The SlimSAR: A Small, Multi-Frequency, Synthetic Aperture Radar for UAS Operation

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***Abstract*— The SlimSAR is a small, low-cost, Synthetic Aperture Radar (SAR) and represents a new advancement in high-performance SAR. ARTEMIS employed a unique design methodology that exploits previous developments in designing the SlimSAR to be smaller, lighter, and more flexible while consuming less power than typical SAR systems. With an L-band core, and frequency block converters, the system is very suitable for use on a number of small UAS's. Both linear-frequency-modulated continuous-wave (LFM-CW), which achieves high signal-to-noise ratio while transmitting with less power, and pulsed mode have been tested. The flexible control software allows us to change the radar parameters in flight. The system has a built-in high quality GPS/IMU motion measurement solution and can also be packaged with a small data link and a gimbal for high frequency antennas. Multi-frequency SAR provides day and night imaging through smoke, dust, rain, and clouds with the advantages of additional capabilites at different frequencies (i.e. dry ground and foliage penetration at low frequencies, and change detection at high frequencies.)**

I. Introduction

Unmanned aircraft systems (UAS) are being used more and more frequently in military, civilian, and scientific applications providing remote-sensing, surveillance,reconnaissance, and environmental monitoring capabilities. Most sensors typically used on small UAS are electro-optic/infrared (EO/IR) instruments, which are limited by obstruction due to clouds, fog, dust, and smoke.

On larger platforms these limitations are overcome using synthetic aperture radar (SAR) which provides high-resolution imagery day and night in all weather conditions. In addition, SAR imagery at different frequencies can provide a variety of information about an area. There would be many benefits of operating a multi-frequency SAR on a small UAS, but the large size and weight of typical SAR systems preclude their use.

The SlimSAR is a new advancement in high-performance, small, low-cost, SAR, suitable for operation on small UAS. This multi-band SAR was designed by exploiting the techniques and technologies developed for previous systems, resulting in increased capability and flexibility, all in a small package.

This paper describes the unique SlimSAR system design and the corresponding performance trade-offs, and also presents examples of imagery from the SlimSAR. In Section II we present the previous work and systems relevant SlimSAR's heritage. In Section III we discuss the system design methodology, and Section IV details the design. The performance trade-offs and system flexibility are explained in Section V. Section VI shows example SAR imagery from the SlimSAR.

II. Previous SAR Work

ARTEMIS, Inc. has been supporting SAR programs for over decade with development and manufacturing. Our receivers, exciters, and up-converters are a part of Global Hawk, U-2, and ASTOR.

Recent experimental programs include the UAVSAR and GLISTEN with Jet Propulsion Laboratory, the NuSAR with the Naval Research Laboratory (NRL) and Space Dynamics Laboratory (SDL), and in association with Brigham Young University (BYU), the MicroASAR.

A. NuSAR

The NRL UAS SAR System (NuSAR) was developed as part of NRL's DUSTER program in a team effort with BYU, ARTEMIS, SDL, and NRL [1]. The NuSAR is designed for UAS flight, operating at L-Band with a variable bandwidth of 500 MHz maximum (resulting in a resolution as fine as 30 cm). It is a low-power pulsed system with a peak transmit power of 25 W and is designed to operate at 2500-6000 ft above ground level (AGL). The addition of a block up/down converter extends operation to other frequency bands, with the system nominally outfitted with an X-band block converter.

B. MicroASAR

Rather than transmitting pulses, the MicroASAR is a continuous wave (CW) SAR system [2]. A CW system is constantly transmitting and receiving and is thus capable of maintaining a high SNR while transmitting much less peak power than a comparable pulsed system. The MicroASAR transmits at 1 W and operates at altitudes 1000-3000 ft AGL. The C-band signal has a variable bandwidth up to 200 MHz. An analog de-chirp on receive reduces the sampling requirements to keep the data rate low.

