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AZIMUTH AND SLOWNESS CORRECTIONS AT BURAR ARRAY ESTIMATED FROM REGIONAL EVENTS OCCURRED IN THE MEDITERRANEAN AREA*

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Abstract. Array processing techniques can characterize the details of arriving seismic waves front for different wave phases. We applied one of these techniques, *f-k* analysis, to estimate azimuth and slowness systematic deviations specific for Bucovina array (BURAR) and to detect significant lateral variations in the lithosphere structure.

BURAR array is a high-quality monitoring system consisting of 10 elements located in the Northern part of Romania, in South-Eastern Carpathians. Data recorded by BURAR during 2004–2007 time interval are collected from earthquakes located at regional distance and sufficiently large (magnitude greater than 4) to have an acceptable high signal/noise ratio. The distribution of the earthquakes shows strong inhomogeneous azimuth coverage: the majority of the earthquakes occurred in the Southern part relative to BURAR. Significant and systematic deviations in azimuth and slowness are emphasized. For comparison the same technique was applied in case of other two arrays, one located in Ukraine (AKASG) and the other one in Turkey (BRTR). The azimuth and slowness deviations are essential for estimating station corrections in order to improve the location quality. At the same time, they indicate the existence of significant lateral inhomogeneities in the lithosphere which can be interpreted in terms of the particular seismotectonics of the region crossed by seismic rays.

Key words: seismic array, azimuth correction, slowness correction, *f-k* analysis.

1. INTRODUCTION

The purpose of this study is twofold: (i) collection of the data base and evaluation of azimuth information and distance dependent correction factors in azimuth and slowness for BURAR array and (ii) preliminary interpretation of the results in connection with the regional structural models.

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Seismic arrays are defined as groups of closely spaced seismological stations with one of the sensors being assigned the role of a reference site, operating as a common time base. The first arrays, such as LASA and NORSAR, were of large aperture, aiming to monitor teleseismic events (Douglas, 1981). Later on, interest was transferred to small aperture arrays, such as NORESS and GERESS that could monitor events in the local, regional and near-teleseismic field (Harjes 1990, Mykkeltveit *et al.* 1990).

The high coherency level across its aperture makes an array a clear different seismic monitoring system as compared with the conventional seismological networks (Schweitzer *et al.* 2002). Since the array sites have common geological setting, similar elevation, the inter-element spacing satisfy destructive noise interference and aperture is small enough when compared to epicentral distance to support a plane wavefront assumption for the arriving signal, specific techniques can be applied to enhance signal to noise ratio. In particular, slowness and azimuth values of the arriving plane wave phases are calculated applying broadband frequency–wave number (*f-k*) analysis algorithms (Kværna and Ringdal 1986).

The *f-k* technique assures an optimum detection of the seismic phases coming to the array (Bungum and Husebye, 1974, Ringdal *et al.*, 1975, Cansi, 1995) and allows a good constrain of the back-azimuth and slowness for the seismic rays traveling from hypocenter to the array elements. This information can be subsequently used in location procedures. The same technique has been used to determine the local structure inhomogeneity beneath the array site area (Tibuleac and Herrin, 1997). Mostly due to the array ability in enhancing signal to noise ratio, seismic arrays are used widely in global monitoring and discrimination of earthquakes and explosions.

The National Institute for Earth Physics of Romania has a permanent seismic array, BURAR, operating in the northern part of Romania, in Bucovina region (see Fig. 1), since 2002. The array was installed and operated in cooperation with the Air Force Technical Applications Center (USA).

BURAR array consists of 10 seismic stations located in boreholes and distributed on a 5 km × 5 km area. Nine stations are equipped with short–period (SP) vertical sensors (GS-21 res) and one station is equipped with a broadband (BB) three-component sensor (KS 54000). The broadband station is located in the same place with one of the SP stations (element number 8 of the array).

The BURAR array is located in the Eastern Carpathian Mountains at an altitude of over 1000 m, in a complex tectonic setting characterized by a continental collision at the contact between the East European Craton and Carpathians orogen area.

