME, by Mode-A/C at 4:06:47, and the fist ADS-B transmission came less than one second later:

```
2015-06-18 04:06:48.018 o8DABD20499453928C80855CBF5DE...HF..43 DF-17 126.99 35.86
   DF-17: PPass, ID ABD204, vel 451; hdg 316; vrate -64; dh=500
```

This is a long (112-bit) code, of data format (DF) 17. The first line is the same format as for Mode-A/C, except that the code is rather longer, the comment is DF-17, and the dome status has been chopped off to fit on this page. The following line is inserted by the Python program for direct/easy interpretation. The parity checks out (`PPass`), and the permanent aircraft ID—which can be looked up at `airframes.org`—is ABD204 (visible in clear text in transmission). This maps to tail number N8606C, a Boeing 737 operated by Southwest Airlines. It was traveling at a velocity of 451 knots at heading 316. The vertical rate is a slight descent at 64 feet per minute. The difference between pressure and geodetic altitude is 500 feet.

Next we get a different DF-17 payload containing aircraft position:

```
2015-06-18 04:06:53.868 o8DABD20458B9857D0F3C69C7A7CE...HF..61 DF-17 126.98 35.88
   DF-17: PPass, ID ABD204, Alt 36000, Lat=32.77906, Lon=-105.66376
```

Here we get the same aircraft ID, altitude 36,000 ft (matches Mode-C info), and the real prize: latitude and longitude. Based on the location of Apache Point, and the telescope pointing at the time (northeast; azimuth 53.02), we can calculate the airplane to be 32 degrees from the boresight at a position angle (east from north) of 91 degrees—meaning it's directly off to the right. The heading suggests it would be seen moving to the left, getting closer to boresight.

After a few more DF-17 codes (alternating heading and position), we get this new one (Mode-S DF-11):

```
2015-06-18 04:06:54.906 o5DABD204CA225F...HF..1C DF-11 126.98  35.89 0
   DF-11: PngID, ID ABD204, interrog: 000002
```

This is an "all-call reply." The airframe ID is in the clear. The parity did not pass outright, but left 000002. When only the last character of the parity residual is non-zero, this signifies an overlay of the ground interrogator's ID code. Sometimes, the parity passes, looking like this (probably air-initiated request):

```
2015-06-18 04:06:54.895 o5DABD204CA225D...HF..1A DF-11 126.98  35.89 0
   DF-11: PPass, ID ABD204
```

Now we get a reply to an altitude request (Mode-S; DF-04):

```
2015-06-18 04:07:02.404 o20001718E1DC6F...HF..EF DF-04 126.97  35.91 0
   DF-04: Par. left ABD204, Alt 36000
```

This gives us confirmation of the altitude. The parity check left a hefty residual, but look—it's the airframe ID again. This is a frequent ploy.

One of the possible DF-17 sub-formats includes a text field, which often contains flight number:

```
2015-06-18 04:07:12.627 o8DABD20420CF9CE0820820196FBF...HF..3A DF-17 126.96  35.93
   DF-17: PPass, ID ABD204, category 0, text=393
```

In this case, the text is just "393" as opposed to a more typical "SWA393". Nonetheless, we know this is an airplane operated by Southwest, and looking up flight 393, prior to August 2015 it went from Austin, TX to Oakland, CA, leaving Austin around 20:30 CDT and arriving in Oakland around 22:00 PDT. The pass, around 22:07 MDT is appropriate. The FlightAware site shows the track often flying to the south of the observatory, turning north at El Paso, but some nights it diverts north and flies just north of Apache Point on a heading consistent with 316 degrees.

The next new type is Mode-S DF-00, which is a reply to an air-to-air altitude request (TCAS):

```
2015-06-18 04:07:54.804 s02E617183F39C6...HF..F3 DF-00 126.93  36.06 0
   DF-00: Par. left ABD204, Alt 36000
```

Much like DF-04, this communicates altitude and overlays aircraft ID on parity.

The ADS-B information (particularly the DF-17 location reports) allows a useful check of TBAD's in-beam reporting. This particular aircraft pass was first seen (in Mode-A/C) at 04:06:47, and the first position report was at 4:06:53, indicating 32° to the right. It progressively worked its way closer to boresight, generating 14 position reports before tripping the "in-beam" condition at 4:07:16 at 14.6° off-axis directly to the right. It proceeded to generate 31 consecutive in-beam position events, ending at 4:07:47 at 14.4°on left side of beam. Following this were 14 out-of-beam position reports, ending at an offset angle of 29.4°. The closest position report puts the airplane 0.2° at 4:07:32. Note the striking degree of symmetry in the behavior.