III. System Design Methodology

The SlimSAR was designed using an innovative methodology [3], [4]. The goal is to find the quickest path from system requirements specification to deployment of a successful

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14. ABSTRACT

The SlimSAR is a small, low-cost, Synthetic Aperture Radar (SAR) and represents a new advancement in highperformance SAR. ARTEMIS employed a unique design methodology that exploits previous developments in designing the Slim- SAR to be smaller, lighter, and more flexible while consuming less power than typical SAR systems. With an L-band core, and frequency block converters, the system is very suitable for use on a number of small UAS?s. Both linear-frequency-modulated continuous-wave (LFM-CW), which achieves high signal-to-noise ratio while transmitting with less power, and pulsed mode have been tested. The flexible control software allows us to change the radar parameters in flight. The system has a built-in high quality GPS/IMU motion measurement solution and can also be packaged with a small data link and a gimbal for high frequency antennas. Multi-frequency SAR provides day and night imaging through smoke, dust, rain, and clouds with the advantages of additional capabilites at different frequencies (i.e. dry ground and foliage penetration at low frequencies, and change detection at high frequencies.)

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solution. The SlimSAR design is based on the tested SAR systems, the MicroASAR and NuSAR. The existing designs were exploited to keep much of the design heritage while best meeting the requirements for the SlimSAR system. The risks associated with new, untested technologies are thus minimized.

Basing the design on an existing SAR system provided benefits for the integration and system testing process. The NuSAR and the MicroASAR were operating during the SlimSAR development period on a small, manned aircraft used as a UAS surrogate. Using the microASAR data from these flights, the data collection, handling, and processing methods were refined then used with very little modification for SlimSAR. The system was therefore ready for initial flight testing as soon as the hardware was completed. Immediate flight testing on the test bed aircraft revealed necessary changes in the SAR system, the processing algorithms, and other supporting systems.

For the SlimSAR, the preliminary design work was done during October 2008 with the first test flight of the LFM-CW version conducted the week of June 15, 2009. Over the next couple of weeks the system was refined in a very quick loop, with feedback from test flights prompting changes in hardware and software with immediate flight testing to verify the improved operation and provide feedback for further improvement. The pulsed version was first tested in January 2010.

IV. The System Design of the SlimSAR

The SlimSAR is designed for multi-frequency operation. The L-band core is a self-contained radar system that weighs only 6 lbs and consumes 150 W including a built-in motion measurement system. Additional frequency bands are available by using a block frequency converter that weighs 2 lbs and consumes about 32 W. Nominally the system is designed with X-band capability, with additional bands in development, frequencies lower than L-band and higher than X-band. Add-ons to the system include a miniature data link and a gimbal for the high-frequency antennas.

A. LFM-CW SAR Signal

The use of a linear frequency-modulated continuous-wave (LFM-CW) signal facilitates compact design, allowing us to achieve a high signal-to-noise ratio while transmitting with less peak power.

For LFM-CW SAR, the received signal is mixed with the transmit signal, resulting in the difference between the signal frequencies. This is illustrated in Fig. 1. Near range targets have a lower frequency than far range targets. The bandwidth of this signal is much less than the transmit signal bandwidth, thus the digital sampling requirements are relaxed.

Transmitting with less power and sampling the data at a slower rate can be done with hardware that is smaller, lighter, and consumes less power than traditional pulsed systems. The disadvantages are that the transmit and receive channels require separate antennas and feed-through between the antennas must be controlled.

