

Geodetic Deformation Monitoring: From Geophysical to Engineering Roles

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Tilting and horizontal movement at and across the northern border of the Adria plate

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Abstract. We report on the analysis of the seven permanent GPS stations of the recently installed Friuli Regional Deformation Network (FReDNet) of NE-Italy for the time period that goes from the moment of installation (between June 2002 and July 2003, according to the station) to 31 December 2004. We first make a comparison of two available solutions, calculated by the Agenzia Spaziale Italiana (ASI, Centro di Geodesia Spaziale "G. Colombo") and by the Centro Ricerche Sismologiche (CRS, Istituto Nazionale di Oceanografia e Geofisica Sperimentale). The rms (root mean square) difference between the two solutions results to be between 4 and 8 mm, depending on the component. The greatest difference is found for the vertical component, the best agreement is found for the NS component. We then proceed with the analysis of the time series, using the solutions of CRS, as this agency has longer time series available. Our attention goes to three classes of signals, which is the high frequency component (several days to weeks), the seasonal and annual signal, and the interpolated linear trend, representative of the average velocity of the monuments. The mutual correlation coefficients of the stations for the same component are between 0.3 and 0.7, with the highest values found for the vertical component, which demonstrates that there is a common signal, which is in phase. The correlation coefficient does not show a distance relation of the stations, which indicates that the origin of the common signal could be due to pressure loading or an incomplete atmospheric correction. In order to determine reliable velocities, we determine the sinusoidal annual and semi-annual oscillations, which are present in all stations. The amplitudes of the yearly oscillation vary between 0.3 mm and 1.4 mm for the horizontal components, and are definitely larger for the vertical component (between 2 and 5 mm). Those of the semi-annual

period range between 13% and 95% of the annual amplitude. At last we determine the relative velocities of all stations with respect to the Trieste station, which can be considered tectonically stable, as it is located on the aseismic Karst. We find that the pedemountain stations have a relative southward motion of about 2-3 mm/year and an uplift rate of 1-2 mm/year. The stations on the Friuli plane have nearly no horizontal movement relative to Trieste, and show a relative subsidence. The observations are in agreement with the expectations from neotectonics, which give subsidence of the Friuli plane and uplift of the pedemountain area. They also agree with north-westward tilting observed with the long-base tiltmeters of the Grotta Gigante station (Trieste Karst). The southward movement of the pedemountain stations fits the picture of the relative movement of the Eurasian and Adria plates, the Trieste and Friuli-plane stations belonging to the Adria plate, the remainder stations belonging to the Eurasian plate.

Keywords. Horizontal and vertical crustal movement, tiltmeters, GPS, Friuli (NE-Italy), Adria plate

1 Introduction

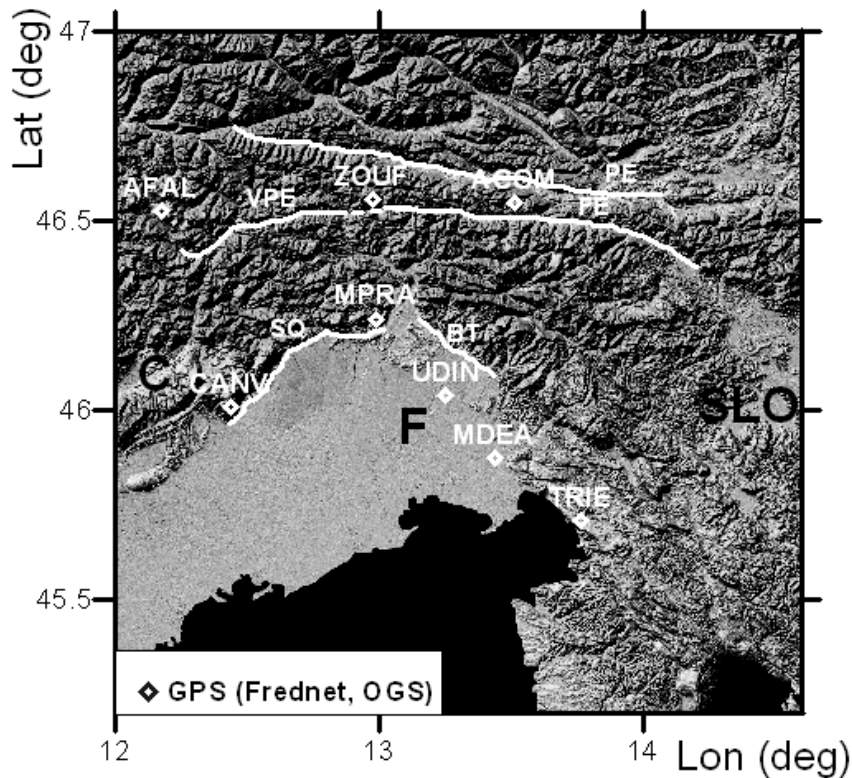
The Friuli area belongs to the eastern portion of the subalpine mountain range located to the south of the Peri-Adriatic lineament. Starting from late Oligocene to present a series of north-dipping shallow angle faults have been activated, that extend from the Garda lake (west) to Slovenia (east) (e.g. Doglioni, 1992). In the western sector of the Friuli area the quaternary front of the subalpine range corresponds to the Aviano and Sequals overthrusts; in the oriental sector, the front of the

