Sentinel-1 Interferometry System in the High-performance Computing Environment

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Abstract

This paper describes the architecture of the system for monitoring deformations based on interferometrical processing of Sentinel-1 satellite data using specific software installed at the facility of the Czech national supercomputing center (IT4Innovations). The system is ready for Big Data storage and processing and leads to partially autonomous competitive environment for following deformation monitoring projects. The processing chain is prepared to be performed using Sarproz software where the reader of specific Sentinel-1 Terrain Observation with Progressive Scans in azimuth (TOPS) data was newly introduced – the reader implementation is described in the paper. First application of the system has been applied to subsiding area of Konya city in Turkey. The processing was performed using a small fraction of the supercomputer power, i.e. using 23 processors running at 2.5 GHz speed, and led to results estimating subsidence in Konya city during 2014-2015 – a subsidence of Konya buildings in the rate of more than 6 cm/year has been evaluated, that is slightly more than the expected values from previous analyzes. The processing strategy of the described system is demonstrated in this case study.

Keywords: satellite radar interferometry, high-performance computing, deformation monitoring, Sentinel-1, Konya city subsidence.

INTRODUCTION

The IT4Innovations national supercomputing centre is a research institution of the Vysoka Skola Banska - Technical University of Ostrava (VSB-TUO). The first part of the supercomputer, the Anselm supercomputer, was installed into temporary mobile units in May 2013. Its theoretical computing performace was at 94 trillion floating-point operations per second (FLOPS). Supercomputer Salomon was put into operation in July 2015 as the 40th most powerful supercomputer in the world in that time. The Salomon cluster consists of 1008 compute nodes, totaling 24192 compute cores with 129TB RAM and giving over 2 peta FLOPS of theoretical peak performance. Each node is a powerful x86-64 computer, equipped with 24 processing cores and at least 128GB RAM running CentOS Linux operating system [1].

Sentinel-1A is a Synthetic Aperture Radar (SAR) satellite launched in April 2014 as part of European Copernicus programme. This satellite generates acquisitions continuously every 12 days for European sites and with a lower revisit frequency for majority of other world areas, with a spatial resolution of around 20x4 m and a very large extent of each distributed image (240x350 km). This is achieved using a specific image acquisition mode called Terrain Observation by Progressive Scans (TOPS). After the launch of the second SAR satellite Sentinel-1B planned in the late 2016, the acquisition frequency in Europe will be increased into an acquisition per 6 days. Depending on stored polarimetric information, the SAR data are distributed in Single Look Complex (SLC) data in the size of 4 or 8 GB per an acquisition, transforming the current data

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processing tasks into Big Data processing strategies.

The SAR Interferometry (InSAR) is a modern remote sensing technology allowing both generation of digital elevation models or measuring geophysical parameters, especially deformation in time, within sensitivity of around a millimeter per year for vertical displacements [2]. Various SAR satellite systems tackle with specific problems for a reliable application in local area monitoring praxis – either their spatial and temporal resolution was low (ERS, Envisat) or the data acquisition was performed only by previous often commercial orders (TerraSAR-X, Radarsat-2). Within the open access and the continuous and high spatiotemporal resolution acquisition strategies applied for Sentinel-1 data, scientists talk about a "golden age of InSAR" making a leap from an experimental technique into a practically applicable technology, since there was never before such feasible spatio-temporal coverage of SAR data.

The aim of the paper is to introduce a competitive InSAR environment installed at IT4Innovations, referenced to IT4InSAR, that allows an effective processing of Sentinel-1 data. As the core InSAR processing tool at IT4InSAR, the Sarproz software [3] is used, implementing a flexible environment allowing for a range of various SAR and InSAR processing techniques, including also the most commonly used Permanent/Persistent Scatterers (PS) technique [4]. Lately, the whole processing chain for importing Sentinel-1 TOPS data, their coregistration and InSAR processing has been implemented. This paper describes the implementation of this specific reader and demonstrates the first analysis performed at IT4InSAR in order to detect subsidence of Konya city in Turkey, based on PS processing of Sentinel-1A data. The previous GPS and InSAR studies show a relatively fast subsidence of the city due to groundwater pumping of up to 5 cm/year during 2006-2009 [5].

