An Innovative GB-INSAR System for Deformation Monitoring and Disaster Management

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Abstract. Disaster management is a critical issue, needs timely reaction to mitigate the risks and to re-establish a safety condition. For that reason, remote monitoring solution play a crucial role to measure structure healthy and slope stability keeping operators and equipment in the safe zones. A clear understanding of displacement and stability of the target is vital to define proper remediation actions, prioritizing the most critical ones. IDS GeoRadar is a provider of radar remote monitoring technology for complex structures and natural hazards, that recently developed an ArcSAR interferometric radar system for deformation monitoring and disaster management. The innovative solution has been designed to have a portable, easy-to-use solution able to monitor the structures and area after few minutes of its deployment. The radar system detects structure displacement and slope fall precursors, triggering early warning to increase safety for emergency operations and to evacuate people and machinery at risk. The new radar system provides sub-millimeter displacement accuracy at a spatial resolution of tens of centimetres, with updated displacement information every 30 seconds. In this paper, the system is described, along with emergency monitoring experiences.

1. Introduction
Ground-Based Interferometric Synthetic Aperture Radar (GB-INSAR) is a well-known remote sensing technique able to provide 2D radar images and to estimate sub-millimeter displacements up to several kilometres distance [1].

GB-INSAR systems synthesize an aperture along azimuth direction by moving the radar head on a rail while transmitting a Frequency Modulated Continuous Wave (FMCW) signal. A range-azimuth image can be focused through proper algorithms, while repeated acquisitions in time of the same scenario can be processed through differential interferometry techniques, obtaining range-azimuth displacements maps.

The use of these remote monitoring systems for medium, long-term monitoring of complex structure and natural hazards has emerged in the last ten years as a standard work and safety practice; the same has not happened for emergency condition, where timely reaction and ease of installation are mandatory to mitigate properly the risks and to re-establish a safety condition.

The HYDRA-G system is a new MMW (millimeter-wave) radar interferometer designed to address the needs of Disaster Management. HYDRA-G is a rotating synthetic aperture radar (Arc SAR): a circular trajectory is used to obtain the synthetic aperture, transmitting, and receiving FMCW signals during movement [2][3].
The Arc SAR technique combined to the use of MMW permits a more compact design and a wider angular coverage with respect to traditional linear SAR systems employed for semi-permanent long-range monitoring. These features appear particularly crucial in emergency scenarios, where transportability and compactness of the system is a must, and where often the reduced available distance between the system and the area/targets to be monitored in urban environment requires a wide field of view.

In this paper HYDRA-G system is presented by describing main hardware components and measurement principles; the radar performance is then evaluated in terms of spatial resolution and interferometric displacement measure accuracy by means of controlled tests; finally, on-field emergency monitoring experiences are shown.

2. HYDRA-G System

2.1 Introduction to HYDRA-G

HYDRA-G is an interferometric radar designed to remotely measure displacements with sub-millimeter accuracy. Like any other radar system, HYDRA-G is an instrument able to detect the presence of objects and measure the relative distance between the apparatus and the object. HYDRA-G performs this task by emitting continuous radio waves with a variable frequency (LFMCW, Linear Frequency Modulated Continuous Wave Radar) and comparing the received echo frequency with the transmitted wave: the difference between the two frequencies is proportional to the two-way flight time from the apparatus to the target and so to the distance between them.

HYDRA-G system is composed by a Survey Unit and a Control Unit (Figure 1).

The Survey unit is a combination of three sensors:

- a MMW 77 GHz radar unit sensor ensuring a range resolution of approximately 20 cm.
- a laser sensor with an accuracy of 10 cm on distance measurement acquiring 3D surface within 50 meters used to display the displacement measurement.
- a wide-angle night-vision camera with integrated infrared (IR) lights which are automatically turn on in dark environment conditions switching the camera sensor to IR mode. The camera provides a real-time visual feedback of the monitored area.

![Figure 1. HYDRA-G system composition.](image)
Radar and laser position are controlled by a Pan/Tilt system while the camera is mounted on the fixed part of the system. The Arc SAR acquisition is performed thanks to the Pan/Tilt circular movement on horizontal plane; the laser acquisition instead is performed doing circular trajectories at different tilt angles.

The Control Unit is composed by:
- a supply and control box providing the supply to the radar system and including an industrial PC where radar data are processed by means of software specifically developed for the monitoring of complex structure and natural hazards.

2.2 Spatial resolution
HYDRA-G is able to distinguish different part of the monitored surface with tens of centimetric resolution. This spatial resolution can be thought as a combination of the range resolution and the azimuth resolution as explained in the following paragraphs.

Range resolution, i.e. the ability to distinguish close targets along the line-of-sight of the radar, depends on the transmitted bandwidth, and for HYDRA-G this is equal to 0.20 m [3].

Azimuth resolution, i.e. the ability to distinguish targets at different azimuth positions, is obtained by means of the SAR technique (Synthetic Aperture Radar). HYDRA-G uses the motion of the radar antenna over a circular trajectory to provide finer azimuth resolution (≈ 14 mrad) than conventional beam-scanning radars.

