Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 263 (2007) 420–428
EPSL
www.elsevier.com/locate/epsl

Estimation of water transport from oscillations of the on-shore telluric field generated by tides

Fernando A. Monteiro Santos [a,b,*], Rita Nolasco [b], António Soares [b], João M. Dias [c], Ivo Bernardo [b]

[a] Universidade de Lisboa, Campo Grande, C8, 1749-016 Lisboa, Portugal
[b] Centro de Geofísica da Universidade de Lisboa-IDL, Campo Grande, C8, 1749-016 Lisboa, Portugal
[c] CESAM, Departamento de Física, Universidade de Aveiro, 3810-193, Aveiro, Portugal

Received 10 January 2007; received in revised form 11 September 2007; accepted 24 September 2007
Available online 29 September 2007
Editor: C.P. Jaupart

Abstract

On-shore measurements of telluric field oscillations have been used together with electric field acquired in a submarine cable crossing a channel (in Aveiro area) to estimate the water transport through the channel. The on-shore N–S dipole was calibrated by correlating the lunar tidal water transport and the corresponding on-shore motionally tidal electric field. A calibration factor of 7350 m^3 s^{-1} for each mV/km, with motionally induced origin, was estimated. Theoretical polarization ellipses of the electric field with tidal origin and telluric field attenuation during inland propagation agreed very well with observed values. The results showed that it is possible to estimate the water transport from on-shore measurements.

Keywords: electromagnetic; motionally induced electric field; tides; mass flux

1. Introduction

The oscillations of the telluric field originated by tides were first predicted by Faraday in 1832 (Faraday, 1832) and were observed by Egedal in 1937 (Egedal, 1937). The physical phenomena that explain those oscillations are connected to the tidal water movement in the earth geomagnetic field (Longuet-Higgins, 1949; Sanford, 1971; Chave and Luther, 1990; Larsen, 1992). The charged particles in the water having a movement component perpendicular to the vertical component of the earth magnetic field are deviated by the Lorenz force. Positively and negatively charged particles are deviated in opposite direction generating electrical fields that spread far inland. The characteristics of these fields depend on: 1) the water flow and the electric properties of the water and 2) the electric structure of the earth in the area. This phenomenon has been used to estimate average water mass transport in straits, channels, throats or even in the open ocean, using submarine cables (Larsen, 1992; Harvey et al., 1977; Flosadottir and Taire, 1997; Palshin et al., 2001; Palshin et al., 2002; Monteiro Santos et al., 2002; Fristedt et al., 2002; Nolasco et al., 2006). These data are crucial, for example, to understand the role of the water mass circulation in global climatic changes.

The estimation of the mass transport using submarine cables has a great limitation associated to their scarcity

* Corresponding author.
E-mail address: fasantos@fc.ul.pt (F.A. Monteiro Santos).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.09.020

all over the world. In fact, cables are expensive infrastructures and their location is not, in general, the best for that kind of studies. Therefore, the search for a less expensive and more adequate tools is of great practical importance.

Mass transport in rivers is used by hydrologists for hydrologic studies and by civil engineering mainly to estimate rates of flow. Because it is difficult to make a direct measurement of the rate of flow, discharge in rivers is commonly computed from river stage and water velocity data collected at a crest-stage gage and with current meters, respectively. This is a relatively expensive method if continuous measurements are necessary at several cross-sections of the river.

In 1988, Junge (Junge, 1988) demonstrated that the telluric field induced by tides that spreads out far inland could be used to characterise tidal phenomenon. This phenomenon opens the possibility to study stream flows in channels or flows occurring close to the coast line, using on-shore electromagnetic measurements. This method has practical advantages over standard methods: the sensors can be easily installed closer to the intended location, globally it is less expensive than standard methods for continuous measurements. In this work we show that it is possible to estimate the water transport in channels, from the knowledge of the magnetic field and the telluric oscillations recorded at on-shore sites located in the vicinity of the channel. This study was performed using the measurements carried out in the Ria de Aveiro (Portugal) where a submarine cable crossing the channel is also installed. The analysis of the data collected in this cable was presented in a previous paper (Nolasco et al., 2006). Some of those results are used here to perform our calculations.