IMPLEMENTATION OF SENTINEL-1 READER INTO SARPROZ CODES

Though Sentinel-1A data are routinely available already since September 2014, there was still only a limited number of software packages in the end of 2015 that were able to perform reading and processing of the standard Sentinel-1 data product – the TOPS. One of the most significant differences that distinguish TOPS mode from typical mode of majority of other SAR satellites (stripmap) is that the antenna will steer from backward to forward in azimuth direction while steering between different subswath in range direction. The steering of antenna will sacrifice the azimuth resolution to a reasonable degree, meanwhile increasing the range illuminating area. Due to this special characteristic of TOPS, the standard processes for generating interferograms between TOPS pairs is different from that of stripmap.

Specifically, there are two important steps that are required by TOPS. Both are originated from the backward-to-forward steering of antenna in azimuth direction. The first step is called deramping. The steering of the antenna introduces an additional quadratic phase term in azimuth direction which doppler frequency exceeds the azimuth pulse repetition frequency (PRF). According to the sampling theorem, in order to resample the slave images during coregistration without aliasing the data, a step named deramping is required to remove this quadratic ramp. After reading the single look complex (SLC) value of TOPS data and before coregistration of interferometric pairs, the quadratic ramp of each image will be calculated and removed. The second step is a sub-pixel coregistration. The appearance of this quadratic term indicates that, in case of even a small misregistration error between master and slave images, there would be a phase ramp in azimuth direction superimposed on the interferogram. It has been commonly acknowledged that an accuracy of 1/1000 pixels of coregistration is needed to ignore the azimuth phase ramp introduced by this quadratic term [6]. To meet this standard, a general sub-pixel coregistration method is needed. This step is usually done after the initial coarse coregistration that is used for the case of stripmap data. The subpixel coregistration is usually achieved by the spectral diversity method that utilizes the overlapping parts between successive bursts. After the subpixel coregistration of TOPS, the common processing steps for generating interferograms will be identical with the stripmap processing.

IMPLEMENTATION OF SARPROZ INSAR SYSTEM INTO IT4INSAR ENVIRONMENT

The Salomon cluster works in the framework provided by CentOS system in connection with a Portable

Batch System (PBS) planner. This makes the environment flexible and very effective especially applying autonomous batch scripts to be performed over a multi-node computing environment. However, license of the commercial Sarproz software doesn't allow multi-node installation and its main functionality is based on an interactive Matlab-based graphical user interface (GUI) that reacts slowly when using direct display forwarding, especially when connected by a slow internet provider. Also for this reason it was decided to prepare an InSAR system into a virtual computer running at only one processing node, offering 24 high speed processors, 128 GB RAM and a shared data storage of 1.3 PB in case of Salomon. This was considered sufficient for the IT4InSAR prototype.

The virtual computer is run using QEMU emulator with a virtual harddrive containing installation of latest Debian testing operating system with necessary applications as Mathworks Matlab, Sarproz, ESA Sentinel Application Platform etc. It allows processing using 23 processors of the node (one processor is left for the flawless work of the virtual computer). The Salomon storage is mapped as a virtual device offering high speed connection with the virtual computer. Internet access is not allowed originally in the Salomon computing nodes for security reasons. A double Secure Shell (ssh) tunnel was prepared to provide a secure exception and establish an internet connection using the Virtual Distributed Ethernet (VDE) in QEMU via Salomon login server node that offers the Internet connection at ports 22, 80 and 443. The virtual computer is run in a temporary (snapshot) mode, thus it defies potential problems with file structure or unwanted user changes of environment of the system.

