Impact and Mitigation of GPS-Unavailability on Small UAV Navigation, Guidance and Control

White Paper

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November 19, 2012

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[*] The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The authors acknowledge the United States Department of Homeland Security for supporting the work reported here through the National Center for Border Security and Immigration under grant number 2008-ST-061-BS0002. However, any opinions, findings, conclusions or recommendations in this paper are those of the authors and do not necessarily reflect views of the United States Department of Homeland Security.

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Executive Summary

This paper examines the impact that denial of Global Positioning System (GPS) services would have on the operation of Small Unmanned Aerial Vehicles (SUAVs) used in law enforcement applications. Autonomous operations of SUAVs requires continuous and accurate measurements of the vehicle's position, velocity and attitude (orientation). Existing commercially available SUAV autopilots rely on GPS for determining position and velocity. They determine attitude using a GPS-aided Inertial Navigation Systems (INS). This means that existing autopilots will have difficulty navigating, guiding and controlling SUAVs when GPS is unavailable. The unavailability of GPS is a credible fault mode which SUAVs need to be robust against.

GPS can become unavailable in a given geographical area because of Radio Frequency Interference (RFI) or a spoofing attack. RFI can be the result of unintentional, off-band transmissions by otherwise legitimate radio equipment (e.g, radios, TV broadcasts, radars, etc.) or a malicious jammer. The effect of RFI is to create a *GPS-stressed* or *GPS-denied* environment. The former is an environment where the quality of GPS is degraded (e.g., intermittent availability, less accuracy) while the latter is one where GPS is completely unusable. A spoofing attack is one where a malicious transmitter broadcasts a GPS-like signal with the intent to deceive GPS users.

For dealing with GPS-stressed environments we propose the use of vector tracking GPS receiver deeply integrated with Inertial Navigation Systems (INS). This is an existing technology for which some military products exist. The existing solutions, however, use export controlled sensors, are costly and may not satisfy the Size, Weight and Power (SWaP) requirement of SUAVs. Thus, developing a prototype of a low cost system which integrates a software-defined vector GPS receiver with inertial sensors is proposed.

To deal with the GPS-denied condition, a non-GPS backup or alternate navigation system is proposed. The proposed system is an aided-dead reckoning navigator which fuses inertial sensors with an aiding sensor. A system that is very similar to the one proposed has been successfully tested in a General Aviation application. The key to adopting this system to SUAV applications hinges on identifying candidate aiding systems. Accordingly, four potential aiding systems are identified: Vision or camera-based navigators; cell phone signal-based navigators; cooperative navigation systems; and signal of opportunity navigation systems. The advantages and disadvantages of the various approaches and what SUAV mission they will be suitable for are identified.

To deal with the spoofing attack, we propose using a GPS signal authentication system. An example of such a system has been developed by the authors of this white paper for cargo and ground vehicle tracking purposes. With minimal modification this system architecture can be integrated into SUAVs and the ground station used to operate them.

A potential work plan for developing and testing prototypes of the GPS backup navigators is proposed. The outcome of the proposed work will be, in part, to develop requirements that can be used by avionics manufacturers in developing SUAV autopilots which can deal with GPS-stressed, GPS-denied and GPS-spoofed environments.

1 Introduction

This paper examines the impact that denial of Global Positioning System (GPS) services would have on the operation of small unmanned aerial systems (SUAS).[1] The term UAS as used in this paper is taken to mean a system consisting of an unmanned aerial vehicle (UAV) and associated support systems including a ground station and data link. UAVs span a wide range in size and complexity, where some of the largest ones such as the Global Hawk, Predator or Reaper, weigh several thousand pounds and are large enough to require the use of an airport for launch and recovery operations. For the applications considered here, the UAVs in question are small and in the 5-to-10-lb weight range. We will refer to these vehicles as small UAV or SUAV hereafter. SUAVs are small enough to fit in the trunk of a law-enforcement squad car for easy transportation. Therefore, they do not require large infrastructure for launch and recovery operations. They fall in the the so-called "Class I" category of UAVs as defined in [1]. They can be operated remotely by a human operator or autonomously by an automatic pilot. It is not uncommon for many SUAS that can operate autonomously during a major part of their mission to nevertheless require a human operator for the launch and recovery phase of operations. In this paper we will further restrict our focus to SUAS operations in support civilian law enforcement applications. In these applications UAVs are used as mobile sensor platforms which can be used to remotely gather data, inspect infrastructure, or serve as nodes for *ad hoc* communication networks during emergencies [2] - [5].

1.1 GPS: Key Sensor for Navigation, Guidance and Control

Autonomous operations of SUAVs requires a continuous and accurate measurements of the vehicle's position, velocity and attitude (orientation). These three quantities together are formally referred to as the UAV's *navigation state vector* or simply the UAV's *state*. The UAV's navigation and attitude determination systems directly measure or indirectly estimate these states and make them available to guidance and control systems. The position state estimates are used by the guidance system to define a safe path (or waypoints) through the sky consistent with the goals of the mission instructions uploaded by the operators from the ground station. The velocity and attitude estimates, on the other hand, are used by the control system to determine how the the control surfaces and throttle should be manipulated to ensure the UAV follows the guidance system instructions. The relationship between navigation, guidance and control is schematically depicted in Figure 1 which is a functional block diagram of a typical SUAV autopilot such as Could Cap's Piccolo [7]; Micropilot's MP2x28 family of autopilots [8]; the open source autopilot Paparazzi I [9]; or the Microbotics autopilot based on the MIDG INS/GPS package[10].

As can be seen in this figure GPS is the key navigation sensor and it is an integral part of virtually all low cost avionics aimed at SUAV operations. It is a low cost, off-the-shelf solution for measuring position and velocity accurately. While GPS can be used to directly and accurately

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[1] GPS is Global Navigation Satellite Systems (GNSS) maintained and operated by the United States Department of Defense. At present the only other operational GNSS is the Russian Federation's GLONASS. In the near future one regional system and two additional global systems will become available. The regional system is Japan's Quasi-Zenith Satellite System (QZSS). The two global ones are China's system known as Compass or Beidou and the European Union's system called Galileo. While the focus of this paper is on GPS, the ideas presented are equally applicable to the other GNSS. More importantly and as will be discussed later in this paper, the availability of multiple GNSS does not solve the GPS- or GNSS-denial problem. This is because, the various GNSS use signals that are similar in design and close in frequency. Thus, in a given geographical area a single jammer or interference source can potentially block all GNSS signals simultaneously.

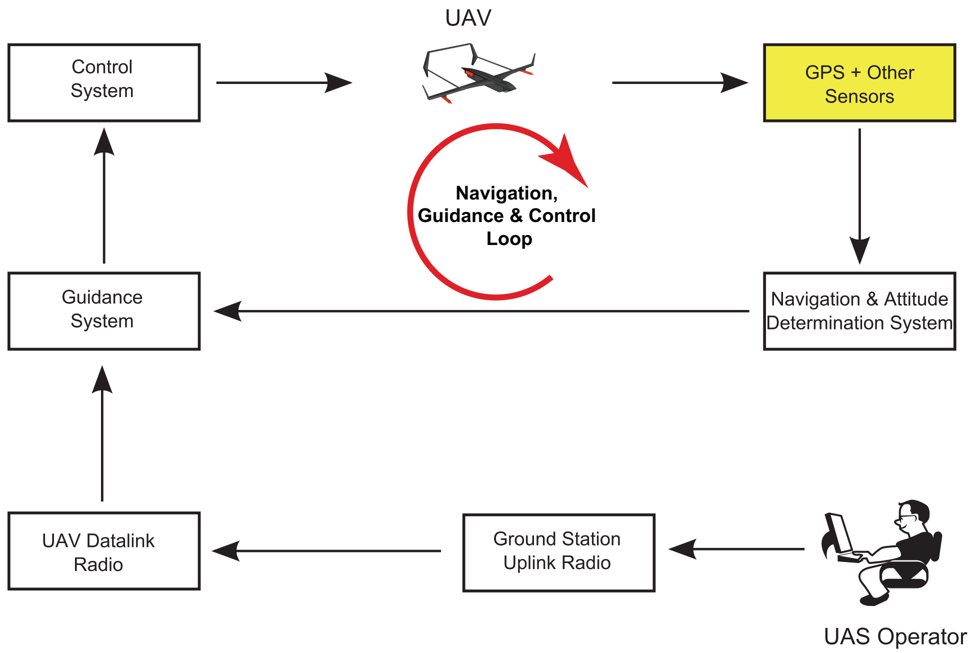

Figure 1: Block diagram of the navigation, guidance and control loop of a generic SUAV Autopilot. Note that GPS is a node in the navigation, guidance and control loop. Its unavailability directly affects navigation and guidance while it indirectly affects control.

measure attitude, it not normally used for this in SUAV applications. This is because measuring attitude this way requires multiple GPS receivers with antennas spaced far apart on the vehicle [6]. Most SUAS are not large enough to allow installation of widely separated antennas. Therefore, the more common approach used for attitude determination in SUAVs is to use the combination of a single GPS receiver/antenna and a low cost Inertial Navigation System (INS). This combination is called a GPS-aided INS.

