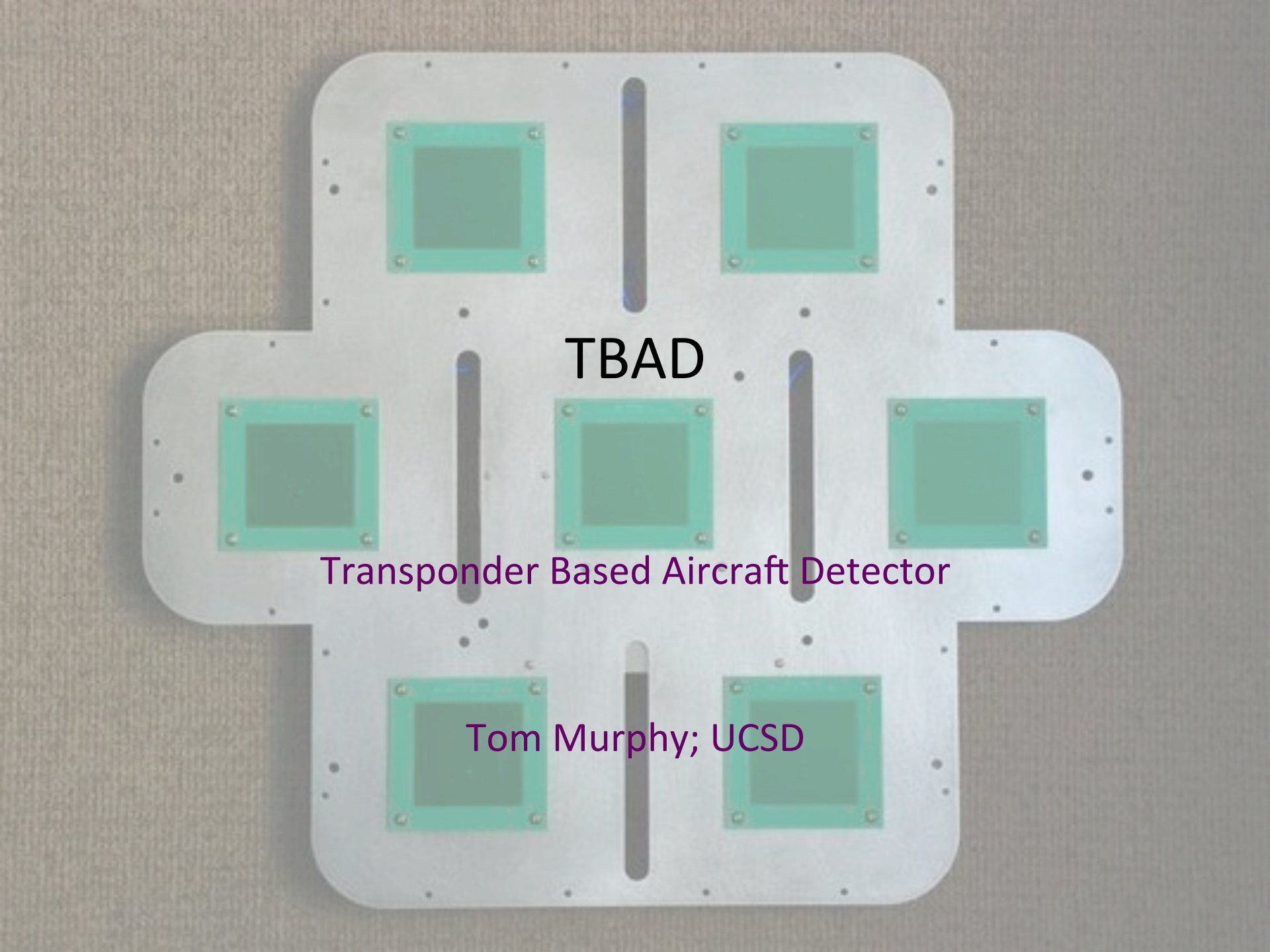


TBAD

Transponder Based Aircraft Detector

Tom Murphy; UCSD

The Problem

- Applications involving propagating lasers into the sky…
  - SLR, LLR, laser guide star adaptive optics, LIDAR
- …require some means to protect against accidental illumination of aircraft

Old School Solution

- Aircraft Spotters watch the sky and activate a "kill switch" if an airplane approaches the laser beam
  - "kill" here applies to the laser—not the plane

Spotty Results

- Spotters are hard to find/schedule in remote locations
- No-shows can disrupt science observations
- Acuity suffers in windy, cold conditions
  - bleary eyes (blurry + teary)
- Attention wanders (it's *very* boring)
- Sustained financial burn rate
  - not just for spotters, but scheduling, training, misc. admin.

Active Radar Option

- Many observatories do not tolerate high-power RF generation near sensitive instruments
- Radar difficulties include:
  - decreased sensitivity to distant aircraft
  - validation
  - rain?, terrain?

A Technology Solution: $1/r^2$, not $1/r^4$

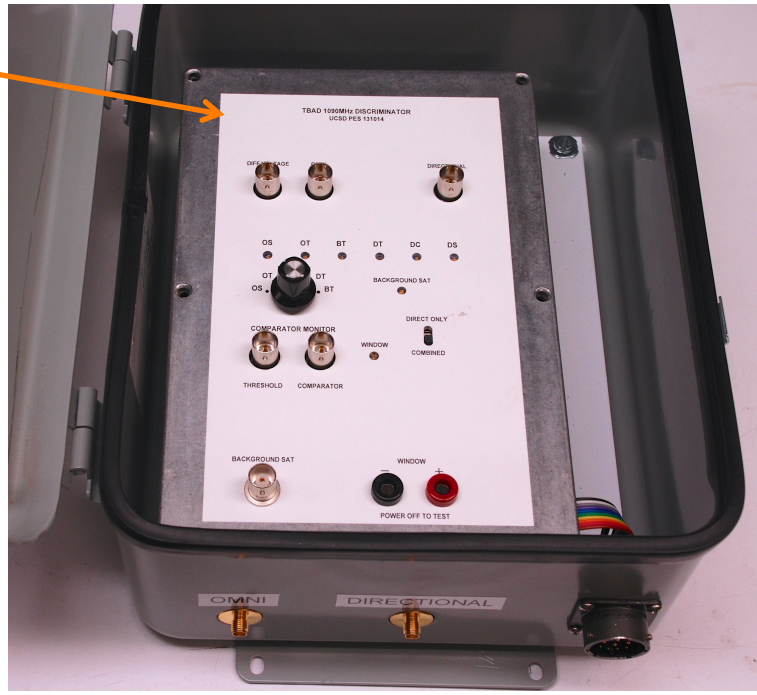
- Electronic Detector
  - eavesdrop on transponder chatter
  - never tires or tears-up
  - sees through clouds
    - > 100 km easy
  - not fooled by birds, bats, moths, meteors, satellites, lightning, rain, terrain
  - relatively cheap
  - FAA-approval precedents
  - Installations on APO 3.5 m; Keck-1; Keck-2; Subaru; Gemini N; Gemini S; LBTO×2 underway
    - 64 meters of linear aperture

TBAD Basic Scheme

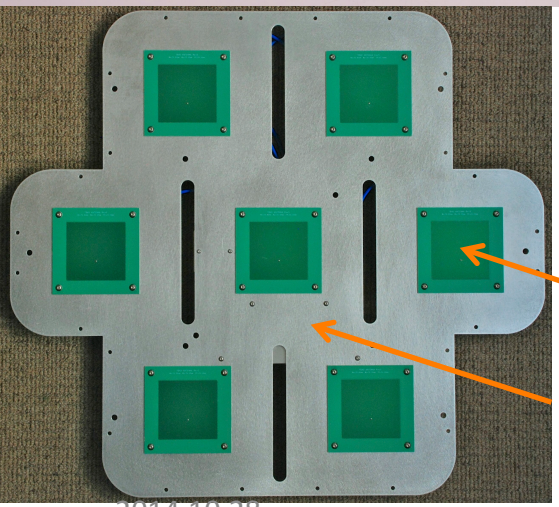
- Interrogations sent out from ground stations and aircraft
  - sometimes called "secondary radar"
- Airplanes respond to interrogation in all directions
  - also spontaneous data transmissions (ADS-B; req. in U.S. by 2020)
  - required on all planes > 10,000 ft (3050 m) and not within 2500 ft of ground
- TBAD simply listens to chatter
  - passive: no interrogations
  - decodes signal to read ID, altitude, or data
- Phased-array antenna determines if source is near boresight
- Issues laser shutter control signal if threat detected
- Also shuts laser if very strong signals detected
- Communication to computer logs all detections