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mountain range corresponds to a series of overthrusts that extend into the Friuli plane, and belong to overthrusts of the previous Dinaric front (Zanferrari et al., 2000). The external margins of the southern Alps and of the Dinarides show signs of recent deformation, that is maximum in the area of the Friuli pedemountain arch. The external margins represent the present tectonic evolution of the area, characterized by overthrusts with a southward movement towards the Adria plate. Presently, the pre-alpine Friuli sector is uplifting, while the frontal plane is subsiding (Zanferrari et al., 1982). The

dextral mechanisms. The Friuli and Cansiglio have been, since historical times, the areas of highest seismic potential. In the 20th century the greatest destructive earthquakes were the Friuli event (May 6, 1976) and the Cansiglio event (October 18, 1936) of eastern Veneto. Slejko et al. (1987) quantified the regional seismicity in terms of number of events with magnitude greater than 3.3 in 1000 km² for the years 1850-1984 and found values of 1 and greater for Friuli and Cansiglio, a value of 0.5 for the Garda lake and Ljubljana (Slovenia) and lower values for the remaining portions. The hypocenters affect the

Fig. 1 Map of NE-Italy and surrounding areas with GPS stations. SLO: Slovenia, F: Friuli, C: Cansiglio. Fault lines: SQ: Sequals, BT: Buia-Tricesimo, VPE: Val Pesarina, FE: Fella Sava, PE: Periadriatic.



Friuli area is located in a ribbon of high seismicity (Fig. 3) that affects the pedemountain range extending from the Garda lake (to the west) to Slovenia (to the east) and bends south-eastwards along the Dinarides front. The alignment of the seismic ribbon follows the orientation of the major tectonic lineaments, which are seen in Fig.1. The seismicity along the E-W oriented faults has preponderantly thrust mechanisms on subhorizontal faults dipping northwards, whereas the events towards the east on the NW-SE oriented faults have

upper crust and are principally located between 5 and 15 km depth, with a peak distribution at 9 km (Braitenberg, 2000). The crustal deformation in Friuli has been monitored by underground tilt and extensometric instrumentation since 1977 (Zadro and Braitenberg, 1999, Braitenberg, 1999). The long data series have allowed to make a good statistic on the observed co-seismic signals and to study the ambient influence due to temperature, atmospheric pressure and hydrology on the crustal deformation measurements. A long-base tiltmeter