1.2 GPS-Aided Inertial Navigation Systems

Inertial Navigation Systems or INS are systems which determine position, velocity and attitude of a vehicle by measuring its acceleration and rotation rates. The sensors used by an INS to measure acceleration and rotation rates is called and Inertial Measurement Unit (IMU). Since an INS relies on an IMU that is installed on the vehicle and does not require interaction with any information outside of the vehicle, they are self-contained navigation systems that can be used in all environments (i.e., underwater, in buildings, caves, etc). While this is the strength of INS, their primary weakness is that the position, velocity and attitude solution they provide have errors that tend to drift with time. This requires that they are periodically “reset” by another navigation sensor or external information. The rate at which the errors drift depends on the quality (and, thus, cost) of the IMU used. A rough rule of thumb for INS error growths is given in Table 1 and the monikers listed in the table are used to identify the IMU. Because of Size, Weight and Power (SWaP), as well as cost consideration, most SUAV autopilots use IMUs in the quality range described as “automotive/consumer” category. The position drift on INS that use this grade of IMU is greater than of 50 meters (150 ft) per minute.

In view of this limitation of INS, virtually all SUAV autopilots use GPS-aided INS for the

Quality Moniker or Label	**Position Error Drift Rate (km/hr)**	**Approximate System Cost**	**Typical Applications Used in**
Strategic Grade	less than 0.001	\$10,000,000+	Submarines, ICBM
Navigation Grade	1.5	\$50,000 - \$100,000	Aircraft navigation
Tactical Grade	20 - 100	\$10,000 - \$20,000	Smart munitions
Automotive/Consumer Grade	100 +	\$100 - \$10,000	Cars, UAVs, Toys

Table 1: Quality moniker and rule of thumb for INS/IMU drift rates. Without any aiding, a “navigation grade” or “strategic grade” IMU would be required to match the performance of GPS.

navigation system. GPS is used to periodically reset the position and velocity estimates made by the INS. This information allows to indirectly correct the attitude errors as well. Therefore, the combined GPS/INS system provides a drift free estimate of position, velocity and attitude. A generic functional diagram of a GPS-aided INS is shown in Figure 2. As will be shown later, when GPS is unavailable, the architecture shown in Figure 2 will have to be modified. The purpose of this paper is, in part, to discuss how this architecture can be modified to support operations in environments where GPS is not available.

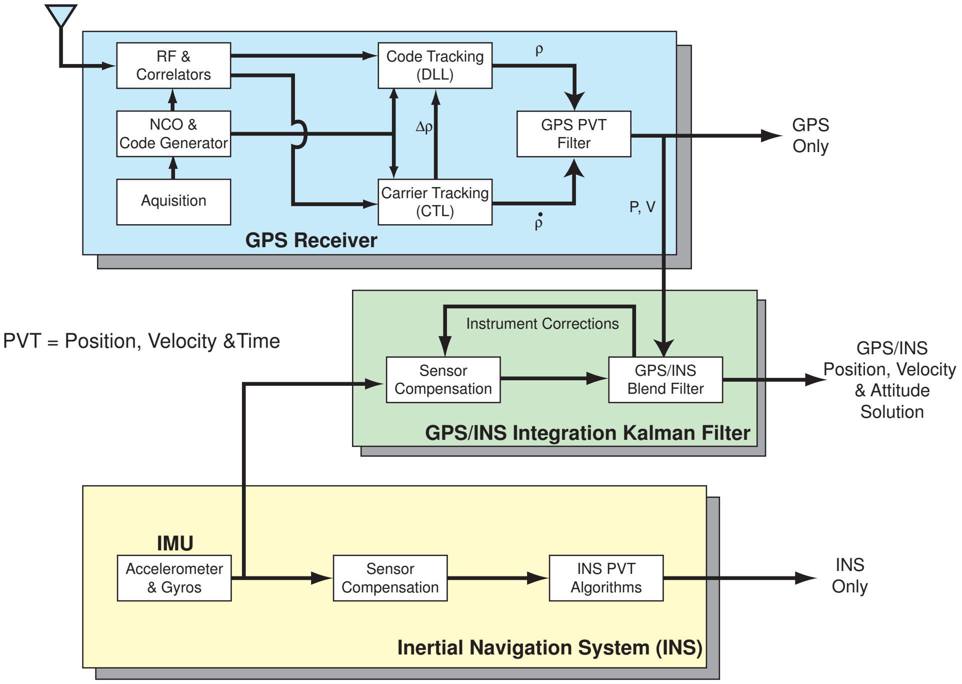

Figure 2: Typical architecture of a GPS-aided INS found in most SUAV autopilots.

1.3 Performance in GPS-Denied Environments

Table 2 lists some commercial, off-the-shelf GPS/INS systems that are used in both small and large UAVs. The third column identifies a key performance metric for the systems which is the expected position and attitude error drift rate if GPS becomes unavailable. This is sometime called the “free-inertial coasting” or “stand-alone inertial mode” performance of the INS. What is apparent from this table is that while there are some GPS/INS systems which can operate satisfactorily for some time after GPS is lost, they do not satisfy the SWaP or cost constraints of most SUAVs. For example, despite being very accurate in stand-alone inertial mode, Rockwell Collins Athena 611 Integrated Flight Control System [12] can be prohibitive from a SWaP perspective. The cost of this unit also precludes its use on low-cost UAV applications. On the other hand, lower end systems such as the MiDG IIC [10] and the MTiG-700 [11] have such a poor navigation solution during extended GPS outages that they can only provide attitude solution which is crucial to maintaining UAVS stability. The attitude solution during these outages is usually obtained using methods such as described in [6] or [13] - [15] and relies on additional sensors such as magentometers and air speed sensors available in most IMU packages.[2] Thus, while it is possible to provide and backup attitude solution during GPS outages, it is not clear how one provides a similar position and velocity solution. The purpose of this paper is to discuss this problem in more detail and suggest potential solutions.

	Product	Size, Weight, & Power	Inertial Coasting Performance (RMS)	Cost
Low Cost Systems	Piccolo SL/Crista IMU	5.1” × 2.34” × 0.76” 0.24 lbs 4 W max	Position Error: N.A[3] Pitch & Roll Error: > 0.6° Yaw Error: >1.8°	$7,000
	MIDG IIC	1.5” × 0.8” × 1.7” 0.12 lbs 1.2 W max	Position Error: N.A[3] Pitch & Roll Error: > 0.4° Yaw Error: >2.0°	$6,750
	Xsens MTiG-700	0.06” × 0.04” × 0.02” 0.12 lbs < 1 W	Position Error: N.A[3] Pitch & Roll Error: >1.0° Yaw Error: >1.0°	$4,950
High End Systems	NovaTel SPAN CPT	5.9” × 6.6” × 3.5” 1.4 lbs 15 W max.	Position Error: 7.2 m/min Pitch & Roll Error: 0.03°/min Yaw Error: 0.1°/min	$25,000 + antenna
	Rockwell Collins Athena 611	6.1” × 4” × 6.8” < 10 lbs 18.5 W nominal	Position Error: 1.5 km/hr Pitch & Roll Error: 0.05°/hr Yaw Error: 0.1°/hr	>$100,000

Table 2: Commercial Off-the-shelf INS/GPS Systems

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[2] We should note that while there are other approaches used to determine attitude using low cost IMUs aided by other sensors such as magnetometers, these methods are not as robust as the GPS-aided INS solution. For example, they may generate an erroneous solution if the SUAV is operated in turbulent air where the vehicle is making *non-coordinated* turns. While they are suitable for a backup mode of operation they cannot be considered a primary mode of attitude determination

[3] During GPS outage, the system degrades to AHRS mode where error drift due to integrating rate gyro output is arrested using aiding sensors such as a magnetometer and an accelerometer triads. Position error drift rate is typically greater than 50 m/min.

1.4 Problem Statement and Paper Organization

In view of the discussion above, it is apparent that the continued availability of the GPS signal is indispensable for safe operation of SUAV. The loss of it would affect the ability of these vehicles to navigate safely and be controlled safely. It is well known, however, that GPS (and any other GNSS) is susceptible to unintentional Radio Frequency Interference (RFI) or malicious jamming and, thus, leads us to ask the following question: *How can we make SUAVs immune or robust to the loss of GPS*? The purpose of this paper is to examine this question in some details. It will also suggest avenues of research and inquiry that should be pursued in order to start developing technical and operation solutions to mitigate this vulnerability of SUAVs to GPS outages.

Accordingly, the remainder of this paper is organized as follows: First, in the section that follows we will describe the issue of GPS vulnerability to interference and jamming while making a clear distinction between *GPS-stressed* and *GPS-denied* operations. In Section 3 we will discuss solutions for dealing with SUAV operations in the GPS-stressed environments. As we will show, dealing with GPS-stressed environments may not require alternate, non-GPS, backup navigation system. Dealing with operations in GPS-denied environments, on the other hand, will require a backup navigation and attitude determination capability. As such, Section 5 will identify candidate backup systems and discuss their pros and cons relative to SUAV operations. Finally, we will discuss some suggestions for future research which will help answer the need for a GPS backup in support of SUAV operations.

Note that another important issue that must be addressed before SUAVs can be used for law enforcement operations is how they can be integrated into the National Airspace System (NAS). In particular, the so-called “sense-and-avoid” problem the mitigation of collision risk associated with it will have to be addressed. While these issues are important and will be briefly addressed in Section 5.4, a detailed discussion of them is beyond the scope of this white paper. The interested reader can find a detailed discussion of these issues in representative papers such as [16] and [17].

