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# SYSTEM DESIGN AND PROPOSED SURVEY WORKFLOW FOR LIGHTWEIGHT UAV-BORNE GROUND-PENETRATING RADAR IN URBAN ENVIRONMENTS

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**Abstract:** Operating ground-penetrating radar (GPR) from a multirotor requires a payload that fits the aircraft's mass limits and keeps the antenna stable enough for repeatable surveys. This conceptual design addresses those constraints for a controlled municipal utility corridor. The proposed unmanned aerial vehicle (UAV) carries a downward-looking antenna on a damped mount and powers the radar from a dedicated battery. A recorder associates each radar trace with the estimated antenna position and retains the original measurement onboard. A reduced preview sent over a proposed 5.8 GHz link allows the operator to monitor acquisition during flight. The workflow defines how to plan survey lines, flag gaps in usable coverage, and verify suspected targets on the ground. A design requirements matrix links payload mass, antenna motion, time synchronization, positioning, and preview throughput to planned acceptance checks. Validation would begin with bench tests and progress to repeated passes over utilities with independently documented locations and depths, using ground-based GPR as a comparator. The contribution is a system architecture and verification procedure. Prototype implementation, simulation, and field validation remain future work.
**Keywords:** Ground-penetrating radar; Unmanned aerial vehicle; Utility mapping; Urban subsurface; Survey design

## 1 INTRODUCTION

Ground-penetrating radar (GPR) is used to locate buried utilities and investigate shallow subsurface features [1-2]. Controlled pipe-model experiments have compared radar responses across pipe materials, burial depths, diameters, and antenna frequencies [3]. A UAV offers another way to survey sections where a cart or vehicle is difficult to operate. In those sections, the aircraft must maintain an antenna height and trace spacing suitable for resolving the target.

Prior work has documented the effects of aircraft motion, antenna positioning, and electromagnetic interference on downward-looking UAV-borne GPR [4]. Position-tagged prototypes have used synthetic aperture processing to image buried targets, including with an antenna array [5-6]. Archaeological field trials have examined how antenna height changes the visibility of subsurface features [7]. These studies help identify what to record during a municipal utility survey, particularly antenna height, trajectory quality, and sampling geometry.

The contribution here is a design and acceptance plan for a controlled municipal utility corridor. Each trace would be linked to a flight record and retained onboard for interpretation after landing. The preview would let operators check acquisition, while coverage checks would guide repeat passes and ground verification. The plan identifies the measurements needed to determine whether this integration can locate documented utilities under the selected survey conditions.

## 2 SYSTEM ARCHITECTURE AND DESIGN CONSTRAINTS

The ground station would receive a preview during flight. The original traces would be retrieved from the onboard archive after landing (Figure 1).

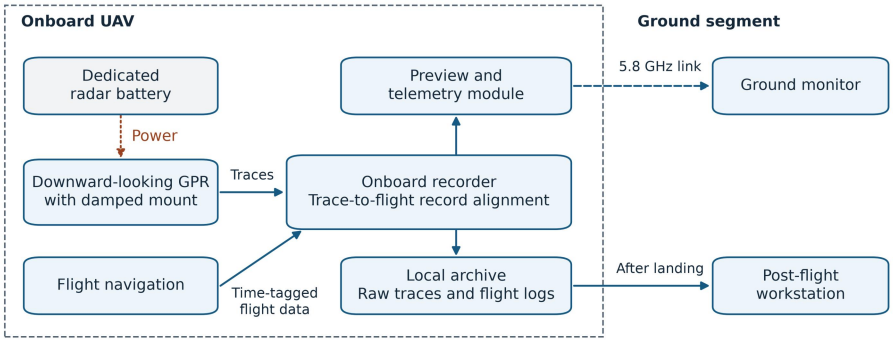



**Figure 1** Proposed UAV-Borne GPR System Architecture Showing Onboard Acquisition, Wireless Preview, and Post-Flight Retrieval of Original Records

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### 2.1 Flight Platform and Payload Integration

The payload includes the downward-looking GPR antenna, radar electronics, damped mount, dedicated battery, onboard recorder, and wireless module. The mass budget must include cables, shielding, and mounting hardware because they also count toward the aircraft's payload limit. Component placement must keep the center of gravity within the aircraft's limits and leave clearance between the antenna and landing gear.

The mount needs enough compliance to reduce vibration transmitted from the motors and airframe. Too much movement between the antenna and the aircraft would make the antenna position and orientation harder to estimate from flight logs. The validation plan therefore compares the damped mount with a rigid mount under the same operating conditions.