Access to the system is provided through open-source X2GO remote desktop framework, based on non-free NoMachine framework. This solution was selected as of the highest performance and flexibility of access from nearly any internet access point. The information exchange is performed by secure ssh connections. Each registered IT4InSAR user will achieve a unique port number for establishing his ssh connection. The IT4Innovations Salomon login server works as a proxy server providing an ssh tunnel to a computing node running QEMU. This node transfers the ssh connection towards the virtual computer. Afterwords, the user is connected to the virtual computer system through X2GO client's ssh threads and works in the environment as it would be installed to his local desktop. The remote desktop offers reentering the system without shutting down the virtual computer itself. The system can additionally be entered also using ssh shell, e.g. for file operations. Figure 1 attempts to basically schematize the configuration of the IT4InSAR system environment at the HPC.

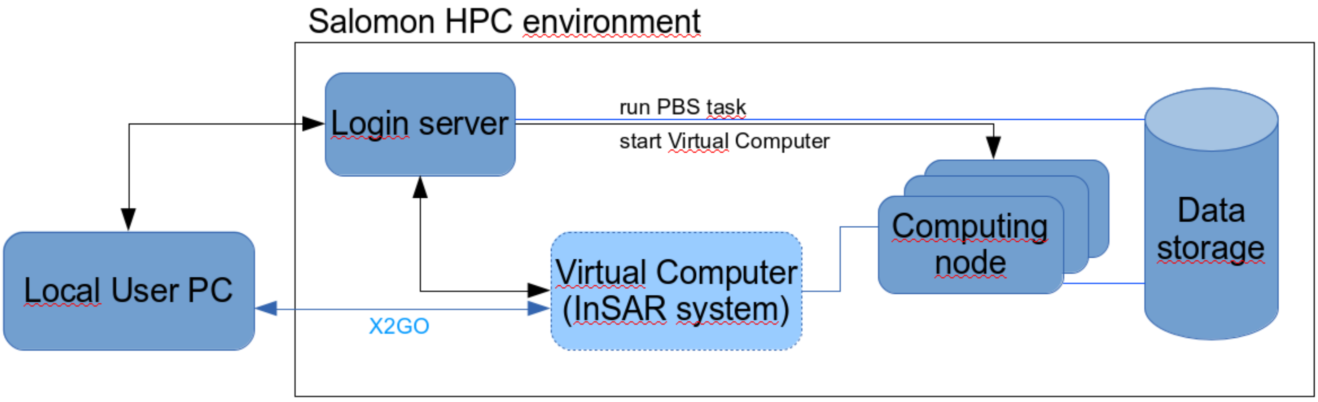


Fig. 1. Scheme of IT4InSAR system configuration as applied at IT4Innovations Salomon HPC environment

IT4INSAR SYSTEM APPLICATION FOR MONITORING SUBSIDENCE IN KONYA CITY, TURKEY

The first area of interest that was processed in the freshly prepared IT4InSAR system was an important subsidence field of Turkish Konya city center and its surroundings located in the biggest closed basin in Turkey and known by significant subsidence. The area has been intensively observed during last years by different engineering techniques such as geological, geodetical and SAR interferometry technologies [5]. The city of Konya is known as the hearth of Turkish agriculture and industrial activities. Its population is more than 1 million (approx. 1,175,000) and the surface area about 39.000 km^2. InSAR has been evaluated as a valuable technique for continuous monitoring of the local subsidence, practically as the only technology that can provide reliable subsidence measurements for a large quantity of points over such large-scale vicinity [7].

The processing chain begins by data download. For purposes of downloading new data as well as updating the existing dataset for new acquisitions, a download script has been prepared based on the batch download script from the official Copernicus Sentinel-1 Data Hub [8]. With the knowledge of center coordinates and desired relative orbit identifier, the script would download all available SLC data and prepare them for the InSAR processing. In case of Konya closed basin (KCB), 30 Sentinel-1A images have been downloaded ranging 16th October 2014 until 4th November 2015.

From these images, a crop of overlapping area of 80x115 km (8150x23500 pixels) from the TOPS Interferometric Wide Swath 3 (IW3) has been prepared, coregistered and stitched. However, two images from the dataset had to be dropped due to coregistration problems. The whole process was finished in several hours; the performance of the prototype algorithm is planned to be further optimized in order to decrease the processing time of the coregistration and stitching, and to allow coregistration of all the overlapping acquisitions.

