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Situational and Terrain Awareness and Warning System Implementation on Android Smartphone for Manned Aviation Applications

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General aviation (GA) aircraft are for the most part not equipped with situational awareness or alerting systems, namely in terms of traffic or terrain collision. This is largely due to lack of regulatory requirements, but also because such systems tend to be costly. By over an order of magnitude, these types of aircraft are the most common in the world's airspace. Their prevalence, combined with their more terrain-proximal flight profiles, make GA aircraft most susceptible to controlled flight into terrain (CFIT) incidents. We introduce an economical situational awareness and alerting system in an attempt to mitigate CFIT accidents in otherwise uninstrumented GA aircraft. We do so using a common smartphone to run an application which interfaces with NASA's Shuttle Radar Topography Mission (SRTM) digital terrain elevation database (DTED).

I. Introduction

According to a report by the Federal Aviation Administration (FAA), there were over 9,000 CFIT fatalities between the beginning of jet aircraft commercialization and 1997.[1] A report by the Centers for Disease Control found that in the decade between 2000 and 2010, the leading cause of aircraft crashes in Alaska included poor visibility, weather, and failure to avoid terrain.[2] Solutions geared towards solving CFIT are generally intended for commercial systems, and smaller GA aircraft might not have access to these solutions. Even today, about 5% of the world's commercial aircraft lack any sort of a terrain awareness and warning system (TAWS).[3] Evidence suggests that such a system could be useful for preventing CFIT.

A. Existing Solutions

The FAA currently mandates that any American-registered, turbine-powered aircraft with six or more passenger seats must use a TAWS. The first widely used TAWS were ground proximity warning systems (GPWS). These systems consisted of a radar altimeter capable of determining the aircraft's altitude above the ground. Beginning in 1974, the FAA required all large aircraft to use GPWS systems. The system's utility was proven in subsequent years. Large passenger aircraft suffered 3.5 CFIT incidents per year between 1946 and 1955.[4] By the early 1970s, this number had dropped to two CFIT incidents a year. Since GPWS became required in 1974, no jet operator in the United States using GPWS has suffered a CFIT incident. One drawback of the system is that it lacks any knowledge of the terrain surrounding the aircraft, providing only the distance between the aircraft and terrain directly beneath it. Thus, rapidly changing terrain could endanger an aircraft flying at a level altitude. This is more of a concern at lower altitudes where GA aircraft tend to fly.

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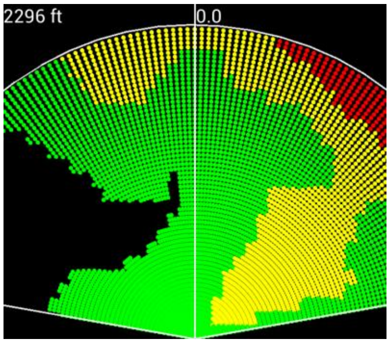

Figure 1. Version of designed terrain display. *Color in the display allows the pilot to quickly determine when surrounding terrain is potentially dangerous, similar to existing systems.*

In the 1990s, the Enhanced Ground Proximity Warning System (EGPWS) was developed. This system relies on GPS to determine the speed, altitude, and location of the aircraft. Elevation databases accessible by the system provide information about terrain surrounding the aircraft. Unlike GPWS, EGPWS utilizes information about the aircraft's state as well as information about local terrain to detect potential collision along the path of the aircraft. Knowledge of the terrain also allows the system to display useful terrain information to the pilot. Contours depicting the aircraft's altitude relative to the surrounding terrain are routinely shown in modern TAWS. Figure 1 shows one of the TAWS displays developed for this application; this type of display is common amongst modern TAWS.

The system described in this paper operates similarly to existing systems. However, unlike these professional and federated TAWS, the smartphone system is much more affordable and does not require installation onto the aircraft, which will perhaps lead to a more widespread adoption rate amongst GA pilots, much like other flight applications have done.

II. Proposed Solution

Smartphones have the potential to become useful tools for aviation. Many smartphone aviation applications currently exist, but aside from providing things like weather and airport information, none utilize the full array of sensors available to modern smartphones. Some available aviation smartphone applications have charts showing the topography over which a pilot is flying, but they do not quantitatively link the ground elevation to the aircraft's current location; nor do they provide any sort of directly usable information as to upcoming terrain or any link to safety by considering vehicle performance capability in its vicinity. In order to enhance the pilot's awareness of the terrain underneath and in front of the aircraft, the developed application utilizes the smartphone's sensors and a DTED database to increase the pilot's situational awareness. Such a system would serve directly as an economical backup of existing systems, including TAWS and some standard flight avionics. It could also serve as a backup to primary systems for uninstrumented or even instrumented cockpits.