### 2.2 Power Supply and Electromagnetic Compatibility

A dedicated battery separates the radar from the propulsion power circuit. Its mass counts against the aircraft's payload allowance, so the battery would be sized for the planned periods of acquisition and standby, with an energy reserve. The radar would enter standby between survey segments and resume acquisition before each line. Bench tests would establish how much time to allow before recording usable traces.

For an illustrative battery sizing estimate, assume 20 W of radar power during 15–20 min of acquisition and 5 W during 5 min of standby. With 20% of the rated battery energy held in reserve, dividing the acquisition and standby energy by 0.80 gives a required rated energy of 6.8–8.9 Wh before conversion losses. This estimate applies to the dedicated radar battery. Final sizing would use measured power in both operating states.

The proposed layout separates the radar, propulsion electronics, and wireless transmitter to limit radiated coupling. Power wiring and signal wiring would run separately. If tests show conducted interference, the radar power input would be evaluated with a suitable filter, and shield termination and return paths would be reviewed against the installed wiring and enclosure layout.

The 5.8 GHz transmitter would be tested for effects on the radar receiver, including blocking, spurious signals, and changes in the noise floor. The tests would vary motor and transmitter activity independently while radar settings and the reference target remain fixed. Antenna separation and any receiver filtering would be chosen after the radar passband and transmitter configuration are specified.

### 2.3 Design Requirements and Acceptance Criteria

Table 1 lists the proposed acceptance criteria and the information still needed to set them. The synchronization calculation is illustrative. The other numerical limits depend on the selected aircraft, target geometry, and survey conditions.

**Table 1** Design Requirements, Provisional Criteria, and Planned Verification

| Design requirement | Provisional criterion or basis | Planned verification |
|---|---|---|
| Payload and balance | Complete installed payload and center of gravity within the selected aircraft limits. Confirm using the component mass budget. | Weigh the installed payload and measure its center of gravity. |
| Antenna motion and height | Set separate limits for antenna movement relative to the aircraft and variation in height above ground, based on target visibility and repeatability. | Compare damped and rigid mounts and record antenna height over a known target. |
| Trace-to-flight synchronization | Allocate part of the along-track error budget to timing. At 2 m/s, a 2 cm allowance gives 10 ms in this illustrative case. | Record a common timing event in both logs and compare timestamps. |
| Positioning quality | Set horizontal and height tolerances from the target and allowable utility-location error. Exclude segments with insufficient positional confidence from usable coverage. | Compare georeferenced responses with independently documented utility locations and depths. |
| Preview throughput | Estimate the payload data rate from samples per trace, bits per sample, trace rate, and compression ratio. Allow for overhead and set delay and loss limits for monitoring. | Measure throughput, delay, packet loss, and completeness of the onboard archive under the same link conditions. |

### 2.4 Module Interfaces and Data Handling

Table 2 specifies what each connection carries and what the receiving component needs.

The proposed 5.8 GHz link would carry the reduced preview for monitoring. The onboard recorder would keep the original traces available for analysis if the wireless link drops packets. Selection of the GPR antenna frequency and bandwidth would depend on target depth, required resolution, site conditions, and payload limits. Published work on multifrequency GPR processing and early-time signals illustrates how signal content affects the depths and features that can be interpreted [8-9].

Near-real-time image reconstruction has been investigated for UAV-mounted GPR using synthetic aperture processing [10]. Real-time detection has also been studied for vehicle-mounted GPR [11]. In the present design, the in-flight

preview is used to check acquisition. If the preview uses lossy compression, the bench test would compare target visibility in the reduced and original recordings before choosing the compression settings.

**Table 2** Proposed Module Interfaces and Data Requirements

| Interface | Proposed data or function | Design requirement |
|---|---|---|
| GPR to onboard recorder | Radar traces, acquisition timestamps, sequence numbers, and radar settings | Preserve original traces and identify interruptions in acquisition. |
| Flight system to onboard recorder | Time-tagged position, attitude, and height above the surveyed surface | Match each trace to the estimated antenna position and orientation using the offset between the antenna and the navigation reference point. |
| Onboard recorder to wireless module | Reduced radar previews and acquisition status | Send monitoring data over the proposed 5.8 GHz link while the recorder stores original traces onboard. |
| Onboard recorder to processing workstation | Original traces, flight logs, and survey settings | Use the records after flight to check coverage, timestamp alignment, and trace integrity. |

## 3 PROPOSED SURVEY WORKFLOW

### 3.1 Survey Planning

The first proposed survey would cover a municipal utility corridor with independently documented pipe locations and depths. Where practical, flight lines would cross the expected utility alignment (Figure 2). The operator would identify obstacles, access restrictions, and sections where the aircraft could not maintain the intended antenna height. Flight speed and trace acquisition rate would be set together to achieve the desired along-track spacing. Pilot measurements would guide the choice of flight-line spacing and acceptable height variation before the full survey.