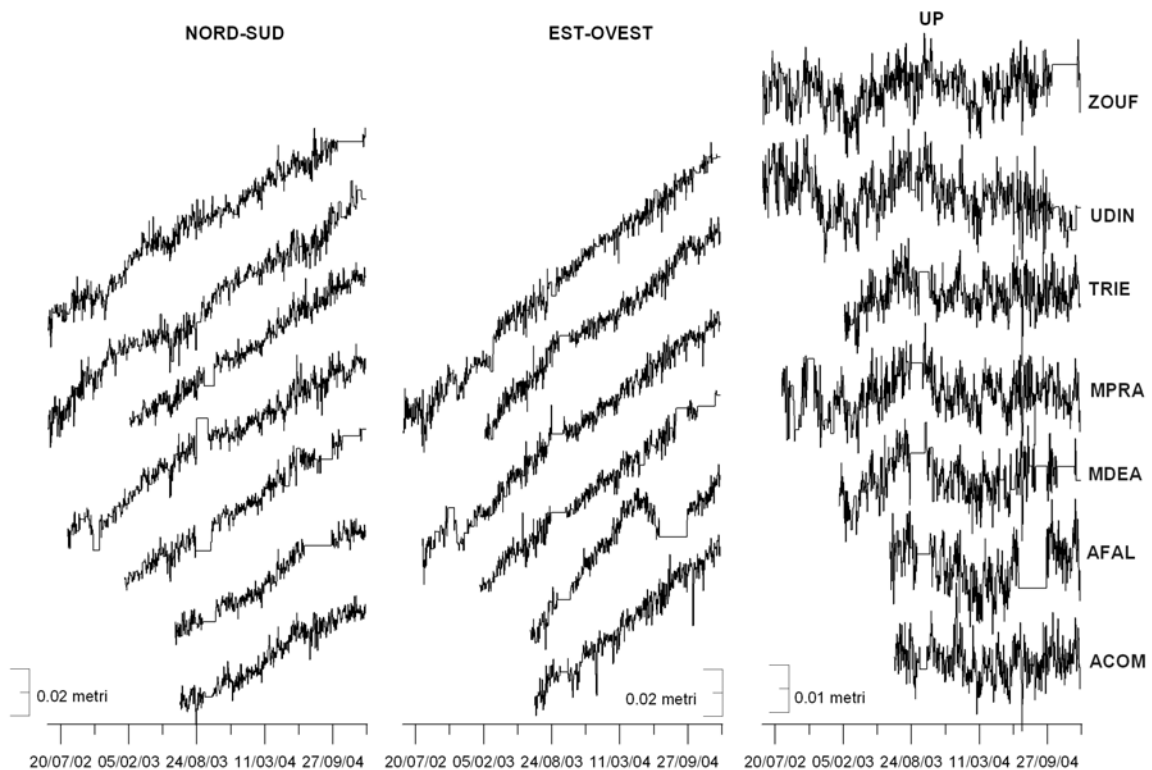


Fig. 2 The daily GPS solutions (CRS) for the seven FREDNET stations (ITRF00 reference frame). Interruptions are replaced by constant values.

station has been active since 1960 on the Trieste Karst to the south of the main seismic area, giving reliable observations of a NW-ward tilting of the Karst block over the recent 40 years (Braitenberg et al., 2005). A tilt should imply a differential vertical movement of the stations aligned along the tilting direction. In the case that the observed tilt is a regional signal and the resolution sufficient, a GPS station to the NW of the Trieste Karst should be subsiding with respect to a station located in the Trieste Karst. Recently (starting with June 2002) a network of continuous GPS stations was installed with the aim of monitoring the surface crustal movement and obtain the geodetic strain rate (Battaglia et al., 2003). All the GPS locations, except the UDIN station, have been carefully chosen in order to be linked to solid rock. The UDIN station was set up in the immediate vicinity of the CRS main building and is mounted on an industrial warehouse, therefore it is less stable than the other stations. The locations of the stations are shown in Fig. 1. The three stations TRIE, MDEA, UDIN, are to the south of the seismic ribbon, and

are located on the Adria plate, with the TRIE station being on the Karst, the two stations MDEA and UDIN on the Friuli plane. The station MPRA is just to the north of the plane and at the southern margin of the seismic ribbon, stations ZOUF and ACOM are just to the north of the central Friuli seismic area, bordering the Fella-Sava and Val Pesarina lineament. AFAL is farther to the west, dislocated from the main Friuli seismicity, about 50km north of the destructive Cansiglio earthquake of 1936.

In the present study we intend to determine the relative velocities of all stations with respect to the Trieste station, which can be considered as tectonically stable as there is no seismicity (e.g. Slejko et al., 1987). The pedemountain stations are located to the north of the transition from the Adria plate to the European plate margins. The determination of the relative velocities is preceded by a study which aims at determining the nature of the high frequency (days to weeks) signal and to clean the data from the annual and semi-annual signal (Pinato Gabrieli, 2005). This analysis was made on the time series from the time of installation

of the stations to 31 December 2004. The stations were installed between June 2002 and July 2003, as reported in Table 1.

Table 1. Time intervals covered by the GPS observations of the FReDNet stations for the solutions of the CRS agency.

