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Aircraft Laser Strike Geolocation System

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Laser strikes against aircraft are increasing at an alarming rate, driven by the availability of cheap powerful lasers and a lack of deterrence due to the challenges of locating and apprehending perpetrators. Although window coatings and pilot goggles effectively block laser light, uptake has been low due to high cost and pilot reluctance. This paper describes the development and testing of a proof-of-concept ground based sensor system to rapidly geolocate the origin of a laser beam in a protected region of airspace and disseminate this information to law enforcement to allow a timely and targeted response. Geolocation estimates with accuracies of better than 20 m have been demonstrated within 30 seconds of an event at a range of 8.9 nmi with a 450 mW laser. Recommendations for an operational prototype at an airport are also described.

I. Introduction

THE number of laser strikes on aircraft is increasing rapidly, as shown in Figure 1 for US incidents reported to the Federal Aviation Administration (FAA). The number of reported incidents almost doubled from 2014 to 2015 and these statistics are likely a significant under-estimate of the true scale of the problem as many incidents go unreported. The majority of strikes involve green lasers which have a wavelength of 532 nm and largest potential effect on vision due to eye sensitivity at this wavelength. Most reported events occur against commercial aircraft, but strikes against helicopters (including medical evacuation flights) and military aircraft are also increasing.

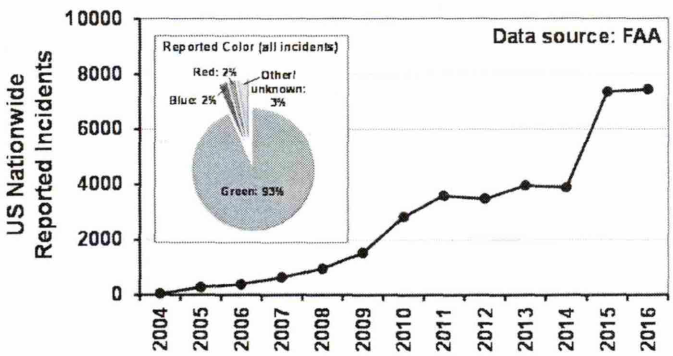

Figure 1. FAA-reported US Laser Strikes

This growing problem is likely driven by increasing availability of cheap and powerful lasers. Figure 2 presents a selection of green laser pointers easily-available through the internet, all costing less than \$200 with power levels ranging from 50 to over 500 mW. Lasers with powers of several watts are available for under \$500. For comparison, a typical presentation-style laser pointer has a power level of 1-5 mW which are considered "eye-safe" under normal

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usage, while a 500 mW laser pointer has a Nominal Ocular Hazard Distance (NOHD) of 500-1000 ft (depending on the beam divergence), can cause temporary flash-blindness to 5000 ft, and be a distraction to over 100,000 ft range [1]. For pilots, any of these effects can severely degrade safety, especially during night-time operation when they rely on dark-adapted vision to scan for threats. Many laser strikes occur during low altitude operation when the pilot's role in collision avoidance is especially critical. When a strike does occur, pilots report approximate range and bearing of the origin of the beam to air traffic control (ATC). This information is passed on to law enforcement whenever possible, but the low accuracy and delayed nature of the information makes it of low effectiveness for perpetrator apprehension.

Figure 2. Selection of High-Powered Laser Pointers Available for Less Than $200
(Black = advertised power level, Red = measured total power level, Green = measured power level in green color)

Section II describes the mitigation options for this problem which motivates the need for a ground-based sensor system to provide persistent protection of high risk volumes of airspace. The development of a proof-of-concept of such a sensor is described in Section III, followed by its testing in controlled environments in Section IV. Finally, needed system enhancements and recommendations for an operational deployment of the system are described in Section V.

II. Mitigation Options for Aircraft Laser Strike Incidents

A number of mitigations exist to the aircraft laser strike problem. Table 1 outlines the available approaches in the categories of policy; hardening the aircraft; and systems to help find the perpetrators. For each approach, their performance against a number of key metrics is detailed.

