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# AN EYE-SAFETY RADAR FOR LIDAR OPERATIONS

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## The problem

Probing the atmosphere using certain wavelengths of visible and non-visible light (lidar) at high intensity can present a visual hazard to pilots of aircraft within a critical range. For the IHOP project [Weckworth, et al], the LEANDRE lidar [Bruneau, et al] was installed aboard a Naval Research Laboratories (NRL) P3 Orion aircraft, a military version of NCAR's retired Electra research aircraft. At minimum beamwidth, the minimum distance at which the LEADRE lidar is considered eye safe is about 7 km. It would be quite possible for an aircraft 7 km away to enter the lidar beam unnoticed by the P3 crew. Therefore, it was deemed necessary to devise another method of detecting aircraft about to enter the lidar beam. A small radar whose beam was coaxial with, but wider than, the lidar beam seemed a logical solution. This solution had been used successfully for ground based lidar systems [e.g. ARM Newsletter].

Size was a serious consideration, whereas atmospheric absorption was not, so 3 cm (X-band) was chosen as the radar wavelength as many aircraft grade components are available for X-band. An 18” aircraft slotted-waveguide antenna with 5 degree beamwidth was purchased. A Furuno marine radar was chosen on the basis of perfomance, reliability, and price. The radar is magnetron based and is capable of producing up to 25 KW peak power at pulse lengths up to 1 microsecond and pulse repetition frequencies (PRFs) to 3 KHz.

The entire receiver chain was replaced in order to improve sensitivity. The original mixer was replaced with a low-noise amplifier followed by a double balanced mixer for improved performance. The local oscillator (LO) was replaced with a unit with very low phase noise in order to operate the radar in a pseudo-coherent mode.

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Radar signal data acquisition was performed using a Binet, Inc., "Sampler Card" [Randall]. The Binet Sampler Card is a PCI bus-based PC card containing a digital receiver as well as automatic frequency control (AFC) circuitry. The actual signal processing for this application was performed in a 1 GHz Industrial PC host computer running MS DOS. Radar and data acquisition timing was established using a separate counter/timer card in the host. The Sampler Card provided a stream of in-phase and quadrature (I and Q) values, one I/Q pair per range gate for each radar pulse. The standard pulse-pair (autocorrelation) algorithm was used to extract power, velocity, and normalized coherent power (NCP) for each range gate, for 100 gates total. [Doviak, et al] A four-pole elliptic IIR (Infinite Impulse Response) clutter filter was available, but was generally not used.

Typical operating parameters during IHOP were:

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| PRF | 1000 Hz |
| Pulse width | 1 microsecond |
| Samples per dwell | 25 |
| Number of gates | 100 |

(Details of the overall system design are presented in a parallel paper in these Proceedings [Pratte, et al].)

## Performance requirements

Most proposed P3 mission profiles for IHOP had the aircraft flying below 10,000 feet, so it was most likely hat almost any aircraft encountering the laser beam would be small general aviation aircraft. Target cross-section tables [Skolnik, 1990] list the typical radar cross-section of small aircraft as 1 meter squared. Using this value, the calculated signal to noise margin at 7 km was about 13 dB. This would theoretically guarantee a 0.99 probability of detection and a false alarm rate of 1.0e-5. We had too little operational latitude during IHOP to gather controlled data to confirm these characteristics.

## The Aircraft Detection Algorithm

After the first test flight in the P3 we noticed that when the aircraft was in level flight the average background echo over flat farm terrain changed very slowly compared to the echo in the presence of a target. As expected, hard targets (such as aircraft) were highly coherent and produced a high value of Normalized Coherent Power (NCP). NCP = |R(1)|/R(0), where R(n) represents the autocorrelation function at n lags. The presence of an aircraft should be signaled by a sharp deviation from the relatively stable background returned power value in one or two contiguous gates. The candidate target should also persist for more than one dwell period of the signal processor. As noted above, the NCP value for the candidate target should be high. Velocity measurements were basically useless as we had no way to correct for aircraft velocity.

The primary channel power return was exponentially averaged with a time constant nominally set to about 1/2 second. Before being added into the exponential average, each gate was tested against the prior value of the exponential average for that gate. The candidate target was allowed to occupy a maximum of two gates (300 meters). If the difference between the current value and the exponentially averaged value for that gate was greater than a preset threshold (typically 10 dB), a 'candidate target' flag was incremented for that gate and the current value of the average was inserted into the exponential average (so anomalies, such as real targets, would not affect the background exponential average). If the difference between the candidate target and the exponential average was less than the threshold, the candidacy flag was reset to zero. NCP for the primary channel was compared with a preset threshold. If the candidacy gate flag count was greater than or equal to 2 (2 consecutive hits in the same gate) AND the candidate target occupied no more than two gates AND the NCP value was above threshold AND the gate range was within the protection range, then the presence of an aircraft in the beam was flagged and the lidar was shut down.

The above scheme worked reasonably well, but was sensitive to specular ground targets illuminated by the antenna sidelobes (steel barn roofs, grain towers, vehicles, etc.). To reduce spurious target alarms resulting from ground targets a second receive-only "guard" channel was added. The original channel was thereafter referred to as the "primary" channel. The antenna for the guard channel was a small X-band horn, which looked at a wide cone pointing downward at about 45 degrees under the lidar/radar beams. The horn was oriented so that its beam pattern had minimal overlap with the main lobe of the primary antenna, but encompassed the first sidelobes of the primary antenna.

The condition was then added that any candidate target in the primary channel was required (in addition to the previous list of conditions) to exhibit a low NCP value in the guard channel, otherwise it was assumed to be a reflection from a ground target and was ignored. The addition of the guard channel drastically reduced the system false alarm rate.

Aircraft roll presented yet another problem. Roll angle and altitude were acquired via a serial feed from the aircraft data acquisition. Using these values, if the beam was computed to strike the ground within the protection distance, the laser was shut off so as not to affect eyes on the ground.

**Quality of operation**

As indicated above, prior to the introduction of the guard channel, the initial false alarm rate was unacceptably high. In one early flight involving mostly low altitude patterns, LEANDRE was shut down 22 times. After addition of the secondary channel criteria and adjusting thresholds this dropped to one or two presumably real target acquisitions per flight. (P3 missions typically lasted five hours or more.) Though aircraft hours were in short supply, we were able to organize two events in which project aircraft (the University of Wyoming King-Air and the DFVLR Falcon) flew off the P3's right wing for a short time at various distances so that we could test the aircraft detection algorithm on known targets.

**Future Development**

The process of deciding whether or not a candidate target is an aircraft is amenable to treatment with fuzzy logic techniques. Membership functions based on linear deviation from exponentially averaged power and on the values of NCP in the primary and secondary channels could be established. With an eye toward this possibility, the capability of recording raw in-phase and quadrature time series from both primary and guard channels was incorporated for the last P3 flight in IHOP. The data set acquired during that last flight does contain candidate targets as determined from both radar response and from visual contact with the aircraft. The data set will be invaluable in developing and testing the fuzzy logic approach for future projects.

The radar is currently being employed in a similar application for ground-based lidars. The beamwidth was expanded for this task by fitting a smaller (12”) aircraft antenna, giving a 7 degree beam.

Consideration is being given to using the radar in yet another airborne lidar application with NCAR's SABL lidar aboard the NCAR C-130 research aircraft.

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