Station	Month of Installation
Acom (M. Acomizza)	July 2003
Afal (Alpe Falaria)	June 2003
Mdea (Medea)	January 2003
Mpra (M. Prat)	August 2002
Trie (Trieste)	February 2003
Udin (Udine)	June 2002
Zouf (Zouf Plan)	June 2002

2 Data Presentation

The GPS solutions have been calculated with daily sampling rate adopting the ITRF00 reference frame. The CRS solutions are computed using GAMIT/GLOBK (M.I.T and U.C.S.D, 2002) software and the time series cover the time intervals given in Table 1.

On routinely basis, the FReDNet GPS stations are also calculated with daily sampling by ASI, which uses the Microcosm vs. 2001 (GEODYN II, NASA, Eddy et al., 1990) software. The available solutions start at a later date (February 2004) than the ones calculated by CRS. A comparison of the two data sets over the common time interval has shown that the rms-difference between the two data series is 3-4 mm for the NS, 4-5 mm for the EW and 7-8 mm for the UP component. The rms difference is slightly higher than that expected given the formal error given by the two agencies (CRS: average 1.5 mm for the horizontal, 4.5 mm for the Up components; ASI: 1mm for the NS and UP, and 0.7 mm for the EW components). The difference in the solutions is probably due to the different software used and to the specific choice of the reference stations used in the calculations. Due to the short common time interval, presently the origin for the encountered differences is unknown and requires further investigation. In the remainder of the study we have used the CRS solutions, as the available data interval is the longest. The observed data from all stations are presented in Fig.2. The

data series are characterized by a near to linear movement of the monuments, a near to yearly variation and a high-frequency variation. The high frequency content is a signal which is common to all stations, as can be verified from the mutual correlation coefficient between the stations. We calculate the correlation coefficients on the detrended time series, and obtain the values reported in Table 2.

Table 2. Mutual correlation coefficients of the FReDNet stations. The relatively high values of the coefficients demonstrate that there is a common signal to the stations.

CORRELATION COEFFICIENTS			
	NORTH-SOUTH	EAST-WEST	UP
MDEA-MPRA	0.47	0.56	0.65
MDEA-TRIE	0.52	0.62	0.63
ACOM-MDEA	0.48	0.42	0.43
ACOM-MPRA	0.38	0.53	0.49
TRIE-MPRA	0.31	0.65	0.67
MPRA-ZOUF	0.55	0.61	0.54
MDEA-ZOUF	0.36	0.58	0.59
ACOM-ZOUF	0.58	0.46	0.57
ZOUF-TRIE	0.43	0.55	0.60
ACOM-TRIE	0.59	0.46	0.55
UDIN-ACOM	0.17	0.22	0.13
UDIN-MDEA	0.34	0.51	0.37
UDIN-MPRA	0.06	0.49	0.48
UDIN-TRIE	0.44	0.48	0.47
UDIN-ZOUF	0.14	0.42	0.36
ACOM-AFAL	0.63	0.01	0.52
MDEA-AFAL	0.48	-0.12	0.47
MPRA-AFAL	0.26	-0.03	0.47
TRIE-AFAL	0.50	-0.21	0.48
ZOUF-AFAL	0.41	-0.20	0.59
UDIN-AFAL	-0.05	0.27	0.02

Generally the highest values are found for the Up component (0.5-0.7), followed by the E-W component (0.4-0.6), the NS component having lower values (0.3-0.6). Exceptions to these general findings are the correlations with the EW component of AFAL, which has very low coefficients with all stations. The latter component though also presents anomalously large deviation from the linear trend, which could be due to a problem on the stability of this station (antenna, monument or other), reflected also in the correlation