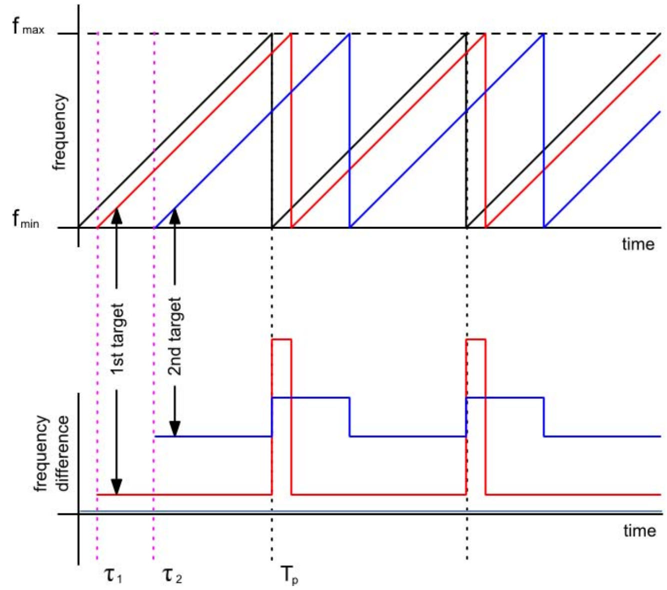

Fig. 1. A line diagram showing the idealized (exaggerated) spectrogram of the received signal before (top) and after (bottom) de-chirping. Note that a delay in time translates directly to a difference in frequency.

B. Delayed Mix-Down Chirp

The system has two direct digital synthesizers (DDS) which generate identical SAR signals, with one delayed by the time of flight to the closest range of the desired imaging area. When the received signal is mixed with this second chirp, the bandwidth is reduced, lowering our sampling requirements.

In LFM-CW SAR, the swath width is usually very limited, but with our delayed mixdown chirp we can increase the width of the imaged area. This swath width is constrained by a number of inter-related factors:

1) The width of the intermediate frequency filter
2) The chirp rate and chirp bandwidth
3) The pulse-repetition frequency and antenna beamwidth
4) The platform altitude (AGL)
5) The maximum data rate
6) The mix-down chirp delay

C. Overall System Design Walk-Through

The core of the system is the L-band portion. An FPGA controls the variable system parameters making sure the DDS's, the ADC, and the data storage are all working together. The DDS's generate the SAR signals which are up-converted to L-band (at different frequencies). The signal is either transmitted through the L-band antenna or up-converted to X-band in the X-band block converter, amplified, and transmitted through the X-band antenna.

The receive signal is amplified, and in the case of the X-band signal, down-converted to L-band. The signal is mixed with the delayed second chirp, offset in frequency, which de-chirps the signal at an intermediate frequency. A SAW band-pass filter with large out-of-band rejection removes the antenna feed-through and signal returns from outside the target area. The reduced bandwidth signal is mixed-down and

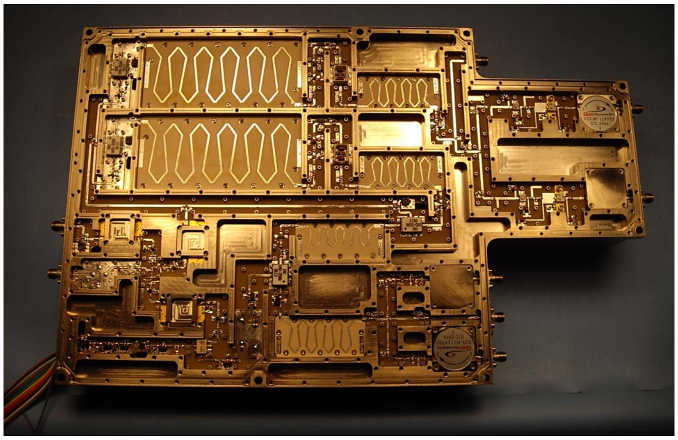

Fig. 2. Photograph of SlimSAR hardware

digitized. The digital signal is streamed via Ethernet to on-board storage, the tactical data-link, and/or and on-board processor. Range-Doppler, frequency-scaling, and backprojection algorithms have been developed for processing the data. The backprojection algorithm allows for non-linear flight paths (i.e. circular).

D. System specifications

The SlimSAR supports a contiguous signal bandwidth of up to 660 MHz. To accommodate restrictions in very heavily utilized spectrum bandsh, the bandwidth and center frequency can be adjusted and notches added. We have an FCC license at 1257.5 MHz with 85 MHz bandwidth. The system is capable of transmitting horizontal and vertical polarization for polarimetric operation.

The X-band up/down converter has two separate sub-bands, one just below 10 GHz, the other just above. These sub-bands are operated simultaneously by alternating each transmitted pulse.

