A Ground-Based Real-Aperture Radar Instrument for Differential Interferometry

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Abstract—**Radar differential interferometry was initially developed using satellite SAR sensors due to the requirements for precise control and knowledge of the interferometric baseline. The development of ground-based radar imaging systems extends this technology to obtain essentially continuous deformation measurements at high spatial resolution. Applications requiring near real-time deformation measurements such as monitoring of landslides, glaciers, and mining can benefit from this technology. We describe a real-aperture ground-based radar system operating at 17.2 GHz developed by Gamma Remote Sensing. Results for observations of landslides, glaciers and a dam in the Alps are presented. Sources of positional and deformation error including decorrelation and atmospheric phase delay along with strategies for reduction of these errors are discussed.**

I. INTRODUCTION

Satellite interferometry has been used extensively for deformation mapping of glaciers, landslides, earthquakes and volcanoes [1] and is currently widely applied using the latest generation of SAR sensors such as Terra-SAR-X [2]. Spaceborne sensors have the advantage of synoptic coverage over long time periods, global accessibility, and the potential for regular acquisitions over long periods. However, there are many applications where in-situ measurement has distinct advantages. These include flexibility in the data acquisition geometry, spatial resolution, tracking of rapid motions, near-real-time analysis, and the ability to suppress tropospheric phase variations via large numbers of acquisitions and imaging geometry.

Recently, a number of ground-based synthetic aperture radar systems have been developed for differential interferometric measurements [3][4]. These systems typically require a stable rail that is mounted on a fixed vehicle or on a concrete foundation. This is due to the requirement for a linear and repeatable synthetic aperture. These early systems have demonstrated the potential for in-situ differential interferometry.

Gamma has developed a portable radar interferometer (GPRI) that utilizes real-aperture antennas to obtain interferometric radar images. Initial tests of the instrument were completed in 2007. The GPRI utilizes linear waveguide antennas that generate a narrow azimuth beam. This beam is scanned about the vertical axis to build up the radar image one line at a time. Because an image line is acquired within a few milliseconds, there is essentially no loss of phase coherence during image formation. Ground-based SAR systems however require that the scene be coherent over the entire aperture time, typically 10-20 minutes. Moving features such as vegetation generally cannot be focused using the rail-based SAR methodology.

Description of the GPRI hardware, performance, and demonstration of the instrument for deformation measurement are discussed in the following sections.

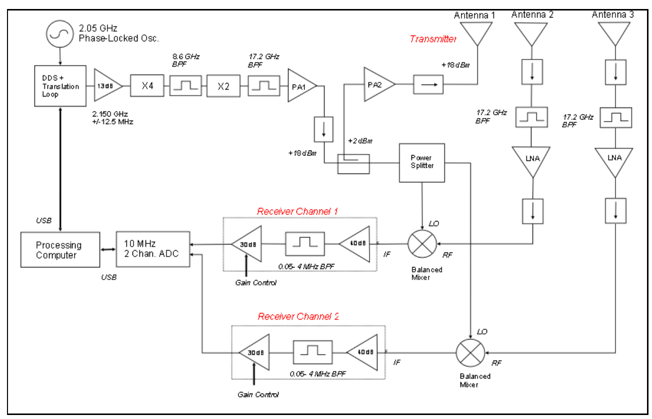

Figure 1. GPRI instrument block diagram

II. THE GPRI INSTRUMENT

The GPRI (see Fig. 1) is an FM-CW radar operating in the frequency range of 17.1 to 17.3 GHz with an output power of +18 dBm. The linear-FM transmit signal is generated by direct digital synthesis (DDS) over a 25 MHz bandwidth centered at 100 MHz. This chirp is translated to the range of 2.1375 to 2.1625 GHz using a phased-locked frequency translation loop. The DDS clock operates at 2.050 GHz and is synthesized from a 10 MHz crystal oscillator. The chirp centered at 2.15 GHz is multiplied in two steps, first by a factor of 4 to 8.6 GHz and then doubled to 17.2 GHz. Cavity bandpass filters are used to

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remove undesired harmonics generated by the frequency multiplication. The 200 MHz bandwidth signal at 17.2 GHz is split between the transmitter amplifier and dual receiver mixers. There are two receive channels to support "single-pass" interferometry using the two receiving antennas to form the baseline.

