# The BYU $\mu$SAR: A Small, Student-Built SAR for UAV Operation

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***Abstract*— Students at Brigham Young University have developed a new, low-cost Synthetic Aperture Radar (SAR) system, the BYU $\mu$SAR. The simple design, based on a linear frequency modulated continuous wave signal (LFM-CW), reduces the size and power compared to a conventional pulsed SAR system. This enables the BYU $\mu$SAR to fly on a small UAV, further reducing the cost of operation and extending the use of SAR into new areas. Design parameters and specifications for the BYU $\mu$SAR are presented in this paper, together with results from experimental data collection and test flights.**

## I. Introduction

Synthetic Aperture Radar (SAR) has been successfully used in a variety of applications such as terrain mapping, reconnaissance, and environmental monitoring. Unfortunately, the costs associated with existing SAR systems have precluded their use in studies requiring frequent revisits. These limitations can be overcome by using a small, low-cost, high-resolution SAR system designed for operation on a small UAV. Such a system has been developed by students at Brigham Young University.

Dubbed the BYU $\mu$SAR, this new system was designed based on the experience gained by previous SAR projects at BYU, e.g. [1]. The $\mu$SAR is extremely small, light-weight, low-power, and inexpensive.

The $\mu$SAR was designed to image Arctic sea ice while flying on a small UAV. The target UAV has a 6-foot wingspan, flies at low-altitudes ($<$ 300m), and has limited power to supply to the payload. The $\mu$SAR was designed to work within the limitations and exploit the advantages of UAV operation. A successful test flights have exhibited the capabilities of the $\mu$SAR system. During a flight in the Arctic, the $\mu$SAR was used to image sea ice floating in the ocean. In addition to the main UAV, an experimental UAV has been built by students at BYU to carry the $\mu$SAR. Test flights have also been conducted on a Diamond Katana over Utah Lake and agricultural areas south of Provo, Utah.

The BYU $\mu$SAR system demonstrates the utility of a low-cost, easy to operate UAV-based SAR. It is anticipated that the $\mu$SAR will facilitate making repeated flights over an area for an extended period of time. This paper outlines the design parameters and specifications for the BYU $\mu$SAR and discusses the implications of the design decisions. Results from a $\mu$SAR data collection test and a test flight are also shown.

## II. BYU $\mu$SAR Design

To meet the power and cost requirements, the homodyne $\mu$SAR design employs a linear frequency modulated continuous wave (LFM-CW) signal, effectively maximizing the pulse length. The long pulse length allows a LFM-CW SAR to maintain a high SNR while transmitting with less peak power than pulsed SAR [2]. While continuously transmitting, the frequency of the transmit signal increases and decreases repeatedly. The time interval it takes for the frequency oscillation to ramp up and down again is considered the pulse repetition interval (PRI) and the number of up/down cycles per second is the pulse repetition frequency (PRF).

A simplified block diagram of the $\mu$SAR design is shown in Figure 1. To simplify the A/D and data storage hardware, the LFM-CW SAR mixes the return signal with the transmitting signal and then samples. The return signal is thus de-chirped and the frequency difference is stored. This simplifies the sampling hardware because the required sampling frequency is lower, although a higher dynamic sampling range is needed.

Designed to minimize size, weight, and cost, the BYU $\mu$SAR system consists of a stack of custom microstrip circuit boards measuring 3”x3.4”x4”. The weight of the overall system is further reduced by using no enclosure. In all it weighs less than 2 kg, including antennas and cabling.

The system architecture is divided into five subsystems which include transmit, receive, power, digital, and A/D systems. Each subsystem is built upon its own custom board, or shared between boards. The subsystems are interconnected through wires and coaxial cables. Component costs of several thousand dollars are kept low by using off-the-shelf components as much as possible.

The UAV supplies the $\mu$SAR with either +18VDC or +12VDC. The power subsystem uses standard DC/DC converters to supply the various voltages needed in the system. Power consumption during operation is nominally 18 W, with slightly more required for initial startup. The $\mu$SAR is designed for “turn-on and forget” operation. Once powered up, the system collects data continuously for up to an hour. The data are stored on-board for post-flight analysis.