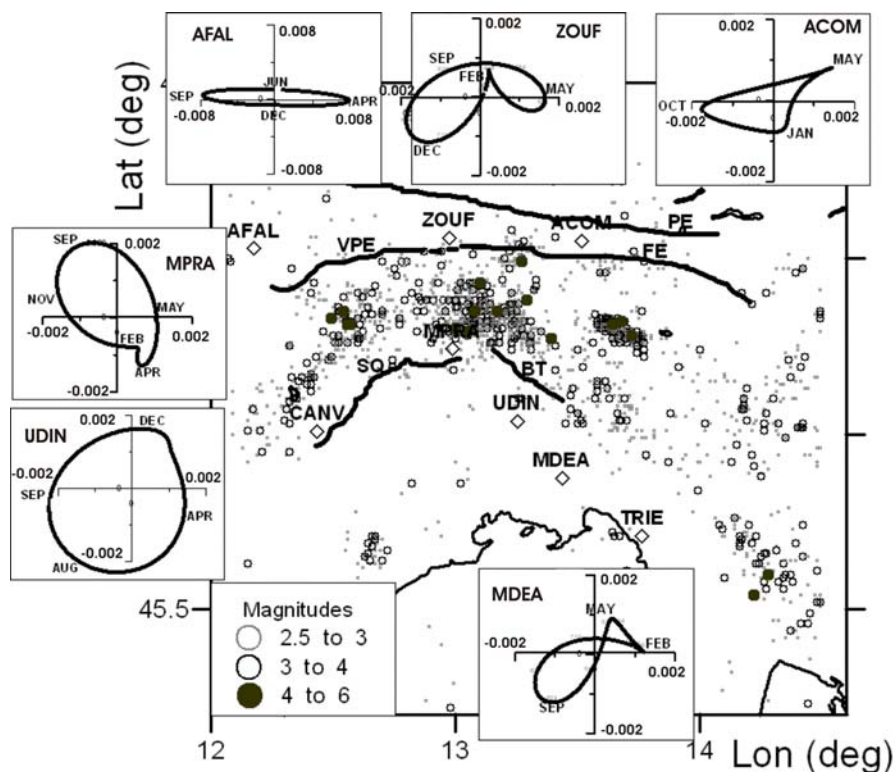


Fig. 3 Graphical representation of the seasonal movements of the monuments in the horizontal plane. The extremal values are labeled with the month of the year. Seismicity (CRS-OGS seismologic network) for the years 1977-2004

coefficients. Also all correlations with station UDIN are generally lower, presumably due to additional noise on this station caused by its relatively less stable position. The generally high mutual correlation coefficients demonstrate that the noise-like high frequency content has a large portion common to all stations. The fact that the coefficient is independent of the mutual distances of the stations, is an indication that the signal is not of tectonic origin but due to atmospheric effects. In fact, atmospheric disturbances and pressure variations are nearly homogeneous over a scale of 100 km (distance scale of the network); these could be the cause of the common signal. Atmospheric disturbances can either influence the range calculation or the movement of the monument (pressure loading, thermoelastic effects, soil condition influenced by humidity and hydrologic effects). By calculating the relative movements of all the stations with respect to one of the stations, this high frequency signal is reduced, and a more

reliable analysis of the station velocities can be made. We choose the Trieste station as a reference station due to its position on the tectonically stable Karst block. Therefore the relative movements we obtain can be considered as being referred to the Adria plate.

3 Seasonal Variation and Relative Velocities

The presence of a seasonal or yearly signal is a known phenomenon, and has been observed in underground measurements (e.g. Zadro and Braitenberg, 1999; Braitenberg et al., 2001) as well as in satellite geodetic observations (e.g. Dong et al., 2002, Williams, 2003, for northern Italy see Caporali, 2003). The driving force of the signal is ascribed to the thermoelastic effects (Pawidodirdjo et al., 2004), hydrologic loading (water table or snow: Heki, 2003), atmospheric pressure loading, ocean loading, or a combination of the above effects (Zerbini et al., 2004). Especially in the case that the available time-series cover only a few years, the

