DEVELOPMENT OF A UAV-BORNE PULSED ICE-PENETRATING RADAR SYSTEM

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ABSTRACT

Ice-penetrating radar is the primary geophysical tool for large-scale measurements of the geometry and internal properties of the Antarctic and Greenland Ice Sheets. These low-frequency radar instruments are typically mounted on crewed aircraft or towed behind snowmobiles, both of which introduce significant logistical challenges and costs. The availability of inexpensive, portable, and fully-autonomous uncrewed aerial vehicles (UAVs) promises to reduce the cost, logistical complexity, and risk of collecting ice-penetrating radar data.

We introduce a chirped radar system built around a software-defined radio (SDR) that can be carried by a low-cost and easily-transportable fixed-wing UAV. The antennas for the radar are fully integrated with the wings of the UAV and have a usable frequency range from 300-450 MHz. We detail the most critical design challenges and the solutions we have chosen.

***Index Terms*—** ice-penetrating radar, UAVs

1. INTRODUCTION

Ice-penetrating radar systems are low frequency (typically sub-500 MHz), nadir-facing impulsive or chirped radar systems used for imaging the layers and bed geometry of Earth's ice sheets (Antartica and Greenland), ice caps, and glaciers. High power systems can penetrate through multiple kilometers of ice [1] and can be integrated with crewed aircraft to perform large-scale surveys. In comparison to borehole measurements and active seismic surveying, ice-penetrating radar is much easier to scale up to large surveys, while offering far better spatial resolution and accuracy compared to gravity inversion approaches [2].

The most prominent use of ice-penetrating radar is for creating maps of the basal topography beneath ice sheets and glaciers. These maps, usually interpolated from relatively sparse radar measurement lines, are critical inputs to ice sheet models used to predict sea level rise. In addition, ice-penetrating radar data is also used to examine the internal layers in ice sheets, interpret the flow history of ice from layer signatures, identify englacial and subglacial hydrological systems, measure the vertical velocity of englacial layers, detect crevasses, and many other applications [1].

Fig. 1. The UAV system presented in this paper. The radar system is enclosed in the nosecone and the antennas are mounted under the wings.

Existing ice-penetrating radar systems are either mounted under crewed aircraft or towed behind snowmobiles. Crewed airborne approaches are both expensive and logistically challenging. As a result, measurements in Antarctica remain sparse relative to the desired spatial resolutions of ice sheet models [3]. Ground-based systems are cheaper and easier to deploy but are limited to small spatial extents over areas that are considered safe for human travel.

Improvements in UAV technology have made fixed-wing UAVs an appealing option for ice-penetrating radar platforms. While a few existing systems have been tested, integration of wide-bandwidth antennas compatible with a system with sufficient a signal-to-noise ratio (SNR) to see the bed onto a platform capable of scientifically useful flight times remains challenging. In this paper, we first briefly review the types of UAV-borne ice-penetrating radar systems that have been tested and outline the challenges they face. Next, we describe potential solutions to these challenges. Finally, we present preliminary test data suggesting that our prototype UAV and radar system is capable of performing experiment-scale scientific surveys.

2. UAV-BORNE ICE-PENETRATING RADAR SYSTEMS

For all radar systems, the SNR is a function of the energy reflected by the target; and the range resolution, which refers to the ability to distinguish two closely-spaced reflecting targets, and is related to the pulse bandwidth. Ice-penetrating radar systems can be divided into two categories: impulsive and frequency-modulated. These systems maximize their energy and bandwidth in different ways. Impulsive system emit a high-power, short pulse; the sharp edges of the short pulse create the system bandwidth and the energy on the target comes from a high peak power during the transmission. Frequency-modulated systems emit a comparatively longer and often lower-power pulse that sweeps (or steps) over a range of frequencies. In this case, the bandwidth comes from the frequency-modulation of the emitted waveform and the energy comes from the product of the pulse length and the pulse power.