The first trial would use a controlled corridor with a defined takeoff and landing area, separation from uninvolved people, and a route screened for obstacles and applicable airspace permissions. The operating plan would specify when to stop a pass or land if safe separation, height control, or flight control cannot be maintained.

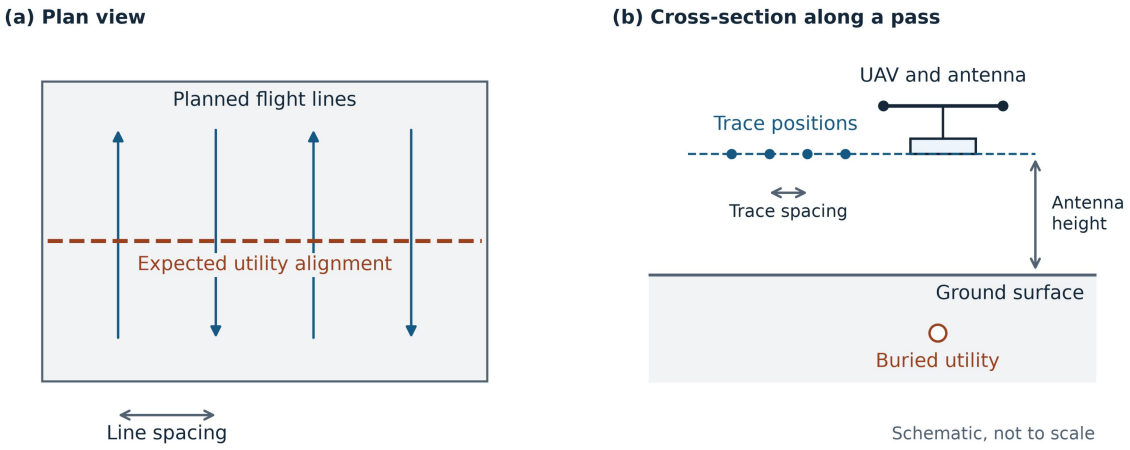



**Figure 2** Proposed Survey Geometry for a Municipal Utility Corridor

Note: (a) Plan view of flight lines crossing the expected utility alignment. (b) Cross-section along a survey pass showing antenna height and trace spacing. Schematic, not to scale.

### 3.2 Data Acquisition and Coverage Assessment

Before takeoff, the operator would check radar recording, timestamp alignment, storage capacity, and the antenna offset from the navigation sensors. The onboard recorder would log the radar traces and flight data together on each pass. At the ground station, the operator would use the preview to confirm that acquisition is running and check for visible breaks in the sequence.

After landing, the operator would compare the recorded track and trace sequence with the flight plan. Missing traces, excessive height variation, and deviations from the planned line would be flagged for review. Only segments with interpretable measurements would count toward usable coverage.

Building blockage and reflected signals can degrade GNSS positioning in urban canyons [12-13]. Where the navigation solution falls outside the positioning criteria in Table 1, the affected interval would be flagged for review and excluded from usable coverage unless its position can be verified. A preview outage would be treated separately from a flight-control fault. With a healthy control link, the operator would check the onboard recording after landing and decide whether to repeat the segment. Flight-control faults would follow the aircraft's contingency procedure.

### 3.3 Processing and Ground Verification

The processing workstation would match each radar trace to the flight log by timestamp. Using the recorded aircraft attitude, it would apply the offset from the navigation reference point to the antenna to estimate the position of each trace. Where trace spacing varies within a continuous segment of usable data, linear interpolation onto a uniform along-track distance grid would produce a distance-referenced B-scan. Coverage gaps would remain flagged for review. Ghanbari et al. used parallel profiles that crossed the expected utility alignment and applied time-zero correction and dewowing before further processing [14]. Liu et al. distinguish preprocessing from target recognition in their review of pipeline B-scans [15]. For this survey, the original traces and the processing settings for each B-scan would be retained. For each candidate anomaly, the operator would record its coordinates, source profiles, and acquisition conditions. A repeat flight could show whether the response recurs. Ground-based GPR would provide a comparison, and independently documented utility locations and depths would provide the reference for assessing positional accuracy. The final report would show usable coverage, gaps requiring follow-up, and the verification status of each anomaly. Figure 3 shows where a coverage gap would trigger a repeat pass or be carried forward to the final report.