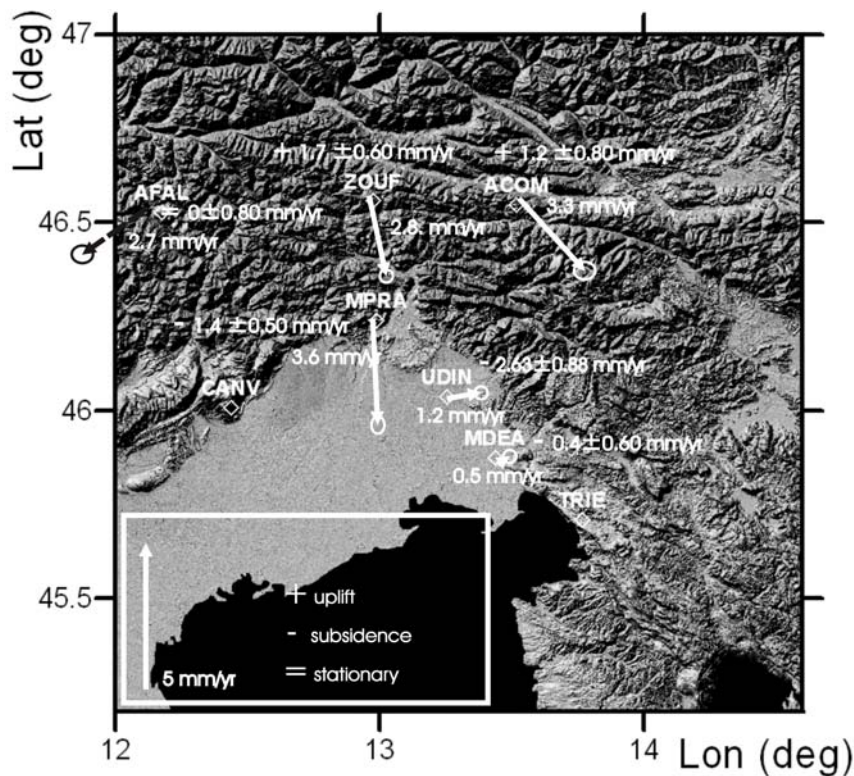


Fig. 4 – Horizontal and vertical velocities of the FREDNET stations relative to the Trieste GPS station. Error ellipses indicate 2 rms error.

annual signal may distort the interpolated linear velocities of the strain, tilt, or crustal movement observations (Blewitt and Lavallée, 2002) and must be corrected for. We model the signal with a combination of an annual and semi-annual sinusoidal variation which we determine by least square approximation together with the linear interpolation. We find that the seasonal variations are successfully extracted by this model, and determine amplitudes and phases of the annual and semi-annual variation. The data gaps (see Fig. 2) are less than 8 weeks long, except one (AFAL, max. 10 weeks) and therefore should have a negligible effect on the analysis (Blewitt & Lavallée, 2002). The amplitude of the semi-annual variation is always smaller than the annual variation, but not neglectable. The amplitudes of the yearly oscillation vary between 0.3 mm and 1.4 mm for the horizontal components, and are definitely larger for the vertical component (between 2 and 5 mm). Those of the semi-annual period range between 13% and 95% of the annual amplitude. The amplitude of the annual period of temperature is about 10° , and the

semi-annual period is not present in the temperature variation. The seasonal movement we find is graphically summarized in Fig.3, which shows the movement in the horizontal plane for every station. At the extremal positions the corresponding month in the year is added. The stations that show an elliptical movement are those for which the annual period is preponderant with respect to the semi-annual period. In Fig. 4 the final linearly interpolated velocities of the FREDNet stations relative to the Trieste station are shown, with the 2 rms error-ellipses. The vertical velocities are given as numbers next to the location of the station. We find a very interesting pattern of the velocities, which is expedient in the frame of plate-tectonics: the stations that are located on the Adria plate have very little horizontal movement (UDIN and MDEA), whereas the stations to the north of the Adria plate boundary (MPRA, ZOUF, ACOM, AFAL) have a definite relative southward movement in the order of a few mm/year. As mentioned before, the EW component of the AFAL station may be affected by an instrumental problem,

and the observed west-ward movement cannot be considered to be reliable. Due to its position, also the station UDIN is not as reliable as the remainder stations. Although the vertical components are noisier than the horizontal components, the result we find is compatible with the general geologic picture: the stations in the mountain are uplifting (AFAL, ZOUF, ACOM), whereas the stations in the plane (UDIN, MDEA) are subsiding with respect to the Karst block. Station MPRA is very close to the transition from the Friuli plane to the prealpine overthrusts, which could be the reason to its anomalous movement, in that it is southward moving, but subsiding.

4 Discussion and Conclusion

Our study is concerned with a detailed analysis of the continuous GPS stations of the FReDNet network situated in the seismic Friuli area in NE-Italy. The GPS solutions are computed with daily sampling rate and the time series cover time intervals that range from 17 to 30 months. We have compared the solutions calculated by the two agencies CRS and ASI over the common time interval of 11 months and find an rms deviation of 3 to 8 mm, depending on the component. The greater value pertains to the Up component, and the NS component has the smallest rms difference between the two solutions for all stations. The rms difference is only slightly greater than the mean rms given by the agencies for the solutions. The time series contain a high frequency signal (period of several days) which we find by cross correlation analysis to be common to all stations, and which presumably is due to pressure loading or a residual in the range correction.