The Carpathian Mountains form a double bend chain marking the locus of Cenozoic closure of a major embayment of the Tethys ocean (Dercourt *et al.*, 1993; Badescu, 1997; Jones and Simmons, 1997). The Carpathians represent the deformed belt of continent-continent collision between Alcapa and Tisza-Dacia terrenes

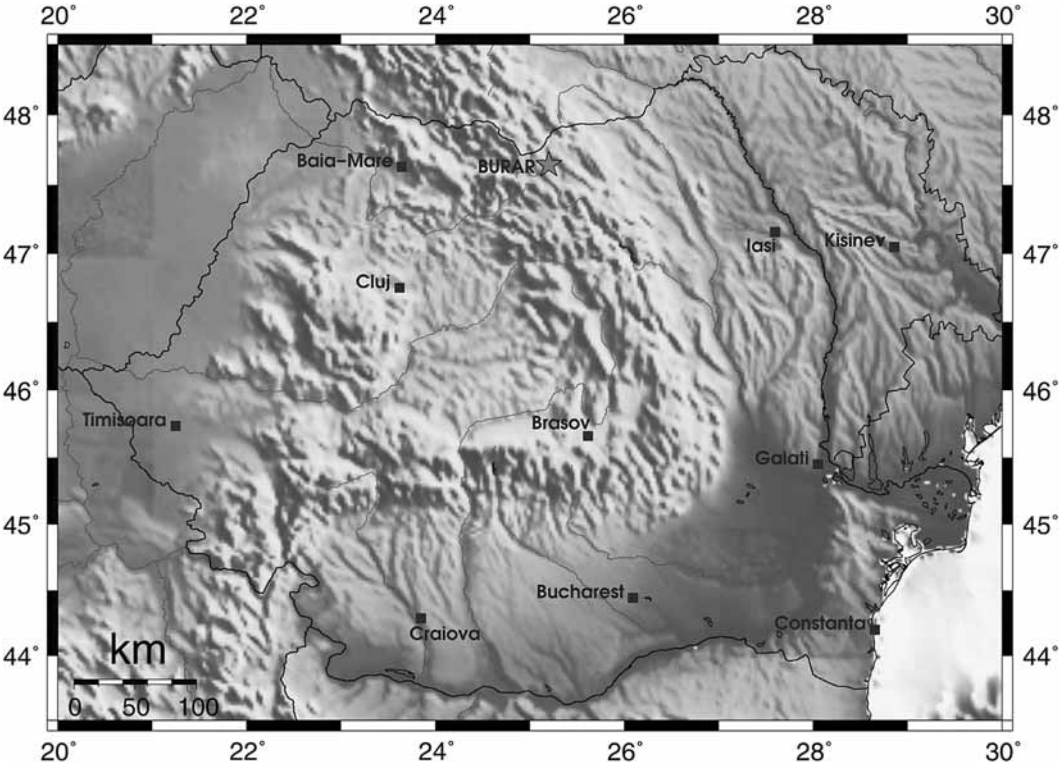

Fig. 1– Romania map and BURAR location (grey star).

(*e.g.*, Csontos and Nagymarosy, 1998), forming the basement of the Pannonian Basin, and the stable continental units including the Moldavian part of the East European Platform, the Scythian Platform, and the Moesian Platform (Radulescu and Sandulescu, 1973; Burchfiel and Royden, 1982). The Carpathian arc is the site of very active intermediate-depth (70 < 200 km) seismicity of the Vrancea zone (Roman, 1970; Fuchs *et al.*, 1979; Radulian and Popa, 1996; Oncescu and Bonjer, 1997; Mandrescu and Radulian, 1999; Wenzel *et al.*, 1998), and of late Cenozoic mafic alkaline, calk-alkaline, and shoshonitic volcanism (Mason *et al.*, 1998).

The Cenozoic history of motions and deformation in the study region is complex in detail, but can be summarized succinctly as eastward and then southeastward motion of the Tisza-Dacia/Alcapa terrains as overriding units of a subduction zone, leading to mainly frontal collision with continental lithosphere of the Moldavian-Scythian Platforms along the Eastern Carpathians during the final stages of subduction of an embayment of Tethys (Radulescu and Sandulescu, 1973; Burchfiel and Royden, 1982; Roure *et al.*, 1993; Linzer, 1996; Linzer *et al.*, 1998; Zweigel *et al.*, 1998; Matenco and Bertotti, 2000). A distinctive and sharp lineament, the Trans-European Suture Zone (TESZ) outlines the contact between the East European plate and Intra-Alpine plate. The TESZ is considered a broad zone of deformation that crosses all of Europe, from the British Isles in the northwest, to the Black Sea area in the southeast, and it most likely continues in North America (Keller and Hatcher, 1999).