TBAD Components

discriminator



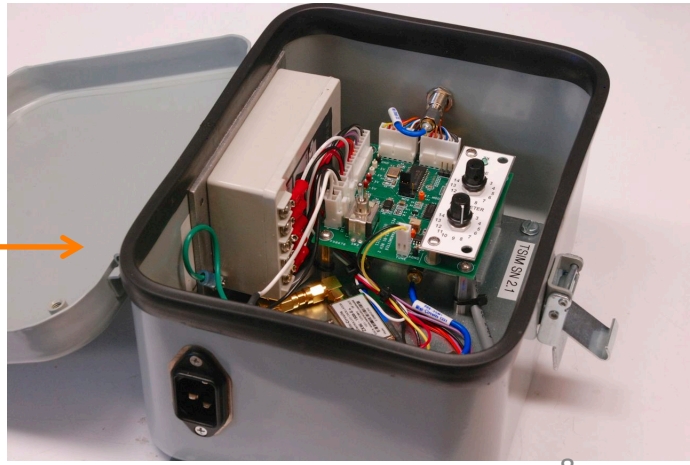
decoder



patch antenna

phased array (7 patches)

TSIM
validation!



Where to Mount the Antenna

As a spotter replacement, it's obvious

right?

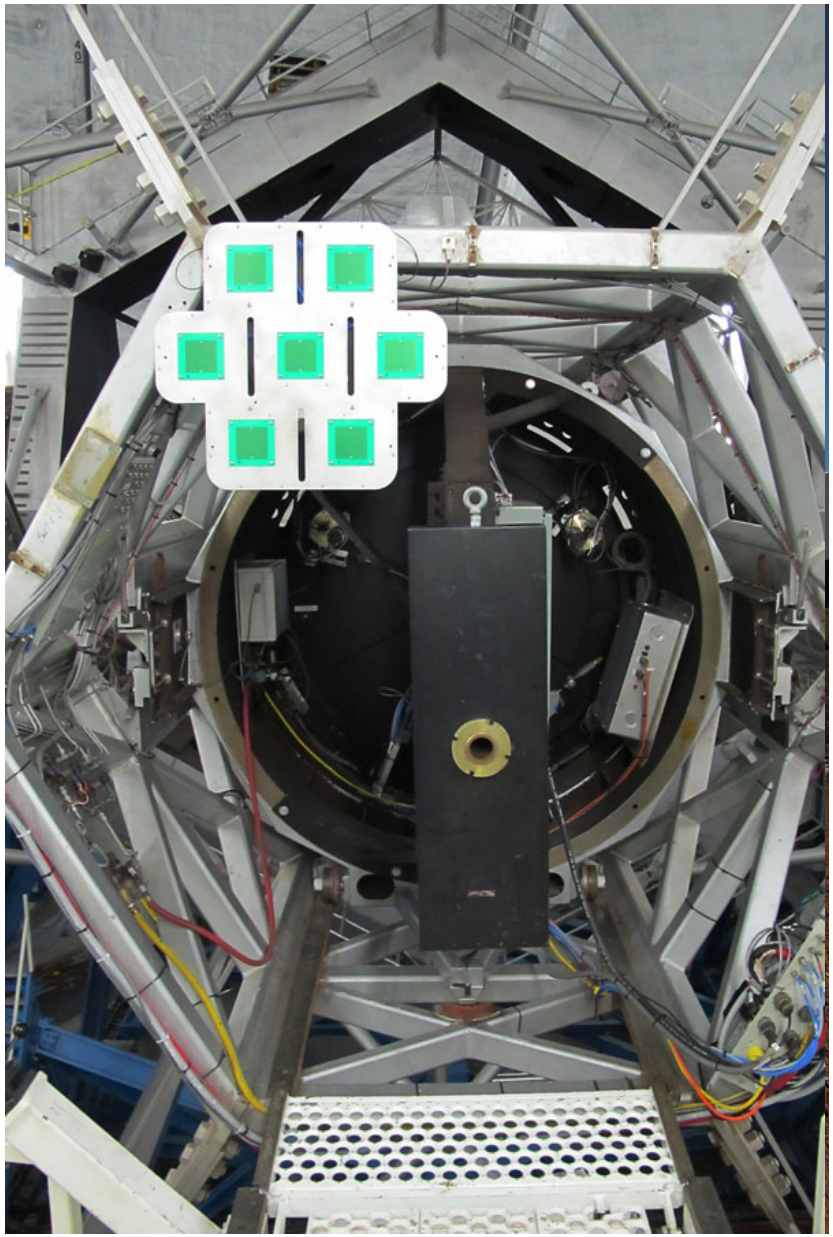
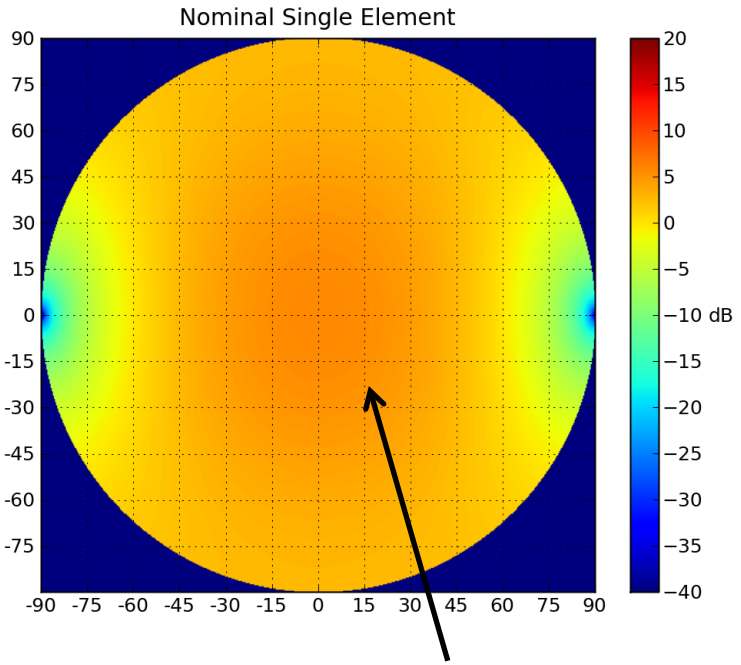
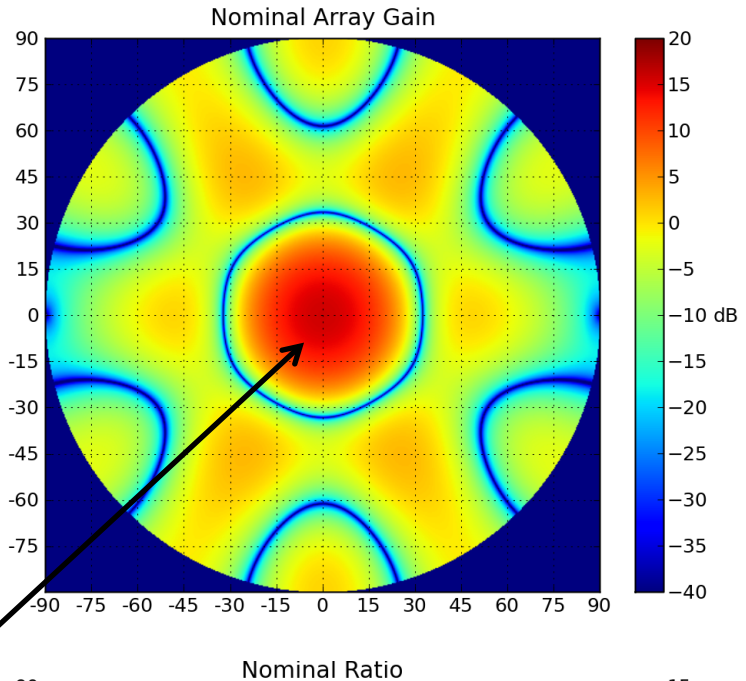
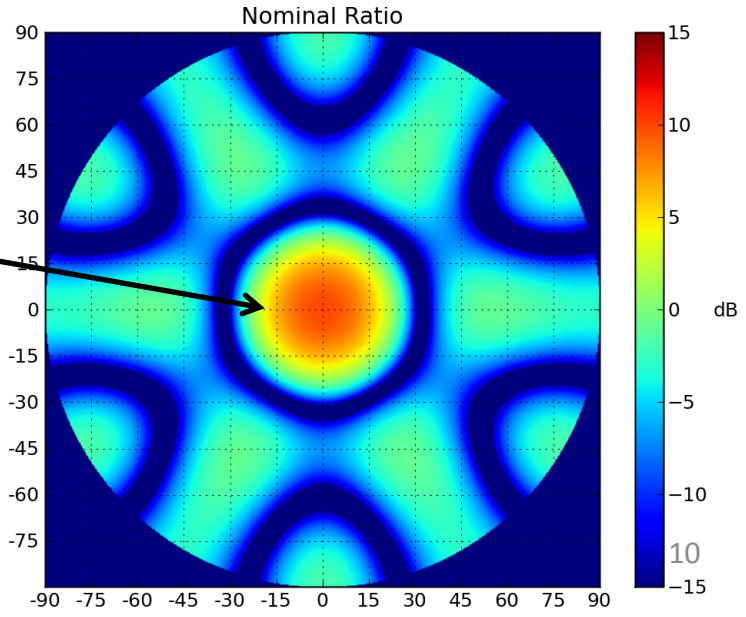


