

EVALUATION OF DEM DERIVED BY REPEAT-PASS X-BAND STRIPMAP MODE PAZ DATA

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ABSTRACT:

This paper, presents the initial results of digital elevation model (DEM) extraction from PAZ Synthetic Aperture Radar (SAR) satellite images using repeat-pass interferometric analysis. We used a multi-temporal high-resolution strip-map mode X-band satellite image that has a single polarization. Five main classes, i.e., volcanic structures, agriculture, settlement, sand dune and plain bareland are considered depending on the structure of the region. Within the category, the coherence value and DEM value are evaluated. In the accuracy assessment analysis, a reference map produced from aerial photogrammetry is used. Additionally, global DEM TanDEM-X data is also tested in the study region. In the analysis, quality metrics, mean error (ME), root means square error (RMSE), standard deviation (STD), and the normalized median absolute deviation (NMAD) are used. The results showed that as the temporal baseline increases the coherence values and the quality of the DEM product decrease. The RMSE values range between 2.36 m to 7.09 m in different classes. The TanDEM-X data provided high accuracies over each class range from 0.88 m to 2.40 m. Since the study area is vulnerable to sinkhole formation, sinkhole-like signals were also observed in the interferograms obtained from different and sequential pairs. The high-resolution repeat-pass PAZ data pointed out its potential for interferometric products generation.

1. INTRODUCTION

Digital Elevation Models (DEMs) are widely used in different analyses as a geospatial source, including landslide susceptibility (Ada and San 2018), deformation studies (Calò et al., 2018; Abdikan et al. 2021), terrain attributes (Gdulova et al., 2020), and geomorphologic analysis (Pasquestti et al., 2019). Thus, the accuracy of the DEMs can play an essential role in the final product of the processes. Synthetic Aperture Radar (SAR) systems that have the capability of day and night imaging in all weather conditions result in being a valuable source for DEM production. The interferometric SAR (InSAR) technique exploits phase difference between two SAR observations from slightly different orbits. It is widely used for local and also global DEM generation. Shuttle Radar Topography Mission (SRTM) and TerraSARX add-on for Digital Elevation Measurements (TanDEM-X) are two main products that are globally available in different spatial resolutions (Gdulova et al., 2020).

The DEM computed from the repeat-pass InSAR depends on the characteristics of the ground objects (Gdulova et al 2020). It can also be affected by atmospheric conditions, terrain, and sensor-based parameters (Ueemaa et al., 2020). SRTM is one of the leading global DEMs that has been used in different applications, and it is still a freely available primary data source. It is based on simultaneous data acquisition from two sensors positioned along-track baseline. It completed its mission within 11 days in February 2000. Although it was generated two decades before, it

provides vertical information for the locations still stable, and it is also used for vertical change detection analysis using other updated global DEMs such as TanDEM-X (Becek et al., 2021). After the launch of TerraSAR-X, several studies used it for DEM generation using a high-resolution repeat-pass stereo radargrammetric approach (Henning et al., 2015) and interferometric approach (Sefercik et al., 2012; Sefercik et al., 2014; Jiang et al., 2014). TanDEM-X is the second X-band satellite identical to TerraSAR-X. The TanDEM-X mission aims to provide high-resolution global DEM using both satellites. The advantage of the mission is to provide bistatic SAR interferometry to reduce the limitation of repeat-pass interferometry that opened a new era in spaceborne radar imaging (Krieger et al., 2007). This new global DEM data that has about ~12m resolution has been used for different analyses and tested on flat to mountainous regions, such as coastal morphology (Pasquestti et al., 2019), building height models (Misra et al., 2018) and vertical change detection (Becek et al., 2021). The new generation X-band PAZ satellite has been continuing its mission since 2018. It is based on the TerraSAR-X/TanDEM-X platform and has identical specifications which aim to create a constellation for short-term image revisit. Its potential for surface displacement (Abdikan et al., 2020, Chang and Stein, 2021), archaeological analysis (Fiz et al., 2021), and combination of bistatic and repeat-pass analysis (Sica et al., 2021) were tested. However, the studies using PAZ data are still very limited in the literature.