The combination of range and azimuth resolution allows the creation of a map of the monitored scenario, where each pixel is a measurement point providing real-time displacement information (Figure 2).

![Figure 2. HYDRA-G field of view and spatial resolution.](image-url)
2.3 Displacement measurement

HYDRA-G measures the amplitude and the phase of the signals reflected by the monitored scenario; the amplitude provides information about the strength of the reflected signal, whereas the phase can be related to the relative movement of the target towards or away from the radar. The displacement magnitude is obtained with the interferometric technique, which relates the phase measurement difference that occurs between a first and a second acquisition to the line-of-sight displacement of the monitored surface according to the following Equation (1) and Figure 3:

\[ d = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1) \]  

(1)

The accuracy on the displacement measurement \( d \) depends on the phase measurement accuracy \( \varphi \) and on the value of the transmitted signal wavelength \( \lambda \). HYDRA-G is capable of providing displacement measurement with an accuracy better than 0.1 mm, by combining a very high phase measurement accuracy (< 0.1 radians) to a short wavelength (4 mm).

After any acquisition, HYDRA-G gives a displacement measure of any resolution cell within the field of view of the system.

![Figure 3. Displacement measurement using radar interferometry.](image)

3. Radar performance evaluation

During 2019, multiple controlled tests have been conducted to verify the radar performance in terms of spatial resolution and interferometric accuracy measured using a micrometric corner reflector at 15 meters and 200 meters distance from the radar. In the next paragraphs, results are reported.

3.1 Short-range test

3.1.1 Test setup. During the short-range test, HYDRA-G spatial resolution performance and the interferometric accuracy have been evaluated using a target at 15 meters distance.

The test setup is depicted in Figure 4: HYDRA-G has been placed at 15 meters distance from a micrometric corner reflector (Figure 5); the position of the corner can be changed with a resolution of 0.01 mm (Figure 6).
Figure 4. Short-range test configuration.

Figure 5. On the left, controlled test setup. On the right, disto laser measurement reporting 15.02 meters.

Figure 6. Adjustable micrometric corner reflector.
3.1.2 Spatial resolution. During the first part of the test, the spatial resolution was evaluated while the micrometric corner reflector was fixed in a single position. Figure 7 shows the radar power map of the test area, where the red dashed line shows the micrometric corner reflector position at 15 meters distance from the radar.

![Radar power map of the short-range test.](image)

**Figure 7.** Radar power map of the short-range test.

The spatial resolution can be calculated as the half-power width (i.e., the -3dB point) of range profiles and azimuth extracted from the power map across the corner reflector position (Figure 8 and Figure 9).

![Range profile of the corner reflector.](image)

**Figure 8.** Range profile of the corner reflector.

Measured range resolution is approximately 0.18 m (Figure 8), comparable with nominal radar sensor performance.
Figure 9. Azimuth profile of the corner reflector.

Measured azimuth resolution is 0.0136 rad \(\approx 13.6\) mrad (Figure 8), which correspond to a cross range resolution of approximately 0.204 m at 15 m.

3.1.3 Interferometric accuracy. In the second test the interferometric performance was evaluated by moving the micrometric corner reflector by known quantities: \(\Delta S_1 = 0.1\) mm, \(\Delta S_2 = 0.2\) mm, \(\Delta S_3 = 0.4\) mm, \(\Delta S_4 = 0.8\) mm; then the displacement induced on the corner micrometre is compared with the measurement of the radar system.

The displacements measured by the radar are shown in Figure 10: \(\Delta S_{1M} = 0.103\) mm, \(\Delta S_{2M} = 0.206\) mm, \(\Delta S_{3M} = 0.416\) mm, \(\Delta S_{4M} = 0.821\) mm; the resulting average error respect to expected values is then 0.011 mm.

Figure 10. Radar-measured corner displacements

3.2 Long-range test

3.2.1 Test setup. During the long-range test, HYDRA-G spatial resolution performance and the interferometric accuracy have been evaluated using a target at 200 meters distance.

The test setup is depicted in Figure 11: HYDRA-G has been placed at 200 m distance from a micrometric corner reflector (Figure 12); the position of the corner can be changed with a resolution of 0.01 mm (Figure 13).
Figure 11. Long-range test configuration.

Figure 12. On the left, controlled test setup. On the right, corner position respect to HYDRA-G. Laser distance meter cannot be used at 200 m, the distance has been directly measured using HYDRA-G. Please see Figure 14.

Figure 13. Adjustable micrometric corner reflector.
3.2.2 *Spatial resolution.* During the first part of the test, the spatial resolution was evaluated while keeping the micrometric corner reflector in a single position. Figure 14 shows the radar power map of the test area, where the micrometric corner reflector is positioned at 200 meters distance from the radar.

The spatial resolution can be calculated as the half-power width (i.e., the -3dB point) of range profiles and azimuth extracted from the power map across the corner reflector position (Figure 15 and Figure 16).

Measured range resolution is approximately 0.20 m (Figure 15), comparable with nominal radar sensor performance.
Figure 16. Azimuth profile of the corner reflector.