2. The Ria de Aveiro Lagoon (Portugal) case

2.1. Observations

The Ria de Aveiro is a shallow water lagoon connected with the Atlantic Ocean through a single artificial channel, the Barra channel of 300 m width and 3 to 25 m depth (Fig. 1). The typical value of the water current velocity

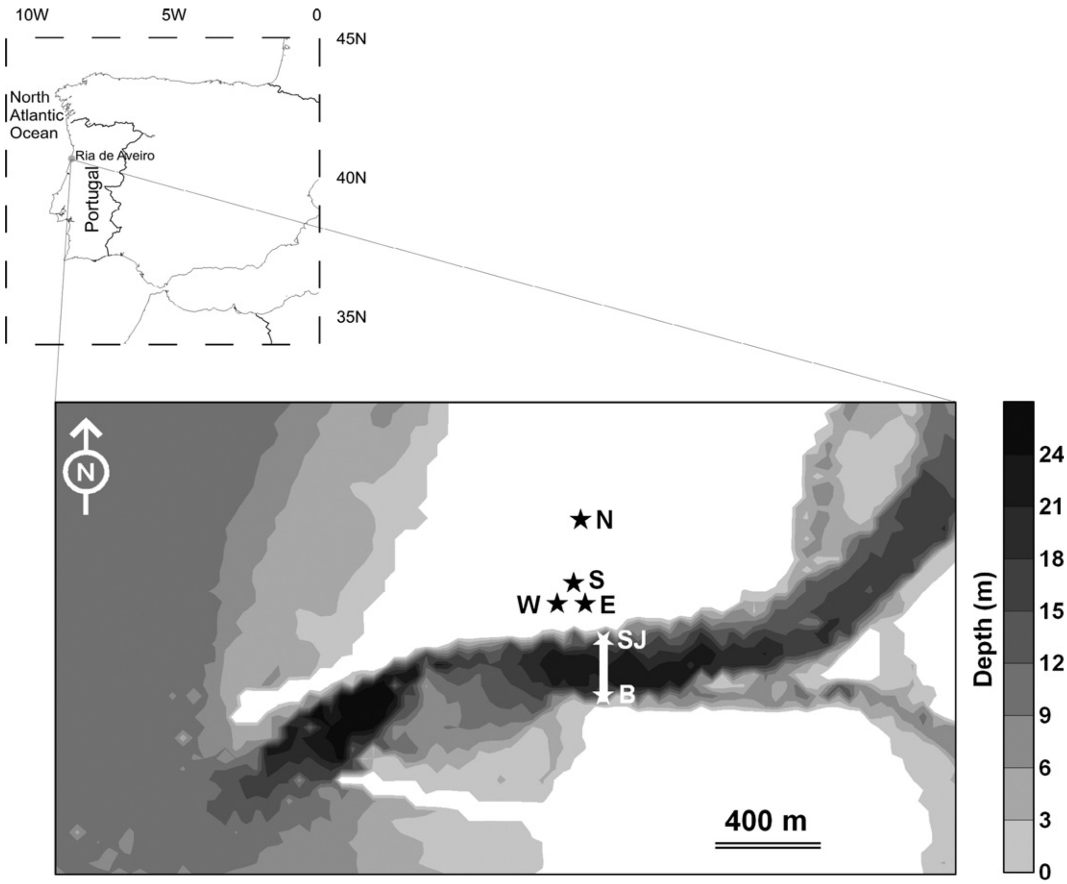

Fig. 1. Location of the Ria de Aveiro lagoon and of the submarine cable (SJ-B) in the Barra channel and of the on-shore electrodes.

across the narrow entrance is of about 1–1.5 m/s (Dias et al., 2003). In July 2002 a system composed by two silver–silver–chloride (AgAgCl) nonpolarizable electrodes (280 m apart), connected to a voltmeter (datalogger) by submarine cables was installed at the entrance of the Barra channel to estimate the water transport/flow at this site. The analysis and interpretation of the data collected in the submarine cable was presented by Nolasco et al. (2006) and have showed that: 1) the main flows at the Barra channel have tidal origin and, 2) a transport of 720 m^3 s^{-1} is associated to each potential difference of 1 mV between the ends of the cable.

At the same time, two pairs of nonpolarizable electrodes (PbPbCl) were installed in the north side of the channel, on-shore and close to the Barra. The electrodes were installed in the N–S (approximately N9°E and 360 m apart) and E–W direction (68 m apart) to investigate the possibility to estimate the water transport/flux in the channel, using on-shore electrical potential measurements. They have been placed in salted bentonite in 1.0 to 1.5 m deep holes. The electric potential was sampled at a rate of 10 s, but only the average of six values over 60 s was recorded.

