Aircraft Illumination Avoidance Using Infrared and Radio Detection

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Abstract

We describe here a dual passive aircraft avoidance system involving both infrared and radio detection of aircraft in the vicinity of a transmitted laser beam. The infrared imager detects image motion of a thermally emissive source against the cold backdrop of space, while the radio receiver detects transmissions at 1090 MHz from the aircraft transponder. Together, these systems form a semi-redundant but complementary scheme for aircraft avoidance.

Introduction

The transmission through the atmosphere of a laser beam whose energy density exceeds the eye-safe threshold requires safety precautions. In the U.S., the Federal Aviation Administration (FAA) recognizes human spotters with laser kill-switches and eyes on the sky as appropriate hardware, but has typically not endorsed possibly more robust and sensitive technological solutions to the problem. We have developed a scheme that may satisfy FAA requirements and transform the way laser-transmitting observatories currently operate. Rather than relying on active radar—which must send powerful pulses of radio frequency (RF) energy in order to cope with the $1/r^4$ signal loss, possibly disrupting electronic activities at the site—we use strictly passive systems that have no possibility of creating local problems. The first we describe is an infrared camera taking video-rate images and sensing motion of an infrared-detectable source within the field of view. The second, and more powerful method is the detection of RF pulse-trains from the transponders installed in virtually every airplane. We describe these systems in greater detail below.

Infrared Camera System

We purchased an infrared camera detection system from Image Labs in Bozeman, MT. The camera images a 5°×7° field of view at thermal infrared wavelengths. A source need not generate power on board to be visible. The thermal emission from the surface of an object at even –20°C (253 K) outshines the cold background sky, which may be well below 200 K within an atmospheric-transmission band. The camera takes 30 images per second, and looks for an object that is moving in three consecutive frames. Software makes a decision about whether the object is likely to be a real aircraft (rather than a bird, bat, or moth) based on trajectory and angular velocity.

The infrared system has a range limit for small airplanes of about 5–8 km, after which the object spans a smaller solid angle than an individual pixel and begins to be diluted. So the infrared system is optimal for nearby airplanes. A worst-case scenario might have a small plane traveling at 100 m/s at a distance of 200 m. The airplane will therefore have an angular velocity of 0.5 rad/s, crossing *half* the roughly 0.1 radian field of view in 0.1 seconds, which is three frames at video rate. Thus the system is *just* capable of protecting against such an extreme (thus rare) event.

Transponder Detector Overview

In the U.S., all commercial airplanes, and all airplanes traveling above 10,000 feet (3048 m)—except within 2500 ft (762 m) of the surface—are required to carry an operating transponder. Periodic interrogations from ground radar stations and other airborne aircraft request a response from the transponder. Depending on the interrogation, the response may be Mode-A (temporary 12-bit aircraft identity), Mode-C (12-bit encoded altitude), or Mode-S (variable length data packets that can be permanent aircraft identification, present coordinates, etc.). In all cases, the transponder sends ~0.5 μs pulses of RF energy at 1090±3 MHz. For small planes, the peak power must be at least 70 W, while for commercial planes, the peak power must be at least 125 W. In no case is the peak power permitted to exceed 500 W. Commercial planes also send unsolicited Mode-S pulse streams once per second even in the absence of interrogations.

The strong signal levels make detection of the pulses straightforward even at distances well in excess of 100 km. In practice, airplanes over the relatively remote southern New Mexico skies transmit about 15–40 transponder pulses per second. But even if this were cut to a single transmission per second, a detection scheme capable of sensing that a source is within 15° of the laser transmission axis would conservatively protect the aircraft at angular rates up to 12° per second, or 0.2 rad/s. This is not as fast as the infrared camera, and it is in this respect that the systems are complementary: the infrared system handles nearby high-angular-rate airplanes, while the transponder system is suited for distant aircraft beyond the range of the infrared camera. However, the two systems have substantial overlap. An aircraft traveling at the speed of sound travels less than 0.2 rad/s at a distance of 2 km, which is well within the sensitivity range of the infrared camera. Because the transponder system is the main innovation in our detection scheme, we spend the rest of the paper discussing the details of its design and operation.