Measured azimuth resolution is 0.0108 rad ≈ 11 mrad (Figure 16), which correspond to a cross range resolution of approximately 2.16 m at 200 m distance.

3.2.3 Interferometric accuracy. In the second test the interferometric performance was evaluated by moving the micrometric corner reflector by known quantities: ∆S1 = 0.1 mm, ∆S2 = 0.2 mm, ∆S3 = 0.4 mm, ∆S4 = 0.8 mm; then the displacement induced on the corner micrometre is compared with the measurement of the radar system.

The displacement measured by the radar is shown in Figure 17: ∆S1M = 0.080 mm, ∆S2M = 0.247 mm, ∆S3M = 0.561 mm, ∆S4M = 0.826 mm; the resulting average error respect to expected values is then 0.063 mm.

Figure 17. Radar-measured corner displacements.

3.3 Summary of controlled tests
Considering the results of both tests, the spatial resolution performance is summarized in the following Table 1:

|                  | Range resolution | Cross range resolution |
|------------------|------------------|------------------------|
| Short-range test (@15 m) | 0.18 m            | 0.20 m                 |
| Long-range test (@200 m) | 0.20 m            | 2.16 m                 |

Table 1. HYDRA-G spatial resolution
The interferometric accuracy, evaluated as average error between measured and expected displacements, is summarized in the following table 2:

| Average interferometric error |       |
|------------------------------|-------|
| Short-range test (@15 m)     | 0.011 mm |
| Long-range test (@200 m)     | 0.063 mm |

### 4. Emergency monitoring experiences

#### 4.1 Piling wall collapse in Rome (Italy)
On February 14th, 2018, in the North-Western sector of the Municipality of Rome (Italy), in the framework of an excavation for building construction, a portion of a piling wall collapsed in an already densely urbanized area. Soil behind the collapsed piling wall slipped inside the excavation site dragging seven cars parked on one side of the road running parallel to the piling wall and affecting some residential buildings located on the opposite side of the road (Figure 18).

![Figure 18. View of the area with the piling wall collapse on February 14th, 2018.](image)

Luckily, no injuries were counted but 20 families living in the buildings next to the damaged wall were evacuated. Right after the piling wall collapse, the Italian Fire Brigade started a continuous monitoring of the affected area thanks to HYDRA-G (Figure 19) to determine the safety condition of the area and judge possible return of the families into their houses.
HYDRA-G has been installed in front of the piling wall (Figure 20) and thanks to his wide range coverage both urban engineered slope and residential buildings were continuously measured (Figure 21).

Figure 19. Fire Brigade monitoring the area thanks to HYDRA-G.

Figure 20. HYDRA-G installation position.
On February 16th, 2018, the system has been moved few meters from the original position to center the three residential buildings into the radar measurement scenario (Figure 22). This shows how easy and rapid is the setup and relocation of the system, matching the emergency monitoring needs along the time.

HYDRA-G is equipped with SurfScan, a real-time monitoring SW able to represent radar displacements information overlapped on camera image, simplify drastically user interpretation even for not expert, making HYDRA-G the right tool for rescue teams.

Referring to measurement data, HYDRA-G detected a displacement of 0.025 m along 2.5 hours on February 15th, 2018 14:00-16:30, located on the right lower part of the measured area (Figure 23, points P138, P271, P339), showing residual movements of the piling walls collapse. No displacements were registered on the upper part of the monitored area where buildings are located (Figure 23, points P1316, P1419, P1644).
On February 16th, 2018 11:15-12:30, the system did not measure any movements showing a stable behavior of the complete area both for urban engineered slope and residential buildings (Figure 24).
4.2 Pomarico Landslide (Italy)
On January 29th, 2019 a large landslide destroyed an important part of the town of Pomarico (Matera area, South of Italy). The landslide interested an area of 43,000 sqm and 56 people were forced to leave their houses (Figure 25).

From the late afternoon, the Italian Fire Brigade led the disaster management for the National Civil Protection and started the monitoring by HYDRA-G.

In the first instance, HYDRA-G has been positioned to measure the landslide and evaluate stability condition of the area for safety reasons (Figure 26).
The system detected during the period of February 1st – February 3rd, 2019 some residual movements of the slope in the order of 0.05 m and 0.06 m respectively located in the lower part and upper part of the area (Figure 27 and Figure 28).

In the second instance, HYDRA-G has been relocated to measure Pomarico buildings to determine the stability condition, to allow rescue teams to accede to the area, and later start the reconstruction activities (Figure 29).
Figure 29. Left, SurfScan SW showing time series of measured points. Right, Pomarico area measured by HYDRA-G

The remote technique allowed to measure unsafe areas with no risk for the rescue teams. Fortunately, no displacements have been observed during the monitoring period.

5. Conclusions
The gained experiences demonstrated the capability of HYDRA-G to operate reactively and efficiently during emergency scenarios, supporting Disaster management. The radar system detects both structure and slope displacements with high accuracy, provides real-time indication about safety condition and stability of the area, helps rescue team to decide on action plans, and finally can be a valid monitoring system during remediation activities.

A large acceptance of the solution is highly suggested to increase safety for the whole Disaster management industry, pushing boundaries to the next level.

References
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