photo by Andrew Cooper

TBAD Antenna “beam” patterns

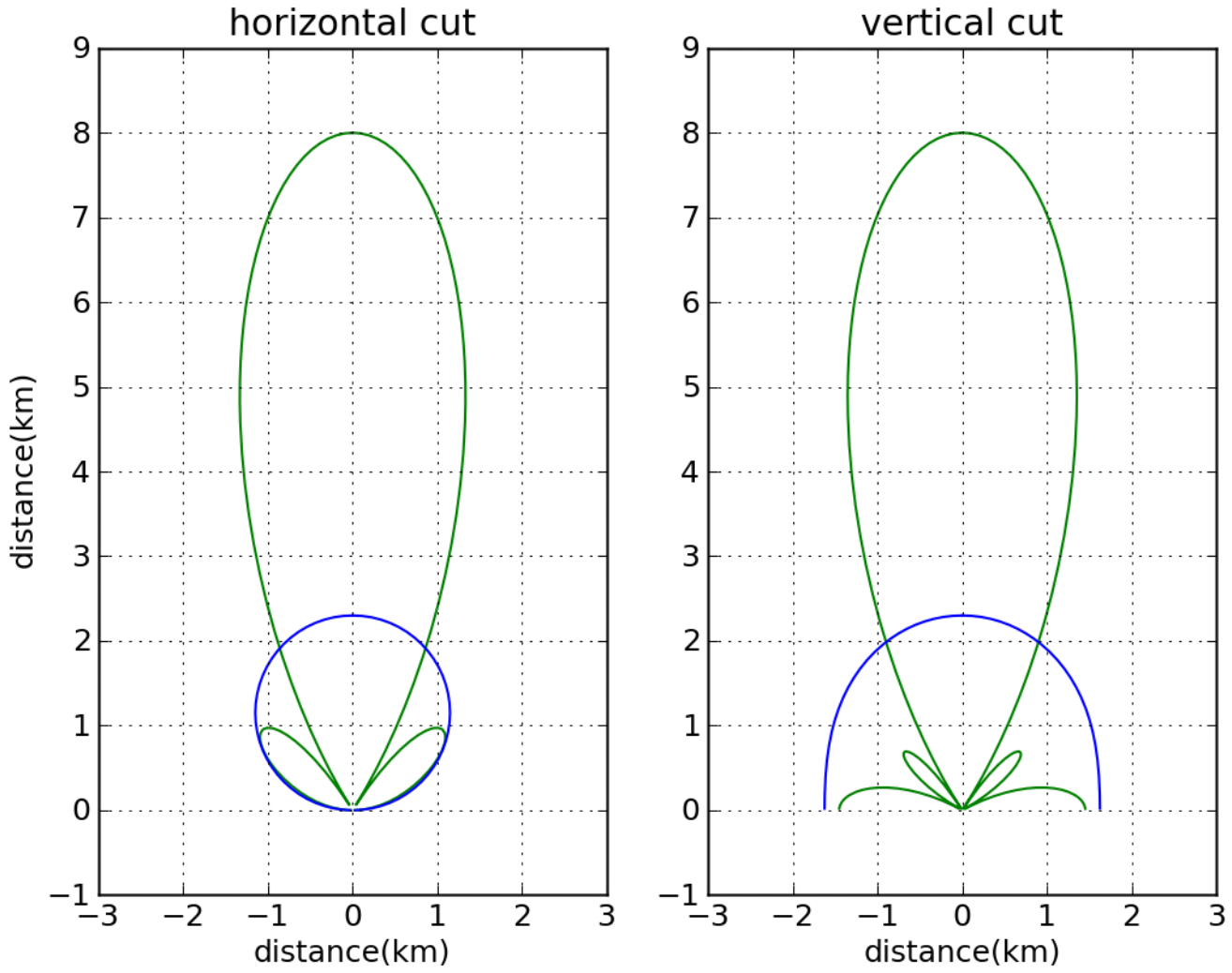






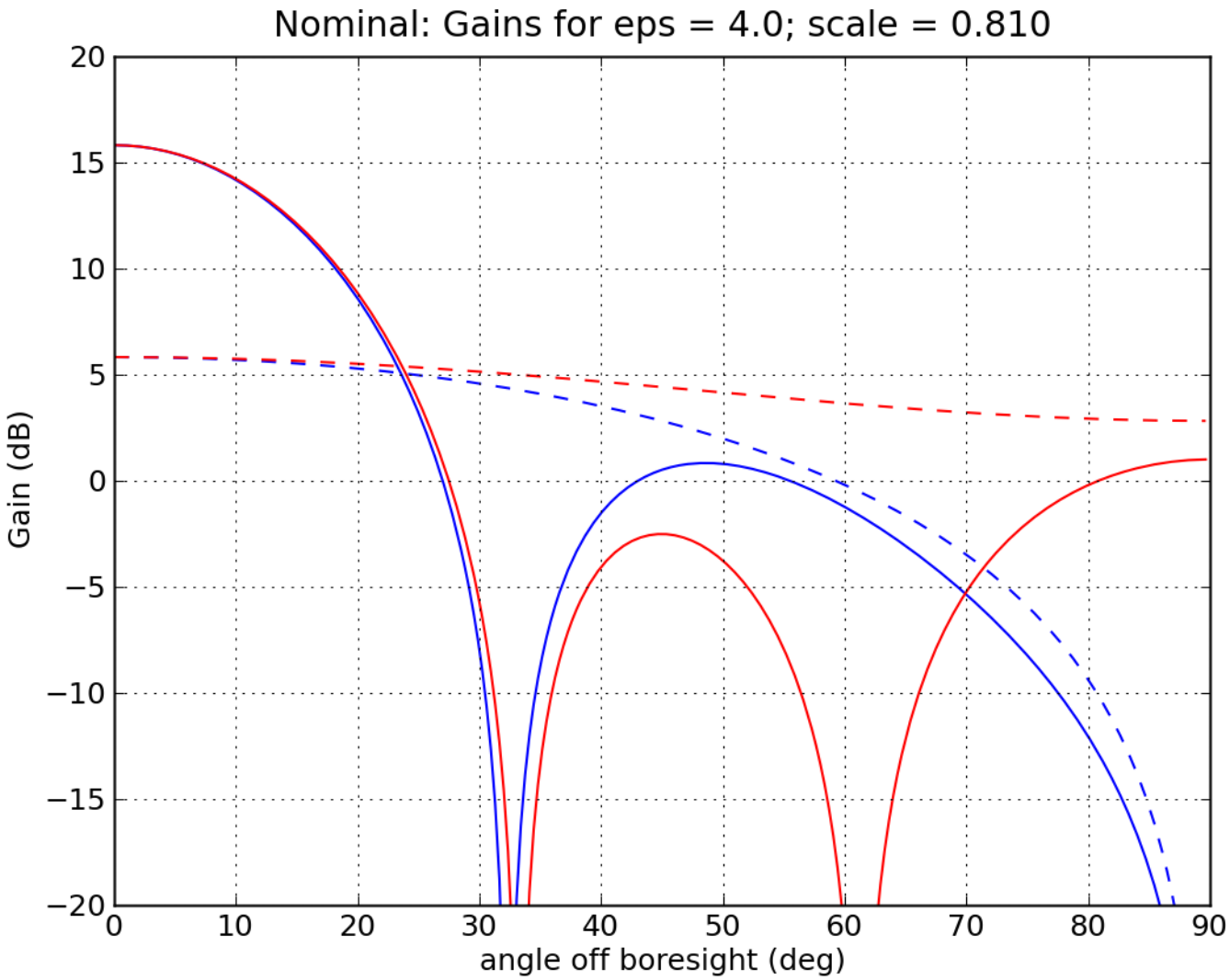
- Each patch has a broad beam (above)
- The array pattern has strong central peak
- The array pattern also has sidelobes/nulls
- Only in the center is the array pattern stronger than the single patch (element)
- Requirement that array signal exceeds single-patch signal by 5 dB results in ~15° “beam” zone
- Refer to array/patch as DIREC/OMNI