The built in solid-state power amplifier is designed to output 4 Watts continuous peak power for the LFM-CW model and 25 W peak for the pulsed version, sufficient for the current targeted operational altitude of 5000-8000 feet above ground level (AGL). An external power amplifier can be added to obtain maintain a good SNR at higher altitudes.

E. Supporting subcomponents

There are several important subsystems which support the generation and exploitation of high-quality SAR imagery. The SlimSAR includes a built-in motion measurement system. A gimbal for the X-band antenna is also available. A gigabit Ethernet interface allows for the integration of a data-link for transferring the raw data to a ground station where it can be processed in near real time. The data is also stored in the 128 GB of on-board solid state storage, which is enough to record several hours of continuously collected SAR data, depending on the data rate.

The motion measurement subsystem includes high-precision GPS and inertial measurement unit (IMU). In order to obtain high-precision inertial measurements while minimizing the necessary payload weight, 3-axis accelerometers and fiber-optic gyroscopes are integrated into the SlimSAR enclosure, eliminating the need for an extra enclosure. Additionally, at X-band (and other high-frequency bands) the antennas use a pointing system because they have a narrow beamwidth. Data from the GPS/IMU system is fed in real time to a two-axis gimbal which controls the elevation and azimuth pointing angles of the antennas, keeping the antennas pointing perpendicular to the flight path even when the aircraft may be flying at an angle to account for wind. The gimbal allows the X-band antennas to rotate 270°, allowing for the use of SlimSAR in spotlight mode and ground moving target indicator (GMTI) mode.

V. System Performance Trade-offs and Flexibility

Every radar system has inherent performance tradeoffs, and SlimSAR is no exception. It is, however, a very flexible system; by simply adjusting some of its operational parameters, the SlimSAR can be made to operate in a wide variety of imaging situations. The pulsed version is subject to more traditional tradeoffs, but the unique nature of the LFM-CW system warrants further explanation.

1) The width of the intermediate frequency filter: As explained in Section IV-A, the received signal in the SlimSAR is mixed with a copy of the transmitted signal. Through this process, time-of-flight delays are translated directly to single frequencies in the spectrum of the resulting signal. The procedure is generally referred to as de-ramping or de-chirping of the received signal because the frequency modulated chirps are converted to single tones. When a transmitted pulse scatters off a target at range R it returns to the receiver after a time-of-flight delay of $\tau = 2R/c_0$. A target at this range is represented in the dechirped signal as the single frequency

$$\Delta f = k_r \tau \tag{1}$$

where k_r is the chirp rate of the transmitted signal. The chirp rate is defined in terms of the signal bandwidth B_T and the pulse length t_p as $k_r = B_T/t_p$. In the special case of CW SAR, the pulse length is equal to the pulse repetition interval (PRI) so that the chirp rate is directly proportional to the inverse of the PRI, which is the pulse repetition frequency (PRF). The chirp rate is therefore rewritten as $k_r = B_T f_p$ where f_p is the PRF.

The SlimSAR adds an additional wrinkle to this relationship by allowing an arbitrary delay between the beginning of the transmitted signal and the beginning of the signal which is mixed with the received signal during the dechirp process. Eq. (1) is rewritten to account for this delay as

$$\Delta f = k_r (\tau - d) \tag{2}$$

The bandpass filter employed in the receiver's IF chain after the dechirp mixer selects a range of frequencies in the dechirped signal and thus effectively functions as a range-gate. Time-domain range-gating is not possible because the radar must be constantly transmitting and receiving. The range-gate function is therefore performed in the frequency domain after the dechirp process.

In order to calculate the IF filter's effect on the width of the imaged swath, we must define the width of the filter. We assume that signals which fall outside of the 3 dB bandwidth of the filter's passband are suppressed. It is also necessary to know the point in the dechirped spectrum to which signals with a zero time-of-flight delay are mapped to. A target with zero time-of-flight delay is equivalent to feeding the transmitted signal directly into the receiver. In other words, we must know the frequency in the spectrum which corresponds to $\tau = 0$ and $d = 0$. This frequency is either DC for a baseband de-chirping scheme, or it is equal to the IF used in the de-chirping process. The difference between the zero time-of-flight frequency and the upper 3 dB point of the filter's passband is defined as $\Delta f_{max})$ and the difference between the zero time-of-flight frequency and the lower 3 dB point of the filter's passband, if any, is defined as Δf_{min}.