Policy mitigations include legislation, public awareness campaigns, licensing and signage. Many countries have legal mechanisms and regulations dealing with laser strikes against aircraft [2]. For example, US federal law allows penalties of up to 5 years in prison and up to $250,000 in fines for anyone who "knowingly aims the beam of a laser pointer at an aircraft … or at the flight path of such an aircraft" [3]. The creation of these laws is relatively low cost and does not require any changes to existing pilot or ATC procedures. However, the challenges of locating the perpetrators of laser strikes means very few incidents currently result in prosecution (e.g., less than 0.5% of incidents were found to have related prosecutions in [4]) and as a result there is little deterrence for perpetrators despite these severe penalties. Indeed, anecdotal evidence suggests that public awareness campaigns sometimes even increases the number of incidents from "copy-cat" perpetrators.

In terms of hardening the aircraft against laser strikes, special glasses worn by pilots are currently available and can be very effective at blocking the specific wavelengths of green, blue and red laser light. However, they typically have ambient light transmissivity of 70-80% which means 20-30% of all other light is blocked and also distort the way legitimate lights of those colors (such as those used in airport lighting systems) appear to pilots. Pilots also need to wear the glasses routinely for them to be effective and non-compliance is a major issue given the problems outlined. Special films or coatings for cockpit windows eliminate the pilot non-compliance issue, but they suffer from the same ambient light transmission and distortion issues. In addition, the cost to equip every pilot with laser glasses or retrofit every aircraft with cockpit coatings would be prohibitively expensive.

The final mitigation category is to increase deterrence for the issue by helping law enforcement to apprehend and successfully prosecute perpetrators. Advanced airborne sensors are available today but are mostly used for military applications and are only effective at geolocating the laser origin if the sensor itself is struck directly. Increasing the availability of these sensors on law enforcement aircraft is being pursued, but the costs associated with protecting a critical mass of the commercial aircraft fleet are again prohibitively high. A complement to the airborne sensor is a ground-based sensor system to provide persistent coverage of high-risk volumes of airspace, such as the low altitude arrival and departure routes around major airports or helipads. If it was capable of rapidly and accurately geolocating the origin of a laser event and communicating this to law enforcement it could act as a powerful deterrence. The sensors should not require any aircraft to actually be struck for a geolocation to occur, would not require any changes to pilot or ATC procedures, and the estimated cost for installation at key airports is one or two orders of magnitude less than the other mitigations. The main challenge is that a ground-based sensor capable of detecting laser beams to operationally-relevant distances is currently unavailable commercially. The sections that follow outline the development and testing of a candidate sensor technology to demonstrate its technical viability.

Table 1. Aircraft Laser Strike Mitigation Options

	Approach	Laser Mitigation Effectiveness	Pilot Effects	Technical Risk	Estimated Relative US-Wide Cost*
POLICY	Legislation, Public Campaigns, Licensing	May encourage perpetrators	None	Available today	$
HARDEN AIRCRAFT	Passive Glasses/ Goggles	Effective for common lasers	Reduces/distorts ambient light, pilot non-compliance	Available today	$$ (all certified pilots)
HARDEN AIRCRAFT	Cockpit Window Treatment	Effective for common lasers	Reduces/distorts ambient light	Available today	$$$ (all commercial aircraft)
FIND PERPETRATOR	Airborne Geolocation Sensor	Effective only if aircraft struck	None	Available today (military)	$$ (police aircraft) $$$ (all aircraft)
FIND PERPETRATOR	Ground-Based Geolocation Sensor Network	No aircraft strike required	None	Need system integration & prototyping	$ (sensors at top 30 airports)