Fig. 2 shows hourly means of the electric field recorded between days 247 and 317 since January 2002, across the channel and in the two on-shore pair of electrodes. The field varies between about −46 and 46 mV/km in the submarine cable. The variations observed in the on-shore dipoles are lesser, mainly in the E–W dipole. The electric variations registered on on-shore dipoles show a

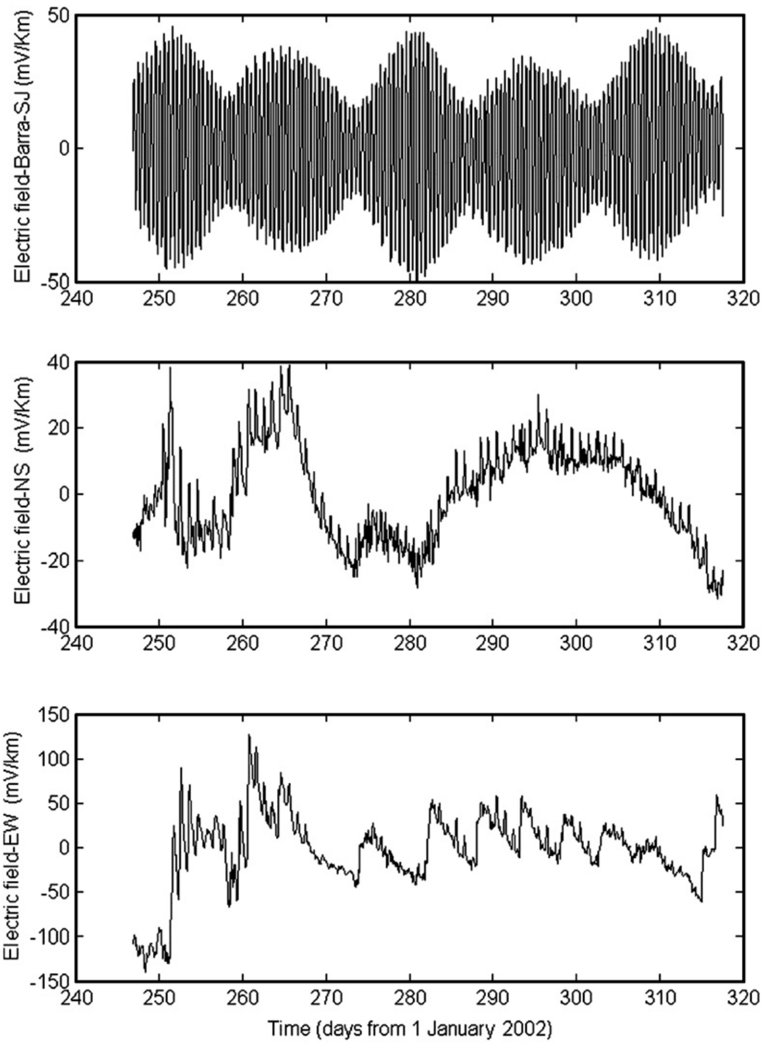

Fig. 2. Hourly means of the electric field measured across the channel (top); with the N–S on-shore dipole (middle) and with the E–W on-shore dipole (bottom).

predominantly N–S polarized electric field in the vicinity of the Barra. Since the orientation of the water flow in the Barra channel is predominantly E–W, the N–S electrodes are the most sensible pair of antennas to the electric signals originated by water transport in the channel.

2.2. Separation of motionally induced signal

The amplitude spectrums of the hourly mean electric field are shown in Fig. 3. The spectrum of the cable data is dominated by semidiurnal M_2, S_2/K_2 and N_2 frequencies. Other frequencies, like P_1/K_1, O_1 and M_4 are also present, with smaller amplitudes. The spectrums corresponding to dipoles are also dominated by the same frequencies (the M_4 is not present in the on-shore dipoles). However, the small importance of the M_2, S_2/K_2 frequencies should be considered. The M_2, N_2, O_1 and N_4 components are mainly of oceanic tidal motional origin. The S_2/K_2 and P_1/K_1 components are a combination of oceanic tidal motion and geomagnetic origin. The 3 cpd (8 h) tidal component is present in the on-shore measured fields but is not revealed in the cable data. Moreover, the 4 cpc (6 h) tidal component, corresponding to shallow water harmonics, is shown in the N–S cable spectrum and is absent in the E–W and cable