Now looking at some other airplane passes to fill out the signal types, we occasionally see Mode-S DF-05 codes conveying the transponder Mode-A identity (squawk) assignment:

```
2015-07-04 10:34:55.952 o2800152E50C293...HF..D0 DF-05 340.88  69.00 0
   DF-05: Par. left A7CC2C, Squawk ID = 0772
2015-07-04 10:34:55.957 o0772...HF.FCB  -----         340.88  69.00 0
```

The parity is overlaid with aircraft ID. Immediately following was a Mode-A transmission verifying the ID code the aircraft was using. This can be handy to unambiguously identify which aircraft is which in cases where multiple airplanes are being reported by TBAD at the same time. If only it were more frequently used. There is one other mechanism that sometimes conveys squawk ID: ADS-B DF-21:

```
2015-06-18 04:37:53.013 oA800022B10011C008400007389E6...HF..AA DF-21 125.85  41.14
   DF-21: Par. left ACC26E, Squawk ID = 2704, text=?Q0?????
2015-06-18 04:37:53.037 o2704...HF.FC8  -----         125.85  41.14 0
```

We have again placed a following Mode-A report for verification.

8 Other TBAD Codes

When TBAD has not received any new events in the last minute, it issues a keep alive:

```
2015-06-18 04:06:01.070 i0000...H...85  ----- alive    127.02  35.74 0
```

The "shutter" field is just the character "i" meaning "informational." Implicitly, the shutter is always open when the keep-alive signal is issued. After a shutter closure event, TBAD opens the shutter once ten seconds has passed with no closure-inducing instances, creating the following log entry:

```
2015-06-18 04:07:59.776 o8888...H...AB  ----- OPEN     126.93  36.07 0
```

The eights in the 'o8888' pattern are not possible in the normal octal ABCD code. Essentially never seen in operation, TBAD also has some warning codes that it will issue once per second when something is wrong. The code 's9999' indicates a problem with the current measurement: perhaps a disconnected cable or a failed component. 's9998' indicates a high signal background possibly alerting to unwanted RF interference in the environment (compromising TBAD's ability to cleanly detect aircraft).

The only other type of code worth pointing out is that the separate TSIM module imitates aircraft Mode-A/C transmissions except that it deliberately omits the F2 pulse and always inserts the X pulse so that it deliberately looks flawed and will not be mistaken for an actual aircraft. Also, the A2 bit is never used (so A must be in [0, 1, 4, 5], while the D1 bit is always on [1, 3, 5, 7]. This prevents TSIM from issuing the VFR code or a number of emergency codes having A=7. The Python interpreting software recognizes this combination as a TSIM pattern. Note, however, that corrupted signals may conspire to match the TSIM pattern. Just because the Python program flags a strange, sporadic signal as TSIM-like, does not mean that TSIM was literally the source. On the other hand, when using TSIM, the signals should be consistently flagged as such for easy recognition.

9 Interpreting TBAD Behavior

TBAD can generate a large amount of data quickly during an airplane pass. Depending on the environment, one may see a few hundred events per second recorded in the log. How does one sift through the data to determine if TBAD is working properly? It can be a bit of an art, but programs can also be constructed without too much effort to do some automatic basic analysis.

The biggest asset when manually examining a file is a text search, and especially one that allows regular expression syntax (like `vi`, `vim`, `less`, `more` on UNIX/Linux/Mac systems). Likewise, the UNIX/Linux/Mac tool `grep` is an amazingly quick and powerful way to look for certain (especially rare) behaviors. Coupled with `wc` (word count), one can quickly assess the number of instances of certain events. These techniques will be demonstrated in what follows, but much of the same could be accomplished by manual inspection/searching and/or a customized program to comb through the file and make a summary.

One may look for failures, like so:

```
grep 9999 150617_xp.log | wc
       0       0       0
grep 9998 150617_xp.log | wc
       0       0       0
grep hF 150617_xp.log | wc
       0       0       0
```

This says there are no lines (tallying number of associated [lines words characters]) containing TBAD error conditions. The last line checks for a lower case rendering of the combined power-good/knob-setting field. To be more general, search for any lower case preceding a capital `F`: `grep [a-z]F`; in this case the knob was on the 'H' setting for the duration of the log file.