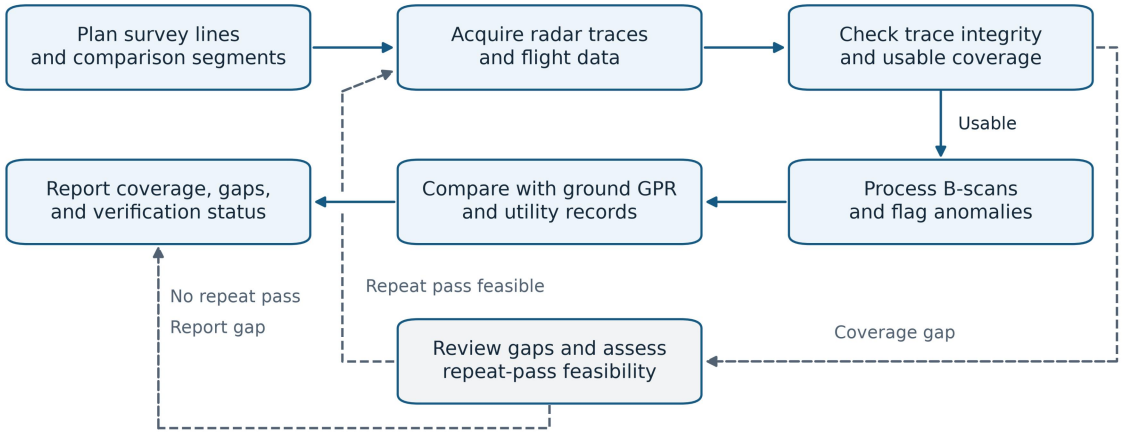



**Figure 3** Proposed Survey Workflow from Flight Planning to Ground Verification

Note: The dashed branches show the options for a coverage gap. If a repeat pass is feasible, acquisition resumes. Otherwise, the gap is recorded in the final report.

## 4 PROPOSED VALIDATION PLAN

Validation would begin with component checks and end with a controlled field survey. The target, site conditions, and acceptance limits would be set before field testing. Table 3 links the procedures and measurements to the requirements in Table 1.

**Table 3** Proposed Validation Procedures, Measurements, and Acceptance Criteria

| Stage | Proposed procedure | Measurements | Proposed acceptance criterion |
|---|---|---|---|
| Payload and power | Weigh the installed assembly, check balance, and measure power in standby and acquisition. | Payload mass, center of gravity, operating power, radar restart time. | Meet platform mass and balance limits. Confirm the selected battery supports the planned radar duty cycle and reserve. |
| Antenna motion and EMC | Compare damped and rigid mounts. Vary motor and transmitter activity with a fixed reference target. | Antenna motion, noise floor, spurious signals, reference echo variation. | Meet motion and height limits. Set allowable echo and noise changes before coexistence testing. |
| Synchronization and positioning | Log a common timing event in both systems. Compare antenna trajectory and georeferenced responses against independent references. | Timing offset, horizontal position error, height error. | Meet the allocated timing error and the site-specific horizontal and height limits. |
| Compression and telemetry | Compare reduced previews with original traces. Test wireless transmission under the planned operating conditions. | Data reduction, target visibility, latency, packet loss, archive completeness. | Meet preview usability limits. Preserve the complete onboard recording during preview interruptions. |
| Controlled field survey | Repeat flight lines over documented utilities. Compare airborne profiles with ground-based GPR and utility records. | Target visibility, positional deviation, repeatability, usable coverage. | Assess against predeclared target-location and coverage criteria, and report gaps. |

The first trial would assess performance for the documented utility targets under the conditions at the test site. Ground-based GPR has also been used to investigate roadway voids [16]. Extending the airborne workflow to voids would require a separate trial with independently verified targets and acceptance criteria for that site.

## 5 CONCLUSION

The concept defines how original radar and flight records would be collected, associated, and archived for a municipal utility survey. The operating rules specify how to handle unverified positioning and coverage gaps. The requirements and acceptance plan identify the evidence needed to judge the design, from payload integration and electromagnetic coexistence to target location in a controlled corridor. These checks remain to be performed before routine use can be assessed.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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