Lobes and Sidelobes

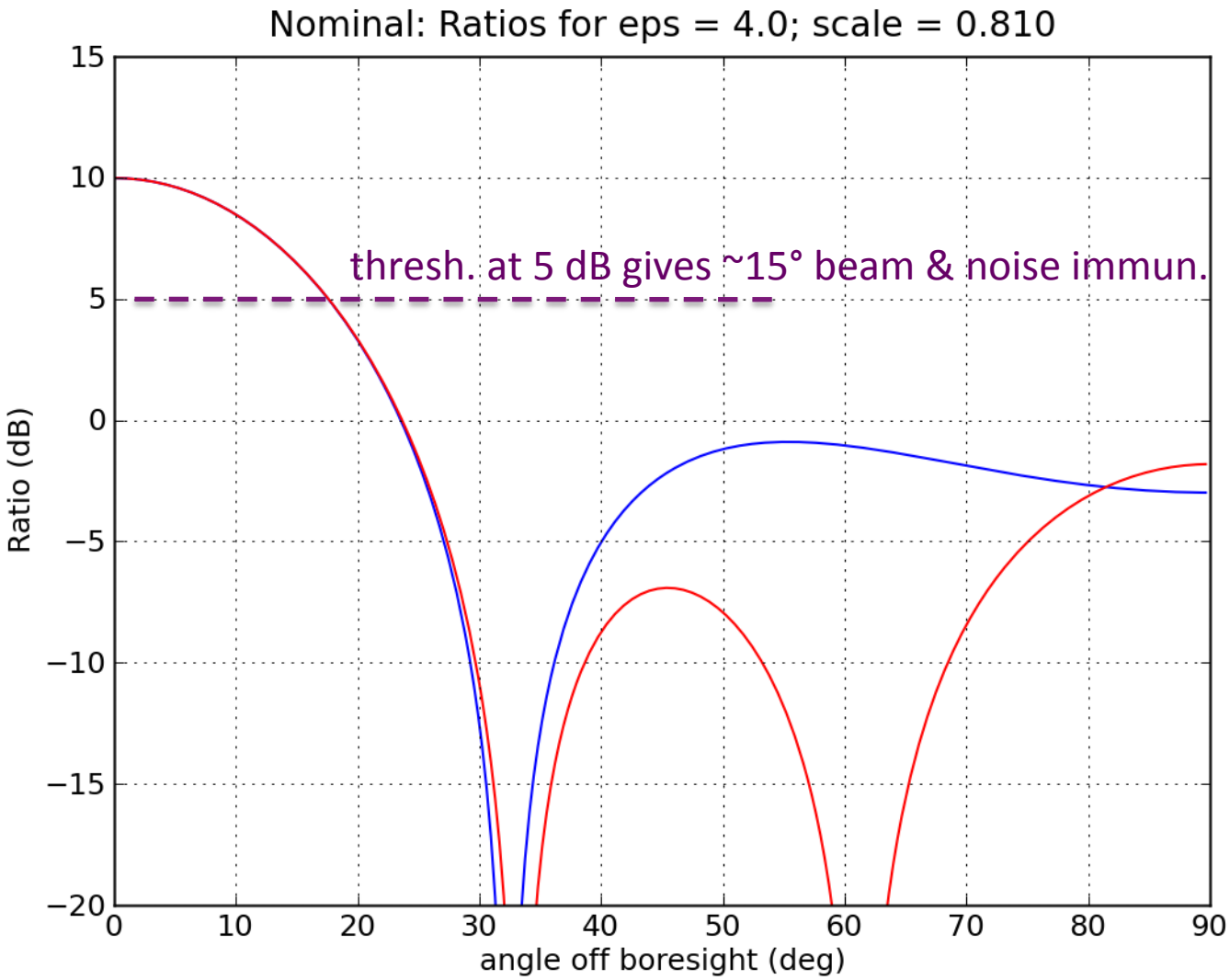


- Beam patterns for single patch (blue) and array (green)
  - note that sidelobes always weaker than single patch, except main lobe

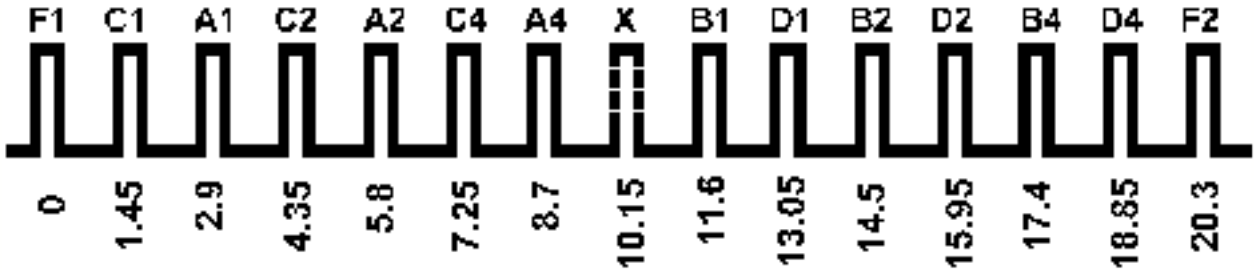
Beam Cuts: Raw Gain



Beam Cuts: Ratio is the Key

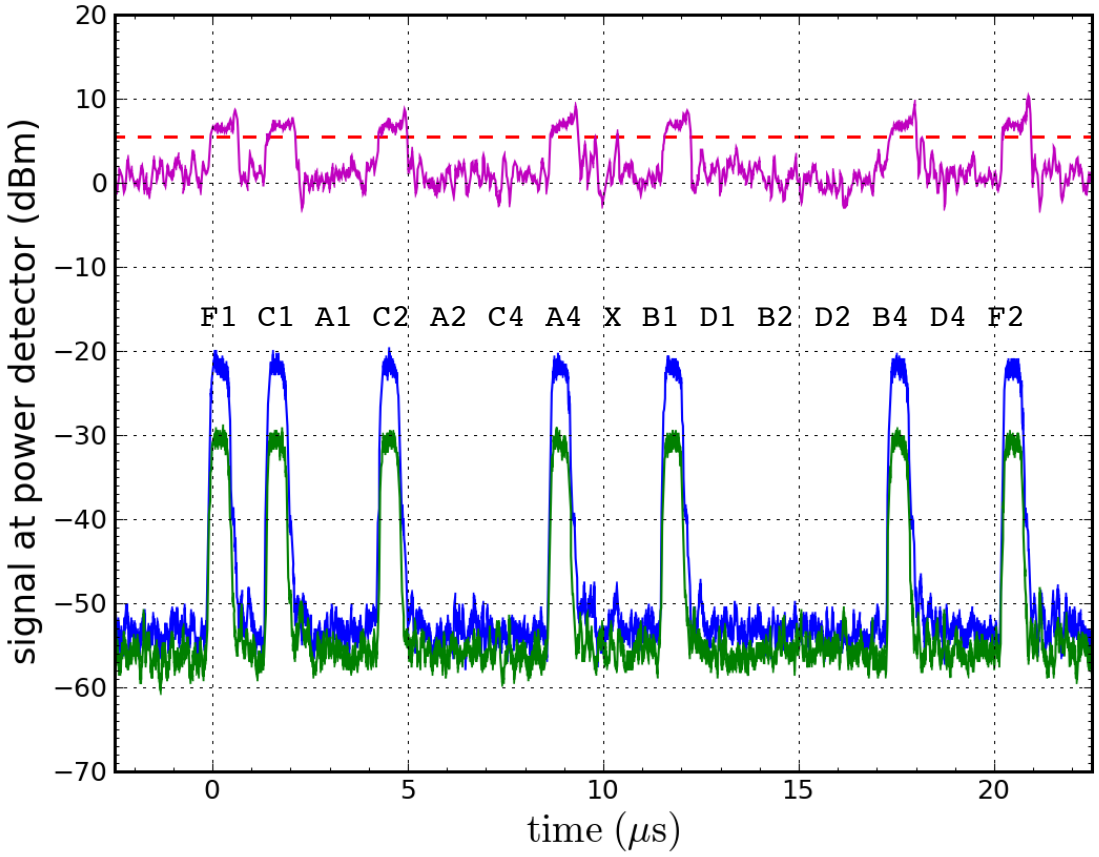


What Signals Be There?