2 GPS Vulnerability

GPS is a GNSS operated by the United States Department of Defense (DoD) which was declared operational in 1995 [18]. This system uses a constellation of Medium Earth Orbit (MEO) satellites which broadcast a continuous signal modulated on L-band radio-frequency carriers. The signal civilian users of GPS need for positioning is broadcast on a carrier called L_1 with a center frequency of 1575 MHz. A second carrier called L_2 at 1226 MHz is used to broadcast signals which can be accessed by DoD authorized users only. Since the positions of the satellites are precisely known, a terrestrial user can determine their position accurately by processing the ranging signals from at least four of the GPS satellites.[4] From the point of view of a SUAV, the threats that can deny the use of GPS can be divided into two categories: Radio Frequency Interference (RFI) and spoofing.

2.1 Radio Frequency Interference (RFI) and GPS

The GPS signal broadcast by the satellites is inherently a low power signal. The signal power seen by terrestrial user is -160 dBw and is due to the fact that the GPS satellites are very distant (approximately 20,000 km above the surface of the Earth). By the time their signal arrives at a

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[4] At least four ranging signals are required as the problem of positioning using GPS has four unknowns that need to be solved for: the three position coordinates of the user and time.

terrestrial user, it has traveled a large distance and has been spread over a large area of Earth. In more intuitive terms, this situation is analogous to the power received in Los Angeles from a 60 Watt light bulb in located New York city. In practical terms this means that the GPS signal received on Earth is below the ambient background noise floor. GPS receivers are capable of extracting the signal out of the ambient noise floor and processing it. However, if the magnitude of the background noise floor is elevated, GPS receivers will have problems extracting the signal. Equivalently, if the background noise floor remains the same but the GPS signal is attenuated on its transit from satellite to user (e.g., by interference from other radio-frequency signals of the same frequency or by obstructions such as buildings, trees, etc), the receiver may have problems tracking it.

Attenuation of the GPS signal caused by obstructions such as building and trees is problematic. Its effect is normally temporary and cleared when the user moves to a new location where there are no obstructions. Furthermore, for SUAV operations this is not a serious concern as most operations would be above obstructing structures.[5] More problematic is attenuation caused by other interfering radio signals which includes so-called *wide band* or *white noise* interferers or jammers. These are radio-signals that increase the ambient noise floor. They are more problematic because it does not have to be very strong to affect a receiver's ability to track the weak GPS signal. This means any "stray" radio signal from legitimate devices or transmitters can potentially interfere with GPS. We use the term "stray" to distinguish that the interference with GPS may not be intentional. For example, failed or low quality electronics in an otherwise legitimate device can cause stray harmonics which will interfere with the GPS signal in their vicinity. This is in contrast to an intentional jammer which deliberately generates a signal to affect or impede the performance of GPS receivers in a given geographical area.[6]

Whether it is an un-intentional interferer or intentional jammer, the effect is the same. Furthermore, since the GPS signal received by all users is carried on the same L_1 frequency, a single interferer can affect all the GPS users in a given geographical area. We will use the the term Radio Frequency Interference (RFI) for any radio signal (intentional or un-intentional) that affects the ability of GPS receivers to track the signals required for navigation. The RFI can be a radio signal at a discrete frequency ("narrow band" or "tone") or a wide-band signal that elevates the noise floor. The key point is to note that a *single* RFI source can deny GPS services to *all* users in a given geographical area.

2.1.1 GPS-Stressed vs. GPS-Denied

The effect of RFI on GPS in a given geographical area is to either make it difficult for GPS receivers to track the signal or prevent them from tracking it all together. We will call the former scenario a *GPS-stressed* environment and the latter a *GPS-denied* environment. In a GPS-stressed environment the GPS signal is altered from its nominal characteristics. Unless special measures are taken, in a GPS-stressed environment conventional receivers will not be able to track the signal properly. The result can be an intermittent GPS position solution or inaccurate position solutions.

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[5] There are operations where this could be a problem. For example, search and rescue operations in steep-walled canyons can cause signal GPS signal obstructions. In addition, there have been envisioned concepts of operation where SUAVs are used to inspect infrastructure such as bridges and dams. In this case, the infrastructure being inspected can end up obstructing the GPS signal.

[6] The GPS constellation is being replenished by newer satellites capable of broadcasting two new civil signal: One on L_2 called L2C and a second new one called L_5 at 1176 MHz. Therefore, future civilian users will have access to three signals which is expected to increase accuracy and potentially enhance GPS robustness to RFI.

There are numerous existing and emerging technical solutions which will allow continued performance in GPS-stressed environments. On the other hand, in a GPS-denied environment RFI has rendered GPS completely unusable. Receivers, regardless of their type, will not be able to track the GPS signal. If the RFI source cannot be located and eliminated, then the only way for a SUAV to operate in a GPS-denied environment is to revert to a non-GPS, alternate or backup navigation system.

Note that a single RFI source can lead to presence of GPS-stressed and -denied environments simultaneously. For example, consider the scenario depicted in Figure 3 which shows the effect of a single RFI source or jammer located at a generic downtown airport. How far away a SUAV is from the RFI source will determine whether it is operating in a GPS-stressed or GPS-denied environment. Closer to the RFI source it will be a GPS-denied environment. As one moves farther away from the RFI source, the $1/r^2$ drop-off of RFI signal power will lead to a slow transition into a GPS-stressed environment. Even farther away, one might transition into a GPS-normal environment. The size of the GPS-stressed and -denied bubbles shown in Figure 3 depend on the strength of the RFI source.

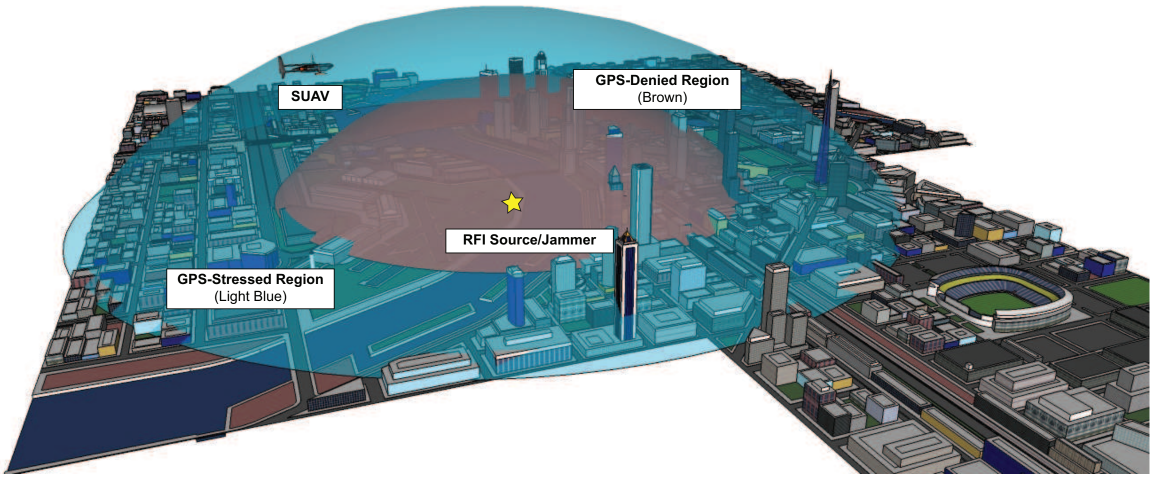


Figure 3: GPS-stressed vs. GPS-denied environments resulting from the presence of a single RFI/jammer source.

2.2 GPS-Spoofing

GPS-spoofing is a denial of service attack whereby a malicious entity generates a GPS-like signal to mislead GPS receivers in a given geographical area. The effect of this is to make receivers “believe” that they are located somewhere other than their actual location. Spoofing attacks are less of an issue for military users of GPS because they have access to an encrypted code on the GPS signal which allows them to reject spoofers. This encrypted code on the current GPS signal is called the P(Y)-code and is sometimes referred to as the *Anti-Spoof Module* [18]. In the future a new code called the M-code will supersede the P(Y)-code. Thus, DoD authorized users are more immune to spoofing attacks.

GPS-spoofing is of more concern for civilian users and specific methods for dealing with it are discussed later in Section 4. At this point, it is sufficient to note that we believe SUAVs should be equipped with a method for detecting the presence of a spoofer. Once a spoofer has been detected, the GPS receiver on the SUAVs should either attempt to ignore the satellite signals that are known to be spoofed or issue an alarm and return to base.

3 Dealing with GPS-Stressed Environments

As noted earlier, GPS-stressed environments are ones in which the GPS signal strength has been attenuated by RFI. Developing GPS receivers that can continue to operate in a GPS-stressed environment has been the subject of research for some time. As a result, several techniques for dealing with GPS-stressed environments have emerged. Of these we will highlight two techniques that can potentially be used on SUAVs to allow operations in GPS-stressed environments: Vector tracking GPS receivers and cooperative/assisted GPS.

For completeness we note that there is a third way to deal with GPS-stressed environments which may not necessarily be practical in SUAV applications. This is the method of using antennas which adaptively adjust their gain to null or attenuate interfering signals. Such antennas are called Controlled Reception Pattern Antennas or CRPAs. There has been a considerable amount of work done to develop CRPAs over the years and there are several commercially available products. While CRPAs will enhance performance in GPS-stressed environments, they are not the solution for GPS-denied operations. Furthermore, from a SUAV point of view, CRPAs may not be a viable solution because most of the do not satisfy the SWaP constraints and/or are very costly.