The FM-CW system approach is ideal for near-range radars for several reasons [5]. FM-CW operation requires that transmitting and receiving occur simultaneously. Long transmit pulses are possible even at close range increasing the average transmit power and consequently the radar SNR. The difference in frequency Δf between the transmitted and received echo in a FM-CW radar is directly proportional to the target distance r:

$$\Delta f = \frac{2rB}{cT} \tag{1}$$

where B is the radar bandwidth, T is the chirp duration and c is the speed of light. The output of the receiver mixer in each channel is already at baseband, and can be digitized at MHz rates using low-cost ADC converters. Chirps used by the GPRI have durations between 0.5 ms to 8 ms depending on the desired minimum and maximum range. The slant-range resolution of the system is $\delta_r = c/2B$. The chirp bandwidth of 200 MHz yields a nominal range resolution of 0.75 meters.

The low frequency cutoff f_l of the video bandpass filter determines the closest range for imaging while the high-frequency cutoff f_h of the filter determines the maximum slant range. The slant range ρ then lies between bounds given by:

$$\frac{f_l cT}{2B} \le \rho \le \frac{f_h cT}{2B} \; . \tag{2}$$

The azimuth antenna pattern determines the GPRI azimuth resolution. The nominal 3 dB beamwidth of the antenna is 0.4 degrees. This agrees well with the measured 10 dB point target beamwidth of 0.43 degrees. This is equivalent to a resolution of 7.5 meters at 1 km distance. A rigid carbon fiber truss is used to maintain antenna alignment.

The radar microwave electronics are mounted physically close to the antennas on the antenna support structure to reduce feed losses. Antenna spacing is 25 cm between the receive antennas with the transmit antenna located 35 cm above the center receiving antenna. The separate transmit antenna is required to obtain sufficient isolation between receive and transmit channels.

The antenna tower itself is attached to an astronomical mount responsible for azimuth positioning. The azimuthal pointing angle is repeatable with an accuracy of better than .04 degrees. Scan time for a 90 degree sweep is approximately 20 minutes and is currently limited by the mount. The entire radar is controlled by laptop computer and communicates with the radar using the computer USB interface. The GPRI instrument is shown in Fig 2. installed overlooking the Gorner glacier in the Valais region of Switzerland.

Figure 2. GPRI instrument at the Gorner Glacier in Switzerland

III. PROCESSING

The radar can be operated to obtain interferometric data for measuring deformation by acquiring images at different times and calculating interferograms between the images. With each azimuthal scan of the radar, two images are also acquired from the upper and lower antennas respectively. An interferogram generated from these images can be used to generate a DEM of the scene knowing the baseline distance and orientation are known. Since the images are acquired simultaneously there is no loss of correlation due to motion in scene, nor is there any atmospheric related phase variation.

A. Generation of SLC and Intensity Images

Processing of the individual images requires windowing of the echoes followed by a Fast Fourier transform. It is also important for generation of DEM data, that the video filters in the upper and lower channels are close to identical with respect to phase and group delay to suppress relative phase errors between the channels. In addition the image phase is corrected for the propagation time. This term is called the range-video phase and is discussed in [5].

Measurements of corner reflector point targets have been performed with the GPRI. A Kaiser window with parameter beta of 3.0 applied to the digitized echo yields a peak sidelobe level of -16.5 dB and a 3 dB range peak width of 0.92 meters. The 10 dB range peak width is 1.6 meters. Azimuth peak sidelobes are -13.5 dB relative to the peak response. Antenna gain is 25 dB with elevation beamwidth of 45 degrees.