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In this study, multi-temporal PAZ data are tested over Konya Closed Basin, central Turkey where different land cover types and geomorphological structures are located (Figure 1). The region is also affected by subsidence due to groundwater lowering that, along with drought and climate change, may cause long-term effects on the environment (Calò et al., 2018). A previous study over the same region compared DEM derived from the high-resolution COSMO-SkyMed and the results are validated with UAV data. The study showed that the InSAR pair with a short temporal baseline (4 days) provided a better result than the longer temporal baseline (440 days). The root means square error (RMSE) ranges between 1.5 m to 5.6 m at different topography with the shortest pair (Torun and Orhan 2021). Another study presented the performance of the high-resolution PAZ data for the extraction of small-scale sinkholes (~200 m diameter) that cannot be identified with Sentinel-1 data (Abdikan et al. 2020).

This study is aimed at exploiting PAZ data for DEM generation. In particular, the main contributions are given as below;

- we explore a new DEM derived from the repeat-pass InSAR method over a semi-arid region where karstic and volcanic structures are present;
- we explore first time the InSAR results of X-band PAZ-based data for DEM extraction in the literature.
- additionally, multi-temporal small scale displacements are also derived using repeat-pass interferograms.

2. MATERIALS AND METHODS

2.1 Study Area

Konya closed basin is located in the center of the Anatolia region. The study case has different geological, archaeological, and cultural areas. Widespread young volcanic formations are one of them. Distributed volcanic shapes and related tectonic paths characterize this area. Climate condition is primarily semi-arid, and with the effect of wind, the sand form can move, and sand dunes structures can be seen (Kaplan et al., 2020). It is also a relevant agricultural area for grain, pulses, and sugar beet production.

For the analysis, five regions of interest such as volcanic structures, agriculture, settlement, sand dune, and plain bareland are considered (Figure 1).

2.2 Dataset

A reference DEM was provided by the department of General Command of Mapping (GCM), Turkey. The data was produced by aerial photogrammetry, and the output product has a 5 m grid resolution. It has vertical accuracy that varies from 1 m (flat areas) to 3 m (hilly areas) (Yilmaz et al., 2015).

The TanDEM-X data over the region is also used for comparison. It provides better spatial resolution and higher accuracy as a global DEM product. It has <10m vertical and horizontal absolute accuracy, and 2-4 m relative vertical accuracy depending on the slope (Ueemaa et al., 2020).

PAZ images were provided by the INTA-PAZ Science Team as part of the research project used for the application and processed through the InSAR technique (Table 1). The temporal revisit time of the PAZ satellite is 11 days. In this study, five images of PAZ data are used and four DEMs are created. The first image of each pair was kept constant, and the second image was changed to produce pairs (Table 2).