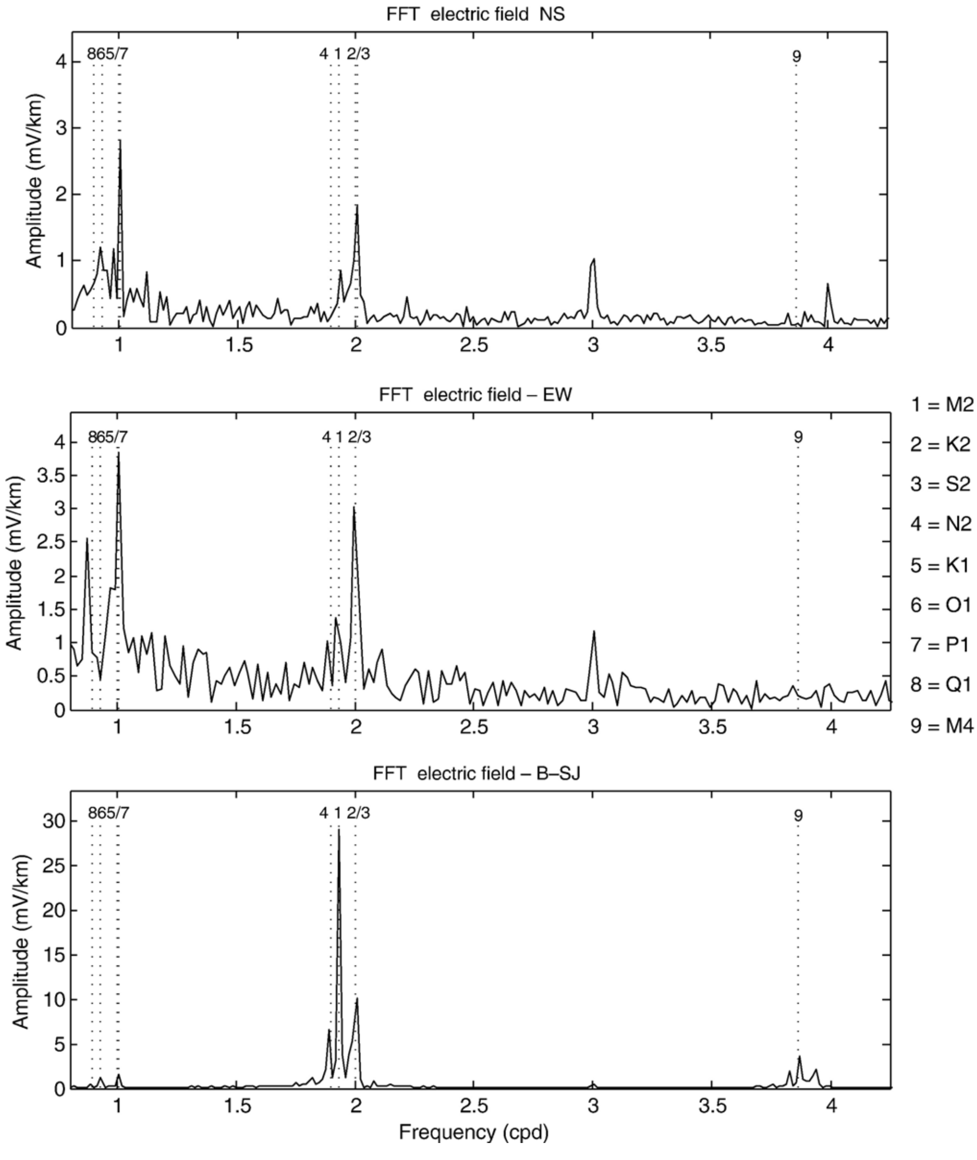

Fig. 3. Amplitude spectrum obtained from data recorded with the N–S dipole (top) and the E–W dipole (middle) and with the submarine cable (bottom).

measured fields. The spectrum for the E–W dipole shows that this component is noisier than the N–S one.

The main objective of this study is to show that one can use on-shore electric potential measurements in the vicinity of a channel to evaluate the mass transport for the water flow in the channel. Therefore, let us concentrate our attention into the M_2 component in the submarine cable and into the N–S dipole. In order to separate this component from the total signal, the measured time series were approximated by a set of lunar harmonics constituents using the least square fitting method. A detailed explanation of the method is presented in Nolasco et al. (2006). The results obtained from the submarine cable and N–S dipole, are presented in Fig. 4.

Nolasco et al. (2006) presented the calibration factor between motional field (measured in the ends of the submarine cable) and the water transport through the Barra channel. The factor was estimated (Nolasco et al., 2006) using results from a hydrodynamic numerical model properly calibrated for the Ria de Aveiro lagoon through comparison between model results and measurements of water surface elevation and current velocity, for several stations distributed along the main lagoon channels (Dias and Lopes, 2006) They estimated a value of 201.6 $m^3\ s^{-1}\ mV^{-1}$ km, which allows them to convert the potential difference values into water transport of tidal origin. They also observed a difference of 2.11 h between the maximum values of the electric field and the sea water surface elevation measured at a tidal gauge located near the south electrode of the submarine cable (lagoon inlet). Fig. 4(top) shows the M_2 harmonics of the electric field measured in the cable and in the N–S dipole together with the water flux/submarine cable calibration. A delay of 3.62 h between the maximum values of the water flux and the electric field measured in the N–S dipole can be noted. Comparing the M_2 component of the electric field measured in the submarine cable with that measured in the N–S dipole, one notes the relation $E_{cable}=36.46E_{N-S}$ between their amplitudes.