The core of the system is a 100 MHz stable local oscillator (STALO). From this single source, the frequencies for operating the system are derived, including the sample clock and the radar chirp. The LFM-CW transmit chirp is digitally created using a direct digital synthesizer (DDS) which is controlled

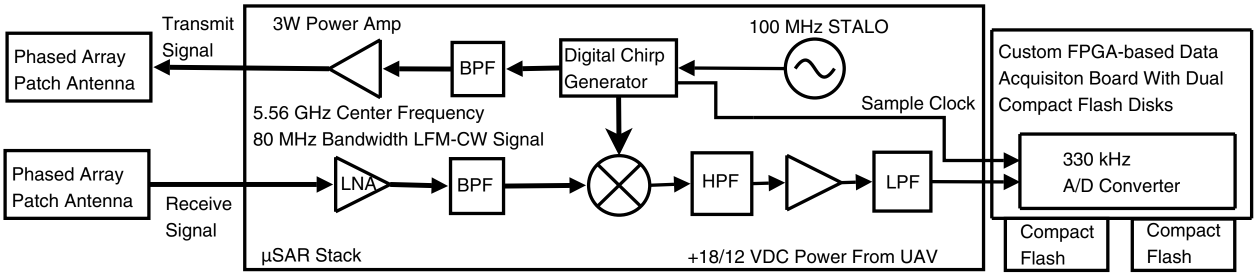


Fig. 1. Simplified BYU $\mu$SAR Block Diagram.

by a programmable IC microcontroller. Switches control the PRF settings, allowing it to be varied (128-2886 Hz) for flying at different heights and speeds. The programmable DDS also generates the sample clock coherent with the LFM signal.

The frequency of the LFM-CW signal is multiplied and the signal is amplified. Then it is split with one copy of the signal being mixed with the return signal and the other copy being transmitted. After amplification, the LFM-CW signal is transmitted with a power of 28 dBmW at a center frequency of 5.56 GHz and bandwidth of 80 MHz. The range resolution of an LFM chrip is inversely proportional to the bandwidth of the chirp, thus the $\mu$SAR has a range resolution of 1.875 meters.

Two identical custom microstrip antennas, each consisting of a 2x8 patch array, are used in a bi-static configuration. The antennas are constructed from coplanar printed circuit boards. A symmetric feed structure is milled on the back of one board and the patch array is milled on the front of another. The boards are sandwiched together with pins feeding the signal through the boards from the feed structure to the patches. Bi-static operation is used to maximize isolation between the transmit and receive signals. The antennas are approximately 4"x12" and have an azimuth 3dB beamwidth of 8.8° and an elevation 3dB beamwidth of 50°.

The azimuth resolution for SAR is approximately equal to half the antenna length in azimuth. This gives an azimuth resolution of 0.15 meters. In creating images from the $\mu$SAR, the data in the azimuth direction is muti-look averaged to yield a final resolution equal to the range resolution.

The return signal is amplified and mixed with the transmit signal. This de-chirped signal is filtered and then sampled with a 16 bit A/D at 328.947 kHz. A custom FPGA board was designed to sample the signal and store the data on a pair of 1GB Compact Flash disks. The data is collected continuously at a rate of 0.63 MB/second.

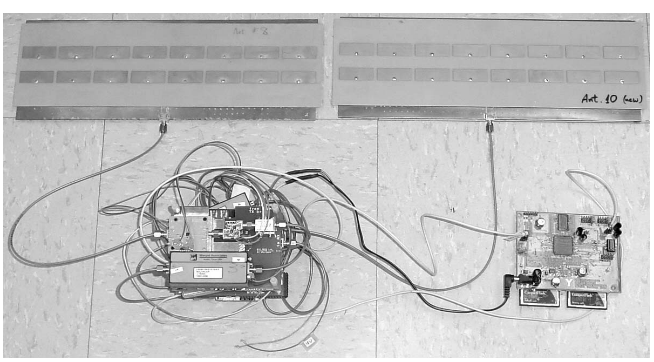

Fig. 2. Photograph of complete BYU $\mu$SAR system ready for flight on a small UAV.