Modern smartphones have a wide array of sensors at their disposal. GPS receivers, barometers, gyroscopes, and accelerometers are commonly found on today's devices. As described, these sensors give the smartphone some of the key components required to create a TAWS. Such a system requires knowledge of the aircraft state (altitude, velocity, flight path angle, etc), knowledge of the terrain, and the computational power to check for collisions and display relevant information to the pilot.

A. Human factors

This paper suggests adoption of an additional navigational aid through the use of this application for GA pilots. As a result, the designed application must be specifically tailored to mimic functions pilots are already familiar with. Some research into this area is presented here.

1. Informing Pilot or Maneuver Suggestion

Because of the numerous assumptions that must be made in providing a maneuver suggestion to a pilot, it might be more worthwhile to provide information to the pilot about the current situation. This generalizes the problem and removes assumptions; the aircraft's speed, rate of climb/descent, and heading are all measured. By providing the pilot with information versus a suggested maneuver, the pilot becomes a better informed decision-maker. Contrary to maneuver suggestions, this passive form of TAWS lacks the ambiguity that would arise from trying to develop an application for different aircraft sizes, flight and environmental conditions.

Considerations about the system's role and scope led to the adoption of an alerting system paradigm, as described by Pritchett.[5] The application being designed could follow several potential alerting system roles. It could serve as an attention-director, in which the pilot is alerted if some signal crosses a threshold. As an example, this system could alert the pilot if the aircraft is or will be too close to the terrain. The pilot could then assess the situation. The benefit of this kind of system is that it constantly checks for collisions, while the pilot's attention might wane or be occupied by other tasks.

Another role the system could fill is that of a resolution assessor. This functionality is achieved when "the disappearance of the alert can serve as a tool for assessing when this condition has been resolved". In the case of immediate or predicted terrain proximity, when the pilot manages to increase the distance between the aircraft and the terrain, the alert will disappear, letting him/her know that the proper actions have been taken to resolve the issue.

2. *Pilot-Centered Design*

In general, such an application should be designed such that the interface follows conventional pilot logic. This was highlighted during the design of the Cockpit Control Language (CCL), as explained by Riley.[6] Riley points out the importance of using interaction logic that is similar to the operational logic pilots are familiar with. For this reason, the CCL was designed such that pilots entered commands syntactically similar to those they were familiar with. The importance of this principle was justified during a case study of the system described here. The smartphone was given to a pilot, and he was shown the method of calibrating the barometer's sea-level pressure. The sea-level pressure was 30.37 in Hg, but this is referred to by pilots as "3037". The pilot proceeded to input "3037", but the application misread this as 3037 in Hg, causing the displayed barometric altitude to be much higher than the real value. The application must be able to conform to the operational logic with which pilots are familiar.

B. Implementation

The smartphone used in this study is the Samsung Galaxy S3 (SGS3) running Android 4.0.4. The SGS3 has a GPS receiver, barometer, gyroscope, magnetometer, and an accelerometer. At the moment, only the GPS and barometer are used for collision prediction. The phone's CPU clock speed of 1.5 GHz and the RAM size of 1 GB allow for sufficient sensor querying rates, logging, and alerting calculations. The 16 GB of flash space allows for the storage of DTED data which is used for collision prediction as described in the following sections. This eliminates the need for any sort of data connection while in flight, leaving the system to be self-contained. These aspects made this particular smartphone a sufficient test platform.

C. Digital Terrain Elevation Data

In order to determine the elevation at the smartphone's location, this application uses topography data from the Shuttle Radar Topography Mission (SRTM). This 11-day mission, performed in February of 2000, consisted of a specially mounted radar array atop the Space Shuttle Endeavor. NASA later revised the data and made it publicly available. SRTM DTED is stored on the smartphone prior to flight. This allows the application to query the elevation given a latitude and longitude. This section covers the basics of SRTM data, as well as the application's use of the data. The SRTM dataset offers a horizontal grid resolution of one arcsecond in the United States. This translates to roughly 30 meters at the equator. The vertical resolution is one meter. The SRTM employed a nadir-pointing radar so that its data is that of measured topography instead of elevation. Its output includes height of trees, buildings, or any other features protruding from the ground. This is preferable, of course, for a collision alert application. Although the SRTM is beneficial because it measures topography and not elevation, there are a few issues that must be noted. The radar signals used in the mission "probably penetrated a little way into some canopies" according to NASA's JPL.[7] The amount of penetration appears to be related to the density of the canopy. A USGS accuracy assessment comparing actual elevation data to the SRTM data notes that deciduous forests produced lower elevation increases than evergreen forests.[8] The USGS suggests that this is due to the fact that the SRTM occurred in February, during the North American winter. Having given up their foliage for the winter, deciduous trees allowed the radar signals to penetrate deeper, offering an explanation for the discrepancy. Furthermore, the SRTM occurred 12 years ago, and new structures and foliage have been erected in that time.