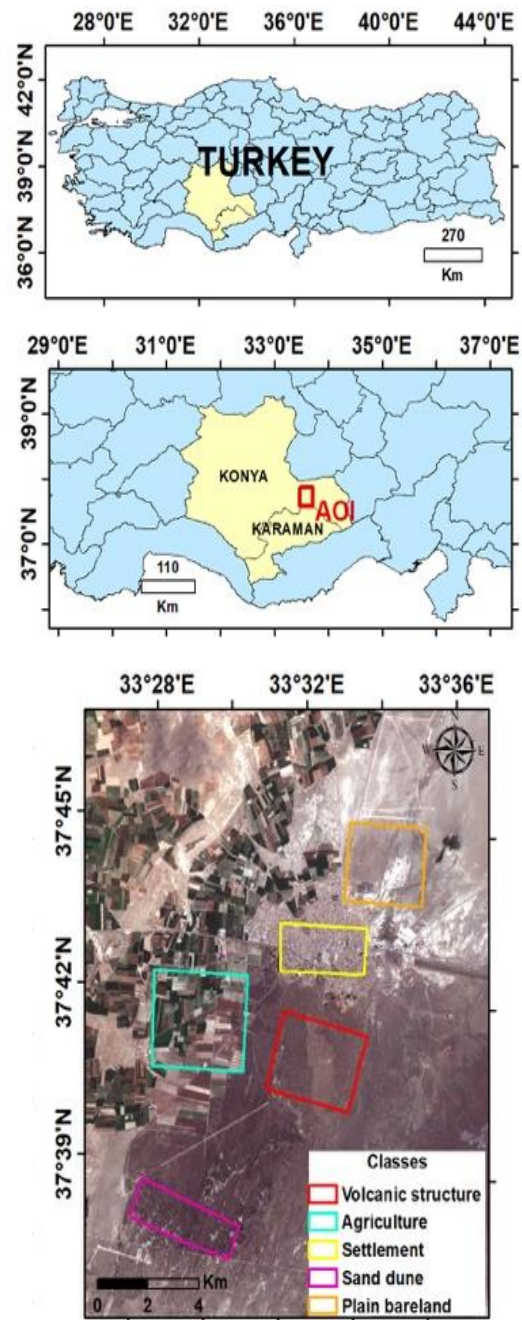


Figure 1. The study area

Specifications	Description
Sensor	PAZ
Wavelength	X-band
Imaging mode	StripMap
Orbit	Ascending
Incidence Angle (°)	38.60° (Far) 35.99° (Near)
Resolution (Rg x Az)	0.90 x 2.04 (m)
Polarization	Single-Pol (VV)

Table 1. Specifications of PAZ data

	Primary	Secondary	B _{perp} (m)	B _{temp} (day)
Pair1	19.11.2020	30.11.2020	168.30	11
Pair2	19.11.2020	11.12.2020	171.74	22
Pair3	19.11.2020	15.02.2021	192.27	88
Pair4	19.11.2020	09.03.2021	109.99	110

Table 2. Specifications of PAZ pairs.

2.3 Repeat-pass InSAR analysis

Image preprocessing was performed with the Open-Source Sentinel Application Platform (SNAP) software. In the analysis, five images of PAZ are used and four interferograms are obtained (Table 2). Using this software, processing steps such as co-registration, coherence and interferogram formation, Goldstein phase filtering, multi-looking, unwrapping, phase to elevation conversion, and terrain correction were carried out. Interferograms were generated in primary and secondary geometry. In the phase unwrapping step SNAPU, a statistical-cost network-flow approach was applied. One arc-second SRTM (30 m x 30 m) was exploited for terrain correction (Figure 2). As the coherence (γ) indicates the cross-correlation coefficient between two co-registered complex data and gives information on the quality of the product, it is also computed for each pair as below (Abdikan et al., 2020);

$$\gamma = \frac{|\langle S_1 S_2^* \rangle|}{\sqrt{\langle S_1 S_1^* \rangle \langle S_2 S_2^* \rangle}} \quad (1)$$

where S_1 and S_2 = complex matrices of backscatter coefficient of the SAR image pair
* = complex conjugation
 $\langle \rangle$ = indicates spatial averaging

We used the mean error (ME), root mean square error (RMSE), standard deviation (STD), and the normalized median absolute deviation (NMAD) to evaluate the results (Gdulova et al., 2020).

$$ME = \frac{1}{n} \sum_{i=1}^n (Z_{DEM} - Z_{REF}) = \frac{1}{n} \sum_{i=1}^n \Delta Z_i \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n \Delta Z_i^2} \quad (3)$$

$$STD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\Delta Z_i - ME)^2} \quad (4)$$

$$MAD = median_i (|\Delta Z_i - m_{\Delta Z}|) \quad (5)$$

$$NMAD = 1.4826 * MAD \quad (6)$$

where, Z_{DEM} is the produced DEM, Z_{REF} is the reference DEM, n is the number of samples, ΔZ_i are the individual errors and the $m_{\Delta Z}$ is the median of the errors.