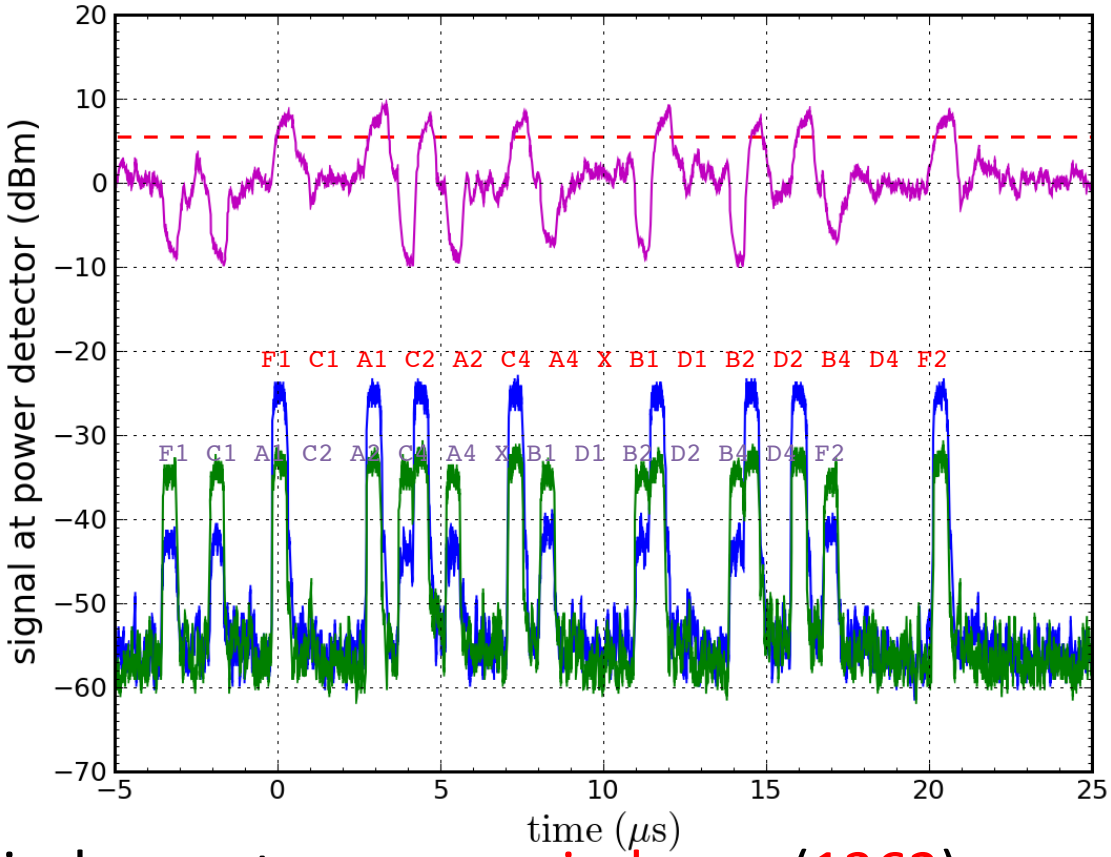
- Mode-A (ident) and Mode-C (altitude) use same pulse code
  - First and last framing pulses (F1, F2), X bit (not used)
  - 12 bits of data → 4096 possible codes (1280 of these map to altitudes)
  - 12 bits broken into 4 3-bit (octal) digits, ABCD
  - 450 ns pulse width, 1 µs gap between (21 µs total duration)
- Pilot sets ID code according to ATC instruction
  - altitude encoded from altimeter automatically

Example Pulse Pattern



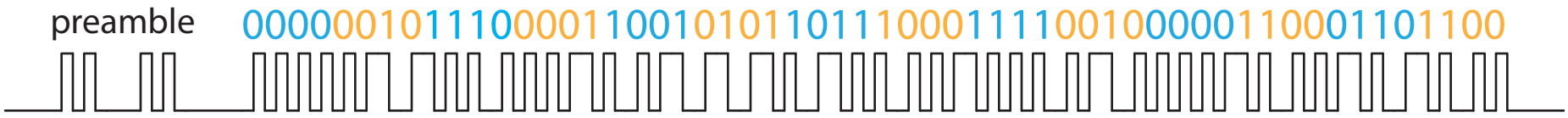
- See F1, C1, C2, A4, B1, B4, F2 → 4530 code
  - *could* mean 3400 feet
  - note: pulses stand out 3 orders-of-magnitude above noise floor

Not Easily Confused



- Two airplanes at once: one in-beam (1362), one out (4650)
  - note reversal of which (DIREC/OMNI) is stronger
  - difference signal (top, magenta) separates cleanly
  - if difference exceeds 5 dB for *any* pulse, deemed beam-worth

Mode-S Example



02E195B8F20C6C: air-originated altitude request.: airframe A4063D; 34000 ft

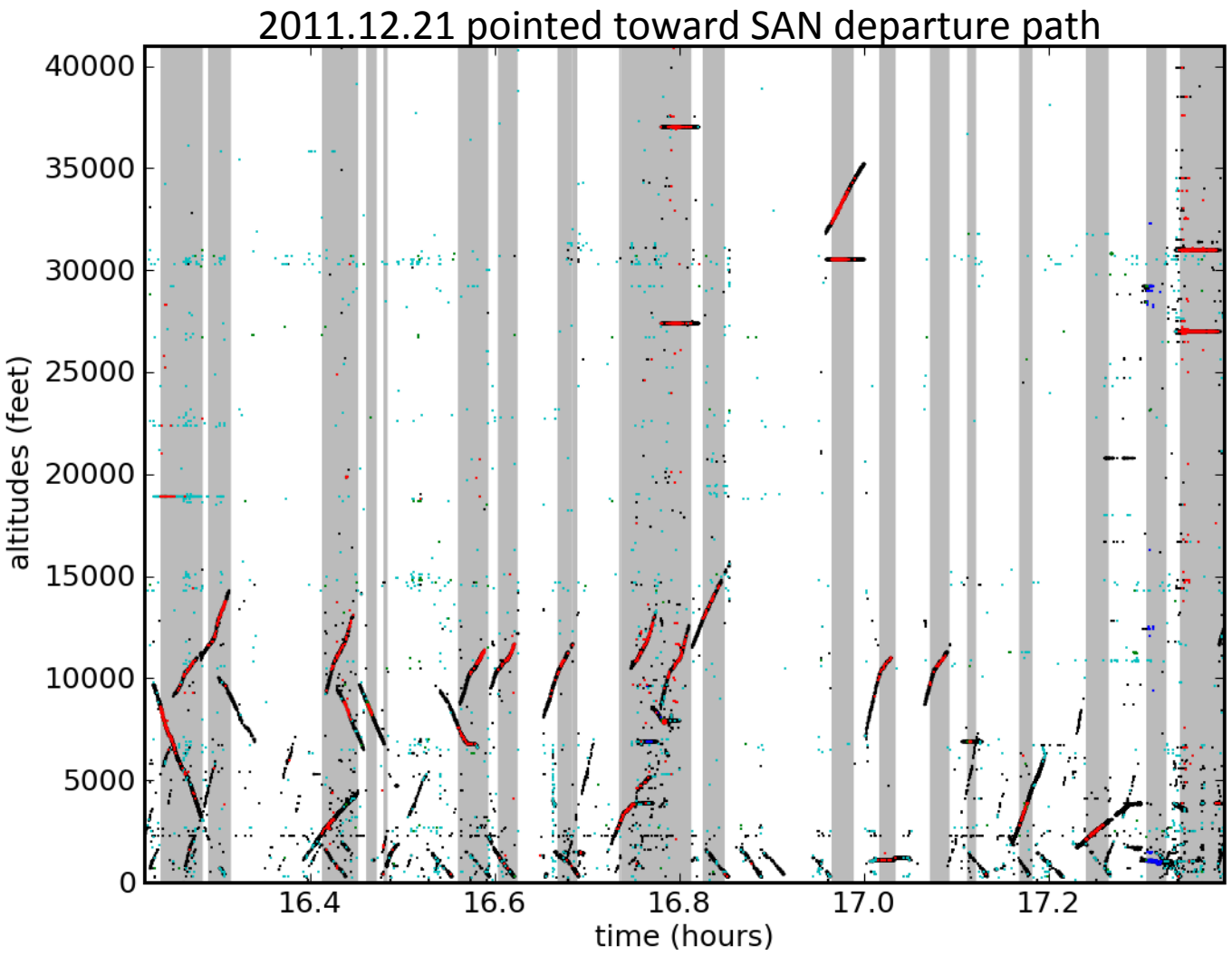
- Longer code; 56 or 112 bits; different encoding
- First five bits denote data format
  - can convey ID, altitude, latitude, longitude, velocity, text (flight number), and lots more
- This 56-bit example is air-to-air altitude request
  - Permanent airframe ID is A4063D
    - Boeing 767 operated by American Airlines, tail number N359AA
  - Flying at 34,000 feet