For a fixed peak transmit power, impulsive systems have a fundamental tradeoff between range resolution (shorter pulse is better) and SNR (longer pulse transmits more energy). Frequency-modulated systems avoid this tradeoff because the longer pulses can both emit more energy and contain a wider-bandwidth signal.

In general, impulsive systems are more widely employed for measurements of temperate mountain glaciers, where low frequencies are needed to penetrate through warm ice, practical antennas have very limited bandwidth, and the depth of the ice is limited to a few hundred meters. Most systems designed for ice sheets employ frequency-modulation. In these cases, higher frequencies are often used to enable more bandwidth for improved range resolution and long pulses help provide the SNR needed to penetrate through kilometers of ice.

Off-the-shelf impulsive radar systems can be carried by large multirotor UAVs [4]. Due to the weight of the payload and inherent limitations of multirotor aircraft, flight times are generally limited to under an hour. For mountain glaciers, this is a reasonable approach. For ice sheets, however, both significantly longer flight times and frequency-modulated radar systems are desirable. One such system has been tested to our knowledge, a custom-built 4.4 m wingspan remote-controlled aircraft with a dual band 14.6 MHz and 34.3 MHz radar system [5]. Both antennas were dipole antennas and the usable bandwidths of the two frequency bands were 1 MHz and 5 MHz, respectively.

3. SYSTEM DESIGN

Our objective is to design a low-cost, portable system based largely on off-the-shelf parts that can be operated in Antarctica by two people. This work leverages the availability of low-cost, fixed-wing UAVs, high-quality open-source autopilot systems, and miniaturized SDRs.

The core of the radar system is an Ettus Research USRP b205mini-i SDR. Weighing only 24 grams while providing 56 MHz of bandwidth, this system was the smallest and lightest option. A Raspberry Pi 4 Model B is connected to the SDR for control and data logging. These components and additional electronics for interfacing with other aircraft systems are housed in an enclosure (Fig. 2) in the nose of the plane. The complete radar system, including the enclosure, is under 350 grams.

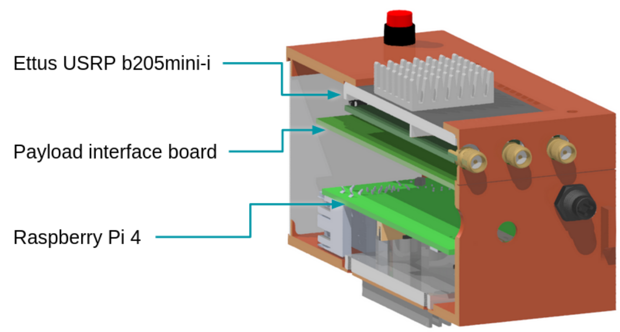

Fig. 2. The radar payload consists of a software-defined radio, a Raspberry Pi single-board computer, and some interface electronics.

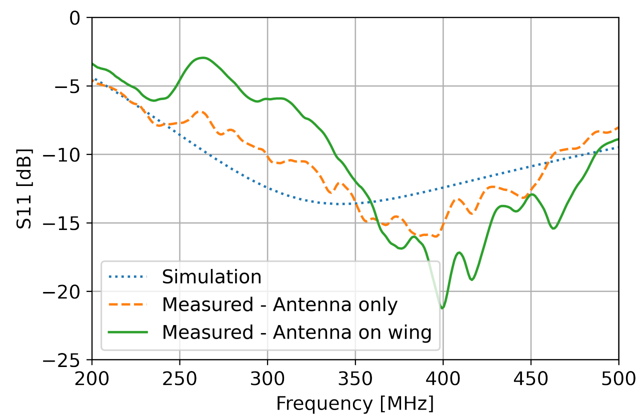

Fig. 3. Return loss (S11) of simulated and fabricated edge-cut bowtie antenna on FR4

The UAV is based on the X-UAV Talon airframe. The low cost, long wingspan, and large payload volume made this an appealing choice. In addition to the radar system, the inside of the aircraft holds an off-the-shelf flight controller running the open-source PX4 autopilot and a suite of sensors to enable autonomous navigation. All of the above mentioned parts are mounted inside the aircraft with a set of custom-designed 3D-printed parts. In addition, the aircraft was modified with wing extensions to increase the separation between the antennas and conductive carbon fiber spars were replaced with fiberglass ones, as discussed in Section 3.2.