3.1 Vector Tracking GPS-Receivers

Vector tracking is an advanced way of processing GPS satellite signals which enhances robustness to RFI. To understand how vector tracking provides an added margin against RFI requires comparing it to conventional GPS receivers. Conventional GPS receivers process the satellite signals internally using an architecture called *scalar tracking*. The key feature of scalar tracking is the fact that each satellite's signal is tracked independently by a single channel dedicated to that particular satellite. This is shown in the functional block diagram of a GPS receiver shown in Figure 4. In the digital portion of the receiver (shown in blue), several parallel channels for signal acquisition, tracking and data demodulation are shown. Each channel is independent in that there is no information exchange between them. In contrast, Figure 5 shows a functional block diagram of a vector tracking receiver. In vector receivers all the satellites are tracked simultaneously using an estimator (normally an Extended Kalman Filter). This simultaneous processing of signals helps because, for example, a satellite whose signal has been attenuated by RFI can be aided by information from the other satellites. In the event all satellites are affected by RFI, their signals can all be "pulled together" to increase their effective power. More details on the workings of vector vs. scalar GPS receivers can be found in [19, 20].

The benefits of using vector over scalar GPS receivers can be seen if we consider Figure 6. This figure shows the performance of a vector tracking receiver in a GPS-stressed environment. The figure shows the results of an experiment where satellite signals collected from a GPS antenna at a given location were recorded and later "played back" in both a conventional scalar GPS receiver and a vector receiver. Note that vector receivers are not readily available on the market

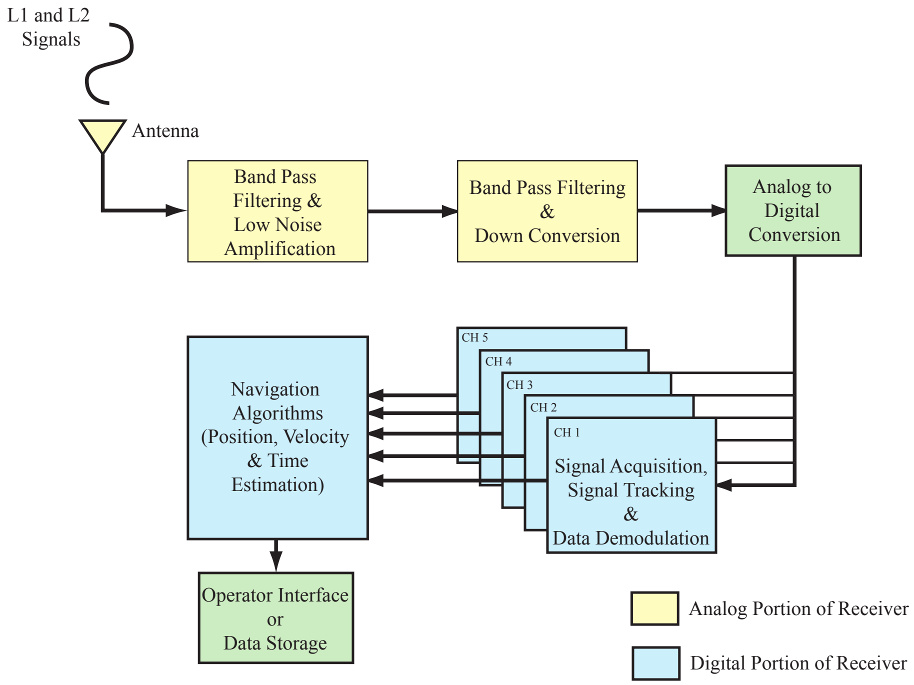


Figure 4: Function block diagram of a conventional GPS receiver.

today. The playback was done in a software-defined laboratory prototype of a vector receiver developed at the University of Minnesota [21] as part of Department of Homeland Security (DHS) sponsored research. We assess the capability of the receiver by calculating the difference between the position solutions generated in a GPS-stressed environment relative to that in a GPS-nominal environment. Viewed another way, we are determining how much degradation relative to a normal GPS environment occurs when the receiver is operating in a RFI environment.

Figure 6 shows the result of this comparison where a vector receiver is attempting to track a signal with various attenuated power levels due to RFI. Attenuation of power to those levels shown in Figure 6 are not uncommon in urban settings. What this figure shows is that the signal can continue to be tracked if a vector GPS receiver is used. While scalar or conventional GPS receivers would stop working at signal-to-noise ratios of less than 40 dB-Hz, vector receivers will continue to work. Even though the accuracy of the position solution of a vector receiver degrades as the the signal power becomes smaller, it can still be used to guide an SUAV out of a GPS-stressed environment.

4 Dealing with GPS-Spoofing

As noted earlier GPS-spoofing is a denial of service attack whereby a malicious entity generates a GPS-like signal to mislead GPS receivers in a given geographical area. The issue is more of a concern for civilian users since DoD authorized users already have a means for dealing with this threat. Recently there has been a number of research efforts which have explored inexpensive ways by which civilian users can counter spoofers [22] - [28].

What these works have shown is that simultaneously spoofing multiple users that can communicate with each other is difficult. This means that a SUAV that is in contact with and can exchange

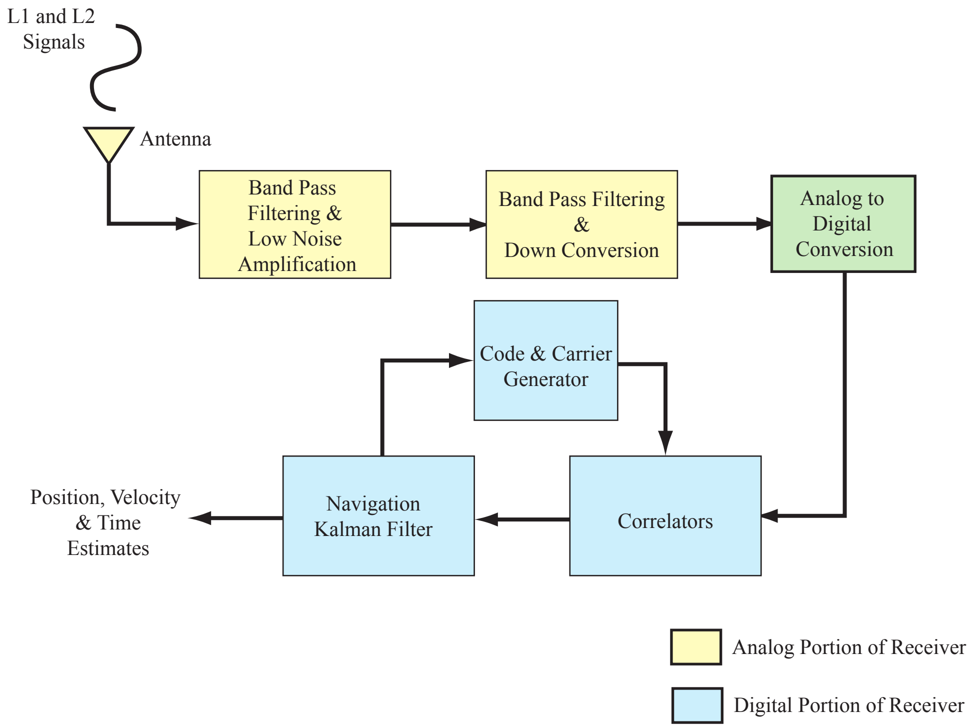
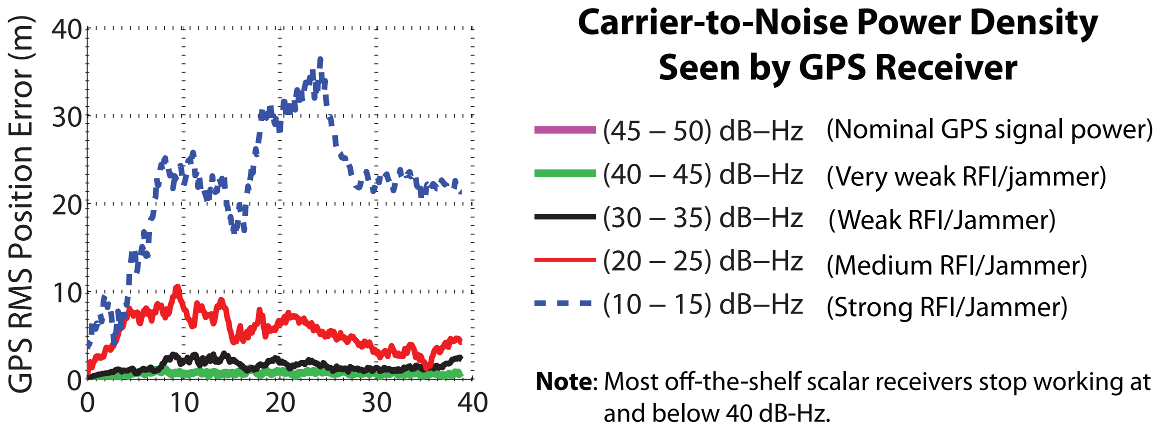


Figure 5: Functional block diagram of a vector GPS receiver.



Note: Most off-the-shelf scalar receivers stop working at and below 40 dB-Hz.