Example Data from APO

```
date/time from log CPU  green from TBAD  alt.          azim  elev  dome
2014-10-27 03:33:09.222 o1524...HF.FCB  34000          7.66  51.06 O
2014-10-27 03:33:09.227 o6667...HF.FD8  -----          7.66  51.06 O
2014-10-27 03:33:09.242 o6667...HF.FD8  -----          7.66  51.06 O
2014-10-27 03:33:09.272 o1524...HF.FCB  34000          7.66  51.06 O
2014-10-27 03:33:09.314 o02E195B8F20C6C..BHF..1F       7.66  51.06 O
    DF-00: parity pass; ID A4063D, Alt 34000
2014-10-27 03:33:09.447 o8DA4063D90AF81C7C09A6ADE3AE6..BHF..78 7.66 51.06 O
    DF-17: parity pass; ID A4063D, Alt 34000, Lat=32.67041, Lon=-105.82855
2014-10-27 03:33:09.668 o8DA4063D994593083804004 26AC9..BHF..00 7.66 51.06 O
    DF-17: parity pass; ID A4063D, vel 407; hdg 279; vrate -64; dh=0
2014-10-27 03:33:09.705 o1524..BHF.FDF  34000          7.66  51.06 O
2014-10-27 03:33:09.809 o6667..BHF.FEC  -----          7.66  51.06 O
2014-10-27 03:33:10.095 o6667..BHF.FEC  -----          7.66  51.06 O
2014-10-27 03:33:10.111 o6667..BHF.FEC  -----          7.66  51.06 O
2014-10-27 03:33:10.118 s1524..BHF.FDF  34000          7.66  51.06 O
```

- ID=6667 at 34,000 ft enters beam, with some Mode-S data
  - shutter closes at end of snippet—here set to respond on 8th offense;
  - sequence above transpires over 0.9 second
  - Mode-S gives lat/lon/vel/alt; A4063D is AAL B-767 (N359AA)

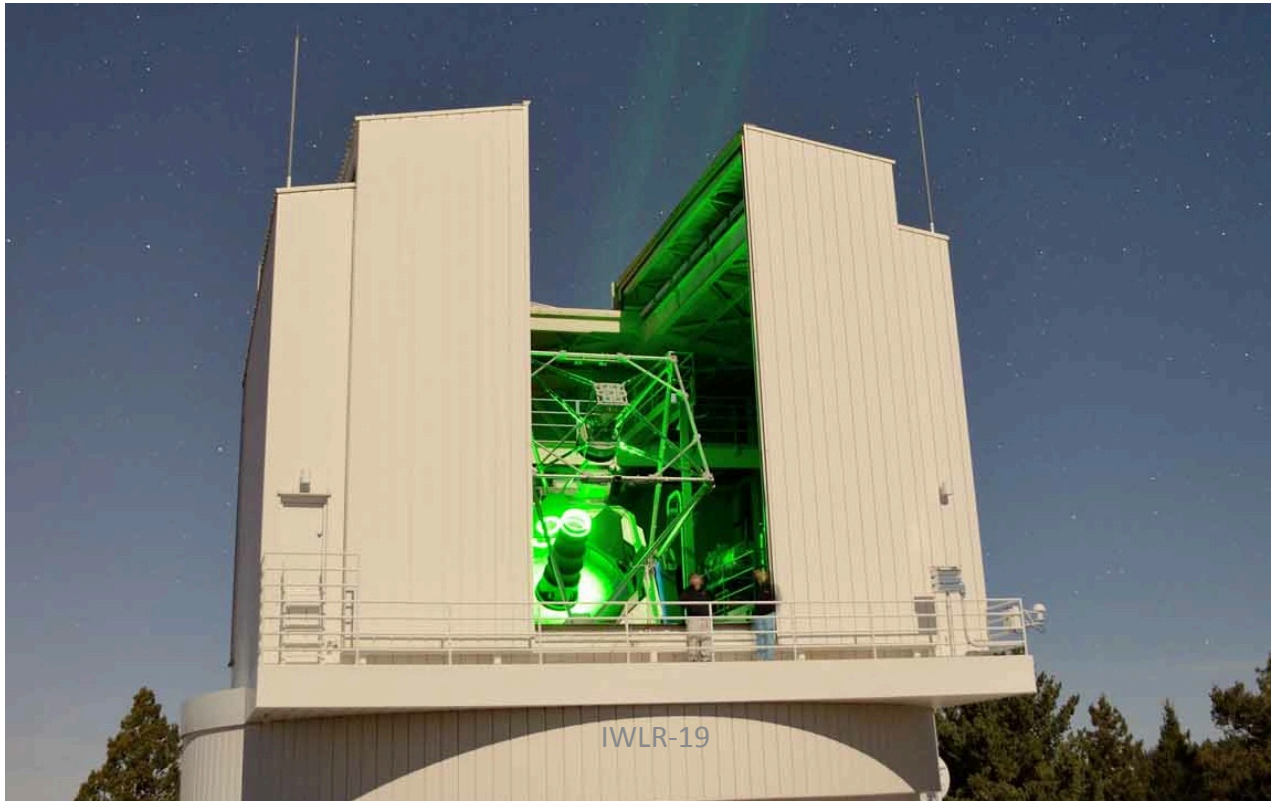
Early Tests: Watch SAN Departures



black: TBAD sees; red: in beam; blue: saturation; cyan: city garbage; gray band: shutter

APO Validation

- Roughly 3-month campaign at APO; Flight Explorer validation
  - 74 nights of at least partial operation
  - 108 alarms for aircraft (most in-beam, 5 from OMNI saturation)
  - Only one Flight Explorer (F.E.) case close to beam went unreported
    - but this case fraught with suspicious F.E. anomalies, so deem unreliable
  - Several robust detections not reported in F.E. (military, private?)