The $\mu$SAR can also be operated in dual-channel interferometric mode. An additional channel is created by adding another antenna and receiver board. When connected to the system, both channels are sampled, the data being interleaved and stored at a rate of 1.26 MB/second.

Processing the $\mu$SAR data is done using custom software. A SAR image is formed via range and azimuth compression using full 2-d matched filtering [3]. In addition, algorithms for chirp start detection, autofocusing, and interference filtering are used. Processing time on a conventional laptop is similar to data collection time.

Processing begins with the stored signal which has frequencies that are linearly related to the range of the target. The discrete Fourier transform is used to separate the signal by frequency and thus the targets are separated in range. For LFM-CW SAR, range compression is simply taking the DFT of the data.

As the SAR platform moves past a target, the phase of the return signal changes as does the range to the target. This phase-change is modeled as a frequency modulated chirp that is calculated for each range bin from the velocity of the platform, taking into account the range-walk. Two-dimensional matched filtering with the range compressed data yields the azimuth compressed image.

The BYU $\mu$SAR continuously transmits and receives. For simplicity the A/D start trigger is not synchronized with the start of the LFM chirp. In order to maintain phase continuity and to predict the azimuth phase, it is vital that the signal be separated at the boundaries between the up and down chirps. Using the data itself, a chirp start detection algorithm finds the offset of the first up/down ramp. A range of possible offsets are predicted and for each one the data are separated into up and down chirp segments. The segments are range compressed and the cross-correlation of each suspected up chirp with its corresponding down chirp is calculated. The offset that gives the highest cross-correlation is assumed to be the correct offset for the start of a chirp.

The $\mu$SAR center frequency of 5.56 GHz was chosen because it is in the unlicensed Wi-Fi band. Other devices using frequencies within the bandwidth of the $\mu$SAR can cause