Transponder Detector Concept

In order to be effective, we need directional sensitivity to radio signals at 1090 MHz, independent of distance or power transmitted. We also would like narrow-band performance so that we may be less sensitive to RF activity away from 1090 MHz. We have therefore chosen to use patch antennas arranged in a phased array to accomplish these goals. Patch antennas are naturally narrow-band (roughly 1% bandpass if fabricated on standard circuit board material), and convenient for mounting on a plate in front of the telescope. We fabricated patches on low-loss circuit board material, with dimensions tuned to deliver 50 Ω impedance (maximizing power received) at exactly 1090 MHz. We studied a variety of array configurations, and selected a hexagonal symmetry employing a central patch surrounded by a ring of six patches. This choice gave the best compromise between beam width and sidelobe levels of the options we studied (also a six-element pattern with five-fold symmetry and a 9-element array on a square pattern).

By comparing the array signal, which has a narrow beam width, to that from a single patch antenna, which has a broad beam width, we may discern when the signal originates from the main beam—independent of signal level. This is possible because the array signal is only greater than the broad signal within the main beam: the array sidelobes are always lower than the broad antenna response. Figure 1 illustrates the antenna response as a function of angle.

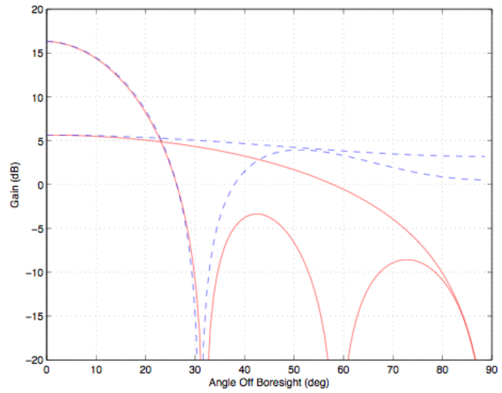

Figure 1. Gain of the broad-beam and narrow-beam antennas as a function of the angular separation of the transponder from the axis. The lines plotted in solid red are H-plane cuts through the gains of the antennas actually used and the lines plotted in dashed blue are E-plane cuts. If the antennas are pointed to zero elevation, the E plane is the vertical plane and the H plane is horizontal. The power received is proportional to the gain.

The ratio of the array signal to the broad signal is then 11 dB in the center of the beam, dropping to 0 dB (equal) at about 23°. The ratio of beams is shown in Figure 2.

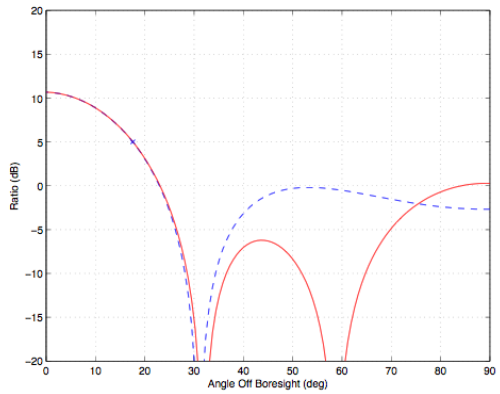

Figure 2. Cuts through the ratio at azimuths $\phi = 0°$ (red solid line) and 90° (blue dashed line), corresponding to the highest sidelobes. The "x" marks a robust detection threshold for concluding that aircraft is too close to the beam axis.

The advantage of the ratio measurement is that details of transmitter distance, power, polarization, etc. are all common-mode and do not impact the ratio. Thus requiring an array/beam ratio of 5.5 dB translates to a beam half-angle of about 17° in our design, which is appropriate for the task.

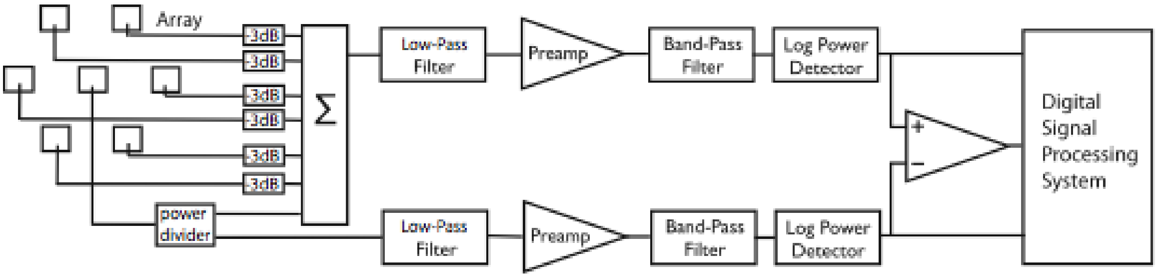

Figure 3. Block diagram of the analog signal flow. The patches are shown with the E-field vertical. The azimuthal angle is defined with respect to the horizontal. The array is drawn approximately to scale. The center patch is used both as an array element and as the broad beam element.