3. RESULTS AND DISCUSSIONS

3.1 The coherence analysis

In the study, environmental characteristics and land cover types such as urban, agriculture, bareland, sand dune, and volcanic structures are investigated for accuracy analysis. The coherence analysis indicated that the Pair-1 shows higher (appear brighter) coherence values than the other pairs (Figure 3). As the temporal

baseline increases, the coherence values decreases. The coherence values of Pair-3 and Pair-4 are very low (close to zero) and appearing dark grey to black on the map.

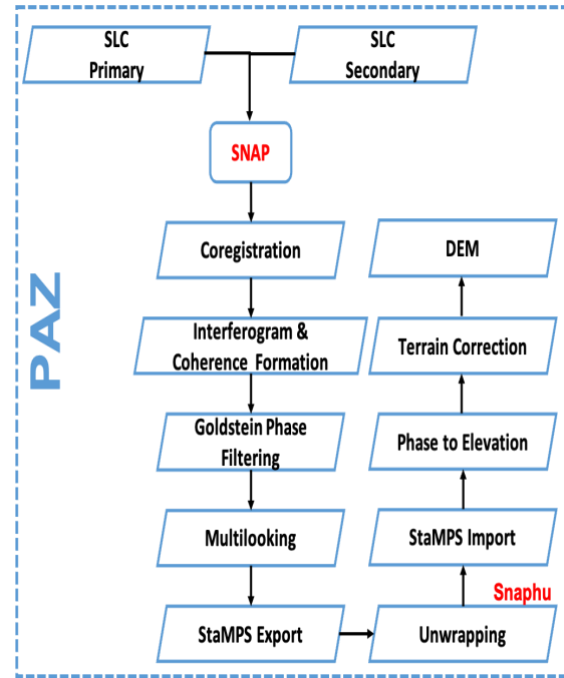


Figure 2. Flowchart of the processing.

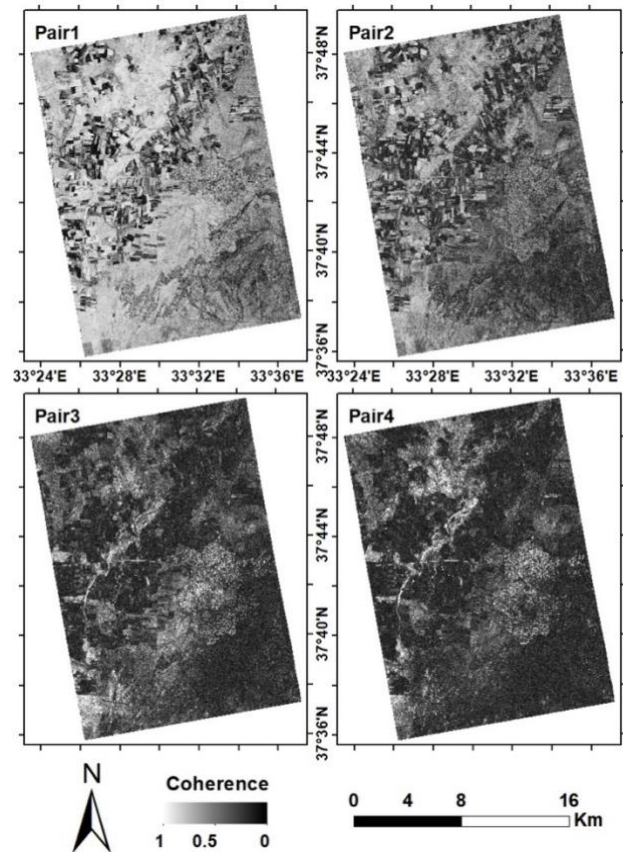


Figure 3. Coherence maps of the pairs (PAZ satellite image © Hisdesat Servicios Estratégicos S.A., 2019.)