The geoelectrical cross-sections show clearly the contrast along the TESZ lineament (Stanica *et al.*, 1999). The BURAR site is located in the neighborhood of this contact area, and from this point of view we can expect significant lateral deviations of the travel times or seismic rays orientation when crossing from one side to the other the two convergent tectonic blocks. These effects should be critical for rays coming from South and South-East direction to BURAR.

The lateral inhomogeneous structure characterizes also the entire Alpine-Mediterranean area which is a wide and complex geophysical system at the confluence of Africa, Arabia and Eurasia blocks. A large amount of research has been focused on explaining and modeling the mantle compressional and shear velocity structure of the area, from scales ranging from regional to local, using different methods and data. On a regional scale, velocity structure has been studied for example by Romanowicz (1980), Spakman *et al.* (1993) and Bijwaard *et al.* (1998). Body wave and surface wave inversions were applied to determine the lithosphere–mantle structure by Panza *et al.* (1980), Calcagnile and Panza (1990), Zielhuis and Nolet (1994), Marquering and Snieder (1996).

Tomographic studies revealed mantle structure of smaller areas using data from local networks or temporary deployments of arrays: in the Betic-Alboran region (Blanco and Spakman, 1993; Calvert *et al.*, 2000), in the Italian peninsula (Panza and Mueller, 1979; Babuska *et al.*, 1990; Solarino *et al.*, 1996; Lucente *et al.*, 1999), in the Carpathian region (Fan *et al.*, 1998; Martin *et al.*, 2006), and in the Hellenic-Aegean area (Ligdas and Main, 1991; Papazachos *et al.*, 1995; Papazachos and Nolet, 1997).

These studies show a complex tectonic structure of the region, combining convergence and subduction, extension in back-arcs, decoupling, rotation and roll-back of plates and microplates, reflected in the heterogeneous distribution of seismic velocities in the lithospheric and sublithospheric mantle.

2. DATA PROCESSING

The data base contains earthquakes recorded between 2004 and 2007 time intervals by the Romanian seismic network (3-component stations) and stations in the neighborhood countries which are connected in real time to the National Data Center in Bucharest. All the selected events were recorded by the BURAR array too. The events location coordinates and magnitudes are taken from EMSC bulletins. The minimum magnitude for the selected earthquakes is 4 and epicentral distance less than 3500 km around BURAR location.

The distribution of the earthquakes shows strong inhomogeneous azimuth coverage. The majority of the earthquakes occurred in the Southern part relative to BURAR (see Fig. 2). The focal depth varies between 2 and 518 km. The deepest events are generated in the Tyrrhenian Sea, and in the Hellenic Arc.