Figure 3 shows the electronic implementation of the transponder detector system. We use the central patch antenna both as an element of the array and as the single broad-beam antenna against which to compare the array signal for a ratio. To do this we split the power from the central element into two equal components, one for the array, and one for the broad-beam receiver. To compensate for this the other array elements must be attenuated by a factor of two (−3dB), so all seven elements are added with equal power levels to form the array output. For each chain, a filtered and amplified signal is presented to a logarithmic power detector. The difference in outputs of these two power detectors is therefore proportional to the ratio of the directional to broad signals. A signal processor then makes decisions about shuttering the laser based on the beam ratio and also absolute strengths of the input signals. For instance, if either of the signals is strong enough to saturate its power detector, the laser should be shuttered regardless of what the ratio comparison reports.

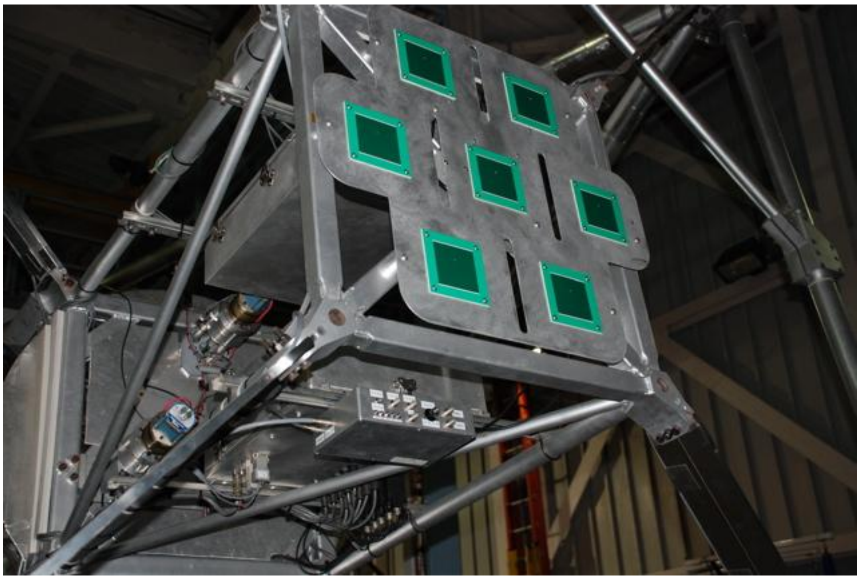

Figure 4. Patch array installed on the Apache Point Observatory 3.5 meter telescope, on the skyward end of the secondary mirror. The small box just below with white labels contains the RF processing electronics.

Figure 4 shows the array as deployed on the Apache Point 3.5 meter telescope in 2008 December. The electronics are split into two boxes—in part to keep the thermal emissions in front of the telescope to < 3 W. The box visible in Figure 4 contains the RF electronics, difference amplifiers, and discriminators that decide when the signal levels merit laser shutter closure. In a separate location is a box containing the power supply and a microcontroller that is used to capture codes associated with received transmissions so that we may understand more about the airplane responsible for the trigger. In this way, we can recover the identification number and altitude of an airplane crossing the beam. Together with telescope pointing information, we may approximate the range to the aircraft.