With these definitions in place, a simple rewriting of Eq. (2) gives an expression for maximum time-of-flight delay that is present in the filtered signal,

$$\tau_{max} = \frac{\Delta f_{max}}{k_r} + d. \quad (3)$$

Replacing Δf_{max} with Δf_{min} results in the minimum time-of-flight delay present in the filtered signal. These results are then converted to slant-range using the relation $R = c_0\tau/2$. The IF filter, therefore, directly affects the width of the imageable swath for an LFM-CW system such as the SlimSAR. The swath width is also affected by the chirp rate k_r, which is a function of the transmitted bandwidth and the PRF. The dechirp delay d does not affect the width of the swath, but rather where it physically begins and ends.

2) The chirp rate and chirp bandwidth: As described above, the chirp rate in an LFM-CW SAR is a function of the signal bandwidth and the PRF. The definition is reprinted here for convenience

$$k_r = B_T f_p. \quad (4)$$

The bandwidth of the transmitted signal is generally made to be as wide as possible because the resolution of the final image is inversely proportional to this value. Thus the chirp rate is modified mainly by changing the PRF at which the radar operates. A lower PRF results in a lower chirp rate, which in turn results in a more compact dechirped spectrum as per Eq. (1).

3) The pulse-repetition-frequency and antenna beamwidth: A SAR system relies on the Doppler shift created while moving past a target to focus in the along-track direction. The Doppler signal is sampled in the along-track by the PRF, which must therefore be high enough to properly record the entire Doppler bandwidth. The Doppler bandwidth is dependent on the velocity of the platform, v, as well as the wavelength of the transmitted signal, λ. Because the Doppler shift increases as the azimuth angle in the along-track direction is increased, the maximum Doppler bandwidth is calculated at the edges of the antenna's azimuth beamwidth, θ_a. A good approximation for the Doppler bandwidth is

$$f_D = \frac{2v\theta_a}{\lambda}. \quad (5)$$

Eq. (5) gives a lower bound on the operational PRF of the SAR system. The chirp rate and swath width can then be calculated for this lower bound.

4) The platform altitude (AGL) and dechirp delay: Platform altitude in a traditional pulsed SAR system is governed mainly by the system's transmit power. The radar signal must be transmitted with enough power to obtain a signal-to-noise ratio (SNR) which is sufficient to image intended targets. For an LFM-CW system, it is also necessary to ensure that the maximum imageable slant-range, as calculated in Eq. (3), produces the desired swath width at the given altitude. A traditional LFM-CW SAR, in which the dechirp delay d is zero, experiences a fundamental limit on platform altitude because the dechirped spectrum has a finite bandwidth and the PRF (and thus the chirp rate) is limited by the Doppler sampling requirement. With the dechirp delay equal to zero, a typical LFM-CW SAR is forced to image the space between the platform and the ground along with the desired swath. If the platform operates too high, the entire sampled slant range may be composed of space between the platform and the ground.

SlimSAR overcomes this limitation by introducing the delay d between the beginning of the transmitted pulse and the beginning of the pulse used for dechirp mixdown. This arbitrary delay does not change the width of the imageable swath, but rather changes its location relative to the platform. Increasing the dechirp delay shifts the spectrum of the dechirped signal down. Since frequency in the dechirped signal translates directly to slant range, this means that targets at a higher slant range will fall within the passband of the IF filter. Thus the SlimSAR can be configured to image a swath of a certain width from almost any altitude simply by increasing the dechirp delay and transmit power.