The SRTM files come in one degree squared tiles. They are named according to their southwest corner. For example, Atlanta is located at 33.7489° North, 84.3881° West. The file name for the tile containing Atlanta is "N33W084.hgt". The structured naming system makes it simple to determine which file is needed based on the current latitude and longitude. The file itself is a 16-bit binary file. There is no header and the file is not compressed. Each 16-bit entry represents the altitude at a particular arcsecond latitude/longitude pair. With 3,601 rows and 3,601 columns, it can be seen that there are a total of 12,967,201 entries. Because each entry is 16 bits, or two bytes, the total file size is 25,934,402 bytes, or roughly 24.7 MB (1,048,576 bytes per megabyte). This allows for multiple files to be loaded onto a phone, because common Android smartphones have internal memories in the range of four to 16 GB. Once the information is stored in the phone, it can be accessed by the application. The application determines which file to look for based on the current GPS latitude and longitude. It then converts the appropriate data into human-readable integers, and stores them in a buffer. By determining the arcsecond value of longitude and latitude, the index within this buffer can be determined. Currently, the buffer is made once, and future data retrievals simply call on this original buffer. Although it is possible to create the buffer each time the latitude and longitude are updated, this wastes a lot of resources, as parsing the 24.7 MB is intensive. By printing the time before and after this task, it was determined that the SGS3 takes roughly half a second to do this. Meanwhile, calls on the already existing buffer are nearly instantaneous.

Due to its format, topographical coverage, and ease of availability, the SRTM data makes sense for smartphone-based TAWS feasibility study. As mentioned, SRTM is not without flaws, and one of these is that it only covers up to 60° North. This only covers the lower part of Alaska. Although there is coverage for the rest of the United States, Alaska is of particular importance because of the number of preventable aircraft crashes that occur in that region. However, SRTM's other benefits made it the proper choice in this stage of the development. Regions such as Alaska can be handled further down the development process.

D. Software: Aircraft State Estimation

Sensor data is passed through a filter to improve linearity of the aircraft's state estimate and provide more consistent collision prediction alerts. In particular, a standard sequential Kalman filter (SKF) is employed. The measurement noise matrix is obtained from recorded GPS and barometer test data. The process noise matrix is determined by the user via the selection of aircraft type.

E. TAWS Implementation

The introduced system has the secondary objective of functioning as a backup flight instrument display. This is accomplished by providing the pilot with data such as position, rates, heading, and so on. The primary objective, however, is of enhancing the pilot's awareness of the surrounding and upcoming terrain and potential threats of collisions. Two methods are in place to that effect. Firstly, terrain is displayed in graphical form to allow the pilot to glean information at a glance about the surrounding terrain. Figures 1 and 2 show examples devised terrain displays. They are similar to existing TAWS displays currently in use.

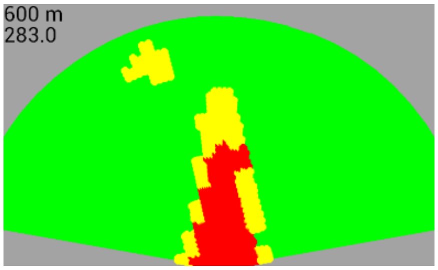

Figure 2. Example terrain display generated by application. C*olors in the display inform the pilot of the surrounding terrain.*

As for its second method, the primary mechanism of the system, the application attempts to predict any impending collisions. Data obtained from the DTED database along with the aircraft's state estimate from the SKF are processed to detect dangerous terrain clearance along the flight path of the aircraft. The detection range is dependent on the resolution of the DTED database used, related notionally to the speed and size of the aircraft. The bigger the aircraft, and generally the faster it is, the lower resolution the DTED database will be to allow for a reasonable load time and thereby warning window. The baseline aircraft for this project, a Cessna 172, cruises at roughly 63 meters/second. The detection radius used is 6-700 m, which gives a Cessna 172 pilot information of terrain that is within ten seconds of the aircraft's position. Future studies can determine an acceptable amount of warning time. Collisions are predicted by querying the SRTM data out along the heading line in front of the aircraft and comparing it to the expected altitude of the aircraft at that location, and an estimate of the maximum climb rate of the aircraft. Bresenham's line algorithm is used to select grid points in front of the aircraft, along the aircraft's direction of motion. The flight path is provided by the GPS. At each of the points tested, the aircraft's altitude on arrival is estimated from its current vertical rate. If the altitude on arrival is lower than the SRTM-provided elevation, the application warns the pilot about the possible collision. As points in front of the aircraft are tested, the resulting elevations of the points are shown to the pilot in a graphical manner. Figure 4 shows the smartphone (black pixel) is safely above the ground level, yellow means the smartphone is closer to the ground, and red means the smartphone's altitude is below the ground elevation at that point.