Figure 6: Performance of a vector receiver in a GPS-stressed environment. GPS-stressed environments are those where the carrier-to-noise power densities are less than 45 dB-Hz.

information with other SUAVs or ground-based users will be difficult to spoof. Stated in a different way, while spoofing attacks are indeed credible there are methods for easily countering them on a moving platform such as a small SUAV. The methods discussed in [25] and [26] can easily be implemented in next generation receivers to detect and issue an alarm in the event of a spoofing attack. More relevant to SUAV applications, the system described in [28] and shown in Figure 7 can be used to protect against spoofing attacks. In this system architecture, the SUAV will periodically send samples of the GPS signal it is using to a trusted authenticator. The samples can be sent over a dedicated data link or a cell phone connection. The authenticator then determines whether the

GPS signal being used by the SUAV is genuine or forged by a spoofer. The check involves looking for watermarks that exist in the the current GPS signal. A prototype of this system built by the University of Minnesota has been tested and shown to be able to detect a certain class of spoofing attacks [28].

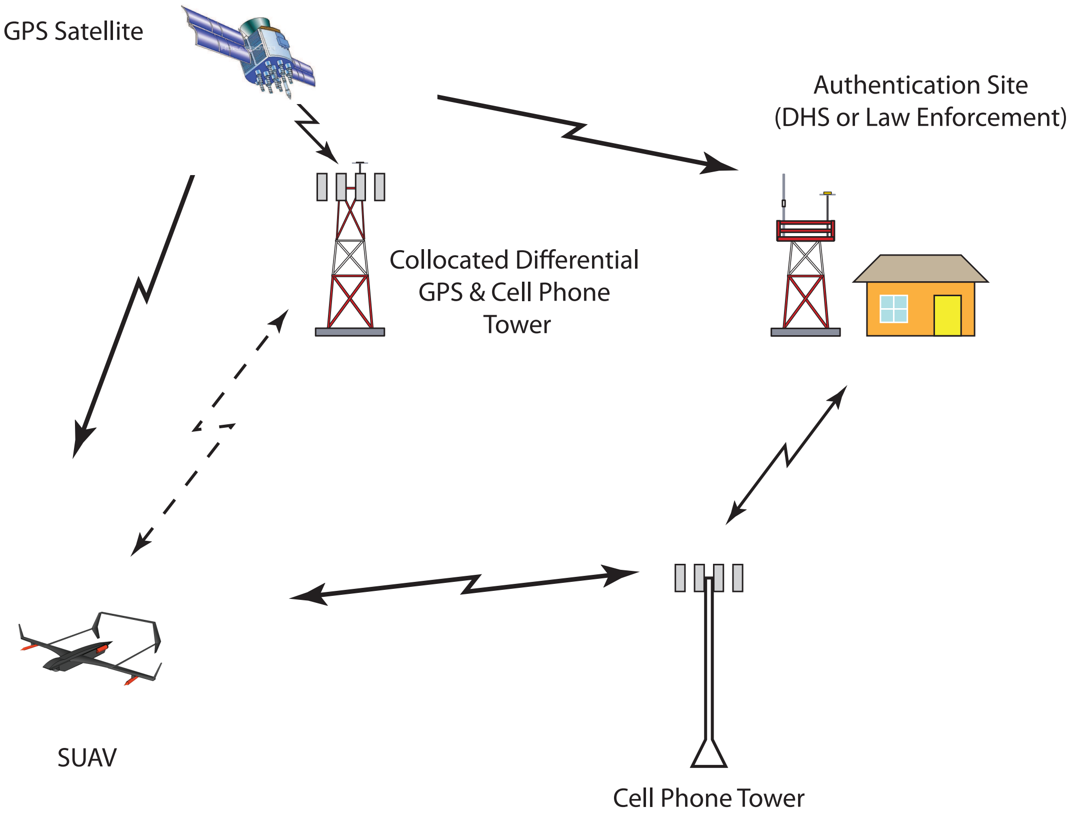


Figure 7: System architecture of a GPS signal authenticator for protecting against GPS-spoofing attacks.

It should be noted that while it is not technically a spoofing attack as defined above, the situation where GPS is being used to track the whereabouts of a remote user presents a similar challenge that has to be dealt with. To illustrate this point, consider the scenario where we are interested in tracking the position of a SUAV launched by someone other than us. This is something, for example, that the Federal Aviation Adminstration (FAA) would do for air traffic control purposes when UAVs are operating in controlled airspace. Another scenario where this might occur is close to a border where a SUAV is being used for civilian purposes and law enforcement wants to track its position continuously so that it is not used for illegal activities. Use of radar to track such vehicles is impractical and a more likely solution would be to use periodic GPS position reports the SUAV makes. In this case, spoofing is a very credible threat. The SUAV with an associate on the ground can use a spoofer to generate a false position report. Thus, those that are tracking the SUAV will think it is one location when in reality it is somewhere else. Once again, however, methods such as those in [23, 28] can be used to deal with this threat.

In summary, GPS-spoofing is a credible threat that needs to be dealt with. While it is possible to spoof a GPS receiver on a SUAV to believe that it is somewhere else than it really is, countering such threat is straight forward. A more sinister threat is the case of remote user whose positions are being tracked using GPS position reports. In this case, a spoofer can be used to easily forge position reports. Methods designed to work with the current GPS signals [28] as well as those intended for future satellite signals [27] will be able to deal with this threat.

5 Dealing with GPS-Denied Environments

For SUAV operations the GPS-denied environment presents the most severe challenge. In a GPS-denied environment RFI has rendered GPS completely unusable and, thus, any GPS receiver will be incapable of tracking a signal. The only way for a SUAV to operate in a GPS-denied environment is to revert to an non-GPS, alternate or backup navigation system. In what follows we will discuss potential non-GPS navigation systems that can serve as a backup system in the event GPS is denied.

5.1 GPS-Denied Navigator Architecture

In GPS-denied environments the typical SUAV autopilot-based navigation system architecture shown in Figure 2 will have to be reconfigured to a system that looks like that shown in Figure 8. The architecture shown in Figure 8 is very similar to a system described in [29] which was flight-tested successfully as a backup navigator for General Aviation applications in GPS-denied scenarios. In simple terms, this system uses a dead reckoning navigator which fuses air speed measurements with an attitude solution derived from an Attitude Heading Reference System (AHRS). The AHRS generates an attitude estimate by fusing rate gyro measurements with magnetometer, airspeed and accelerometer measurements using methods described in [6]. Since the air speed/AHRS dead reckoning solution drifts with time, periodic updates from an aiding system are used. The aiding system is some form of a position fixing system as shown at the bottom of Figure 8. In the case of [29], the aiding system used was Distance Measuring Equipment (DME) . However, for SUAV applications DME may not be an appropriate aiding sensor. This is because, in part, because DME signals are not always available at the altitudes and environments in which SUAV are expected to fly. Therefore, other candidate aiding systems need to be used. In the lower right corner of Figure 8 potential candidate aiding systems suitable for SUAV applications are identified. In the discussion that follows we discuss each one of these aiding systems.

Before we proceed, it should be noted that it is unlikely that a backup system will perform at the same level as GPS with respect to accuracy. It is our belief that, the backup system should be seen as a system that allows the SUAV to navigate out of a GPS-denied environment and return to base. That is, is should be a system that allows the SUAV to metaphorically “limp back home.” Expecting a backup system that is as good as GPS may not be realistic at least for now. While it is possible that such system will become available in the future, waiting until such a system is realized would be to postpone reaping the real benefits that can be realized from using SUAVs in law enforcement operations today. The approach taken in this paper is that of viewing the backup system as a method that allows an SUAV to return to base safely in the event GPS is stressed or denied. We do not view it as a system that will allow launching a mission when it is known *a priori* that GPS is unavailable.

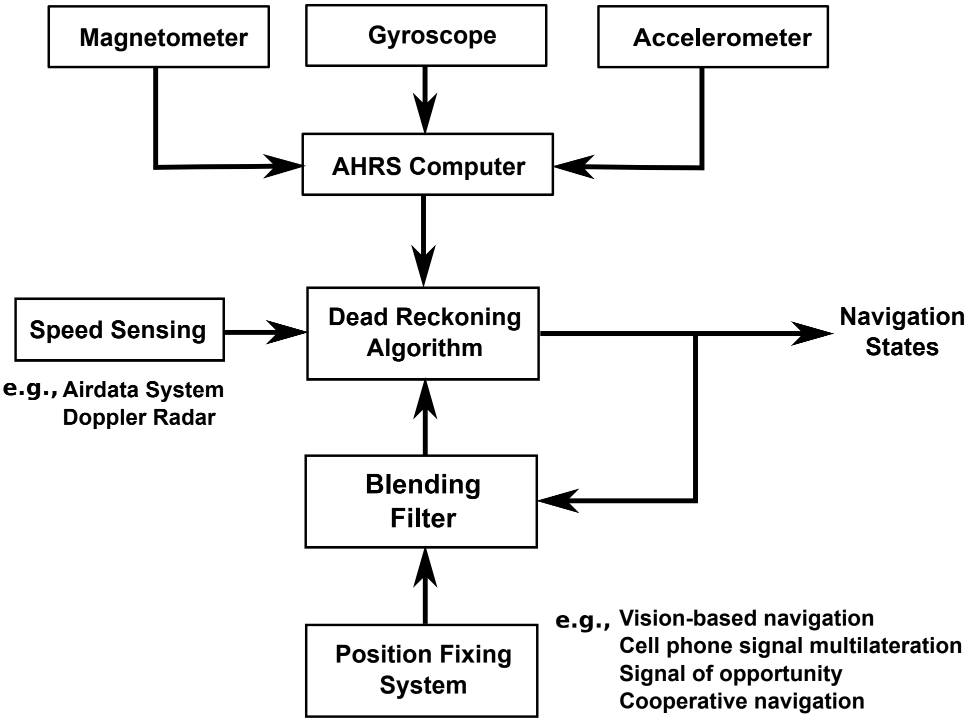


Figure 8: System architecture of a GPS-backup, aided dead reckoning navigator.