5) The maximum data rate: The SlimSAR uses an analog dechirp process to partially compress the SAR data before sampling and storage. It is therefore only necessary to store samples at a rate which is high enough to reliably digitize the bandwidth of the dechirped signal instead of the bandwidth of the transmitted signal. Much in the same way that the data rate of a pulsed SAR can be reduced by employing a range-gate to narrow the imaged swath, the data rate of the SlimSAR may be reduced by decreasing the bandwidth of the dechirped signal and sampling at a lower rate. The same effect can be achieved by increasing the operation PRF, which stretches the dechirped spectrum, and then averaging adjacent received pulses in order to reduce the effective PRF.

The SlimSAR contains a relatively wide IF filter and samples at an offset video frequency so that filtering, downsampling, and presumming operations can be performed digitally. This gives the device a great deal of flexibility when making the tradeoff between wide swath images and low data rate.

6) Example Operating Configurations: In order to illustrate the flexibility of the SlimSAR, examples of possible operating configurations are given here. The system parameters can be tailored to meet varying requirements for swath width, altitude, data rate and other constraints.

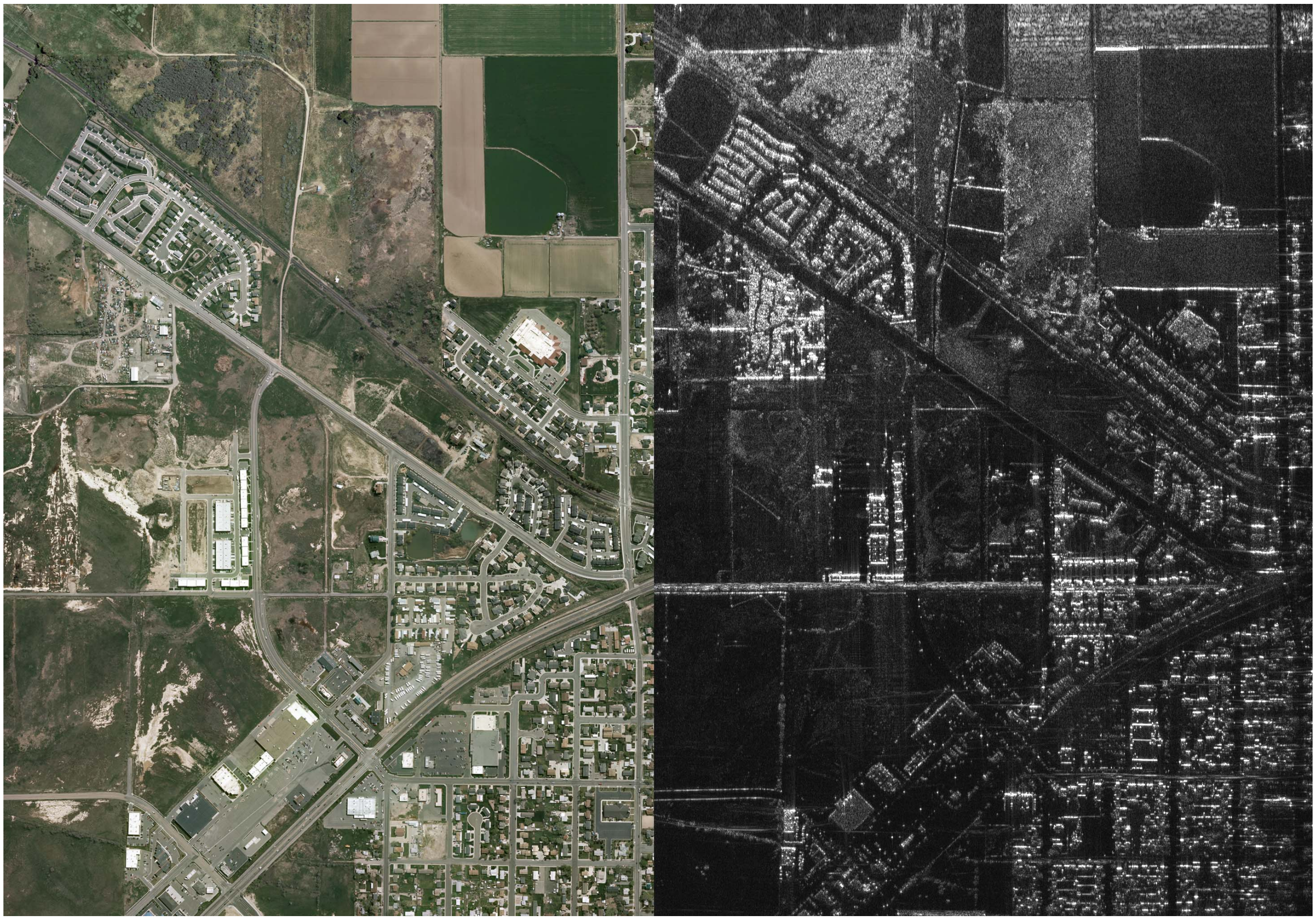

Fig. 3. At left, an optical photograph (courtesy of the State of Utah), of an area at the north end of Spanish Fork, Utah is shown. At right an 85 MHz bandwidth, pulsed, HH-pol, L-band SlimSAR image is shown. The scene is illuminated from the top and measures 1.45 km by 2 km.

Assume the radar is operating at L-band with 185 MHz bandwidth. The L-band antennas in this case are quite small, and so have an azimuth beamwidth of 50 degrees. The platform is at 5000 ft. AGL and flying at a speed of 100 knots. Eq. (5) is used to calculate the minimum PRF which prevents aliasing in the Doppler domain. The dechirped spectrum is filtered to 12 MHz. Using Eqs. (3) and (4), the maximum possible swath width is calculated to be approximately 11 km in slant range. This result assumes that all 12 MHz of the dechirped spectrum is sampled at slightly more than Nyquist, which results in slightly over 24 Msamp/sec. If samples are stored with a precision of two bytes, the resulting data rate is nearly 50 Mbytes/sec.