* $ = M$tens, $$ = M$hundreds, $$$ = M$thousands

III. Laser Aircraft Strike Suppression Optical System (LASSOS) Concept

A. Concept of Operations

MIT Lincoln Laboratory is developing the Laser Aircraft Strike Suppression Optical System (LASSOS) to meet the need for a ground-based sensor system described above. The LASSOS concept of operation is presented in Figure 3. When a perpetrator shines a laser at an aircraft, particulates and aerosols in the atmosphere scatter a small portion of the light, leaving a faint streak along the laser's path. Two or more sensors with large aperture lenses, narrow bandpass filters and imagers having single-photon sensitivity can capture this scattered light at a range of several miles, forming an image of the laser streak. The images are processed to improve the signal-to-noise ratio and are passed through a series of line segment detection and refinement algorithms to identify and position laser streaks in the plane of the camera. The sensors are spaced a distance apart so they capture the laser streak from slightly different angles. The streak on each sensor defines the edge of a geometric plane in real-world coordinates, which can be determined from the processed images and the finely calibrated sensor positions and attitudes. The intersection of these planes, found by geometry, represents the true location of the laser beam in geodetic coordinates. The laser is then projected down to a topographically accurate model of the Earth's surface, providing the latitude, longitude, and terrain altitude of the laser origin. This information can be converted to the nearest street address if desired and transmitted to law enforcement for response. Details about the laser strike event, together with the time stamps associated with each image, can be correlated with recorded aircraft flight tracks in a post-event analysis to provide strong evidence for law enforcement that the perpetrator was attempting to lase an aircraft to support prosecution activities.

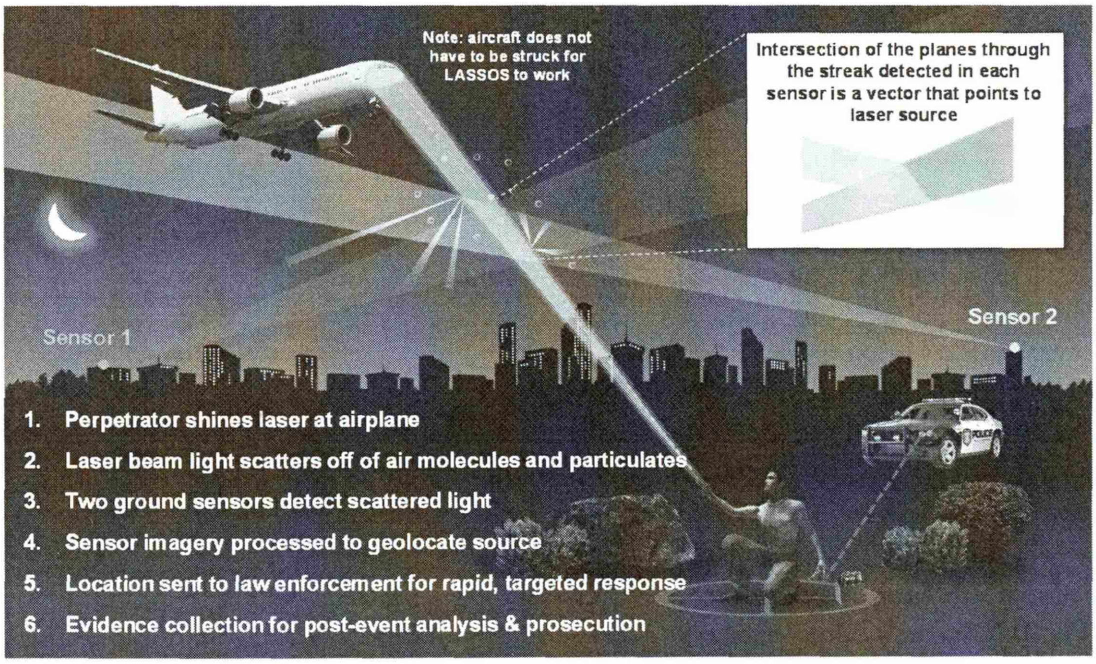

Figure 3. LASSOS Concept of Operation

B. Proof-of-Concept Prototype Details

A proof-of-concept prototype of the sensor and processing to execute this concept of operations has been developed at Lincoln to de-risk technology elements. The system has been designed to detect laser strikes up to a 10 nmi range to make it as operationally flexible as possible. The prototype is built around a sensor system illustrated in Figure 4, combining an astronomy-grade charge coupled device (CCD) sensor, a fast optics lens, a line filter to remove all but the wavelengths of light emitted by laser pointers and a star tracker to allow accurate attitude determination of the sensor by comparing to a known star field.