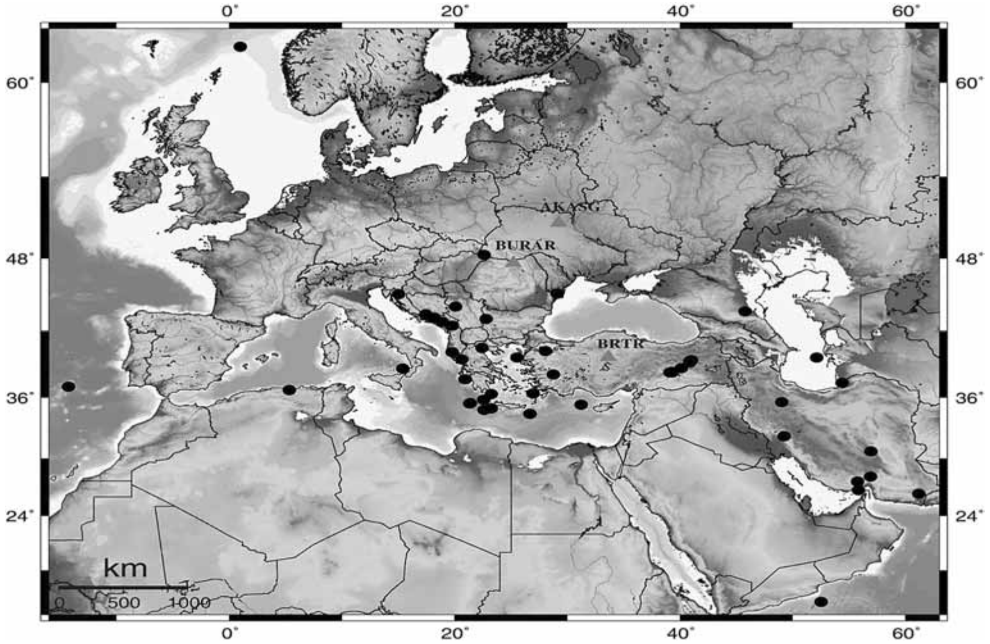

Fig. 2 – The epicenteral map. Black dots are epicenters of data base events recorded between 2004 and 2007; BURAR, AKASG and BRTR arrays are represented by gray triangles.

Since the seismic activity is strongly inhomogeneous in the studied area, we can not equally cover the entire azimuth domain. Naturally, the corrections will be better constrained for the south-southeast azimuth.

The systematic deviations of the azimuth and slowness of the seismic waves as recorded at the array are ascribed to lateral variations in the structure of the medium between the focus and the site. To measure these deviations we compare the values of the azimuth and slowness estimated by *f-k* analysis (Schweitzer *et al.*, 2002) with the values calculated from the location for a standard one-dimensional structure (ak 135 model, Kennett *et al.* 1995) using Seisan program (Havskov and Ottemöller, 1989).

For comparison, we applied the same procedure using recordings at other two arrays; one located in Ukraine (AKASG) and the other in Turkey (BRTR) (see Fig. 2).

A description of frequency-wavenumber analysis may be found in Capon (1969). This method has been further developed to include wide-band analysis, maximum-likelihood estimation techniques, and three-component data (Kværna and Doornbos, 1986; Kværna and Ringdal, 1986; Ødegaard *et al.*, 1990).

The *f-k* analysis is done in the frequency domain. The principle is beamforming in the frequency domain for a number of different slowness values. Normally we use slownesses from –0.4 to 0.4 s/km equally spaced over 51 by 51 points. For every one of the 2601 points the beam power is evaluated, giving an equally spaced grid of 2601 power points.

An example of such a power grid in the slowness space is displayed in Fig. 3 with the slowness ranging from –0.2 to 0.2 s/km. It is obtained at BURAR array for an earthquake occurred in Vrancea area on January 7, 2007 (01:55). The power is displayed by isolines of dB down from the maximum power. A process is used which will find the maximum power in the grid, and the corresponding slowness vector is the resulting estimated slowness. The azimuth of the position of the maximum power is measured from the North.

The *f-k* plot in Fig. 3 also represents the color-coded relative power of the multichannel signal for 51 by 51 points in slowness space.