5.2 Vision-Based Navigation

Vision-based navigation systems determine the position and attitude of a user from images taken by a digital camera. Since the process of taking a digital image and extracting a position and attitude solution is a computationally intensive process, current computers that satisfy the SWaP constraints for SUAVs will not be able to generate a vision-based solution at a high rate. Thus, on their own vision-based navigation systems cannot be used for SUAV navigation, guidance and control. If the high update rates required for SUAV control are necessary, vision-based navigation system will have to be coupled with an INS or dead reckoning system. When coupled, the INS or dead reckoning system will provide the high rate position and attitude solution needed for SUAV navigation, guidance and control. The vision-based navigation solution is used periodically to provide updates which bound the drift of the INS or dead reckoning solution.

5.2.1 Description of the Method

In operation of a vision-based aiding system, the first thing that happens is that a camera takes a picture of the scene below the SUAV. Then the image is processed by a feature extraction program to identify and catalog *feature points*. The feature points are objects in the image that can be easily identified as discrete entities. For example, a manhole cover in an image may be a feature point. Note that sometime feature extraction programs will identify a collection of points that do not necessarily constitute a discrete object as a feature. A situation like this would be, for example, if part of a manhole cover and a lane marking next to it were lumped together as a feature. Regardless, once the features are identified, they are cataloged and stored in a temporary database. How these feature points are used to determine position and attitude depends on whether the vision-based

Vendor (Model)	Est. Price (USD)	Size (W x H x L) (mm)	Weight (g)	Power (W)
Elphel 353	$3,000	44 x 45 x 118	235	2.4-5.8
Intersense IS-1200	$1,000	47.7 x 29.4 x 25.8	58	1.7

Table 3: Specifications for the Elphel 353 Intersense IS-1200 camera-IMU systems.

navigation system is operating in an *absolute mode* [30, 31] or *relative mode* [32].

In the absolute mode the vision-based navigation system will determine the global position coordinates (like GPS) of the SUAV. It does this by comparing the just-captured image with a reference image and matching feature points in both images. The reference image is an image of the area below the SUAV which includes the scene just captured but was prepared before hand. This preparation includes assigning position coordinates to each point in the image. For example, if the there is a manhole cover in the reference image, the position coordinates of the manhole cover will have been identified prior to the image being used. We use the terms *surveying* or *geo-tagging* to the process of assigning position coordinate to points in an image. The surveying or geo-tagging can be done *a priori* when GPS is available. In the GPS-denied environment when the just-captured image is compared to the reference image, the position (or world) coordinates of the matched feature points will be known. Knowing the world coordinates of the feature points and their pixel coordinates in the image plane of the camera allows determining the position and attitude of the SUAV.

In the relative mode of vision-based navigation, the first image taken by the SUAV serves as the first reference image. However, unlike the reference image used in the absolute mode this image will not be surveyed or geo-tagged. Therefore, when subsequent images are compared to this reference image, the position and the attitude of the UAV relative to position and attitude where the first image was taken will be known. Once the SUAV has flown far enough where the scene below does not overlap with the first image taken, a new reference image is selected from one of the images taken subsequent to the first reference image. The process is, therefore, one of “bootstrapping” a position and attitude solution from a series is images. The relative mode is easier to implement than the absolute mode in that it does not require the time consuming and tedious process of surveying or geo-tagging. It is less accurate, however, as any errors introduced during the process of bootstrapping from one image to the next will propagate forward in time and continue to build-up.

5.2.2 Pros for Vision-Based Navigation

There are two major advantages for using vision-based navigation as a backup in a GNSS-denied environment. First, the hardware technology required to implement these system is, for the most part, in existence. Figure 9, for example, shows two separate off-the-shelf, integrated camera-IMU systems that can be used to implement a vision-based navigation system. The specification for these two sensor systems is given in Table 3. From this table it can be seen that cost of the either system is rather modest and they both easily satisfy the SWaP requirements of most SUAVs. The second advantage of vision-based navigation systems is that they are completely self-contained and do not require infrastructure external to the SUAVs.

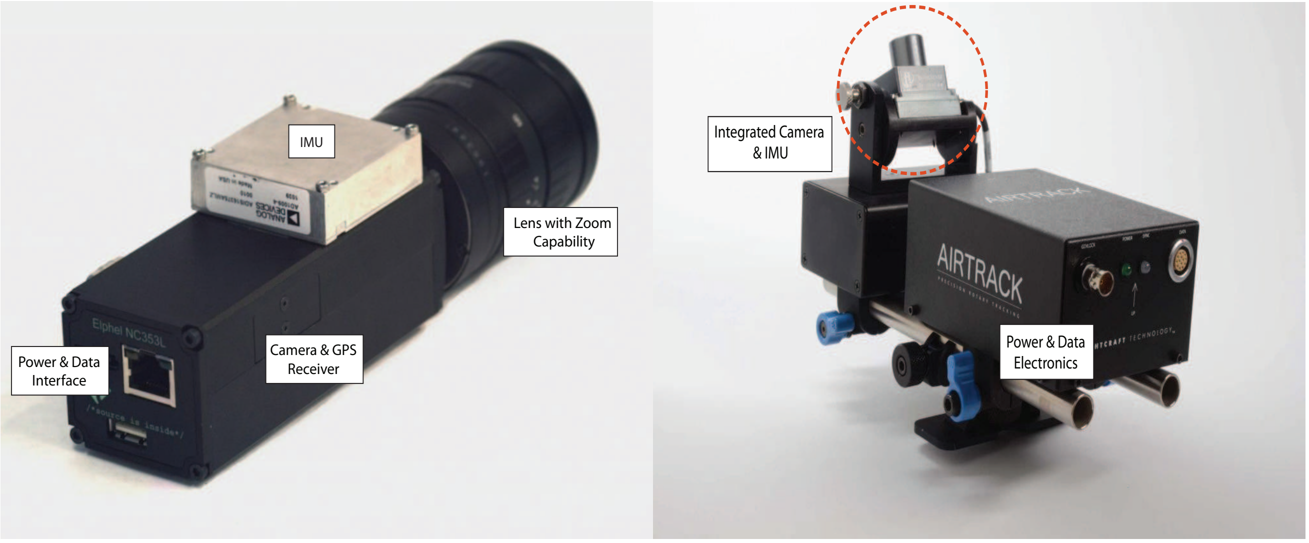


Figure 9: Examples of off-the-shelf, integrated camera-IMU systems. (a) Elphel 353 (left) from [33]. (b) Intersense IS-1200 (right) from [34]

5.2.3 Cons for Vision-Based Navigation

One of the major disadvantages of vision-based navigation is that it is susceptible to weather and environmental effects such as smoke, fog and haze. These will affect the ability of the camera to identify features in captured images. Furthermore, lighting effects that can widely vary during a given day will have a significant impact on the ability of the cameras to capture images from which feature points can be extracted easily. Operations over terrain that lacks contrast for feature detection (e.g., snow covered terrain or large bodies of water) are also problematic. The combination of these factors implies that a vision-based navigation system is not an all-weather/all-terrain solution for dealing with GPS-denied scenarios.

Another issue that needs to be considered is the complexity of the algorithms. In the case of the absolute mode of vision-based navigation, a large database of geo-tagged reference images will have to be carried by the SUAV. This in itself is not that significant of a limitation as only a small subset of the database needs to be uploaded to the flight computer of a SUAV for each individual flight. However, the ability of the small flight computer to process the information in a short period of time and generate accurate and unambiguous position solution is not clear. The relative mode of vision-based navigation will obviate some of these problems since large image databases are not required. The shortcoming of the relative mode, however, is that position error grows with time and, thus, cannot be relied on for a long GPS outage. Furthermore, while the relative mode problem has been studied in some detail for ground robotics applications, it has not been examined closely in UAV applications. There is a significant difference between the terrestrial robotics application and the UAV applications. In the UAV problem all the feature points are *below* the vehicle while in terrestrial robotics application feature points are all around the vehicle. Furthermore the speeds involved in UAV flight are greater which means the scene below the UAV will be changing rapidly. Thus, the utility of the relative mode of vision-based navigation for a low flying UAV is still unclear and is an area that needs close examination.

In summary, vision-based navigation is potentially a good candidate for a backup navigation system. However, while there has been an extensive amount of work done on characterizing the algorithms for doing vision-based navigation in terrestrial robotics application the same level of treatment for UAV application has not been done. The UAV problem is significantly different and will require further study. Furthermore, the vision-based navigation approach is not an all weather solution. This does not mean that it should not be considered for the GPS-denied scenarios. Rather, it will have to be one of many solution that are used simultaneously by a SUAV to negotiate a path out of a GPS-denied environment.