In each pair, the coherence values were checked to investigate the behavior of the classes over an increasing temporal baseline. The descriptive statistics show that minimum and maximum values are close to each other for each class (Figure 4). As expected the maximum values of settlements are higher compared to the other classes (Table 3). The mean values from Pair-1 to Pair-4 showed that they gave decreasing behavior in each class. The mean values are ranging between 0.65 and 0.26.

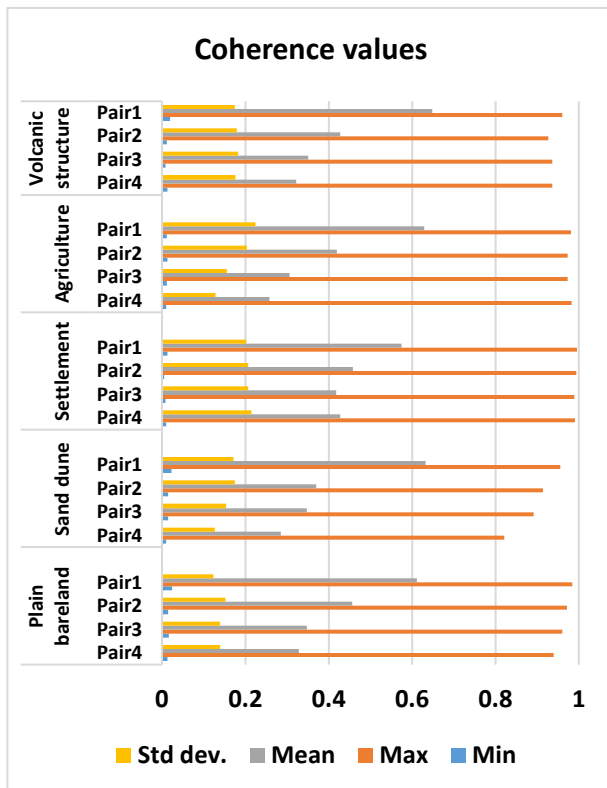


Figure 4. Descriptive statistics of coherence values of the pairs

3.2 DEM analysis

The DEMs are generated with a resolution of 4 m pixel spacing. The results indicated that the first pair with a shorter temporal baseline provided better results compared to the other pairs, which is similar to the results achieved by Torun and Orhan (2021) (Figure 5). In the first pair, plain bareland showed the lowest RMSE (2.36 m) compared to the other classes. Torun and Orhan (2021) analyzed similar regions using UAV as a reference and showed that the plain area has less than 2 m RMSE. In this study, the RMSE values are higher than in the previous study, which has smaller regions, probably due to the decorrelation level between the pairs. Considering the cover types and structures, plain bareland showed the lowest RMSE value. The maximum RMSE is extracted in both cases over the sand dune structure. This might be due to the dynamic structure of the sand dunes between the reference and the PAZ dataset because wind erosion causes mass movement and degradation. Vegetation was planted against erosion and less mass movement was observed in the planted areas. (Youssef et al., 2010; Kaplan et al., 2020). The temporal change of vegetation may also have caused the coherence value to decrease.

In this study, the mean coherence value of the settlement part, which also included roads, is about 0.58 and 0.46 for Pair1 and Pair2, respectively. Meanwhile, the density of the buildings is not

very high and there are unoccupied parts of the city. As the resolution is high the shadow effect is noticed nearby the tall buildings, which cause low coherence and a decrease in accuracy in the produced DEM. The lowest RMSE value is obtained in the Pair-1 as 6.89 m and the worst value is 17.53 m with Pair4. The analysis shows results similar to the previous studies that used spotlight and stripmap mode of TerraSAR-X. Sefercik et al. (2014) determined ~7-8 m RMSE using high-resolution spotlight TerraSAR-X pair and Sefercik and Yastikli (2014) determined ~13.6 m RMSE using stripmap mode of TerraSAR-X pair over urban areas of Istanbul. Sefercik and Yastikli (2015) determined a similar result as 8.99 m and 8.85 m RMSE on densely distributed built-up areas of Istanbul using the spotlight TerraSAR-X (154 days) and Cosmo-SkyMed (20 days), respectively. They also indicated 8.19 m and 7.33 m RMSE values in open areas using TerraSAR-X and Cosmo-SkyMed, respectively. Arief et al. (2020) estimated ~1.8 m and 3 m RMSE on buildings and roads respectively, using a single stripmap mode TerraSAR-X pair with 11 days temporal baseline, and LiDAR data as a reference. They indicated that the coherence is 0.92.