III. Application Verification and Flight Test Results

Verification of the application was carried out with tests against known landforms and in four flight tests. Testing the terrain display against known landforms allowed for the basic concept and software to be validated. The flight test data was analyzed to determine the smartphone's reliability as a sensor platform.

A. Comparison to Known Landforms

The landforms used to test the application were Yerba Buena Island in the San Francisco Bay and Seal Point Park, also in California. Figure 3 shows screenshots taken from the application as it was driven over Yerba Buena Island. The freeway on the Bay Bridge crosses the island in a northeasterly direction. The particular terrain viewing format is fixed (does not rotate with bearing) with the phone represented by the black dot in the center. As can be seen, the landmass displayed by the terrain display closely follows that shown in the satellite image.

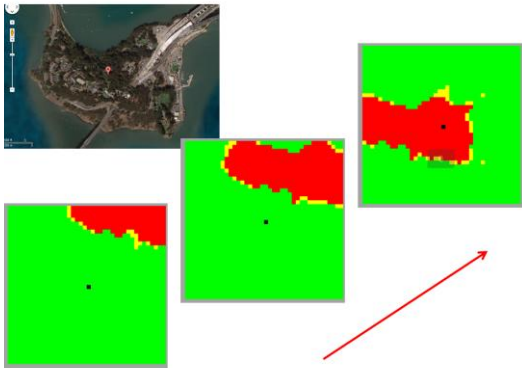

Figure 3. Verification against Yerba Buena Island, CA. *The terrain displayed by the application matches that shown by the satellite imagery.*

A second such verification also took place at Seal Point Park. At the center of the park there is a large hill, running east to west. It is about 18 meters higher than the rest of the park. Figure 4 shows the viewing format from the phone while traveling mostly west along the top of the hill. In this slightly updated terrain viewing format, the trajectory is shown by a black line. Terrain ten meters or more beneath the smartphone's location is shown in green; terrain within five to ten meters is yellow, and any other terrain is red. As Fig. 4 shows, the shape of the terrain returned by the application follows the shape of hill as provided by the satellite imagery. Figure 2 shows a fan-type display of the same information that rotates with the user.

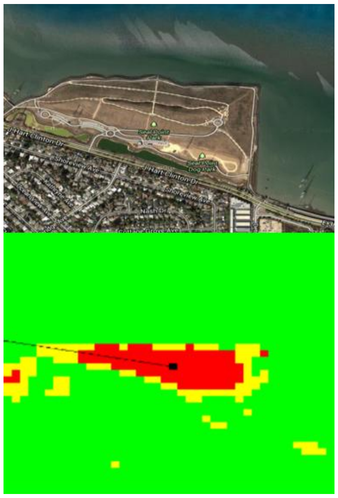

Figure 4. Seal Point Park, California. *Terrain display of the hill at Seal Point Park while moving WNW (below) resembles satellite imagery of park (above).*

B. Flight Tests

The application was also flown in four flight tests: two rotary wing tests and two fixed wing tests. The former tested the sensors and basic functionality. Once this was established, fixed wing tests were performed to determine the application's viability in its intended role.

1. *RMAX Helicopter Tests*

Rotary wing tests were performed to test the sensors and software for basic functionality, including data logging. The tests were performed on the UAVRF's Yamaha RMAX helicopter, shown in Fig. 5. The vehicle is outfitted with Differential GPS (DGPS) and sonar altimeter which provides a sufficiently accurate truth comparison.

The test provided a quantitative test of the sensor system in terms of estimated altitude. The results are shown in Fig. 6. Note that the smartphone GPS does not sufficiently track that of the DGPS for the TAWS application, although general altitude trends are captured, which may be sufficient for a faster flying vehicle such as a fixed wing. This is expected due to the dilution of precision suffered inherently in the vertical channel due to relative constellation geometry. In addition, the phone was mounted under the radiator which obscures the phone's view of the sky.

Although the GPS altitude profile does not sufficiently match the actual profile flown, the barometer tracks it more closely. As can be seen in Fig. 6, the major features in the flight profile are captured by the barometer. However, there are two problems with the barometer data—it is noisy and it seems to have a systematic error, overpredicting the actual altitude of the vehicle.

Once the data had been collected, a SKF using data from both the barometer and the GPS was developed. As can be seen from Fig. 6, the SKF's estimated altitude follows the trend of the barometric altitude, while eliminating much of the nonlinearity inherent in the barometric measurements. Note that the estimated altitude favors the barometer data due to the high covariance of the GPS measurements. The results of the filter on the estimated rate of climb are shown in Fig. 7.