5.3 Positioning Based on Cell Phone Signals

These days cell phones and cell phone towers/transmitters are ubiquitous. It is well-known that cell phone signals are used to determine the position of individuals making E-911 calls. Even though the position solution generated by using cell-phone signals may not be as accurate as GPS, they can, in principle, be used as an aiding source for an INS or a dead reckoning navigator in GPS-denied environments.

5.3.1 Description of the Method

Signals from cell phone towers can be used in at least two ways to determine a position solution. The first approach is method sometimes referred to as “finger printing.” At any given location where there is cell phone coverage one normally receives signals from multiple cell towers. The strength of the signal received from a particular cell tower depends on many things but one of them is distance. Therefore, at a given location the relative strengths of signals from multiple cell towers will have an identifiable pattern or relation which can be used as a “finger print” of the location. A catalog or map which relates position to finger print is generated ahead of time when GPS is available. The catalog or map can be updated regularly to take into account new cell phone towers or factors which affect the signal strength in a given location.

Once the map described above is made then in a GPS-denied environment a machine learning algorithm can be used to determine position of an SUAV relative to this map. In [35] it was demonstrated that this method can achieve accuracies on the order of ± 200 m. As demonstrated in [29] this accuracy is sufficient to aid a low cost dead reckoning navigator like the one shown in Figure 8. The second method in which cell phone signals can be used is in the traditional multi-lateration approach. If cell towers, whose position coordinates are known (or can be determined) can be used as ranging or signal-direction-of-arrival sources, then a multi-lateration position solution can be computed.[7]

5.3.2 Pros for Cell-Phone-Based Navigation

There are two major advantages of using cell phone signals as a backup in a GPS-denied environments. The first advantage was noted earlier and it is the fact that cell phone towers and signals are ubiquitous in and around urban settings. Second, the technology for extracting information from cell phone signals that can be used for navigation exists and, thus, a prototype system for evaluation can potentially be put together quickly. More importantly, because of the large user base of cell phones, the hardware required for such a system may not be very expensive.

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[7] Multi-lateration is a term used to express the generalized idea of triangulation. While the term triangulation implies only three ranging or direction measurements are used, multi-lateration implies that more than four measurements can be used.

5.3.3 Cons for Cell-Phone-Based Navigation

One obvious disadvantage of using cell phone signals lies in the fact that coverage may be sparse in areas where there is definitely interest in using SUAVs. For example, in border security application there are areas which are very remote where the use of SUAVs would be beneficial but cell phone coverage is sparse (e.g., stretches of the US/Canada border in northern Minnesota).

In areas where coverage is not sparse there are some technical unknowns that need to be addressed before cell phone signals can be considered acceptable as a backup for GPS-denied scenarios. Perhaps one of the key unknowns has to do with the obtaining range measurements for the multi-lateration approach. Ideally in multi-lateration systems range measurements are determined by one- or two-way transmission times of radio signals. This requires access to components of the cell phone signal that service providers are not willing to release. Range measurements can still be obtained indirectly without having to measure signal time flight by relying on Received Signal Strength Indicator (RSSI). Signal strength (as measured by RSSI) is an indirect indication of or ("surrogate" for) how far a cell tower is. Unfortunately, however, RSSI-based range estimation is not as accurate as direct time of flight measurements. Finally, the precise position coordinates of cell tower are not always publicly available. In theory these position coordinates can be determined ahead of time when GPS is available by inverting the multi-lateration problem. However, it is not clear what the accuracy of this approach is.

In summary, while the coverage issue can only be solved by adding more cell towers, the other technical issues need more research and study before one can definitely conclude that cell phone-based positioning is a viable GPS-backup for some SUAV applications.

5.4 Navigation using Cooperative Methods

GPS (and GNSSs) operate principally by users obtaining range measurements from *beacons* at known locations. In the case of GPS, these beacons are orbiting satellites, however the same principle can be applied to navigate by means of other beacons. Any source with a known location, and from which relative measurements can be obtained can provide a means to navigate with respect to that source. If the absolute position of the source is known, then navigation in an absolute frame can be continued. If radio transmitters on SUAVs or other law enforcement vehicles are used opportunistically as navigation beacons, then we can have *cooperative navigation*. The radio transmitters on the various vehicles are referred to as *collaborators*. This terminology reflects the fact that, unlike GPS satellites, the relative measurements require active cooperation between the user SUAV and the collaborating beacons. A functional block diagram of cooperative navigation is shown in Figure 10. Here we present the general framework of cooperative navigation as a backup to GPS for SUAVs, as well as several hardware systems that can be used.

5.4.1 Description of the Method

A GPS-denial scenario can affect an entire geographic location where a SUAV may be operating. Neighboring areas where potential collaborators may exist will either be included in the GPS denied environment, or possibly be outside of the affected zone. In the latter situation, these collaborators may continue to rely on GPS or other navigation sources for updating their state estimate. Naturally a static collaborator will only need an initial position fix, and thereafter would be immune to any onset of GPS interference. The collaborator intermittently broadcasts its own estimated position, which is to be received by the SUAV. Additionally, the collaborator would respond to any

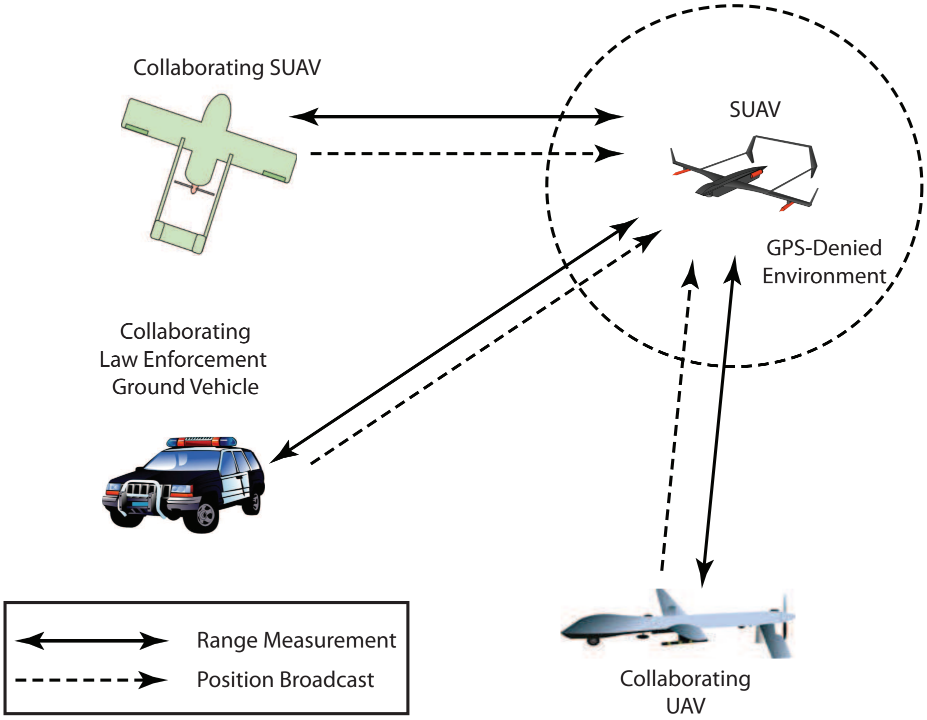

Figure 10: Architecture for a cooperative navigation system involving a SUAV.

interrogation signal from the SUAV, which could enable range measurements, derived from round-trip timing, to be obtained. The combined range and location information of the collaborator can help mitigate the error growth of the low-cost INS on board the SUAV. Even a single collaborator could greatly reduce the rate of error growth. If three or more collaborators are available, the SUAV could triangulate its position, independent of the on board INS solution. The requirement is that the collaborator have an estimate of its own position. Therefore the collaborator should either be static, or be equipped with a sensor suite which would allow it to continually broadcast a position estimate with reasonable quality, even when GPS is denied.

Two possible hardware implementations are presented. The first system is based on the Traffic Collision Avoidance System (TCAS) and Automatic Dependent Surveillance-Broadcast (ADS-B). In May of 2010 the Federal Aviation Administration instituted a Final Rule which requires the majority of aircraft to have ADS-B hardware and software installed by the year of 2020 [36]. This enables aircraft to share their current position with ground receivers or with ADS-B equipped vehicles. Mode S transponders with ADS-B In/Out capability are commercially available for UAVs. The SWaP specifications for one such product from Sagetechcorp [37] is in line with a variety of SUAV applications:

- Size and Weight: 3.5” x 1.8” x 0.7”, 100 grams
- Power: <5 Watts
- Price:$3.5-4.5K

On the other hand, the authors of this paper are unaware of any commercial TCAS products for SUAVs. TCAS solutions for UAVs in general, is an open problem and there is no simple extension of current TCAS systems, designed for manned aircraft, to UAVs. A set of recent studies by MIT Lincoln Laboratory analyzing the use of TCAS on the Global Hawk remotely piloted vehicle confirms that TCAS, or perhaps an extension of TCAS, is actively being explored for UAVs as part of the solution to the *see and avoid* (or *sense and avoid*) collision avoidance problem [38].

An alternative system could again use ADS-B for position broadcasts, but rely on data modems for range measurements derived from round-trip timing. The collaborators in this case could be other UAVs, presumably outside of the GPS-denied zone, or even the ground station. One suggestion is for this to be integrated with the law enforcement vehicles, thereby not requiring any additional ground infrastructure. Another potential system that can be considered in this regard is Locata$^{\text{TM}}$[39]. Locata is a commercially available multi-lateration system based on specially designed radio transmitters and receivers. The system is being evaluated for use in military test ranges to provide sub-meter accurate positioning in GPS-denied environments [40].