3.1. Antenna Design

A major obstacle to using a frequency-modulated radar system with a fixed-wing UAV is integrating the antennas with the UAV structure. The goals of this integration are that the

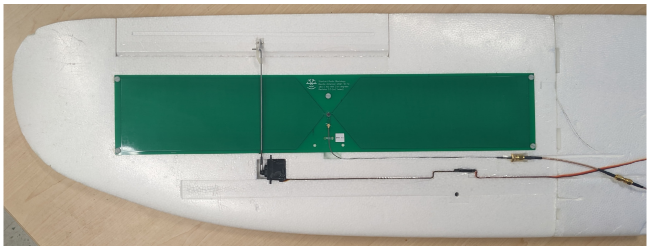

Fig. 4. Fabricated edge-cut bowtie antenna on FR4 installed on the underside of a UAV wing

antennas have minimal impact on the control or aerodynamic drag of the UAV and that the antennas meet the required RF specifications when mounted in the presence of conductive elements of the UAV, such as carbon fiber structural components and wiring.

Existing UAV-borne ice-penetrating radar systems have used various types of dipole antennas. While simple to construct, they offer small fractional bandwidth. Our design uses a bowtie-style antenna. In order to fit the bowtie antenna in the area provided by the wing, the full bowtie is cropped to a maximum width of 10 cm. This approach has previously been suggested for ground-penetrating radar antennas [6] and has worked well for our system in both simulation and testing.

We simulated the design in HFSS, empirically tweaking the length, flare angle, and maximum width. The simulated and measured reflection coefficient is show in Figure 3. The antennas are fabricated as printed circuit boards (PCBs) on a standard FR4 substrate. This approach reduces the cost of the antenna, makes it easy to replicate, and allows for a balun and connector to be easily included in the design. Each antenna is tuned to 200 ohms with a 1:4 RF transformer integrated onto the board for 50 ohm matching to the rest of the RF system. A fabricated antenna is attached to the underside of each wing using plastic bolts and tapped anchors, as shown in Figure 4.

The use of an EPO foam wing significantly reduces the integration complexity. As shown in Figure 3, mounting the antenna on the wing has relatively little impact on the antenna performance. In contrast, installations on molded carbon fiber elements require significant separation between the antenna and the wing or more complex antenna designs.

A number of other designs were also considered, including log-periodic and Vivaldi antennas. Both of these types of antennas could provide wider bandwidth and higher directivity, however their end-fire beam pattern and size required to operate as low as 300 MHz makes integration with a small UAV difficult. Representative log-periodic [7] and Vivaldi [8] antennas operating in similar frequency ranges had sizes of around 40 by 50 cm. In comparison to a maximum chord of 32 cm and a ground clearance of less than 14 cm, this size of antenna would be difficult to mount and would be expected to have a large impact on the flight characteristics of the aircraft. These types of antennas, however, are promising options for significantly larger UAVs.

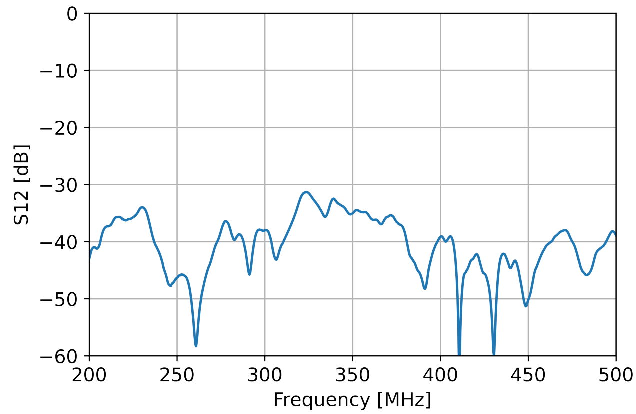

Fig. 5. Measured direct coupling between transmit and receive antennas mounted on UAV wings