In the agricultural part, the error is highly dependent on the time difference between the SAR images. The vegetation type, phenology, and harvesting periods may affect the results of the product in short periods. The RMSE values of the pairs also increase in time. The volcanic structure also indicated increasing RMSE values in parallel to increasing time between the pairs.

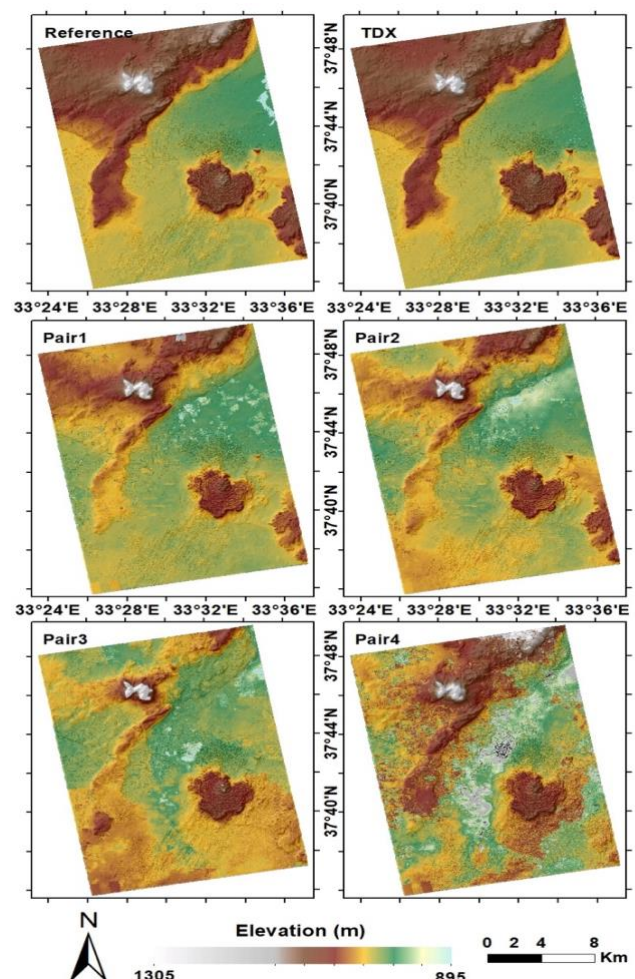


Figure 5. Reference and produced DEMs (PAZ satellite image © Hisdesat Servicios Estratégicos S.A., 2019.)

The comparison between the reference data and TanDEM-X showed minimum descriptive statistics. The RMSE values range between 0.88 m on bareland and 2.4 m on settlement. The lowest RMSE of TanDEM-X is detected on bareland which gave the lowest RSME with PAZ data (Table 3). Some studies also indicated close results for flat regions, e.g., Pasquetti et al., (2019) estimated RMSE (LE90) 1.19 m over coastal areas of the Argentinian regions, Misra et al (2018) estimated higher results as 3.35 m RMSE at build-up region of Yangon, Myanmar.