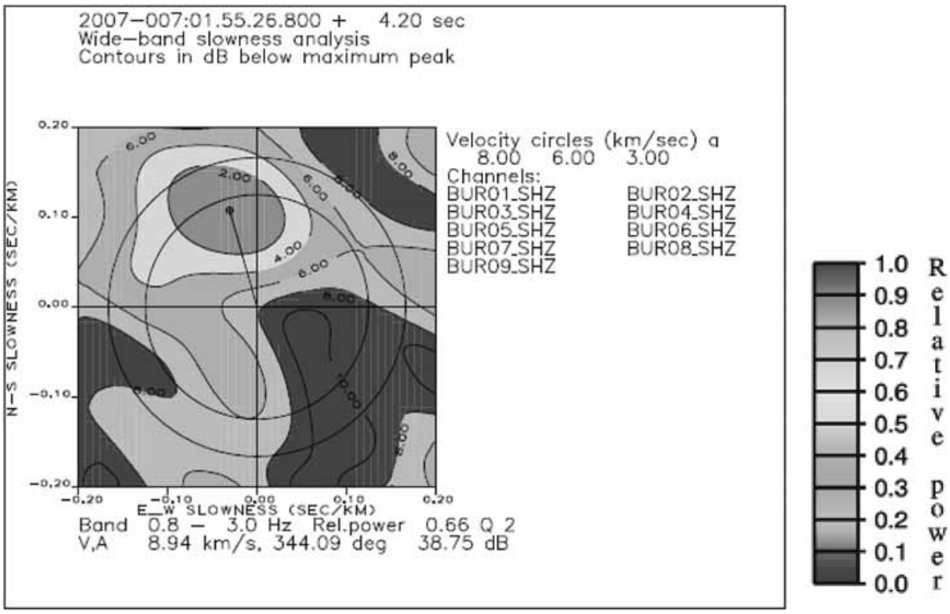

Fig. 3 – Result from the *f-k* analysis of BURAR data from a 3.5 second window around the signal. The isolines are in dB from maximum peak and the color-coded relative power is a measure of signal coherence.

4. AZIMUTH AND SLOWNESS DEVIATION ANALYSIS

The azimuth deviations relative to standard location geometry in case of a one-dimensional structure are represented in Fig. 4.

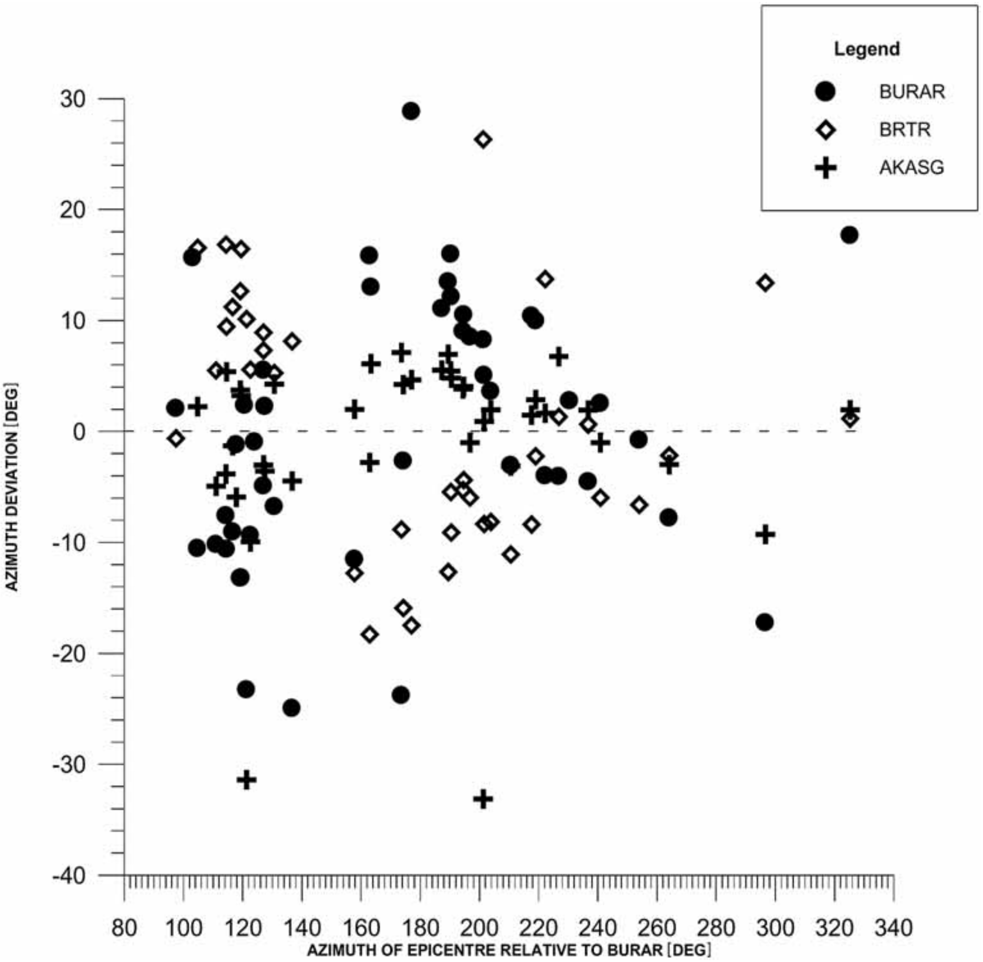

Fig. 4 – Distribution of the azimuth deviation for BURAR, AKASG and BRTR stations.