A calibration factor for the on-shore antenna can be estimated using the correlation between the water transport in the channel (or their equivalent electric

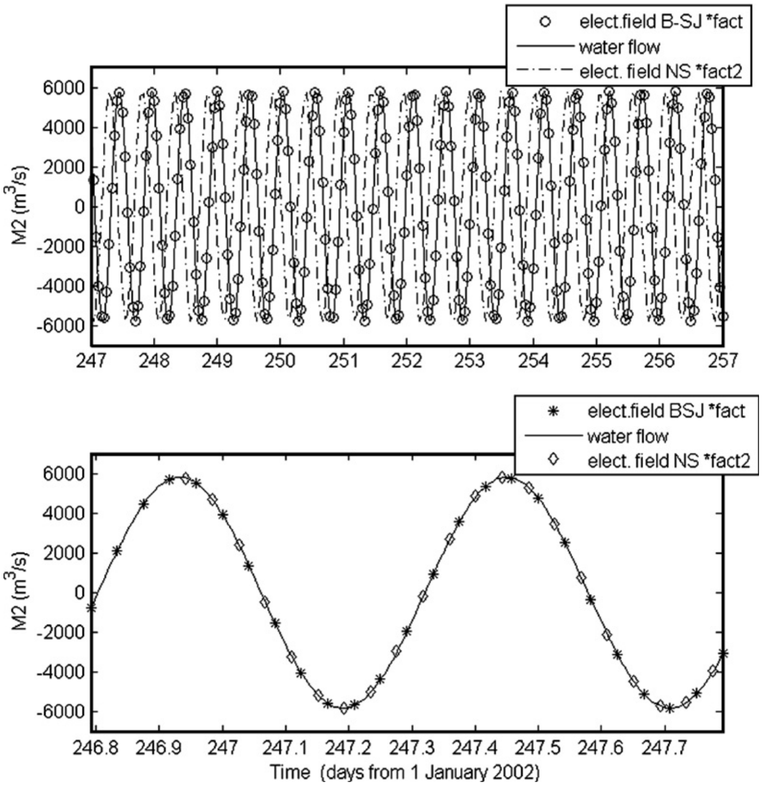

Fig. 4. (Top) Comparison between the M_2 components of the electric field measured with the submarine cable and the N–S dipole with the water transport. The cable electric field values were multiplied by the factor 201.6 $m^3\ s^{-1}\ mV^{-1}$ km, whereas the N–S field values were multiplied by the factor 7350 $m^3\ s^{-1}\ mV^{-1}$ km. (Bottom) Zoom of the electric fields measured in the submarine cable and N–S dipole and of the water transport, showing the adjustment between the curves. The N–S values were shifted of 3.62 h.

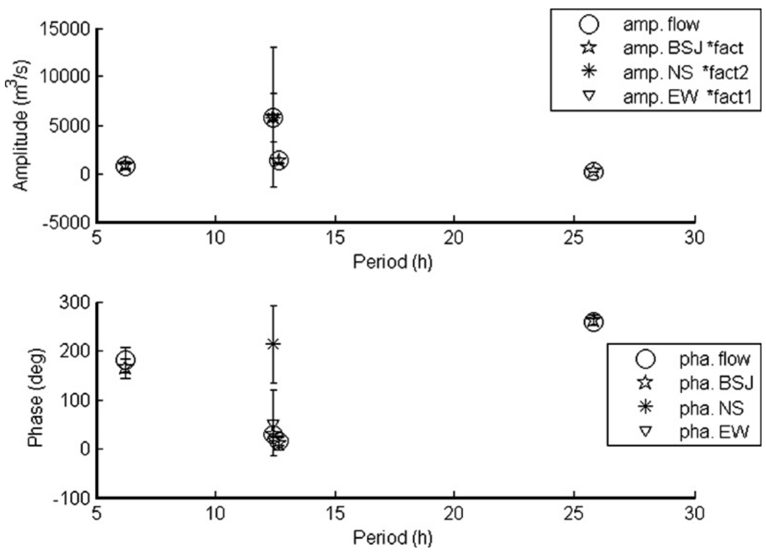

Fig. 5. Amplitude and phase of the lunar tidal constituents for water transport, electric field in the submarine cable and on-shore dipoles determined by least square fitting approximation of the data with 95% confidence interval.

potential in the cable) and the electric potential differences with tidal origin measured in the N–S dipole. The method allows an estimation of a water transport of 7350 $m^3 s^{-1}$ for each mV/km in the N–S on-shore dipole and of 5476.9 $m^3 s^{-1}$ for each mV/km in the E–W dipole. Fig. 4 (bottom) shows a detail of the fit between the water transport and the potential differences, for a period of two tidal cycles.