In order to reduce the data rate, the bandwidth of the dechirped signal may be narrowed. This results in a narrower swath, which is the obvious tradeoff. A swath that is 2 km in slant range, for instance can be obtained with a data rate of close to 7 Mbytes/sec. Even lower data rates may be obtained by narrowing the Doppler bandwidth by slowing the platform, lengthening the antenna, or filtering the data after sampling. In this way, data rates significantly lower than 5 Mbytes/sec may be obtained. It is important to note that with the delayed dechirp the 2 km slant range need not extend from the aircraft toward the ground, but can be made to begin at any arbitrary point on the ground and extend for 2 km. For this reason, the SlimSAR is limited in altitude only by its transmit power and can be configured to operate at a much wider range of altitudes than previous LFM-CW systems.

Unmanned aircraft are particularly useful when long duration flights preclude a human pilot, or where remoteness and harshness of the environment puts pilots and manned aircraft at risk. Autonomously controlled vehicles can often conduct missions lasting more than 20 hours. With ample on-board storage, the SlimSAR can collect SAR data throughout the duration of the mission.

VI. Sample SAR Imagery

The SlimSAR has been flown in a variety of locations. In Fig. 3, an area at the north end of Spanish Fork, Utah is imaged with the pulsed version of the SlimSAR. In Fig. 4, sample multi-frequency imagery from the LFM-CW SlimSAR and the microASAR, collected near Everett, WA, is shown.

VII. Conclusion

The advantages of a strong design heritage combined with rapid testing and integration are evident in the design of the SlimSAR. The quick schedule of going from initial concept designs in October 2008 to flight testing the week of 15 June