A careful analysis of Fig. 4 shows three segments with relatively distinct behavior. A segment for rays coming in the azimuthh range between 100° and 140° to BURAR (from eastern Turkey, Iran, Caspian Sea), another segment for rays between 160° and 220° (western Turkey, Balkan region, Hellenic Arc) and a last segment for rays coming with azimuth above 220° (Adriatic Sea, Italy, western Mediterranean region). Since systematic differences are noticed among these segments, we consider it is better to estimate the corrections separately on each segment. Thus, the average corrections are as follows:

$\Delta\phi = -5.18° \pm 8.84°$ for 100°–140° (Middle East Asia),

$\Delta\phi = +7.58° \pm 12.43°$ for 160°–210° (Balkan Region),

$\Delta\phi = +0.06° \pm 5.86°$ for 210°– 270° (Western Mediterranean Area).

Note a tendency of reducing the scattering in the last segment for all the considered arrays.

As can be seen in Fig. 4, the azimuthal distribution at BURAR is close to that at AKASG, which seems to be a reasonable result having in mind the geographical proximity of the two stations and the probable similarity of the geological structure crossed by the rays propagating to them. By contrary, the azimuthal variation seems to be in anti-phase with that of BRTR station. This discrepancy can be tentatively explained by a significant lateral variation in the lithosphere located between Carpathian orogen and Black Sea region: oceanic-type lithosphere toward south (Black Sea) and continental-type lithosphere toward north (East European Platform). An increase of the velocity, specific for the continental shield, could in principle explain the lateral negative change (deviation to west from the

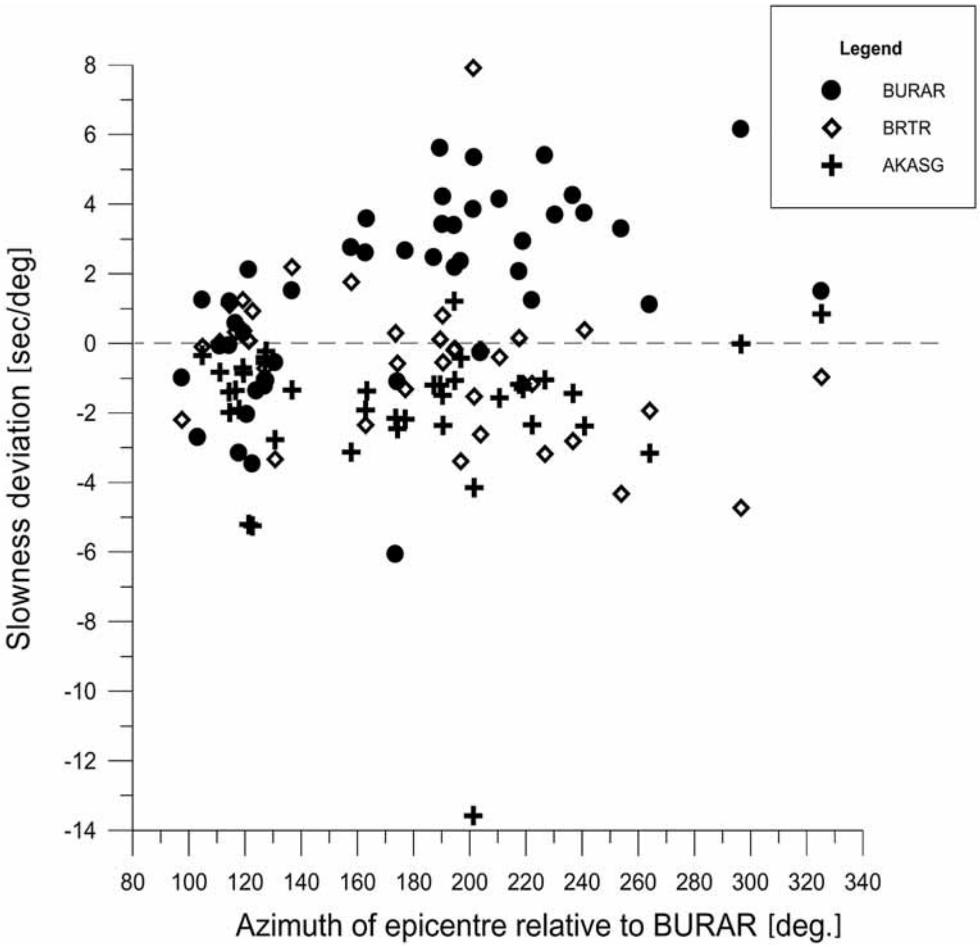

Fig. 5 – Distribution of the slowness deviation as determined at BURAR, AKASG and BRTR stations.

undisturbed ray) in the azimuth of the coming rays, which characterizes the azimuths obtained at BURAR for rays coming from SE (100°–140°).