Amplitude and phase lag for tidal components for water transport, electric field in the submarine cable and in the on-shore dipoles (with the errors of the least square fitting) are plotted in Fig. 5. The adjustment between the series regarding amplitude and phases is very good, except for the E–W on-shore dipole where a significant error is observed.

3. Modelling

In this section we shall adopt the model proposed by Junge (Junge and ISO-3D team, 2001) to explain some of our on-shore observations. Fig. 6 gives a schematic view of the current at the Barra channel with tidal origin for a fixed time t_0. As the ions in the water moves perpendicularly to the vertical component of the earth

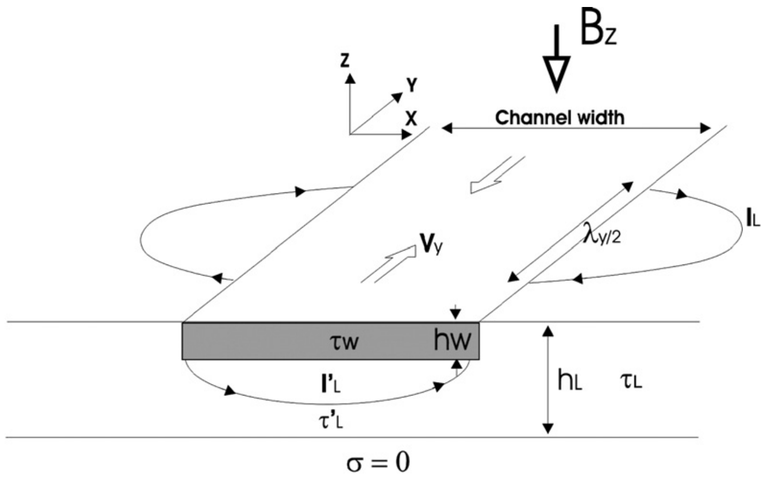

Fig. 6. Schematic view of the tidal current in a channel and induced telluric currents at a fixed time (adapted from Junge (Junge and ISO-3D team, 2001).

magnetic field ($\vec{B}$), the charges separation takes place. These charges will cause electric currents in vertical planes in and beneath the water. The scale length of the horizontal water current, characterised by its wavelength λ_y, exceeds the thickness of the uppermost conducting earth layer with an integrated conductivity τ_L. The vertically integrated electric current density $\vec{I}$ is:

$$\vec{I}(x,y,t) = \int_{z_1}^{z_2} \vec{J}(x,y,z,t)dz \quad (1)$$

where z_1 and z_2 are the lower and upper boundary of the conducting layer and $\vec{J}$ is the current density which is given by (see Larsen, 1992), $\vec{J} = \sigma\left(\vec{E} + \vec{v}\times\vec{B}\right)$. Integrating Eq. (1) we obtain

$$I_L = (\tau_w + \tau'_L)E_x - \tau_w B_z v_y \quad (2)$$

or

$$I_L - I_w - I'_L = -\tau_w B_z v_y \quad (3)$$

where τ_w and τ'_L are the integrated conductivities of seawater and conducting sedimentary layer beneath the channel. The right side of Eq. (3) is the current source and the left hand side represents the different parts of the resulting currents in the vertical and horizontal planes.

Considering that the current along the "Ria de Aveiro" I_L varies harmonically with the period $T_{M_2}(=12.4206\,\text{h})$ and the Greenwich phase $\varphi_{M_2}(\approx 28°)$, the potential $V(P,t)$ at $P(x,y)$ distant of r_P from the current source at y_0, is (Junge and ISO-3D team, 2001)

$$V(x,y,t) = \int_{y_A}^{y_B} V^*(x,y,t;y_0)dy_0 \quad (4)$$

where $V^*(x,y,t;y_0) = \frac{I_L(t)}{\pi\tau_L}\ln\left(\frac{1}{r_P}\right)$ represents the logarithm potential at P originated by the current I_L at y_0. Here, $r_P = \left[x^2+(y-y_0)^2\right]^{1/2}$ and

$$I_L(t,y_0) = I_{L0}\sin\left[2\pi\left(\frac{y_0}{\lambda_y} - \frac{t}{T_{M_2}}\right) + \varphi_{M_2}\right] \quad (5)$$

where I_{L0} ($=h_w\ v\ \sigma_w\ B_z$) is the mean maximum amplitude of the integrated electric current density. Therefore, the components of the electric field with motionally origin are (Junge and ISO-3D team, 2001):

$$E_x(x,y,t) = \frac{I_{L0}}{2\pi\tau_L}x\int_{y_A}^{y_B}\frac{1}{x^2+(y-y_0)^2}\sin\left[2\pi\left(\frac{y_0}{\lambda_y}-\frac{t}{T_{M_2}}\right)+\varphi_{M_2}\right]dy_0 \quad (6i)$$

$$E_y(x,y,t) = \frac{I_{L0}}{2\pi\tau_L}\int_{y_A}^{y_B}\frac{y-y_0}{x^2+(y-y_0)^2}\sin\left[2\pi\left(\frac{y_0}{\lambda_y}-\frac{t}{T_{M_2}}\right)+\varphi_{M_2}\right]dy_0 \quad (6ii)$$

y_A and y_B are the limits of integration in the direction of the channel flow. It should be noted that this model does not consider the contribution of the currents parallel to the coast line. In this study and for the Aveiro particular case, it was assumed that these contributions are negligible.