A typical data acquisition covers an angular sweep on the order of 80 degrees, however full 360 degree imaging is possible. This is a major advantage of polar scanning relative linear rail based systems. The data are collected and processed in polar format. The data can then be resampled into rectangular format using bicubic spline interpolation. Terrain geocoding of the data is also possible and has been demonstrated.

An example of polar and rectangular format intensity images is shown in Fig 3. Maximum slant range is 1.5 km. A resampled GPRI image of the Gorner and Zwilling glaciers is in the Valais region of Switzerland is shown in Fig 3. The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the ETH in Zurich have been observing dynamic deformation of the glacier during the seasonal draining of a lake through the glacier. They funded a series of GPRI observations of the glacier during this critical period lasting several days in late June of 2008.

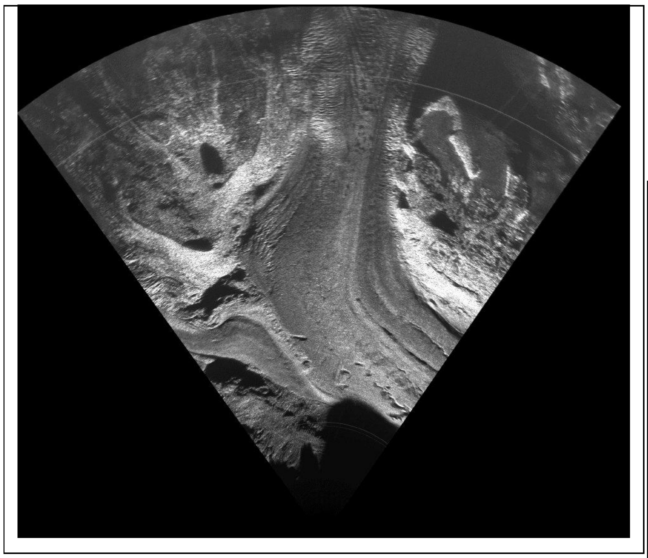

Figure 3. Radar intensity imaeGorner, Zwillings, and Grenz Glaciers in Switzerland imaged with GPRI. 74 deg. angular swath in rectangular format.

B. *Differential Interferometric Processing*

One of the advantages of in-situ interferometric imaging is that the baseline is essentially zero, therefore avoiding phase contributions due to topography. This is not the case with spaceborne or airborne repeat pass systems. The differential interferometric phase ϕ is related to the displacement δ_r along the radar line of sight (LOS) via:

$$\phi_{diff} = -\frac{4\pi}{\lambda}\delta_r + \phi_{atm} + \phi_{noise} \qquad (3)$$

In Fig. 4 we show differential interferograms acquired with a time intervals of approximately 18 min and 5 hours of the moving glacier. In the upper regions of the glacier velocities up to 300 m/year occur. Note that the correlation remains high during the 5 hr interval except in the upper regions where the motion related phase was under-sampled. Each fringe represents a displacement of 8.7 mm.

Stacking of multiple images is the most robust method for suppressing the atmospheric phase variation. In these interferograms we observe variations in the atmospheric path delay of approximately 10 mm. Stacking of multiple interferograms can be used to reduce this phase variation to estimate the average deformation rate for the set of images:

$$\dot{\delta} = \frac{\lambda}{4\pi} \frac{\sum_{j=1}^{N} \Delta t_j \phi_i}{\sum_{j=1}^{N} \Delta t_j^2}, \qquad (3)$$

where Δt are the time intervals and ϕ are the unwrapped interferometric phase measurements.

A series of test measurements have been performed to evaluate the intrinsic deformation sensitivity of the instrument. A small 15 cm corner reflector was set up at a distance of approximately 285 meters. The corner reflector was mounted on a micrometer mount (Fig 5) that permitted moving the reflector along the LOS by small increments. The phase of the point target was measured with the radar looking at the target at rate of about 4 Hz.