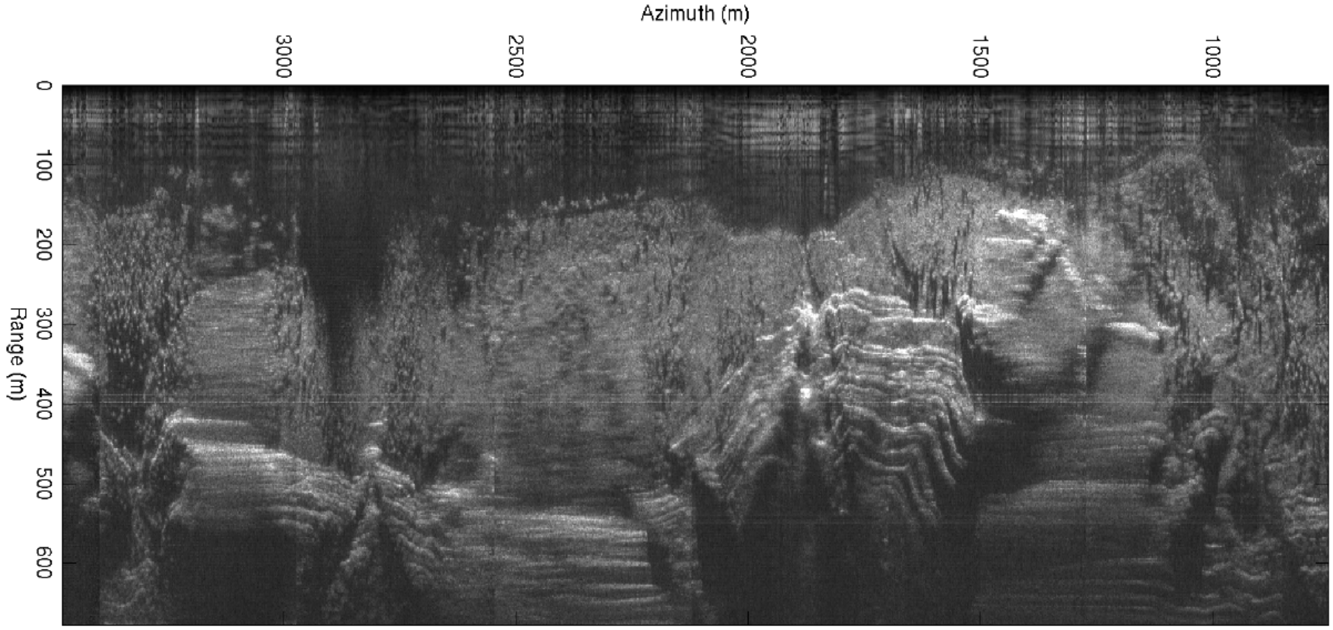


Fig. 3. Example $\mu$SAR image from a van driving up Provo Canyon, UT. Blurred sections result from the curving highway up the canyon. The canyon walls are naturally terraced and appear layered in the image.

interference in the received signal. The effects can be reduced by filtering sections of higher than average power in the raw data [3].

The velocity of the $\mu$SAR platform varies and is often imprecisely measured. The performance of the azimuth compression algorithm is highly dependent on accurate velocity measurements. An auto-focusing algorithm is used to adjust the velocity used in azimuth compression to produce a better image. Azimuth compression is performed over a range of velocities centered at the assumed velocity. The velocity that produces an image with the sharpest, brightest point targets is used to generate the final image. Each collection is split into separate velocity windows and the velocity is determined for each section to account for changes in platform velocity during collection. The final image is geolocated using the calculated velocities to estimate the position of the platform during collection.

## III. Experimental Results

The $\mu$SAR system was initially tested using a ground vehicle. The antennas were mounted on the side of a van and data were collected as it drove past a variety of scenes, including urban and rural areas and a canyon. The canyon test simulates the geometry of an airborne SAR and produces images that resemble an airborne SAR image (see Fig. 3).

On 15 March 2006, the $\mu$SAR collected data while flying in a Cessna 185 over the Arctic Ocean. The images created show the structure and texture of sea ice. These were the first aerial images from the $\mu$SAR. A subsequent test flight over and area south of Provo, Utah in April of 2006 yielded images of the rural areas near Utah Lake (See Fig. 4).

BYU has built a small UAV which flies by programmable autopilot or by remote control. Programmable GPS navigational waypoints are loaded onto the autopilot for efficient imaging of large areas and exact flight-path replication for subsequent revisits. A series of unfortunate, but spectacular, incidents have thus far prevented the collection data using this platform.

The $\mu$SAR is also being tested as a stationary interferometric radar operating in differential mode to assess the possibility of detecting small shifts in mining highwalls that may be indicative of imminent failure [4]. Recent tests have been encouraging, suggesting that the $\mu$SAR is suitable for conducting further experiments to determine the limits and possibilities of using this kind of system for detecting mining hazards. Future tests would include evaluating the reliability and stability of the system while collecting data during small rock slides, simulated rain, and testing in a variety of environmental conditions.

From the beginning the BYU $\mu$SAR has been a student project. A number of graduate and undergraduate students have been involved in a variety of capacities. Students developed the original designs and built prototypes for each subsystem. Then they modified the designs according to the results from the prototype tests. The final $\mu$SAR units were assembled and tested by students. They also developed the processing software. They ran field tests to verify operation and added a second channel for interferometric operation. The students continue the development of the $\mu$SAR and have further tests planned to demonstrate the utility of this new system.

## IV. Conclusion

In this paper the design and the development of the BYU $\mu$SAR has been presented. The approach taken in designing the system to minimize size and cost has also been discussed. The successful operation of the $\mu$SAR has show the viability of a low-cost, small SAR. The use of an LFM-CW signal facilitates