Figure 5. Yamaha RMAX Helicopter. *Used for flight test data.*

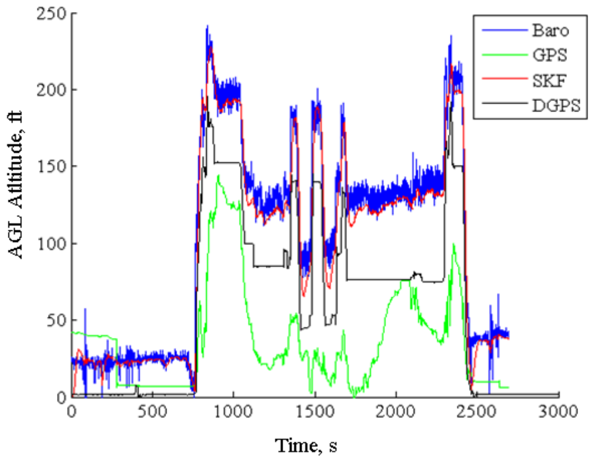

Figure 6. RMAX flight test data. *The GPS fails to follow the major features of the data as provided by the more accurate DGPS. The barometer is able to follow the major features, but has noise. The SKF reduces this noise.*

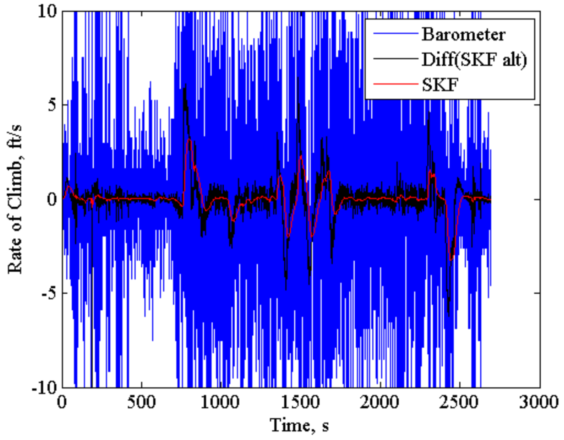

Figure 7. Rate of climb during RMAX test flight. *The SKF reduced noise while preserving the major features of the data.*

Because the barometric measurements are so noisy, the estimated rate of climb from differentiation is unusable. Differentiating the SKF altitude measurements provides markedly improved results. Including the rate of climb in the SKF, however, yields the best results, as major features of the climb rate are preserved while minimizing noise.

The SKF was tuned such that the state estimates matched the major features climbs and descents visible in the data, while reducing its noise. Figures 6 and 7 show that the filter gain was reasonably selected for the type of test flight flown by the RMAX helicopter. However, the parameters differ when the filter is to be used on a typical GA flight.

2. Cessna 172 Tests

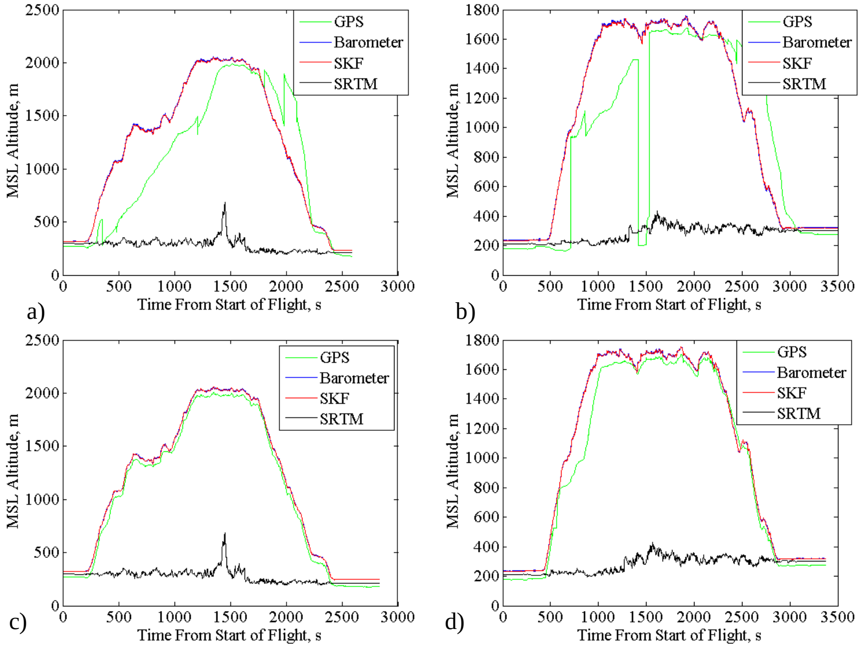

Figure 8. Altitude log of Cessna 172 test flight between PDK and DNN. *a) SGS3-1, PDK to DNN. b) SGS3-1, DNN to PDK. c) SGS3-2, PDK to DNN. d) SGS3-2, DNN to PDK.*

The rotary wing tests showed that the smartphone's sensors, if properly filtered, are capable of capturing major features in a flight profile. The application was then tested on a fixed wing platform, in order to test the collision-detection algorithm and further test the sensors. Cessna 172 aircraft were selected because of their prevalence in GA. Because truth data are unavailable for the Cessna test flights, the appropriateness of the aircraft state must be judged qualitatively.