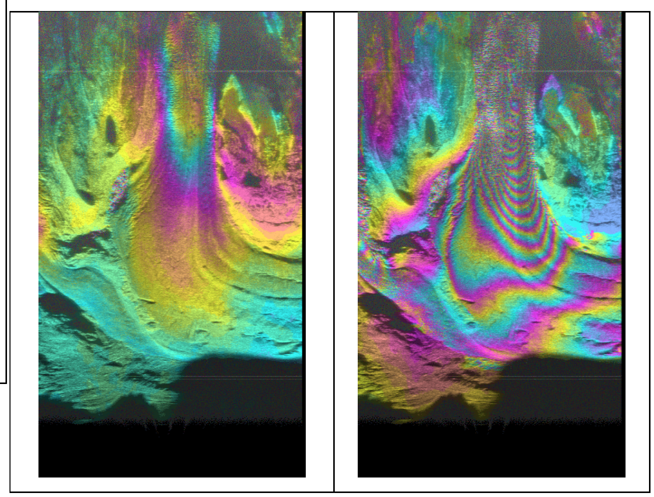

Figure 4. Differential Interferometric phase for the glaciers viewed from the Gornergrat. One fringe is 8.72mm of displacement along the LOS. (a) images acquired 2008-06-22 at 12:27 and 12:45 18 min interval. (b) Images acquired at 20080624 at 21:33 and 20080625 at 2:36, intervale 5:03.

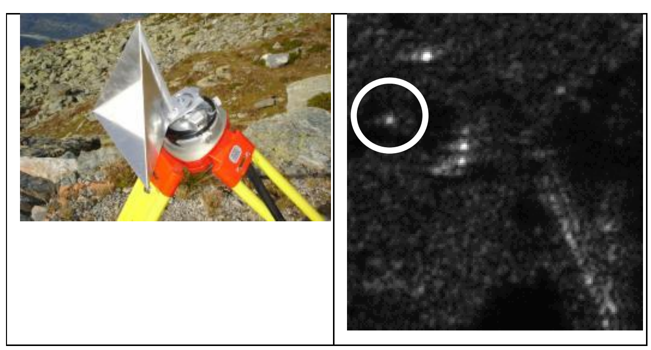

Figure 5. Corner reflector used for test of the deformation sensitivity of the GPRI. Image of the corner reflector in radar image is circled.

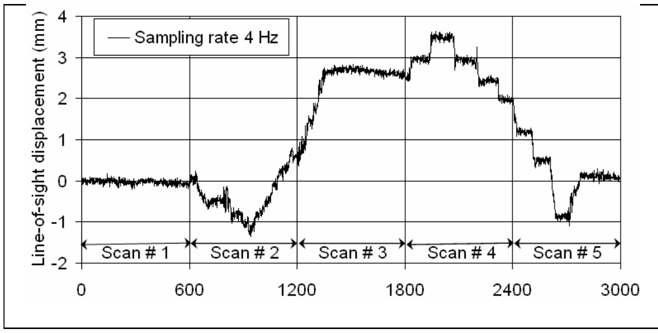

Figure 6. Deformation history of the corner reflector along the LOS..

The measured LOS displacement of the reflector is shown in Figure 6. The standard deviation of the displacement is 0.075mm measured over period of minutes.

CONCLUSIONS

We have demonstrated the operation of a ground-based radar interferometer for generation of differential interferograms. The polar scanning capability of the GPRI can image over large angular spans that is not possible for rail-based SAR systems. Furthermore, image formation does not require phase coherence of the scene. The GPRI instrument can acquire data for the generation of DEMs using a spatial baseline and perform differential interferometry. Zero baseline differential interferometry simplifies the analysis of ground-based data relative to satellite systems. Operating at a frequency of 17.2 GHz the instrument has demonstrated deformation sensitivity on the order of 0.1mm. Phase variations due to changes in the tropospheric delay are the principle limitation to the accuracy of differential interferometric measurements both for satellites and ground-based measurements. The capability of ground–based measurements to make continuous measurements of deformation and atmosphere permits stacking of measurements to reduce this error source. For near-range measurements we have observed less atmosphere phase due to the reduced path length relative to satellite-based radar observations.

ACKNOWLEDGMENT

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