3.2. Antenna Coupling

The small size of UAV platforms limits both the size of antennas that can be used and the separation between those antennas. The edge-cut dipoles described in the prior section, for example, have a simulated directivity of approximately 2.4 dBi, compared with about 7.5 dBi for the same antenna with an appropriately spaced back reflector. This and the physical proximity of the antennas required by the wingspan significantly increase the RF coupling between the antennas. In order to minimize this coupling, wing extensions were added, as shown in Figure 2 and the two primary carbon fiber spars in the wing were replaced by fiberglass spars, resulting in greater than 30 dB of isolation between the antennas over the frequency range of interest (see Figure 5).

The challenge introduced by this coupling is that the transmit pulse can easily saturate the analog to digital converter (ADC) on the receiver. This leaves two options: limit the power of the transmit pulse to avoid saturating the receiver or make the transmit pulse sufficiently short that data collection can begin after the transmit pulse. Assuming a maximum flying altitude of 400 ft AGL (the limit in most cases under FAA Part 107 rules), a pulse that saturates the receiver must be 0.8 μs or shorter in order to still see the surface. In practice, the minimum time must be even shorter to account for switching time or saturation recovery time.

Table 1 shows a comparison of three sets of radar parameters that would yield approximately the same returned energy from the surface. The first column shows parameters similar to a conventional airborne ice-penetrating radar system (roughly based on one iteration of the MCoRDS system [9]). The second column shows an example set of parameters for a UAV-based system where the pulse must be short enough to finish transmitting before the surface reflection comes back. The third column shows an example where this requirement does not apply, either because there is sufficient antenna separation or the pulse power is low enough not to blind the re-

	Conventional Airborne System	UAV Short Pulse	UAV Long Pulse
Altitude	500 m	120 m	120 m
Geometric Spreading Loss	-84.5 dB	-72.1 dB	-72.1 dB
Transmit Power	500 W	35.5 W	0.58 W
Pulse Length	1 μs	0.8 μs	50 μs
Equivalent Pulse Energy	1.78 pJ	1.78 pJ	1.78 pJ

Table 1. Comparison of radar parameters yielding approximately equivalent pulse energy returned from the surface

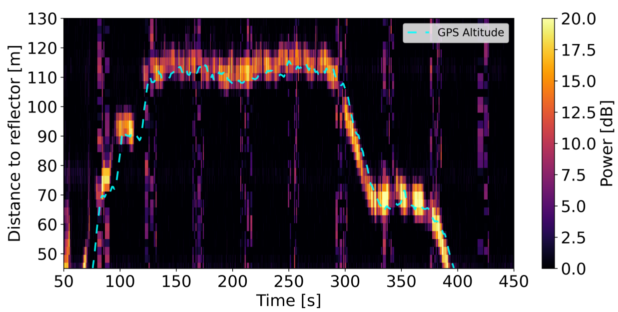

Fig. 6. Radargram showing reflection off of a dry lake bed during a test flight

ceiver during the transmit pulse. Both approaches are quite feasible for a UAV-borne system. The longer pulse approach, however, is appealing because it reduces system complexity and allows for the possibility of flying lower over the ice and further reducing the power requirements.

4. INITIAL TESTING

Initial system testing was performed over a dry lake bed on the Stanford University campus. Given that the frequencies employed would be expected to have almost no penetration into soil, the objective of the testing was to see a reflection from the surface that corresponds with the estimated aircraft altitude. Figure 6 shows a radagram from this flight with the GPS-derived altitude overlaid as a dashed white line. The reflection from the lake bed is clearly visible throughout most of the flight. The periodic higher noise that obscure the echo appears to be due to external interference.

The signal is lost entirely during periods of the ascent (due to steep pitch angles) and roll-dependent fading can be observed during the extended loiter period at the max altitude. These effects will be explored in more detail in future work.

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