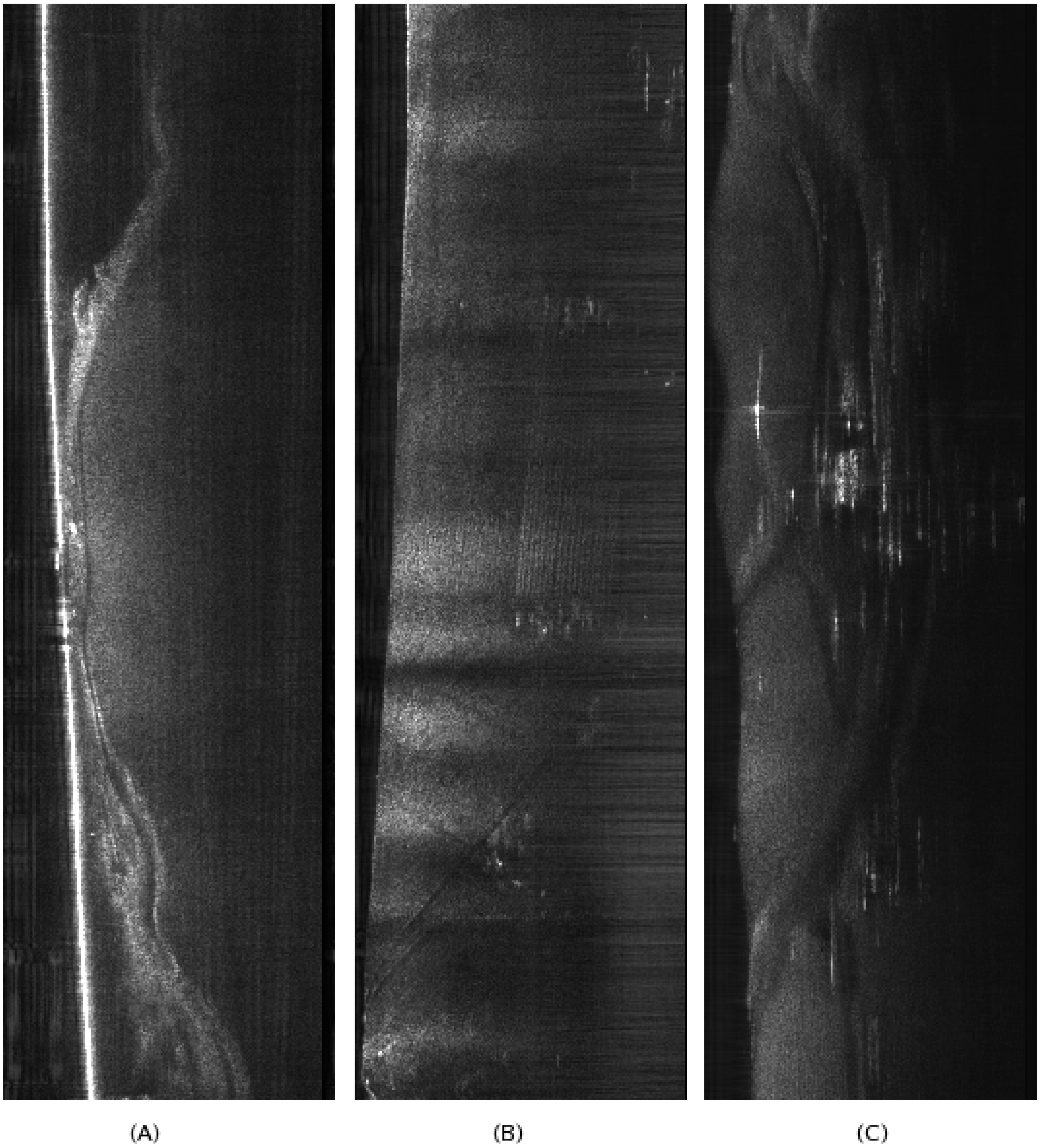


Fig. 4. Aerial $\mu$SAR images from Utah Lake and areas south of Provo, Utah. Section A shows the shoreline of Utah Lake, notice the bright nadir return from the surface of the water. Section B is an agricultural area with fields and orchards. Section C shows a number of man-made structures that show brightly in the image.

system miniaturization and low-power operation which make it possible to fly the $\mu$SAR on a small UAV. The ease of operation and low operating cost make it possible to make extended SAR studies of an area without a large investment and permit exploration into new applications of SAR systems.

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