The results of the first flight test are summarized in Fig. 8. This test included a flight from DeKalb Peachtree Airport (PDK) to Dalton Airport (DNN) near Atlanta, Georgia, as well as the return flight (Flight 1 and Flight 2, respectively). Two SGS3 smartphones were used, in order to compare the sensor results between them. As Fig. 8 shows, the GPS sensors performed poorly. SGS3-1 had worse results, with the GPS suggesting, during the return flight, that the vehicle had gone subterranean. The GPS results did not match the general altitude trends qualitatively observed during the flight, whereas the barometer did, adding to its credibility. This matches results from the RMAX test flights.

The second flight test only used one SGS3 smartphone (SGS3-1), but was focused on testing the collision detection algorithm described previously. The results of this algorithm and the flight test are summarized in Fig. 9. In order to test the collision detection algorithm, three landing attempts were performed, with the first two being touch-and-goes. Because landing is a controlled approach to the ground, the ground-collision algorithm should detect collisions during the approach. Note that collisions were properly detected during the approaches. The system is capable of determining in advance that the aircraft will is on track to hit the ground.

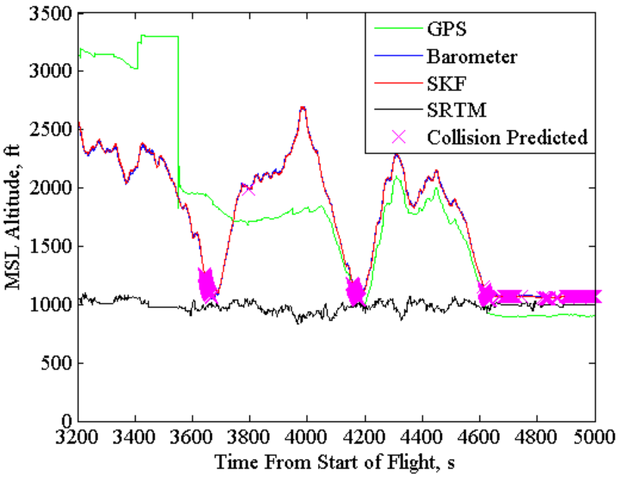

Figure 9. Collision detection results during three landings from second Cessna flight test. *The system correctly predicts collisions during landing.*

C. Sensor Measurement Analysis

The experimental setup and data has been presented. Several drawbacks and areas for improvement have been identified. This section covers work done to characterize and improve the utility of the smartphone's sensors.

1. *Barometer*

The barometer has proven to be a useful instrument in the determination of the aircraft's state. As by the test flights, it provides a far more precise measure of altitude than the phone's GPS receiver. However, it has displayed an important drawback: it systematically provided a higher altitude than the actual, despite being calibrated to local sea-level pressure. Flight tests aboard the UAVRF's RMAX helicopters show that the barometric altitude returned by the smartphone was systematically higher than the "truth" data provided by the more highly trusted DGPS used by the helicopters. It was initially posited that the barometric altimetry suffered due to the cold weather at the time of the flight tests, which were performed in late November and early December. A correction for cold weather was implemented.

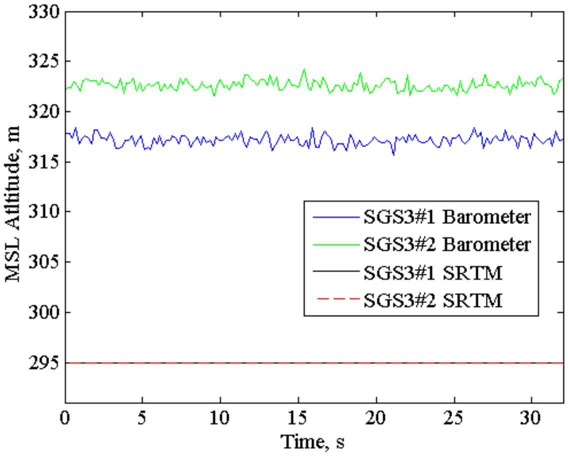

Figure 10. Comparison of both smartphone barometric altitudes before takeoff. *Both smartphones systematically overpredicted the altitude .*