Afterwards, the PS processing itself has been performed for a selection of 130,000 points with appropriately high values of the SAR reflection (amplitude) stability through the multiple acquisitions. These points of a high amplitude stability correspond mainly to urban structures, rocks or a bare soil in KCB area. Since the area is urbanized and of a semi-arid character, the number of appropriate points for PS analysis is high. The number of SAR images in the analysis and the density of PS points per a km^2 conforms with the common conditions for a reliable analysis (should be more than 15 SAR images and at least 2-3 points per a km^2) [2].

A more strict subset of 3,000 PS points of a very high amplitude stability forming a more or less regular network throughout the scene was selected in order to perform a spatio-temporal analysis estimating so-called Atmospheric Phase Screen (APS). This represents SAR phase errors due to a variability of atmosphere-caused signal delays, assuming these delays have a spatially correlated character but don't involve any trend in PS point time series [2]. The APS estimated from the network of connections of this subset of points is then interpolated for the whole scene and removed from the whole selection of PS points in the final PS processing. Here, the SAR phase contribution causes within the Sentinel-1 data time series could be distinguished between due to a topography effect (residual heights after the removal of the coarse SRTM digital elevation model) and due to physical changes in PS points (a linear deformation trend in time). The whole process (including estimation of APS) took 2 hours that is considered a very short time for such processing.

The resulting estimates of the linear trend of phase changes at the PS points were recomputed into the mean velocity (mm/year) in the satellite line of sight (LOS), that is inclined in 38-39° from nadir direction in this IW3 area. These results were georeferenced and are presented as colour-coded points in the Google Earth environment as seen at Fig. 2 and Fig. 3 (both figures plot only a relevant subset of data over Konya city area affected by a subsidence) . The detected subsiding areas visible in Fig. 2 conform with expected locations of subsidence depressions known from previous studies [7].

Fig. 3 shows time series of a selected subsiding PS point corresponding to a location of the municipality cadastre building. This building is known to be subsiding and a permanent GPS station is installed on top of the building for a continuous monitoring of subsidence. The Sarproz PS InSAR processing estimates the subsidence trend of -47.5 mm/year in the Sentinel-1 IW3 LOS, with a standard deviation of 2.04 mm/year. The incidence angle at the point corresponds to ~38.3°. Based on [9], it is possible to recompute the LOS value into the vertical direction, assuming no horizontal movements of the point. This leads to a simplified equation Eq. 1 leading to the recomputed value of subsidence of 60.5 mm/year ± 2.5 mm/year. This result can be compared with the reference GPS data once made available.

$$d_v = \frac{d_{LOS}}{\cos \theta_{inc}} \qquad (1)$$

where d_v is deformation in the vertical direction (neglecting horizontal deformation of the point), d_{LOS} is the original value in LOS direction and θ_{inc} is the incidence angle.