The sensor outputs are processed by laser streak detection and geolocation algorithms to produce the laser origin coordinates. The image processing system in the initial prototype includes a first stage for signal detection and characterization and a second stage for signal synthesis and geolocation.

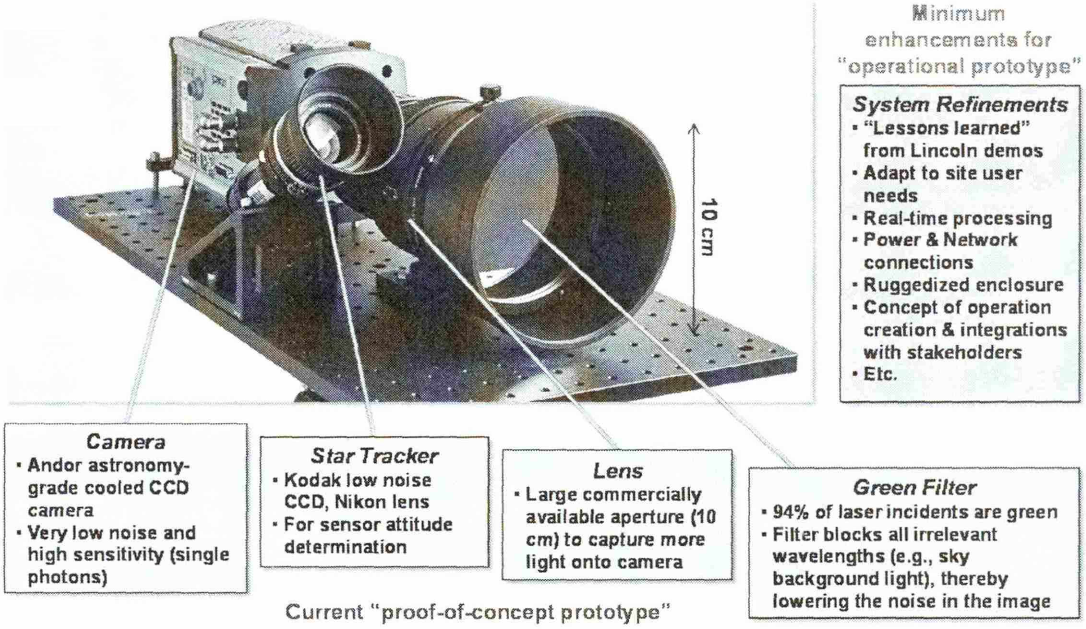

Figure 4. LASSOS Prototype Sensor

In the first stage, images are processed to improve the signal-to-noise ratio. Processing steps in this stage include: frame stacking (image summing), background subtraction, pixel re-binning, spatial or temporal filtering and thresholding. The processed images are analyzed via Hough transform to identify line segments in the image that could potentially be laser strikes. Basic features of the detected line segments are used to rule out obvious false positives such as, for example, line segments that are horizontal, are shorter than a certain number of pixels or the slopes of both line segments differ by more than is physically allowed by the sensor baseline geometry. The pixels that comprise the detected line segment are passed through a weighted-least-squares linear regression algorithm to determine the position and orientation of the line in pixel-space with greater accuracy than is afforded by the Hough transform. The weights are chosen to be a function of the pixel value, i.e., pixels with a higher photon count are given more weight in the regression. The center of each pixel is assigned a local azimuth and elevation value based on a pre-calibrated azimuth and elevation of the image center and the instantaneous field of view (IFOV) of the sensor. The local spherical coordinates of the two outermost points of the detected line segment and the known sensor location form a triplet of points that define a unique plane.