3.1. Results

The width of the current is of about 300 m, the mean water depth is 16 m, and its wavelength is about 40 km (Dias, *personnel communication*). The vertical water flow will be assumed as negligible compared to the horizontal one, which will be $v_y = 1$ m/s. The conductivity of the sea water will be considered uniform (3.33 S/m), as well as the water depth and water velocity. The vertical component of the mean magnetic field at the time of the observations was 36,245 nT. Then, the mean maximum amplitude of the integrated electric current density is $I_{L0} = 1.9\times10^{-3}$ A/m. The water conductance is $\tau_w = 53.3$ S.

It was observed that the electric field measured in the N–S dipole is about 1/36.46 lesser than the electric field measured in the submarine cable. Our model does not allow for the modelling of the electric field in the cable, therefore we compare the theoretical electric field calculated at the N–S dipole site with that one calculated at a point 5 m apart from the source current located at the northern edge of the channel. The value of τ_L is unknown. A time domain electromagnetic survey was carried out in the vicinity of the dipoles to investigate the conductivity distribution in the earth. However, the results correspond to a very thin layer (about of 70 m) and cannot be used to estimate the value of τ_L. For this reason, we proceeded by trial-and-error. A value of 1/32.1 for the ratio E_{N-S}/E_A was obtained with $\tau_L = 1200$ S. In this case the calculated ratio is closer to the observed value and the conductance value was assumed for the next step.

Fig. 7 shows the comparison between the measured and theoretical telluric ellipse calculated at a location corresponding to the middle of the N–S dipole. The figure shows two measured ellipses calculated from the extreme values of the lunar tides constituents of the E–W electric field component. The theoretical ellipse has the major axes approximately in the NNW–SSE direction. The agreement of the theoretical and experimental ellipses can

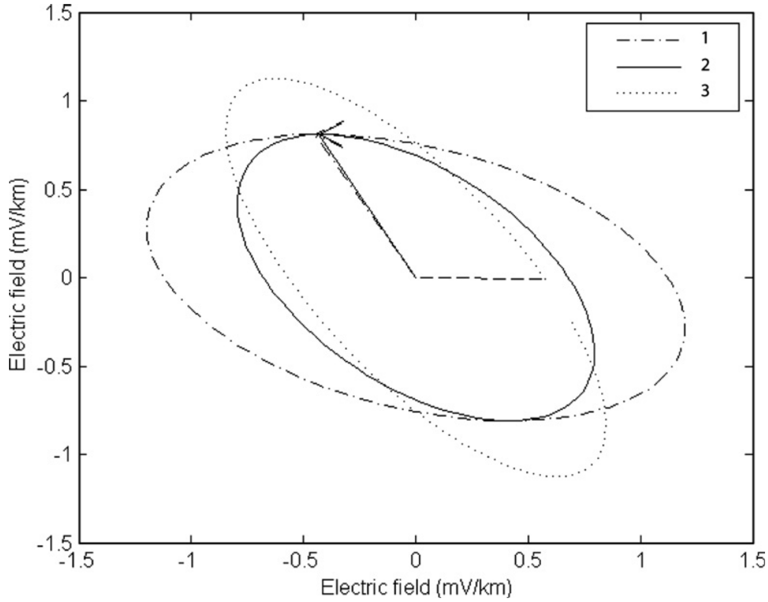

Fig. 7. Comparison between observed (solid and dash-point lines) and theoretical (pointed) telluric polarization ellipses. Lines 1 and 2 represent the ellipses calculated using the extreme values of the lunar tides constituents of the E–W electric field component.

be considered good, taking into account our simplified model and the errors in the E–W electric field component.

4. Conclusion

Electric fields data have been acquired in a submarine cable crossing a channel (the Barra in Aveiro area) and in two one-shore dipoles installed in the vicinity of the cable and processed for tidal analysis. It was shown that the dominant tidal component (period) in the submarine cable and N–S data is the semidiurnal lunar period of 12.4602 h (the well known M_2 component). It was demonstrated that one can use the on-shore lunar harmonics to estimate the water transport verified through the Barra channel. To achieve this, the on-shore N–S dipole was calibrated by correlating the water transport tidal lunar and the on-shore motionally tidal electric field. A calibration factor of 7350 $m^3\ s^{-1}$ for each mV/km, with motionally induced origin, was estimated for the N–S on-shore dipole.