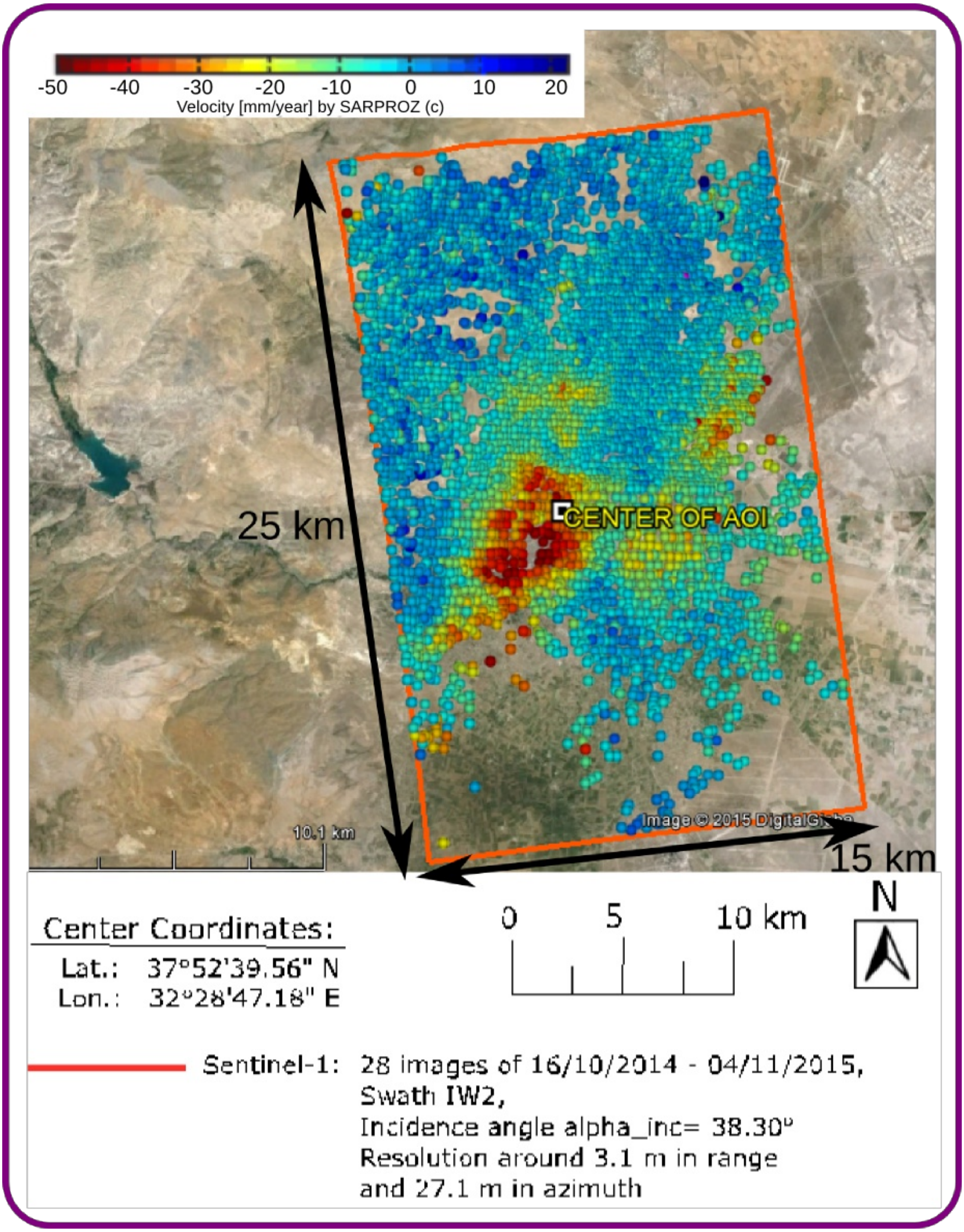
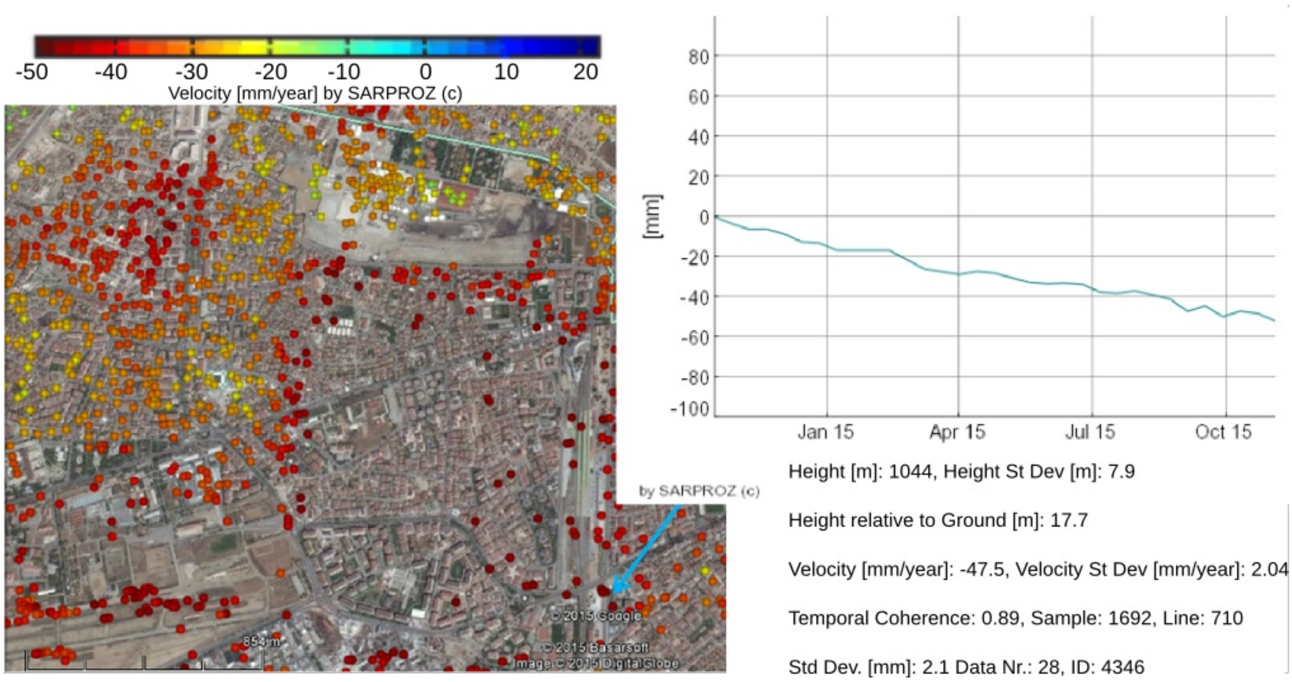