Now for a tally of normal activities:

```
wc 150617_xp.log
    17701  127017 1229893
grep 8888 150617_xp.log | wc
       5      39     354
grep alive 150617_xp.log | wc
     162    1296   11497
grep HF 150617_xp.log | wc
   16588  119495 1174722
```

So far we see that the entire file has 17,701 lines. The shutter opens from a closed state 5 times (once at the beginning of the night after power-up). There are 162 quiet minutes with no air traffic (keep-alives). There are 16,588 lines with HF, which all healthy TBAD signal codes should possess (when the front panel knob is set to 8, therefore the `H` character; other knob positions will produce other characters). Almost all of the non-HF lines are either keep-alives (162) or Mode-S/ADS-B interpretive lines (831) interspersed in the log file. Let's now look at how many lines indicate an open shutter, how many indicate closed-shutter, and how many in-beam, omni-saturation, and directional-saturation events we have:

```
grep "[0-9] o" 150617_xp.log | wc
   11344   81476  800564
grep "[0-9] s" 150617_xp.log | wc
    5248   38051  374442
grep BHF 150617_xp.log | wc
    2947   20635  210581
grep "O..HF" 150617_xp.log | wc
       0       0       0
grep ".D.HF" 150617_xp.log | wc
       0       0       0
```

Note that the "." character in the grep argument is a wild-card, matching any character, and not a literal period. Also, terms within brackets allow any single character in the range indicated. The majority of lines have the shutter open (non-threatening traffic). There are about 3,000 in-beam transmissions, but no saturation events all night. Let's now look at Mode-S/ADS-B activity:

```
grep "[0-9A-F] DF-" 150617_xp.log | wc
     831    5817   61852
grep "[0-9A-F] DF-17" 150617_xp.log | wc
     212    1484   18020
grep "[0-9A-F] DF-11" 150617_xp.log | wc
     273    1911   19286
grep "[0-9A-F] DF-00" 150617_xp.log | wc
     222    1554   15686
grep "[0-9A-F] DF-04" 150617_xp.log | wc
     104     728    7366
```

We see a total of 831 such transmissions this night, 98% of which are accounted by DF-11, DF-00, DF-17, and DF-04 codes.

Other things to look for are that the shutter closes ('o' goes to 's') after the appropriate number of in-beam events according to the front panel knob on TBAD. An example follows:

```
2015-06-18 04:07:15.177 o7325...HF.FCC  -----          126.96  35.95 0
2015-06-18 04:07:15.184 o5724...HF.FCD  36000          126.96  35.95 0
2015-06-18 04:07:15.184 o7325...HF.FCC  -----          126.96  35.95 0
2015-06-18 04:07:15.289 o0010...HF..A4   -800 pulse?   126.96  35.95 0
2015-06-18 04:07:15.553 o0010...HF..A4   -800 pulse?   126.96  35.95 0
2015-06-18 04:07:15.685 o5724..BHF.FE1  36000          126.96  35.95 0
2015-06-18 04:07:15.781 o7325..BHF.FE0  -----          126.96  35.95 0
2015-06-18 04:07:15.792 o5724..BHF.FE1  36000          126.96  35.95 0
2015-06-18 04:07:15.793 o7325..BHF.FE0  -----          126.96  35.95 0
2015-06-18 04:07:15.798 o5724..BHF.FE1  36000          126.96  35.95 0
2015-06-18 04:07:15.804 o7325..BHF.FE0  -----          126.96  35.95 0
2015-06-18 04:07:15.810 o5724..BHF.FE1  36000          126.96  35.95 0
2015-06-18 04:07:15.819 s7325..BHF.FE4  -----          126.96  35.95 0
2015-06-18 04:07:15.819 s0010...HF..A8   -800 pulse?   126.96  35.95 0
2015-06-18 04:07:15.824 s5724..BHF.FE5  36000          126.96  35.95 0
```

We see the first lines are not in-beam event (no `B` before `HF`). Then the beam events set in, and the shutter closes on the eighth such event, as is expected for the knob setting. Note that this particular TBAD is configured with the lookback jumper in place, so that slowly-rising pulses (DME pulses being among these) fail to trigger the in-beam condition.

10 Log File Comments

Most of the following material has already been covered, but this section serves as a handy guide for interpreting the Python output log. Rather than alphabetical, the order mirrors the decision tree in the Python program.

VFR	code 1200: used for visual flight rules air traffic
glitch	code 0000, but no X or F2, so single edge interpreted as F1
zeros	code 0000, no X, but F2 present: often military use this code
alive	code 0000, no F1, X, or F2; only happens for keep-alive (no RF signal at all)
pulse?	code 0010, no X, no F2: single transition longer than 1.5 μs so C1 sample hits
DME	code in [0110, 0011], no X, no F2
ModeS	code not 0000 or DME, in [4737, 4637, 4537]: may have missed preamble
TSIM	A2=0; D1=1; X present, no F2
OPEN	code 8888: shutter moves from closed state to open
CLOSE	code 9999: shutter held closed due to TBAD fault (cable disconnect or current wrong)
BAKGRND	code 9998: background saturation condition causes shutter closure
ODD	does not satisfy previous list, or else '`F.F`' (F1, no X, F2) not present
DF-xx	in case Mode-S/ADS-B preamble tripped, indicates data format of packet (xx=0–31)

Table 1 shows TBAD statistics for several recent nights at Apache Point. Most nights (log files spanning 24 hours) were picked because of higher-than usual activity—in order to provide more complete statistics. The 150617 log file contains the events from UTC 2015-06-18 highlighted above. The 150724 log file has a low event count, but stands out in other ways because this is a night when TSIM was tested (producing more OPEN and saturation events). Later that night, the telescope dome was open for a partial night, during which there were four detected aircraft (no closure events).