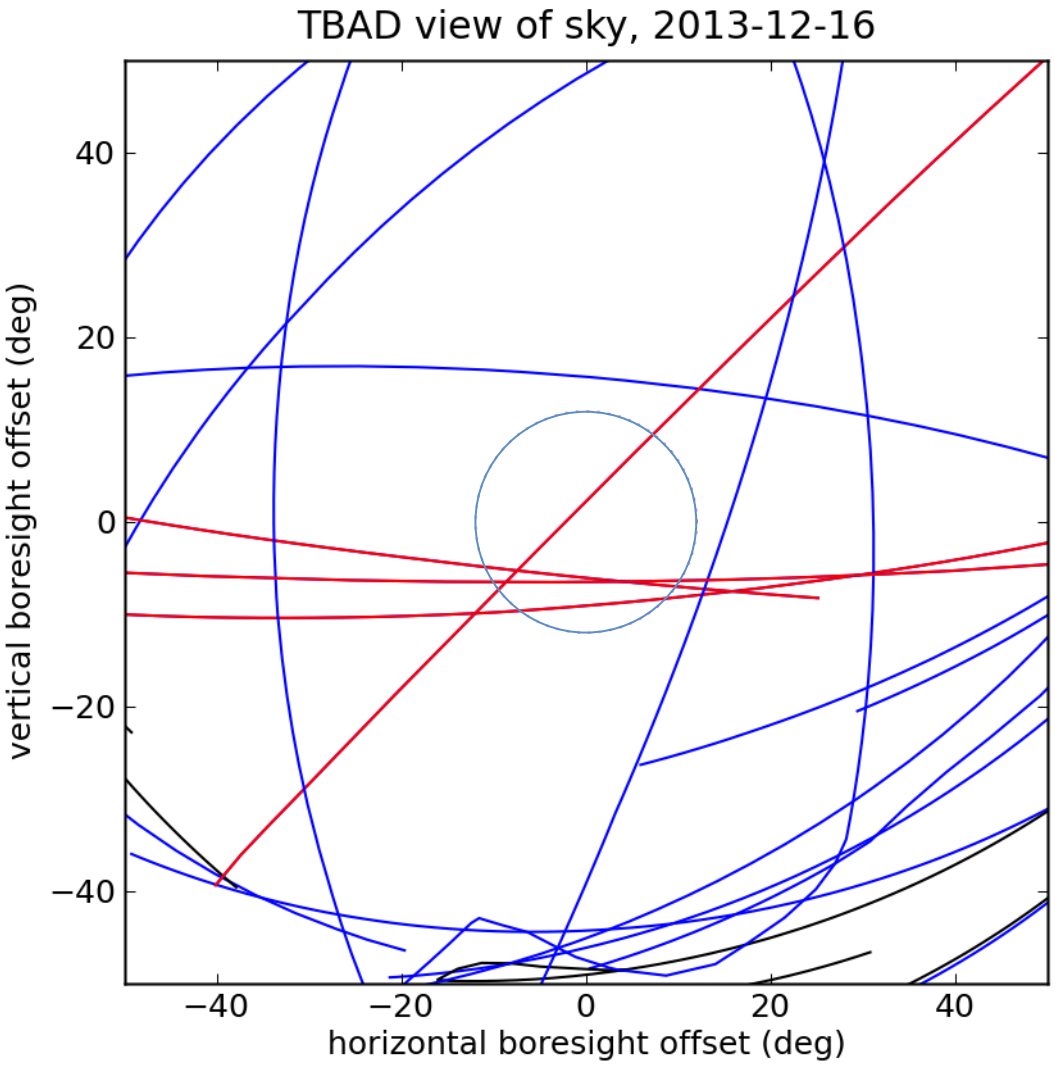
Flight Explorer

- Set up zones (cylinders) of interest
- Any ATC-tracked traffic in cylinder gets logged ~1/minute
- Flight Explorer gives flight details

```
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
```

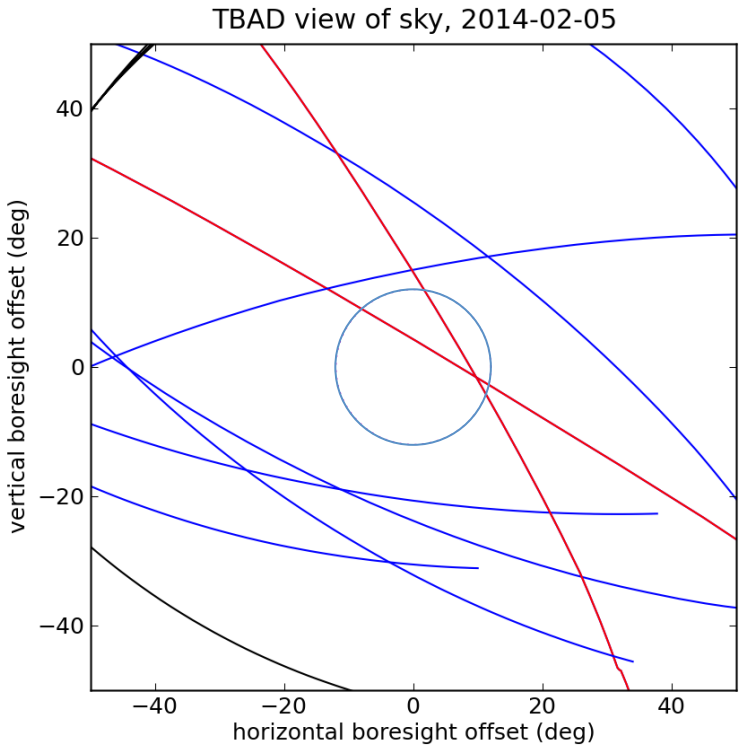
  - flt#,zone,orig,dest,type,depart,arrive,flight-level,knots,lat,lon,heading
  - Jet Blue 278 Airbus 320 SFO to FLL; 34900 ft; 563 knots, heading 100°
- Unreliable time steps: ~5 min offset; jumpy

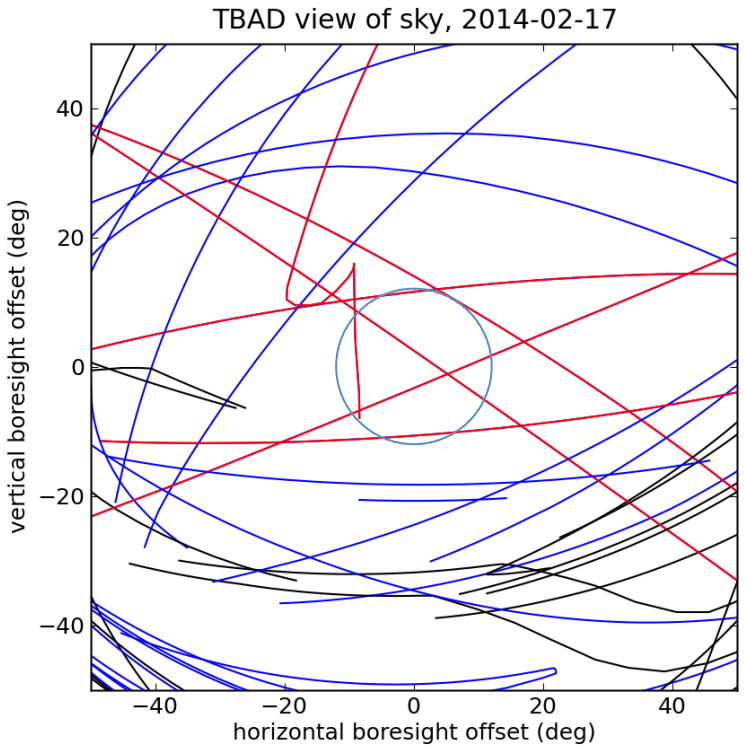
What Does TBAD See?