Fig. 2. Mean velocity map of PS points movements in Sentinel-1 IW3 LOS over Konya city area based on semi-automatic PS InSAR processing at IT4InSAR system



Height [m]: 1044, Height St Dev [m]: 7.9

Height relative to Ground [m]: 17.7

Velocity [mm/year]: -47.5, Velocity St Dev [mm/year]: 2.04

Temporal Coherence: 0.89, Sample: 1692, Line: 710

Std Dev. [mm]: 2.1 Data Nr.: 28, ID: 4346

Fig. 3. PS InSAR-based estimation of the mean velocity of movements within 10/2014-11/2015 in the Sentinel-1 IW3 LOS – a zoomed area in the Konya city center with time series plotted for the selected pixel corresponding to a municipal cadastre building.

CONCLUSIONS

A functional environment for satellite-borne SAR interferometry processing in the modern HPC infrastructure has been arranged with a view of routine monitoring of selected sites especially using the modern European Copernicus Sentinel-1 satellite SAR system. This system can be used as a basis for projects with a need of a moderate and supervised performance. Especially the expert supervision over the processing chain is often necessary in the majority of current InSAR-focused projects. Therefore the modular approach where each authorized user may run the IT4InSAR environment at only one processing node per a moment is not a real limitation. However, activities to provide the power of other nodes within the virtual computer can be expected in future in order to extend the performance of the system. A full automation of the system can be planned once it will be possible to batch script the coregistration and stitching operations of the Sentinel-1 TOPS data.

The first processing results over Konya city shows a good performance of Sentinel-1 data for monitoring subsidence. Though at the moment of preparation of this work, there was no data for comparison of results available to the team, the results show very similar outputs compared to the previous studies using older GPS and InSAR data of ERS, Envisat and Alos satellites [5,7]. In addition to those, more PS points could be evaluated by Sentinel-1 processing thanks to the high revisit rate and other advanced characteristics of Sentinel-1 indicating also a high reliability in the estimation of velocity rates of the movement of points.

ACKNOWLEDGEMENT

This work was supported by the European Regional Development Fund in the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070), The Ministry of Education, Youth and Sports from the National Programme of Sustainability (NPU II) project „IT4Innovations excellence in science – LQ1602" and the TUBITAK in Turkey (Contract No.110Y121, Project Name: Monitoring of land subsidence in Konya Closed Basin using geodetic methods and investigate its causes). Authors are grateful to Dr. Daniele Perissin for offering a free license of Sarproz software for the testing purposes.

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