Table 1: Instance (line) counts for TBAD nights at Apache Point

pattern	150603	150617	150627	150724	150803	150804	150806
all events	50913	16588	48299	4337	54491	28315	21888
VFR	0	1	12325	0	0	97	173
glitch	1	0	1	1	0	1	0
zeros	37	1	5	0	730	2	1
alive	427	162	387	181	344	487	512
pulse	185	1549	2995	37	1516	105	159
DME	427	1319	2393	63	488	18050	536
ModeS	1	0	1	1	1	0	0
TSIM	46	9	61	189	121	4	2
OPEN	5	5	3	13	3	1	2
CLOSE	0	0	0	0	0	0	0
BAKGRND	0	0	0	0	0	0	0
ODD	1176	500	1297	71	933	739	393
DF-xx	485	831	1778	305	148	264	591
beam	677	2947	901	193	345	1	944
omni sat	3	0	1	17	0	0	0
direc sat	0	0	0	36	0	0	0

11 Faults and Fault Recovery

As described in Section 8, in the absence of fault or signal activity, TBAD issues a keep-alive (’`i0000`’) once per minute. A monitor can therefore confirm TBAD to be healthy and operational on minute timescales. Depending on whether a shutter-closed condition stemming from detected aircraft is considered to be a “fault,” recovery from this condition is automatic: TBAD will release the shutter after ten seconds have transpired with no new shutter-closing conditions being met. Note that this recovery time is a *minimum*. If TBAD is receiving in-beam events very rapidly and then this condition stops abruptly, it may take ten seconds for the number of in-beam events in the last ten seconds to clear (during which time an “active” closure condition is still present), plus an *additional* ten seconds of clear-condition-status before the shutter releases. Moreover, if TBAD is receiving signals at a high rate (over 100 per second, for instance), the serial transmissions can actually bog down the internal counter that marks time. The result is a time-stretching. This stretching is on the side of safety: it takes fewer events per *actual* 10 s to trigger a closure, and the shutter is held closed longer.

There are a few faults for which recovery is not automatic. These may come in three generic flavors, two of which are easily detectable and close the shutter until the fault is addressed.

First, if either the current flowing to the discriminator from the decoder is out of bounds, *or* the signal cable is interrupted, TBAD will close the shutter and issue a ’`s9999`’ code once per second. Also, the field in the serial transmission indicating the knob position for number of events per 10 s (Sec. 5.1) will change to lower case. The condition will persist until the cause of the fault is remedied. This could be a disconnected external cable (signal and power share the same physical cable), a severed or partially severed external cable, an unseated connector within the discriminator or decoder boxes at the circuit board, or a component fault on either circuit board either impacting the current drawn by the discriminator or the signal as conditioned by the line drivers/receivers. Having a spare circuit board is a quick way to isolate the problem, should it occur.

The second "caught" problem is high RF background. If the antenna array average RF input to the discriminator exceeds the 'DC' threshold setting on TBAD, a 's9998' signal will be sent once per second, and the directional saturation ('DS') flag will be set. The shutter will remain closed until the condition is remedied. The first action is to check the 'DC' threshold on the discriminator, and also the DIREC output level (expect about 1.8 V and 2.0 V, respectively). The measured RF level on the DIREC output should be greater than the DC threshold setting for a "low background" condition. The next action may be to disconnect the RF input (array/direc) into the discriminator to ascertain whether it is truly an airborne RF transmission causing the problem. If it is discovered that a new and unusual background does exist, effort should be made to identify the source. TBAD will not allow itself to function as long as the DIREC signal spends significant time "lower" (stronger) than the DC threshold setting. While one *could* simply adjust the DC threshold to circumvent the problem, this is not the ideal choice.

One fault that is not automatically caught is a disconnected or otherwise malfunctioning antenna. Very little can go wrong with the robust patches and passive summing/splitting components, so the fault is more likely in connections. An SMA torque wrench is provided with each TBAD unit so that proper connections may be made and maintained without breaking the semi-fragile patch–SMA solder joints. The chief means of detecting problems in the antenna connection is via signals from TSIM and/or aircraft. TSIM offers a means of establishing a baseline (signal strength and beam pattern) that may be used to validate performance expectations on a periodic schedule.