However, fixed wing test flights performed in April showed that the barometric altitude was systematically higher than the altitude displayed by the cockpit barometric altimeter. Figure 10 shows that both smartphones overpredicted the altitude, even when sitting at the airport before takeoff. The air temperature during this flight was certainly above the threshold required for the low-temperature correction. Regardless, the application is calibrated using the sea-level pressure provided by the airport, and therefore the barometric altitude should not be different than the elevation when the aircraft is on the runway, regardless of the temperature. Other reasons for the discrepancy were considered. In both the rotary and fixed wing cases, the phone was located in the wash of the propeller; under the RMAX radiator for the helicopter test, and in the cockpit of the Cessna flights. The barometric altitudes reported by the smartphones before and after the props were spun up were compared. No significant difference was noted on either vehicle.

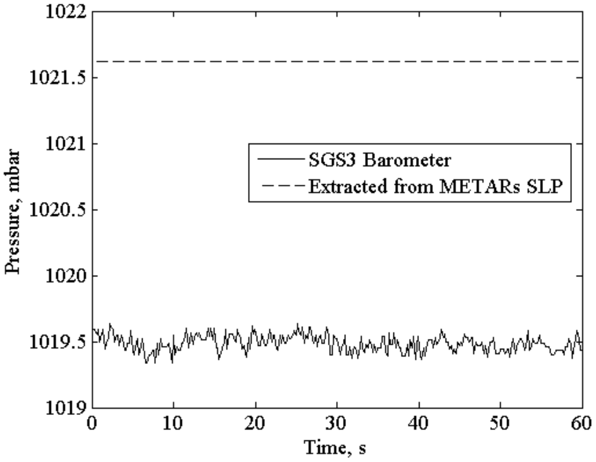

Figure 11. Comparison of smartphone pressure and that predicted using METARs data. *Local pressure derived from station altitude and sea-level pressure.*

Upon further testing, it was concluded that the smartphone barometer systematically returned air pressures lower than actual, leading to the higher calculated altitudes. Figure 11 shows this occurring at SQL (airport in CA).

This systematic error is important because the GPS has proven unreliable as a method of calculating the altitude. The barometer can be thought of as an enabling technology—without it, most contemporary smartphones will not be able to track the vertical position of the aircraft sufficiently well to serve as a TAWS. Thus, future efforts will focus on detecting and mitigating this source of error. One proposed solution is to detect and calculate this systematic error. This could be done when the pilot is at the airport and knows both the local sea-level pressure and the airport elevation. If the phone were held still for a short period of time, the systematic error to the expected altitude could be determined. A correction could then be applied to the sea-level pressure used in calculations. Future research and flight tests would have to determine whether such a correction would be valid over the range of altitudes to be encountered in a GA flight. Such a correction, however, seems feasible.

The downside to such a correction is that it would require another action by the pilot. Having the pilot input the local sea-level pressure does not represent a new requirement to a GA pilot. A pilot should calibrate the aircraft's barometer before flight, so it would be intuitive to expect to have to do the same for the application. However, the added step of correcting the systematic error will require the pilot to go through an extra step as well as have the airport elevation on hand. Though by no means challenging, the additional, unfamiliar step makes it more likely that this critical task will be forgotten or ignored. Despite this, it is probably the best solution to the problem. Solutions relying on the specifications of the particular barometer used are short-sighted at best. With the constantly changing selection of smartphones available, solutions must be flexible to different models and even variations amongst the same model.

Another drawback of the barometer is that it can only serve as an altimeter if the pressure experienced by the smartphone is the same as the ambient pressure outside the aircraft. For example, the barometer can only be used in unpressurized aircraft. Despite this, it is possible that environmental differences between the cockpit and the environment could cause errors in the barometric altimetry. This is deemed unlikely, considering that the Cessna 172 has an alternate static port located in the cockpit, meant to be used in the event the outer static port cannot be used. Because of this, the smartphone's barometer can be used in the cabin of a GA aircraft without much fear of degradation; it would act much like the alternate static port, suggesting negligible errors. Future research could attempt to quantify this error.

2. *GPS*

Flight tests performed on the RMAX helicopter showed that the GPS sensor's altitude measurement could not follow the vertical motion of the helicopter sufficiently to function as a TAWS, as can be seen in Fig. 6. The first fixed-wing flight test, including two short flights with two identical Samsung Galaxy S3s, provided more data to this effect, as was shown previously in Fig. 8. The main failure of the GPS was the inability to follow the vertical profile painted by the more trusted barometer, which matched the observed path travelled by the aircraft. It is interesting to note that SGS-2 performed flawlessly in the first flight, while diverging from the barometer results during the first half of the second flight. This suggests that the flaws shown by SGS3-1 are not isolated, and GPS errors might be common enough amongst smartphones to warrant general skepticism about their reliability.