5.4.2 Pros for Cooperative Navigation

The primary benefit of cooperative navigation systems is the flexibility and scalability of the method. If more than two collaborators (e.g., squad cars, UAVs, or equipped aircraft) are available, a SUAV may be able to continue its mission even in the absence of GPS. The requirement for a position broadcast and receiving system is actually in line with evolving standards for UAVs. The International Civil Aviation Organization (ICAO) has recommended equipping UAVs with altitude reporting Mode S transponders [41], which is at the heart of ADS-B. This makes the SUAV visible to other equipped aircraft as well, something of great interest for safely integrating UAVs into the national airspace [42]. Therefore the only real hardware requirement is a means for obtaining range measurements.

5.4.3 Cons for Cooperative Navigation

As implied from its name, cooperative navigation requires active cooperation from other collaborators like ground stations or neighboring aircraft. This introduces several disadvantages, namely limiting the availability of cooperative navigation to where collaborators exist and are within communication and measuring range. A minimum number of the collaborators themselves must be robust to GPS denial, and should continue providing position estimates. This would require the collaborator to either be static, or be equipped with a sensor suite enabling them to continue providing reasonably accurate position estimates. Threats like collaborator spoofing would need to be considered as well. Finally, if left unrestricted, cooperative navigation can introduce error loops which can amplify positioning errors. However, these challenges are not new and insights from existing systems can be used to design a suitable cooperative navigation system for SUAVs.

5.5 Signal of Opportunity Navigation

Signal of Opportunity or SOP navigation is the idea of opportunistically using any and all signals for determining a navigation solution. The term “opportunistically” indicates that we are using signals that were not intended for navigation purposes. In other words, we are opportunistically extracting information from these signals. For example, if we used AM radios, FM radio or High Definition TV (HDTV) signal for navigation that would be a case of SOP navigation. While the term SOP has been normally used to describe opportunistic radio-navigation, the signals used opportunistically do not have to be radio-frequency signals. For example, the Earth’s magnetic field as altered by man-made objects (building, transmission wires, etc) can be used opportunistically to determine the position of a SUAV or any other object.

5.5.1 Description of the Method

There are many approaches to SOP navigation described in the literature. For the discussion here we can break them up into the following categories: single-user systems and cooperative systems. In the single user systems, a user determines their potion by processing signals from varied SOPs without having to cooperate with other users. Systems that fall in this category include a system that uses HDTV signals [43] and the commercially available service Skyhook$^{\text{TM}}$[44]. Cooperative systems are ones where users exploits available SOPs and also information exchange with other users. They use the same sets of signals that a single-user system would process but in addition exchange information with cooperating users. As discussed in [45, 46, 47] the cooperation allows dealing with robustness issues that are encountered in single-user systems. However, cooperative systems have the same issues that come with having to rely on a community of users as described in the Section 5.4 earlier.

5.5.2 Pros for SOP Navigation

In the future, there are going to be more and more radio-frequency signals. Thus, the potential for SOP navigation should be enhanced. What is more, the diversity of signals should make SOP navigation systems robust. Since it opportunistically relies on signals that are being used for other purposes, there should be no or little infrastructure cost for the user.

5.5.3 Cons for SOP Navigation

However, the biggest drawback to SOP navigation is that it is a nascent technology. Therefore, more research and development work or evaluation of existing system that purport to do SOP navigation must be done. This is particularly true when it comes to SUAV navigation because unlike other users SUAV must be able to extract position as well as attitude information from SOP systems. A SUAV has six degrees of freedom which means motion constraints that are available to other types of users (ground robots, persons) cannot be leveraged.

6 Recommendation for Future Work

We have discussed the impact GPS-stressed and GPS-denied situations would have on SUAV operations. It was shown that either situation will severely impede the ability of currently available autopilots designed for the autonomous operation of SUAVs. While it is obvious to see how the loss of GPS impacts navigation and guidance, its effect on the ability to control a UAV is indirect. This is because control of SUAVs requires that an accurate attitude solution be available. The attitude solution of most commercial autopilots is generated from a low cost inertial navigation system (INS) aided by GPS. In the absence of GPS, the attitude solution generated by the INS will drift and become unusable. Without a reasonably accurate estimate of attitude it is difficult to control SUAVs.

While several candidate backup systems were identified, it is unlikely that any of them will be as capable as GPS in the near future. Furthermore, each of the identified backups has strengths and weaknesses which makes them suitable for different applications. For example, vision-aided navigation systems would not work in conditions where the ground below the UAV is obscured by weather or lacks distinguishable features (e.g., operations over snow covered terrain or large bodies of water). On the other hand, cell-phone based multi-lateration would work in these situations but may not be a viable solution far away from urban settings. This means that the applicable backup system depends on the operation and operational environment the SUAV will be deployed in.

In view of the above, we note that future work to develop and validate backup navigation capability must take into account the concept of operations (CONOP) of the SUAV and cannot be viewed separately from it. This suggests the following key tasks for future work:

1. Develop a method for formalizing SUAV navigation, guidance and control avionics capability requirements which takes into account CONOPs.

2. For CONOPs that are similar and will potentially have a large number of users, develop and validate the capability of suitable backup systems.

Each of these items is discussed separately below.

6.1 Formalize SUAV Avionics Capability Requirements

The idea of formalizing the avionics capability requirements is depicted graphically in Figure 11. What this figure suggests is the GPS-backup systems suitable for a given CONOP will not necessarily be the same for another mission. For example, if the requirements of the CONOP are that the mission continues regardless of GPS availability (e.g., search and rescue/first responder operations) then the backup system must have a capability close to that of GPS.

On the other hand if the CONOP requires that the vehicle terminate the mission and “limp back home,” then the capability required will be different. Other than GPS and very expensive inertial navigation systems, there are no viable solutions that are universal at the moment. Thus, CONOP requirements will drive what type of capability is required. While it is not practical to write requirements for all possible CONOPs, we can identify common features in different CONOPs with respect to operations in GPS-stressed or -denied environments. This is similar to the work discussed in [3] and [4].

6.2 Develop, Test and Validate GPS-Backup Systems

In this paper we have identified candidate systems that can serve as backups for GPS. Two systems that hold promise are vision-aided INS and cell-phone based multi-lateration. Therefore, a systematic testing and validation effort should be undertaken to develop benchmarks and requirements which can be used by avionics manufacturers to produce systems with backup navigation capabilities.

Vision-aided navigators are good candidates to examine first because the required mechanization sensors already exist on board most SUAVs. As we noted earlier two examples of these systems include the Elphel 353 and the Intersense IS-1200 system. These systems can be used as prototypical systems to develop benchmarks for avionics system requirements. Cell phones are also considered a good candidate because of the ubiquity of their signals and the fact that products that integrate all the sensors required to mechanize these systems are easily obtainable.

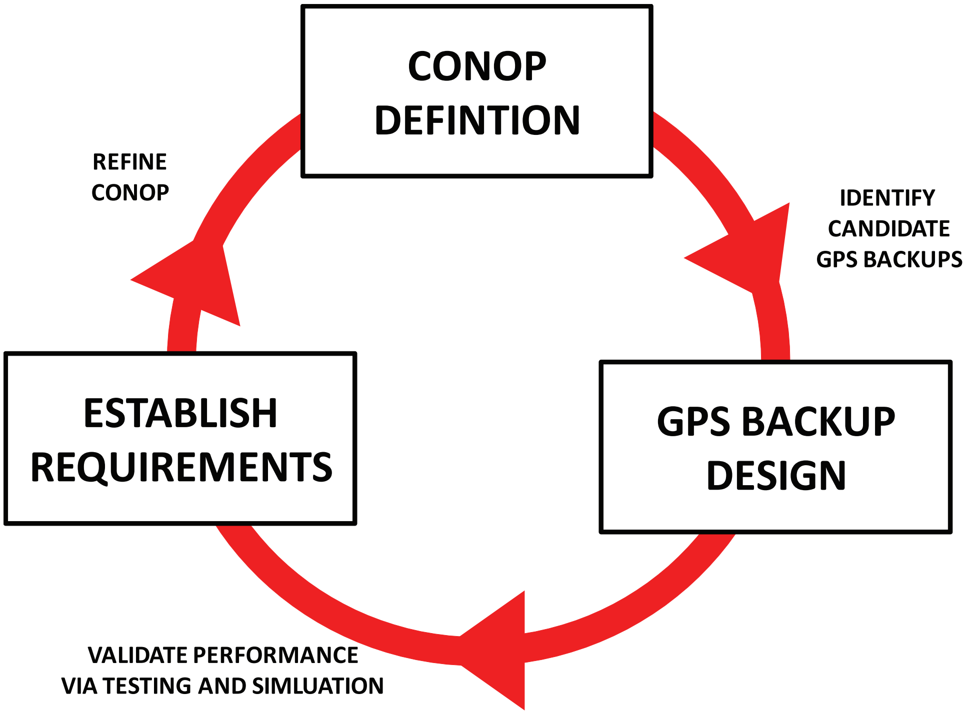

Figure 11: Process for defining GPS-backup requirements and refining SUAV CONOPs.

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