In the second stage, the two planes detected and characterized in the first stage described above intersect along a single line which is the true location of the laser streak. The equation for this line is found using planar geometry. The line is extrapolated down to the point at which it intersects the surface of the Earth. The surface of the Earth is modeled by placing digital terrain elevation data (DTED) on top of an appropriately-chosen reference ellipsoid and geoid. The longitude, geodetic latitude and ellipsoidal height of the point of intersection gives the predicted location of the perpetrator (the origin of the detected laser streak). Integration with Google Earth allows powerful visualization, and automatic alerting capabilities through email. The spatial coordinates, together with the equation for the laser streak, allow the calculation of other quantities of interest, such as the local direction (azimuth and elevation) that the laser was pointing and the precise distance to the perpetrator. The details about the laser strike event, together with the timestamps associated with each image, can be correlated with recorded aircraft tracks in post-processing to provide strong evidence for law enforcement that the perpetrator was attempting to lase an aircraft.

IV. LASSOS Prototype Testing Activities

Initial testing of the prototype sensors and algorithms has been conducted at MIT Lincoln Laboratory in Lexington MA. Two sensors of the type illustrated in Figure 4 were positioned approximately 1 nmi apart, one on a roof at MIT Lincoln Laboratory and one on the roof of a hangar at Hanscom Field. A number of candidate test sites were identified at different distances from the sensors in order to test their performance with lasers of different powers and at different ranges. In order to receive FAA approval for high-powered laser testing, it was necessary to identify the likelihood of aircraft overflights at the test sites at different times of the day. Figure 5 shows overflight densities over a two week period (from FAA radar track data) relative to the full set of candidate test sites identified by the red squares. The table at the bottom of the figure presents the number of overflights during the two week analysis period for all the test sites to the north of the sensors as a function of local time from 9:00pm through 5:00am. It was seen that aircraft overflights for all but one site reduced to 15 or less per hour after 11:00pm, and to 7 or less per hour after midnight. Based on this analysis, plus the plan to have aircraft "spotters" so testing could be immediately postponed if an aircraft was identified near the test region, approval was granted to conduct laser testing from several of the test sites after 11:00pm.

TEST SITES NORTH OF LINCOLN — Local time	Total Flights Within 2 NM of Test Site (2/13/16-2/26/16)							
	2100-2200	2200-2300	2300-0000	0000-0100	0100-0200	0200-0300	0300-0400	0400-0500
Bedford Recr Dept, 2.1 nmi +	103	111	126	44	7	8	5	24*
Fawn Lake, 3.4 nmi	36	29	15	7	0	2	2	2
Rehanis Park, 4.8 nmi	37	31	11	5	0	5	2	1
Rotary Park, 7.0 nmi	37	24	13	5	0	3	2	2
Tewksbury Recr Dept, 8.9 nmi	37	20	11	7	2	2	1	4
Ipswich River Park, 10.5 nmi	37	24	14	4	1	2	1	2
Ronan Mcelligott Park, 11.6 nmi	19	10	2	5	1	1	0	1
Andover Skate Park, 13.0 nmi	16	7	3	5	1	0	1	1
Mt. Vernon Park, 14.1 nmi	19	11	3	6	0	0	1	1
Keaney Park, 14.5 nmi	164	147	132	46	22	5	2	7*
Alekel Memorial Park, 17.5 nmi	21	16	12	7	2	0	0	0
Plug Pond (MA), 21.3 nmi	7	0	1	1	2	1	0	0

Key: >20 10-20 <10 overflights/hour

+ Under approach path from west
* Red-eye arrivals

Figure 5. Test Site Overflight Analysis

Testing was conducted at a number of these sites to assess the performance of the prototype sensors as a function of range and laser power. These tests led to a number of refinements to the system to improve image processing and geolocation accuracy. Figure 6 presents sample results from testing of the 450 mW laser at the Tewksbury test site at an 8.9 nmi range i.e., near to the 10 nmi design limit. The top left shows an unaltered standard digital camera image of the laser beam from close range. The green laser is clearly visible, but beyond approximately 100 ft a standard camera (and the human eye) is no longer able to see the scattered light from the beam. The lower left shows an image of the same beam at the full range of 8.9 nmi (over 54,000 ft) from one of the prototype sensors with just a 1 second exposure. The panel on the right shows the geolocation estimates from three different test locations (corresponding to the bases on a ball field at the test site) using the prototype sensors, with the circles being the true test locations and the diamonds corresponding to the geolocation estimates from the system. In this case, geolocation estimates were produced within 30 secs with errors of less than 5 m (approximately 15 ft). Geolocation accuracies of 20 m or better are typical.