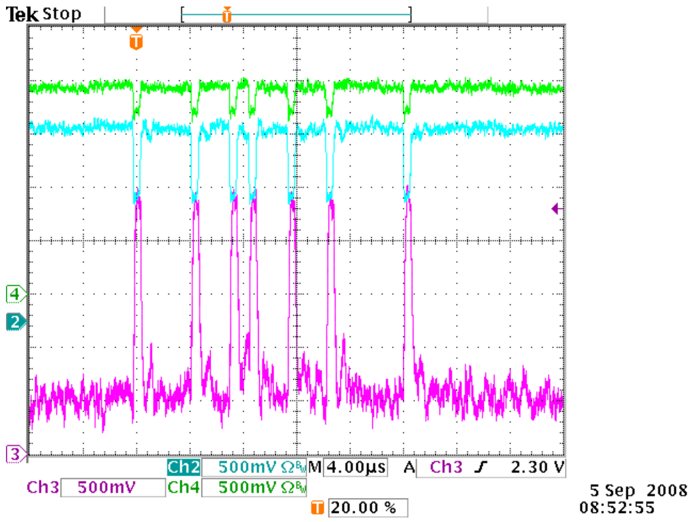

Figure 5. Example pulse train obtained in San Diego, showing both the broad antenna signal (green) and the directional signal (cyan), as well as the output of the difference amplifier (magenta) with a gain of four. The pulse pattern represents the code 4360, which could either be a Mode-A identity or a Mode-C altitude (corresponding to an altitude of 4600 feet). The broad and directional baselines are offset for clarity, and sit at about 2.0 V when no signal is present. In this case, the directional signal is far stronger than the broad signal, indicating that the source is within the primary beam of the array.

Figure 5 shows a representative pulse pattern captured for a plane at an altitude of 4600 feet. A simple threshold on the magenta signal provides an alert to an aircraft in the beam.

The antenna system was deployed on the Apache Point Observatory 3.5 m telescope on 19 December, 2008 (Figure 4). Setting the detection threshold to sense airplanes within 20 km at 70 W peak power, or 52 km at 500 W, we typically record about 12 airplanes per night through the slit of the telescope enclosure, when open. This is based on the first ten full nights of open-dome operation. Note that the solid angle of visible sky is restricted by the dome to a range of 1.9–2.7 steradians depending on telescope elevation angle, averaging only 36% of the sky. Of the ~12 detected planes per night, about three cross the threshold to qualify as an "in-beam" detection, resulting in an average of 100 s of shuttered time per night, out of about 44,000 s of open time (~0.2% closure). As yet, there have been no false closures not associated with aircraft. Typical detection rates are about 15 events per second during a pass, about 40% of which are associated with Mode-C altitude codes, 25% associated with Mode-A identity codes, 30% with distance measuring equipment (DME: also at 1090 MHz) pulses, and 5% identified as Mode-S information packets. We decode and record the Mode-A and Mode-C information, but cannot decode the Mode-S information with the present microcontroller. Figure 6 demonstrates the behavior of a typical beam-crossing detection. The metal dome shields the antenna from line-of-sight detection at large angles, which results in a relatively tight truncation of the sequence. The central beam crossing is robustly detected in 408 events, roughly centered in the crossing of the open dome slit.

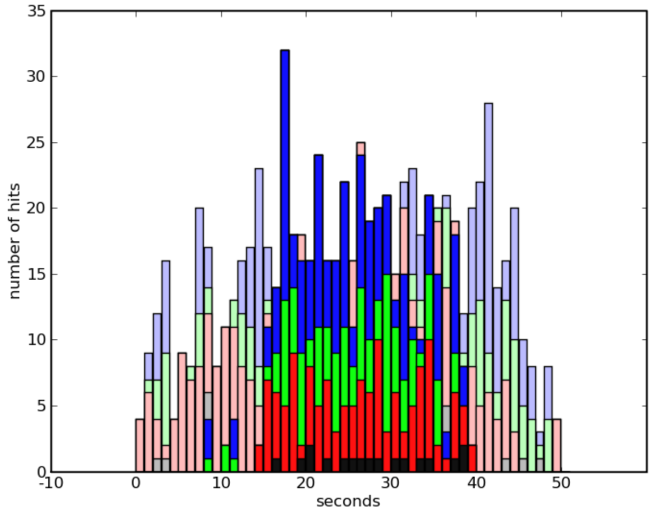

Figure 6. Event rate in 1 s bins for a pass acquired on 31 December 2008, for an airplane squawking identity code 6755 at an altitude of 39,000 ft, while the telescope was at an elevation angle of 54°. Event types are coded as blue for identity (Mode-A), green for altitude (Mode-C), red for DME, and black for Mode-S. Saturated shades represent those detections deemed to be in the central beam by the ratio criterion.

More details on the design and construction of the transponder antenna array will soon be published in Coles et al. (2009).

References

W. A. Coles, T. W. Murphy Jr., J. F. Melser, J. K. Tu, A. A. White and K. H. Kassabian, *Publications of the Astronomical Society of the Pacific*, in preparation, (2009)