Another evident signal is the annual and semi-annual variation, which we have studied by least mean square approximation with two sinusoids of period of 365.25 days and 182.6 days, respectively. At this stage of the analysis we have determined the amplitude and phases of the oscillation with the aim of obtaining a reliable estimate of the linearly interpolated station velocities. Therefore the investigation on the cause of the oscillation remains to a follow-up study. The semi-annual oscillation cannot be due to a temperature effect, as the temperature variation does not contain semi-annual variations but is exclusively annual.

The third evident signal contained in the observations is the relative movement of the

continuous stations with respect to the Trieste station. We find a clear difference in the horizontal velocities of the stations which are located on the Adria plate (TRIE, MDEA, UDIN) and the stations which are located on the European plate (MPRA, ZOUF, ACOM, AFAL). The difference in velocities is confirmed by the findings of D'Agostino et al., 2005. The analysed time period is relatively short for a reliable velocity detection. Nevertheless, the differences in the velocities of the pedemountain stations and the stations in the plane are so great that we are confident that the availability of longer time series will not alter the results. What will presumably change in the future will be the values of the relative velocities. The recent TRANSALP geophysical section which crosses the Adria-Eurasian plate boundary 100 km westwards of the Friuli area revealed the European plate dipping southwards beneath the Adria plate. The crustal structure in the collision zone could though not be resolved (Transalp Working Group, 2002; Kummerow et al., 2004). It remains controversial whether the Adria Moho south of the Alpine orogen remains flat (Kummerow et al., 2004) or is dipping northwards towards the orogen (Transalp Working Group, 2002). Teleseismic tomography (Lippitsch et al., 2003) indicates subduction of the European plate below the Adria plate west of the TRANSALP profile, and a change in the subduction pattern towards the east, with the Adria plate subducting below the European plate. The fault plane solutions of the seismicity are an indication of the northward movement of the Adria plate with respect to the European plate, with shallow angle N-dipping thrust faults in the central Friuli area, dextral strike slip events at the eastern border of the Adria plate and sinistral strike slip events at the western border (e.g. Caporali et al., 2005). The transition from the Adria plate to the European plate can be set at the northern margin of the Friuli plane, north of which the pedemountain overthrusts are found and the seismic belt begins. Our analysis finds that the head-on NS oriented convergence rate of the Eurasia and Adria plate is of about 2-3 mm/year, averaged over the interval of 2.5 years (2002 to end 2004). The two stations on the Friuli plane (UDIN, MDEA) and the Trieste station have nearly no relative horizontal movement. The stations on the plane are subsiding with respect to the Trieste station with a rate of 0.4 mm/yr or greater (UDIN being not totally reliable due to its location). The subsidence of the plane has

further geomorphologic evidences on the basis of the following observation: a karstic cave at the depth of -180 m has been found 30 km northwest of Trieste by drilling a borehole (Albrecht and Mosetti, 1987). The cave must have been formed above sea level, as subsurface water erosion was responsible for its formation. Another observation was that of a sequence of submerged marine terraces in the gulf of Trieste. The uppermost terrace at the level of -20 m was attributed (Antonioli et al., 2004) to the MIS 5.5 (marine isotope stage, about 125 ka). This marine terrace was correlated by Albrecht and Mosetti (1987) to a sediment horizon of the drill-log seated at the depth of 75 m. If the timing of those features is correct, this observation would imply a relative subsidence of 0.4 mm/year (55 m depth difference in 125 000 years), which is in the order of magnitude of our observations. A northward tilting, in accordance with the geological evidences, comes from the Trieste long-base tiltmeter station, which has recorded an average NW tilting of 41 nrad/year of the Karst block over a time window of the recent 40 years (1966-2004) (Braitenberg et al., 2005).

The good agreement between the GPS relative velocities and the movements expected from the geological consideration gives us confidence that our results are reliable and can be used for further studies concerned with the estimate of seismic risk based on the observed geodetic strain rate.

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