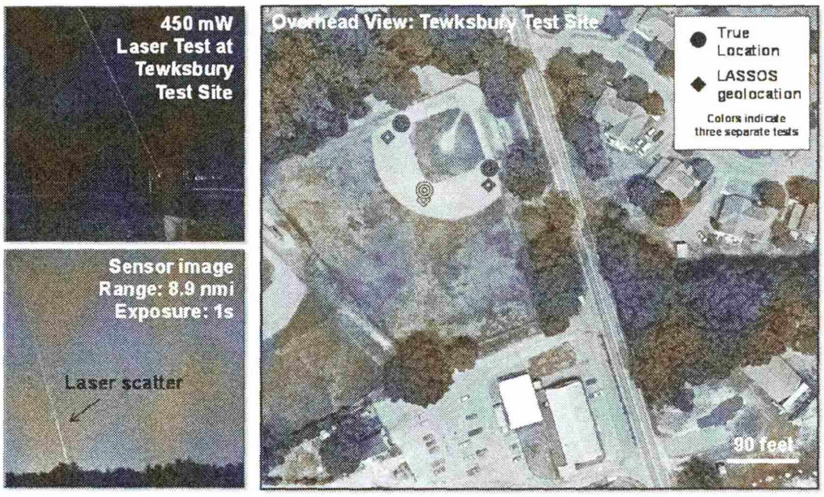

Figure 6. Sample Test Results

A prototype user display has also been created as shown in Figure 7. It contains live imagery from the two sensors at the left. Whenever a laser beam is detected in one of the sensor images, the streak estimate is overlaid as shown by the green line, which is then also inserted in a Google Earth image shown on the right side. A screenshot of the estimated laser origin location can be automatically sent to any pre-determined email list, allowing smart-phone equipped police officers to digitally reconstruct the laser strike event and respond in near-real time.