Plain bareland (3054 points)				
	ME	RMSE	STD	NMAD
TDX	0.670	0.877	0.567	0.514
Pair1	-0.301	2.361	2.342	2.313
Pair2	4.661	6.886	5.070	4.589
Pair3	20.137	21.242	6.764	6.4723
Pair4	16.254	25.333	19.434	14.423
Sand dune (2064 points)				
	ME	RMSE	STD	NMAD
TDX	0.575	0.944	0.749	0.623
Pair1	11.715	11.891	2.040	1.848
Pair2	24.281	24.831	5.200	4.351
Pair3	29.049	30.829	10.324	8.035
Pair4	12.181	24.46	21.200	19.050
Settlement (2025 points)				
	ME	RMSE	STD	NMAD
TDX	0.037	2.402	2.402	1.240
Pair1	4.357	6.897	5.347	3.383
Pair2	12.577	14.310	6.828	5.828
Pair3	1.855	7.918	7.699	5.9023
Pair4	2.453	17.539	17.371	12.890
Agriculture (4550 points)				
	ME	RMSE	STD	NMAD
TDX	-0.140	1.041	1.031	0.712
Pair1	4.088	6.402	4.928	3.277
Pair2	8.204	11.311	7.787	6.709
Pair3	0.687	12.151	12.133	12.266
Pair4	-24.424	49.125	46.628	36.648
Volcanic structure (3436 points)				
	ME	RMSE	STD	NMAD
TDX	0.678	1.329	1.143	0.786
Pair1	6.565	7.094	2.688	2.669
Pair2	8.485	9.933	5.164	5.486
Pair3	17.963	19.254	6.932	6.746
Pair4	16.133	19.833	11.537	9.963

Table 3. Statistical analysis of the results in meter

3.3 Small scale deformation

In addition to DEM production, sequential repeat-pass interferometry was applied to indicate local displacements over the region (Figure 6). In the previous study, local displacements were identified with two PAZ pairs (Abdikan et al., 2020). Here, the analysis is extended to the following acquisitions in the same location to investigate the sequence of displacements. It pointed out that the displacement continues in the same region, however, it has not been observed on the pairs used for the DEM generation, given in table 2. Interferometric fringes generated by processing high-resolution repeat-pass PAZ data can be profitably exploited to detect sinkhole phenomena that occur in this semi-arid region on a variety of scales (Calò et al. 2018). As the area is prone to sinkhole formation due to water level decrease, a long-term repeat-pass analysis might be helpful as a clue to possible sinkhole formation.

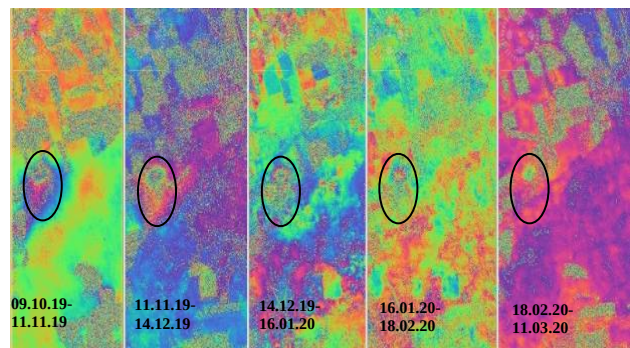


Figure 6. Sequential analysis of interferograms (PAZ satellite image © Hisdesat Servicios Estratégicos S.A., 2019.)

4. CONCLUSION AND FUTURE PERSPECTIVES

In this paper, the potential of repeat-pass interferometry products of PAZ data was presented. The analysis showed different PAZ pairs that have shorter to longer temporal baselines, to get more insights into the DEM accuracy in the region. We also exploit the coherence values of each class for a more detailed analysis, aimed at investigating the performance of PAZ data on DEM generation. The shortest temporal revisit (11 days) indicated the highest accuracy compared to the reference data and the results are in the same line compared to those of TerraSAR-X. It is expected to shorten the revisit time to 4 and 7 days using the constellation of PAZ, Tandem-X, and TerraSAR-X data for repeat-pass interferometric purposes.

Global TanDEM-X data provided highly accurate results. Especially, for the flat regions, it has lower error while it increases with the slope. A further detailed analysis of the slope areas over the region will be carried out.

Future works will also include multi-seasonal repeat-pass SAR data and time series analysis to investigate the seasonal effects. In addition, new acquisitions collected along both ascending and descending orbits will be analyzed. Finally, a long-term InSAR analysis will also be conducted to determine surface displacements over time.

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