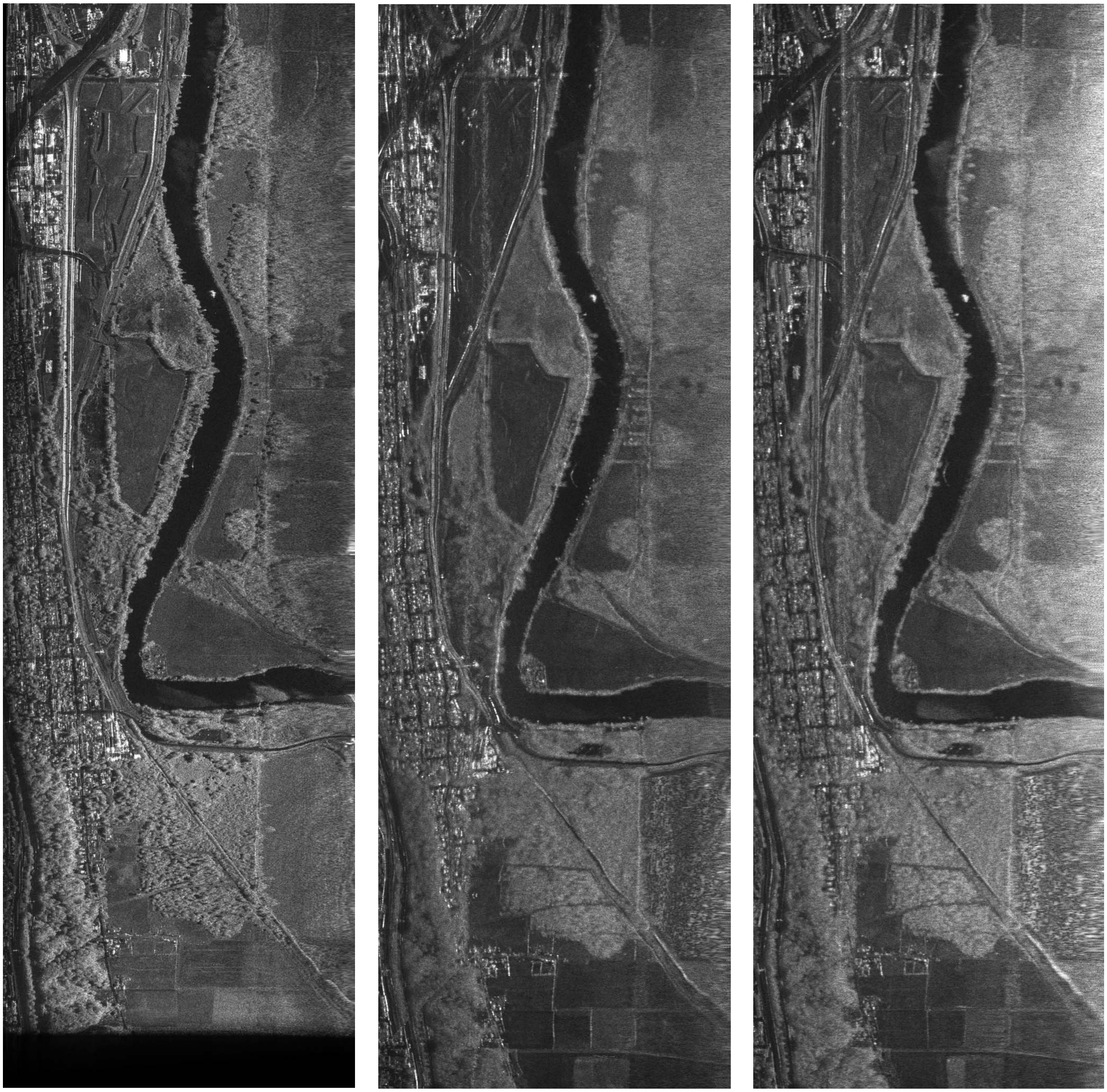

Fig. 4. Simultaneously collected SAR images of an area south of Everett, Washington (the scene is illuminated from the right). The leftmost image is a C-band microASAR image with a range resolution of 88 cm. The center image is an L-band HH-pol SlimSAR image with the rightmost being L-band VV-pol SlimSAR image. The SlimSAR L-band images have a range resolution of 1.76 m, corresponding to the 85 MHz bandwidth. The area shown is 1.4 km wide by 4.2 km long.

2009 has demonstrated the utility of our design methodology. The flight tests are aimed at proving and improving the SlimSAR and readying the system for integration onto a small UAS. The flexible design allows for future modifications such as alternative frequencies, higher bandwidths, and specific applications such as GMTI, interferometry, littoral and maritime modes, and polarimetry.

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