Red: TBAD triggered B; Blue: TBAD logged/saw; Black: analysis software did not disentangle

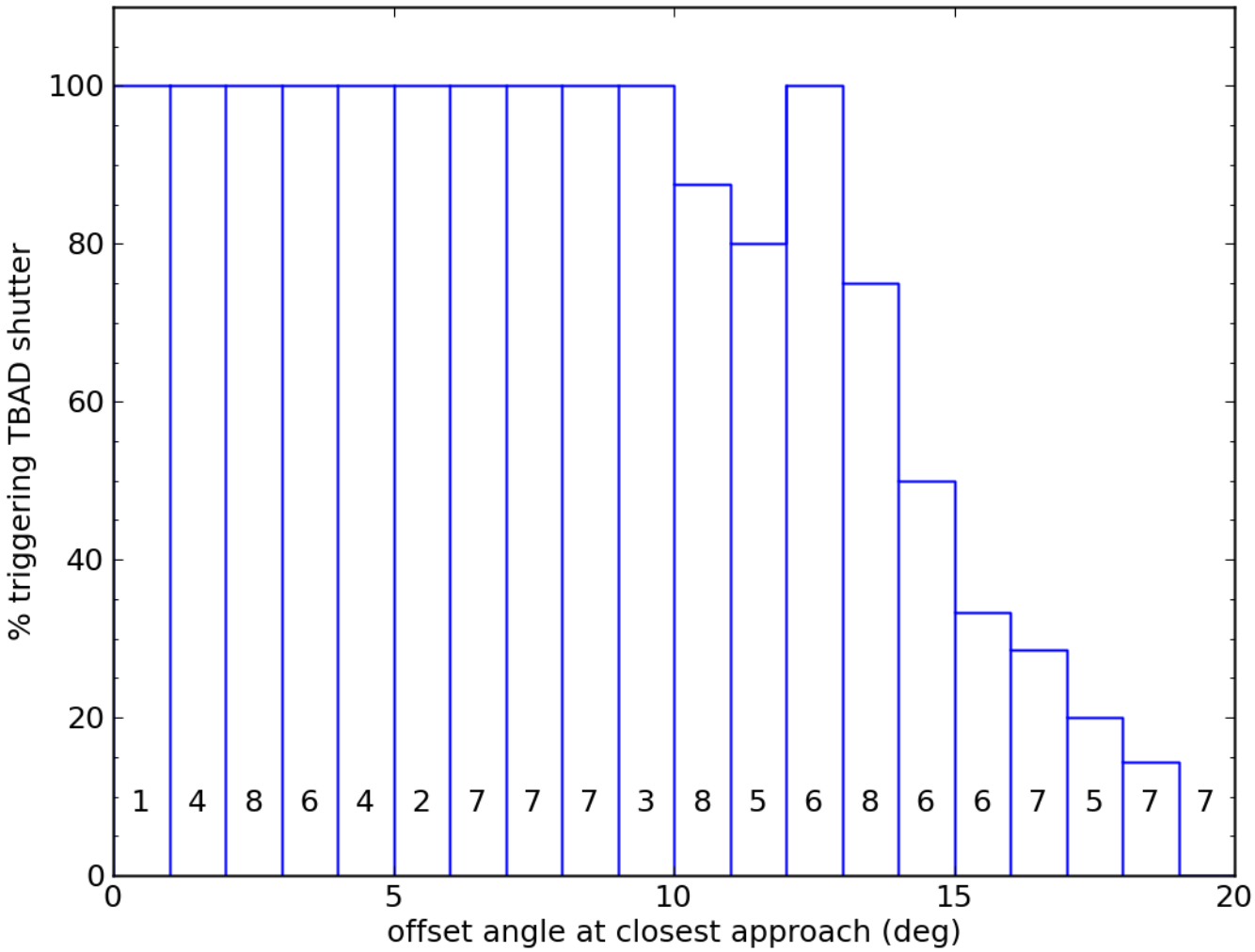
Typical & Super-Busy nights





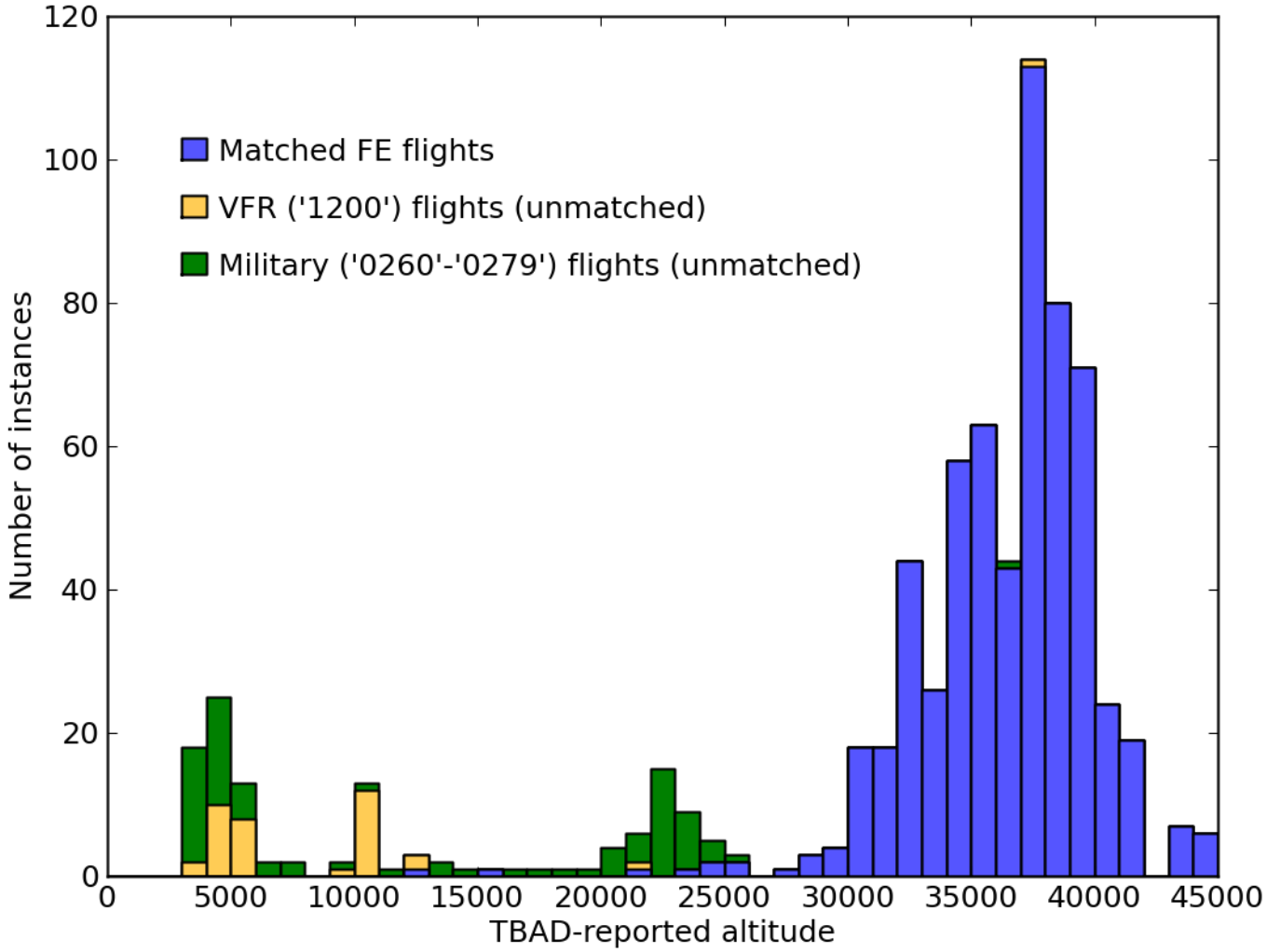
By comparison, Keck had to wait 6 months to see first non-horizon beam crosser (medical emergency diversion LAX-SYD → HNL!)

Inferred Beam Size



within 10°, perfect record of in-beam detection; soft-ish edge

Where are the Airplanes?



APO is at 9,200 ft; valley floor 4500 ft (Holloman AFB)

FAA Disposition

- SAE G-10T committee produced AS-6029A document on functional requirements for automated avoidance
  - FAA commissioned report to serve as recommendation
  - Paul Stomski of WMKO served on this committee
- Stomski documented TBAD as AS-6029A-compliant
  - this, plus NASA overflights resulted in Keck-2 spotter free
    - rubric is self-certification of safe operation
  - this, plus charter flight resulted in Keck-1 self-certification
- Murphy, at APO pursuing different route
  - 3-month analysis resulted in FAA granting temporary 1-spotter operation
  - after 3–6 month operation without incident, expect spotter-free permission

TBAD Graduation

- After 5 years at UCSD, TBAD is ready to leave the university environment
  - R&D phase is over; becoming production exercise
  - no longer appropriate use of university facilities
- Starting a company to build TBAD
  - Aircraft Avoidance Systems (AAS): aircraft-avoid.com
  - the same people will continue involvement (Tom Murphy, Bill Coles, Allen White, George Kassabian, Mike Rezin)

Summary

- TBAD reliably detects airplanes near telescope boresight
- FAA is getting on board, thanks to substantial WMKO contributions

- aircraft-avoid.com
- Publ. Astron. Soc. Pacific 124, 42 (2012)