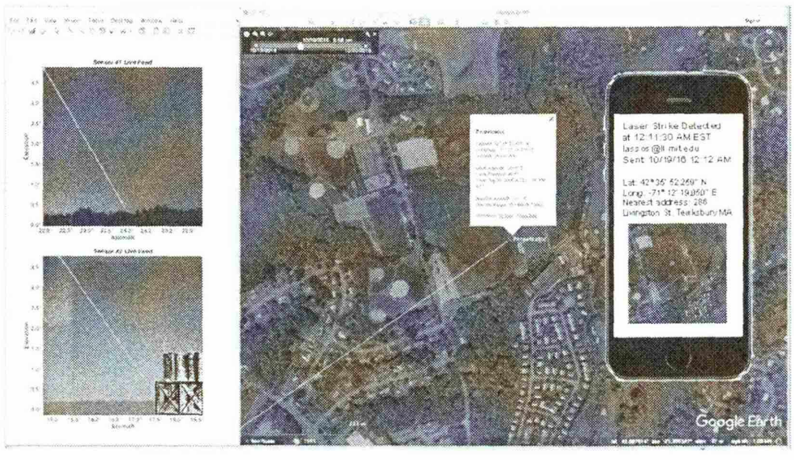

Figure 7. Prototype LASSOS Display

V. Next Steps & Operational Testing Recommendations

The testing described in the previous section demonstrates the technical feasibility of the LASSOS concept. The recommended next step is to further refine, automate and harden the system so it is suitable for an extended prototype deployment in an operational setting (e.g., at an airport). Recommended system enhancements are shown on the right side of Figure 4 to allow long duration, all-weather operation, including automating many of the manual calibration steps, installing the sensor inside a ruggedized enclosure and improving the real-time processing algorithms. A notional setup at an airport is illustrated in Figure 8. This assumes a system designed to protect near-airport airspace, such as the final 10 nmi of final approach to an airport. Two sensors are located on the airport approximately 1-2 nmi apart in locations which are optimized for the dominant arrival and/or departure flows. Given the airport configuration on any given night, the sensors would be oriented in the direction of the aircraft paths. Automated laser streak detection algorithms would be running continuously, and when a streak is detected the geolocation algorithms would be triggered. Expert user verification may be appropriate (e.g., while the system is being tested or tuned for a new application), followed by law enforcement alerting via appropriate mechanisms. For example, this may involve a display in a police dispatch center, or automated email being sent to appropriate law enforcement personnel to allow a rapid response. Finally, post-event analysis activities could involve event reconstruction to support prosecution, for example calculation of closest point of approach between the laser beam and the aircraft and whether the laser beam was tracking the aircraft flight path to indicate intent of the perpetrator to interfere with a flight.

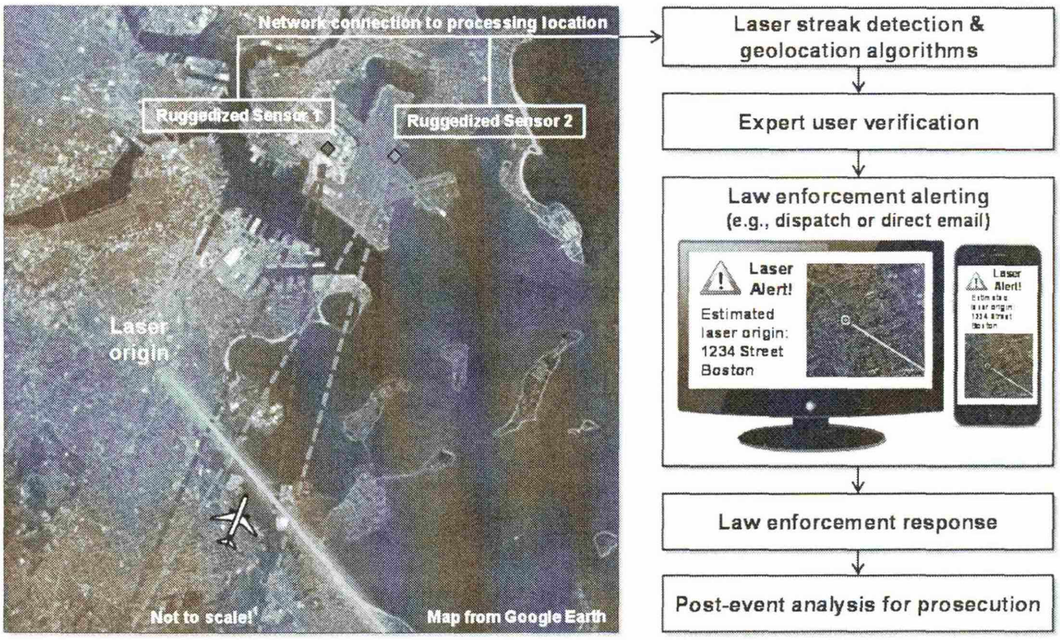

Figure 8. Notional LASSOS Operational Prototype System

VI. Conclusions

Laser strikes against aircraft have increased greatly in the last decade, driven by the availability of cheap powerful lasers and a lack of deterrence due to the challenges of locating and apprehending perpetrators. Although some mitigation options exist, there is an important role for a persistent ground-based sensor which can rapidly and accurately geolocate the origin of a laser beam in a protected region of airspace and disseminate this information to law enforcement to allow a timely and targeted response. This paper has described the development and testing of a proof-of-concept ground based sensor system to perform these tasks. Recommendations for an operational prototype at an airport have also been presented.

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