Regardless, SGS3-2 had better, if still inadequate, results, so potential causes for the discrepancy between the two SGS3s were considered. The most promising considered was the location of the smartphone. SGS-2 was located in the front of the aircraft, where it had a more unobstructed view of the sky. The less accurate phone was located in the backseat and under the wing. It is possible that the wing obstructed the receiver's view of the GPS constellation. To test this theory, SGS-1 was used in a second flight test, the latter part of which was shown in Fig. 9. SGS-1 was specifically put in the front of aircraft, rather than in the back. However, despite being in the front of the aircraft, the SGS-1's GPS sensor was unable to follow the aircraft's altitude satisfactorily. The discrepancy between the receivers is under investigation.

If a smartphone has a barometer, it is not critical that the GPS receiver is unable to reliably follow the altitude profile of a typical GA flight. The barometer has proven capable of providing information about the altitude. However, the GPS is needed to provide an estimate of the horizontal position of the aircraft, which is then used to search the DTED for the local elevation. Fortunately, the Android API provides the horizontal accuracy of the GPS readings related to horizontal dilution of precision (HDOP). The values are provided as standard deviation radii. Figure 12 shows the horizontal accuracy of the GPS during part of the second test flight, and compares it to the GPS and barometric altitudes during the same portion of the flight. It can be seen that large one-sigma radii (low GPS accuracy) correspond to GPS altitudes that disagree greatly with the barometric altitudes. A correlation between the horizontal and vertical accuracy is useful, allowing the application to determine when the GPS altitude data is unreliable. Although the results suggest that horizontal accuracy can vary widely throughout the flight, the application's ability to detect this inaccuracy allows it to provide this information to the pilot, allowing him or her to decide how best to proceed.

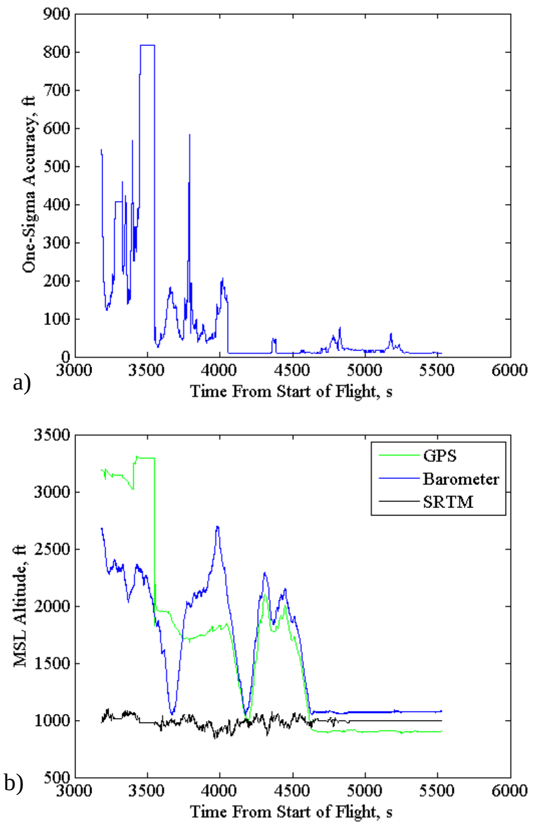

Figure 12. Correlation of GPS horizontal and vertical accuracy. *a) Horizontal accuracy. b) Vertical discrepancies against barometer.*

IV. Conclusion

The research presented in this paper suggests contemporary smartphones could feasibly serve as a platform for a TAWS implementation for GA aircraft, with some caveats. Results suggest the GPS receivers found on a typical, contemporary smartphone are not generally able to capture the altitude state of the aircraft. To accurately measure this, the smartphone should have a barometer. It was shown that the noise of barometric measurements can be mitigated with a SKF. Future research could characterize the systematic error inherent in these measurements, thereby making the barometer a reliable method to determine altitude and rate of climb. The SRTM datasets used provide real-time information about the terrain surrounding the aircraft, allowing the pilot to achieve some terrain situational awareness. Additionally, potential collisions are detected by this specific application, suggesting a rudimentary TAWS might be feasible on such a platform.

These results suggest many avenues for potential future research. The first is improving the data provided to the pilot. The afore-mentioned reduction in systematic error for barometric measurements is an example. Another concern is the reliability of the DTED used. Basic functionality and feasibility were explored in this research, so the accuracy of the DTED was left for future research. However, in a fully-developed TAWS, the DTED selected will have to be thoroughly tested and reliable. Another extension to this research is the inclusion of live ADS-B data to turn this from a TAWS to a more general situational awareness system. A software defined radio dongle is used to connect to the phone and is tuned to 1090 MHz. Interfacing software is currently being developed for this purpose.

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