The situation is different for the rays coming from south (160°–220°): deviations are mainly positive at BURAR and AKASG, while negative at BRTR. This could be due to the lateral structural variation related to the subducting lithosphere beneath Vrancea region. For the rays generated by the earthquakes in the Mediterranean area, no visible deviation is noticed at any of the three stations.

The slowness deviations relative to the standard one-dimensional structural model are represented in Fig. 5. Again, systematic deviations are visible for different azimuth segments:

$\Delta s = -0.61$ s/deg. ± 1.61 s/deg. for 100°–140° (Middle East Asia),
$\Delta s = 2.43$ s/deg. ± 2.61 s/deg. for 160°–210° (Balkan Region),
$\Delta s = 3.24$ s/deg. ± 1.57 s/deg. for 210° –270° (Western Mediterranean Area).

The analysis of the slowness anomalies shows systematic differences between the rays coming from southeastern domain and those coming from south-southwest relative to BURAR. The anomalies are larger for the rays propagating from Balkan region and western Mediterranean area, indicating a significant decrease of the velocity values in the mantle along these paths.

5. CONCLUSIONS

The BURAR array recently installed in the northern part of Romania provides high-quality data from teleseismic and regional events. The possibility to apply multiple-station techniques offers an essential tool for increasing the capability to monitor the seismic activity in the eastern and southeastern Europe area and in the Middle Asia.

The main goal of the present study is to estimate the corrections for azimuth and slowness which characterize the BURAR site in order to improve the detection and location for the regional events generated around. Since the available dataset consists primarily of earthquakes occurred in the Mediterranean area, we restrained our interest to this area.

To estimate the corrections we applied frequency-wavenumber technique. The corrections represent deviations of the station-epicenter azimuth and slowness, as estimated by *f-k* technique relative to the station-epicenter azimuth and slowness resulted from a standard location using a standard one-dimensional velocity model. The same procedure was applied for other two arrays one from Ukraine (AKASG) and other from Turkey (BRTR) respectively.

Since the rays coming from the hypocenters located toward SE from BURAR site pass through a region with significant lateral variation in the lithosphere structure (the region of contact between the Black Sea oceanic lithosphere with the East European continental shield), negative azimuth deviations are characteristic for BURAR and AKASG arrays, in contrast with BRTR array. Negative azimuth deviation means that the ray as observed at BURAR deviates to the east relative to the ray expected for a standard one- dimensional velocity model.

We can expect also that the positive deviations in azimuth at BURAR observed for the rays coming from south (Greece and Ionian Sea) are caused by the encounter of the deep lithospheric root beneath Vrancea region (against the significant shallower lithosphere to the north-west, in the Panonnian region).

The deviations in slowness are associated with higher average velocity in the structure located SE from BURAR and lower average velocity in the structure located toward S and SW from BURAR.

The relative large values of the deviations show that the lateral inhomogeneities in the structure are very important in the South-Eastern Carpathians area. The low accuracy of our results is caused mainly by the instabilities in the *f-k* diagrams due to relative high level of noise in many cases. As soon as new data from larger earthquakes will be available, we expect a better constrain of the azimuth and slowness corrections.

The azimuth and slowness correction factors associated to different seismogenic areas in the Mediterranean area will be incorporated in the location procedure. As a first investigation and interpretation, they correlate well with the regional modeling features that characterize the study area. Therefore, we assume that the obtained corrections measure the main lateral variations in the lithosphere at regional scale, for the southern range from BURAR (back azimuths between 90° and 270°). The new parameterization and calibration will be applied to enhance signal detection and seismic phase identification in case of local and regional earthquakes recorded by BURAR array.

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