Preliminary theoretical studies enabled us to calculate the theoretical polarization ellipse of the electric field with tidal origin and its attenuation during inland propagation, that agree quite well with the observed values.

A very promising development of the work here presented will be the voltage measurements on three different sites located close to the west Portuguese coastline. These measurements will start during the summer of 2006. The comparison and correlation between all these on-shore antennas may provide a valuable tool for monitoring the oceanic current flow in the vicinity of the coast.

Acknowledgements

This study was developed in the scope of the projects PROTEU (PDCTM/MAR/15275/1999) EMNOCM (POCTI/CTA/44062/2002) and AMDRAPHYD (POCI/AMB/57928/2004) funded by Fundação para a Ciência e Tecnologia (FCT) and by FEDER. One of the authors, R.N., was funded by a grant of the FCT (PRAXIS SFRH/BPD/10256/2002). The authors thank the Administration of the Port of Aveiro, Irmãos Cavaco, Xavisub and Área Militar de S. Jacinto for all aid along the equipment installation and data collection. The authors thank I. Rio for her help in improving a first version of this paper.

References

Chave, A., Luther, D., 1990. Low-frequency, motionally induced electromagnetic fields in the ocean. J. Geophys. Res. 95, 7185–7200.

Dias, J.M., Lopes, J.F., 2006. Implementation and assessment of hydrodynamic, salt and heat transport models: the case of Ria de Aveiro Lagoon). Portugal. Environ. Model. Softw. 21, 1–15.

Dias, J.M., Lopes, J.F., Dekeyser, I., 2003. A numerical model system application to the study of the transport properties in Ria de Aveiro lagoon. Ocean Dyn. 53, 220–231.

Egedal, J., 1937. On the lunar-diurnal variation in the earth-currents. Terr. Magn. 42, 179–181.

Faraday, M., 1832. Experimental researches in electricity—Bakerian lectures. Phil. Trans. R. Soc., Lond. 122, 163–194.

Flosadottir, A.H., Taire, K., 1997. Observations of ocean currents using submarine cables. Proceedings of International Workshop on Scientific Use of Submarine Cables, pp. 10–15.

Fristedt, T., Sigray, P., Lundberg, P., Crona, L., 2002. Salt-wedge observations in Oresund by direct measurement of the motionally induced voltage. Cont. Shelf Res. 22, 2513–2524.

Harvey, R.R., Larsen, J.C., Montaner, R., 1977. Electric field recording of tidal currents in the Strait of Magellan. J. Geophys. Res. 82, 3472–3476.

Junge, A., 1988. The telluric field in northern Germany induced by tidal motion in the North Sea. Geophys. J. Int. 95, 523–533.

Junge, A., ISO-3D team, 2001. Oscillations of the on-shore telluric field generated by oceanic tides. Final Report of the ISO-3D project, pp. 101–116.

Larsen, J., 1992. Transport and heat flux of the Florida current at 27 N derived from cross-stream voltages and profiling data: theory and observations. Phil. Trans. R. Soc., Lond. 338, 169–236.

Longuet-Higgins, M., 1949. The electrical and magnetic effects of tidal streams. Mon. Not. R. Astron. Soc. Geophys. 5, 285–307.

Monteiro Santos, F.A., Soares, A., Trindade, L., Nolasco, R., Rodrigues, H., ISO-3D team, 2002. Voltage measurements over the CAM-1 submarine cable between Madeira Island and Portugal mainland. Earth Planets Space 54, 393–398.

Nolasco, R., Soares, A., Dias, J.M., Monteiro Santos, F.A., Palshin, N.A., Represas, P., Vaz, N., 2006. Motional induction voltage measurements in estuarine environments: the Ria de Aveiro Lagoon (Portugal). Geophys. J. Int. 95, 523–533.

Palshin, N.A., Vanyan, L.L., Medzhitov, R.D., Shapiro, G.I., Evdoshenko, M.A., Utada, H., Shimizu, H., Tanaka, Y., 2001. Use of the Nakhodka-Naoetsu submarine cable for studying the temporal variability of integral water transport in the Sea of Japan. Oceanology 41 (3), 447–457.

Palshin, N.A., Vanyan, L.L., Poray-Koshits, A.M., Matyushenko, V.A., Kaikkonen, P., Tiikkainen, J., 2002. Measurements of motionally induced voltage in the coastal zone of the Throat of the White Sea. Earth Planets Space 54, 433–441.

Sanford, T., 1971. Motionally-induced electric and magnetic fields in the sea. J. Geophys. Res. 76, 3476–3492.