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Tree Motion: following the wind-induced swaying of arboreous individual using a GNSS receiver

Movimento dell'albero: analisi dell'oscillazione indotta dal vento di un individuo arboreo utilizzando un ricevitore GNSS

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Abstract. Climate-induced stresses, more than in the past, expose trees to hazards possibly compromising their stability, with serious risk for people, objects, structures and infrastructures. In order to prevent trees falling phenomena, a constant improvement of the knowledge of relations between trees and meteorological events (trees-wind in particular) is crucial. Any new technology able to support research and monitoring in this direction must therefore be studied, tested, and finally adopted in order to create an infrastructure that would bring indisputable advantages from a social, economic and environmental point of view. The aim of this study is to test the applicability of GNSS receivers for monitoring wind-associated tree movements. The case study reported here refers to an experimental analysis carried out on an Italian stone pine (Pinus pinea L.). The analysis was carried out by applying a single-frequency GNSS receiver (an u-blox M6 evaluation kit available on the market at 300$) at the top of the tree and evaluating the results obtained in term of velocities and positions. Then, values obtained were correlated with wind characteristics by a sonic anemometer installed very close to the pine tree (within 15 meters), in order to independently record the impacting wind fields (velocity, direction). This allowed us to study the correlation between the wind velocity (cause) and tree movements (effect). Statistic outputs evaluation provides very promising results, showing the capability of this instrumental solution in the analysis of movement patterns. The study, indeed evidenced that accuracy of measurements and their relative errors are enough for the research purposes.

Keywords. Tree movement, GNSS, Positioning, Wind, Risk prevention.

Riassunto. Le sollecitazioni indotte dal clima, oggi più che in passato, espongono gli alberi a rischi che possono comprometterne la stabilità, comportando gravi rischi per persone, cose, strutture e infrastrutture. Al fine di prevenire i fenomeni di caduta degli alberi, è fondamentale un costante miglioramento della conoscenza delle relazioni tra alberi ed eventi meteorologici (alberi-vento in particolare). Ogni nuova tecnologia in grado di supportare la ricerca e il monitoraggio in questa direzione deve quindi essere studiata, testata e adottata a livello nazionale al fine di creare un'infrastruttura che apporterebbe indiscutibili vantaggi dal punto di vista sociale, economico e ambientale. Lo scopo di questo studio è quello di testare l'applicabilità dei ricevitori GNSS per il monitoraggio dei movimenti degli alberi associati al vento. Il caso studio qui riportato si riferisce ad un'analisi sperimentale effettuata su un pino cembro italiano (Pinus pinea L.). L'analisi è stata effettuata applicando un GNSS a singola frequenza (un kit di valutazione u-blox M6 disponibile sul mercato a 300$) in cima all'albero e valutando i risultati ottenuti in termini di velocità e posizioni.
Successivamente, i valori ottenuti sono stati correlati con le caratteristiche del vento attraverso i dati ottenuti da un anemometro sonico installato molto vicino al pino (circa 15 metri), al fine di registrare indipendentemente i campi di vento (velocità, direzione). Questo ci ha permesso di studiare la correlazione tra la velocità del vento (causa) e i movimenti degli alberi (effetto). La valutazione statistica delle uscite ha fornito risultati molto promettenti, dimostrando la potenzialità del metodo proposto nell'analisi dei modelli di movimento. Lo studio, infatti, ha evidenziato che l'accuratezza delle misure è sufficiente ai fini della ricerca.

Parole chiave. Movimento dell'albero, GNSS, Posizionamento, Vento, Prevenzione del rischio.

INTRODUCTION

Weather and climate variations exhibit vegetated environment to risks that could jeopardize tree stability causing serious hazards and severe economic losses both in an urban and forest context. (Alexander, 1964; Alexander, 1967; Neustein, 1965; Persson, 1975; Lohmander and Helles, 1987; Chirici et al., 2017; Motta et al., 2018). To prevent the falling of trees, close monitoring is the key to the early detection of problems and hence finding the best management options. The roots strength, the crown shape and dimension, the stem and stump elasticity and resistance, are the most important parameters affecting trees' stability. The interaction of these parameters affects the tree motion patterns under wind action, making these a reliable proxy of the overall tree's stability.

Several studies have been produced to investigate the tree-wind relationship using fundamental physics, empirical experiments, and mechanistic model-based approaches in interaction (Baker, 1995; Baker, 1997; Brüchert et al., 2003; Achim et al., 2003; Achim et al., 2005; Cucchi et al., 2005). As reported in James, 2010, the instruments and technology used by researchers to study the trees-wind relationship, has developed over many years a large range of methods. These include stopwatches (Sugden, 1962; Mayhead, 1973b) accelerometers (Blackburn et al., 1988; Peltola, 1996b), displacement transducers, (Gardiner, 1995; Kerzenmacher and Gardiner, 1998; Milne, 1991; Roodbaraky et al., 1994), prism based systems (Hassinen et al., 1998), lasers (Baker, 1997), tilt sensors (Flesch and Wilson, 1999b; Sellier et al., 2003; Sellier et al., 2006; Gilman et al., 2008; Rudnicki et al., 2001) and video based techniques (Peltola, 1996a). More recent technology and electronic instruments such as strain gauges, displacement sensors and portable data loggers have been used to obtain more accurate information on tree response under static and dynamic loading (Brüchert et al., 2000; Milne, 1991; Baker and Bell, 1992; Gardiner, 1995; Rodbaraky et al., 1994; Flesch and Wilson, 1999b; Hassinen et al., 1998; Holbo et al., 1980; Sellier and Fourcaud, 2005). The instruments used depend of course on what the researcher is going to demonstrate and each one presents advantages and disadvantages depending on circumstance. Stopwatches, for instance, are very cheap and simple to set up but it presents, on the other hand, low accuracy and reliability. Accelerometers on the other hand offer a convenient method for measuring the motion and frequency response of trees in two coordinate directions. As evidenced by Hassinen et al., (Hassinen et al., 1998) anyway, with an accelerometer, a guess has to be made of the initial position of the tree and any error is compounded when double integrating to obtain displacement. This leads to an accumulating error in calculated displacement and an exaggeration of the low frequency response of the tree (White et al., 1976; Blackburn et al., 1988; Peltola et al., 1993; Peltola, 1996; Gardiner, 1992; Gardiner, 1995). This is why displacement transducers and video-based techniques are considered more reliable and accurate for measuring stem displacement. In addition, video techniques easily allow the definition of the initial position of the tree, which is difficult to do with accelerometers or displacement transducers (Peltola, 1996). The limit of image interpretation is that the procedure is complicated and cumbersome.

Global Navigation Satellite Systems (GNSS), indicate the set of all the constellations of artificial terrestrial satellites for user navigation. GNSS technology was always

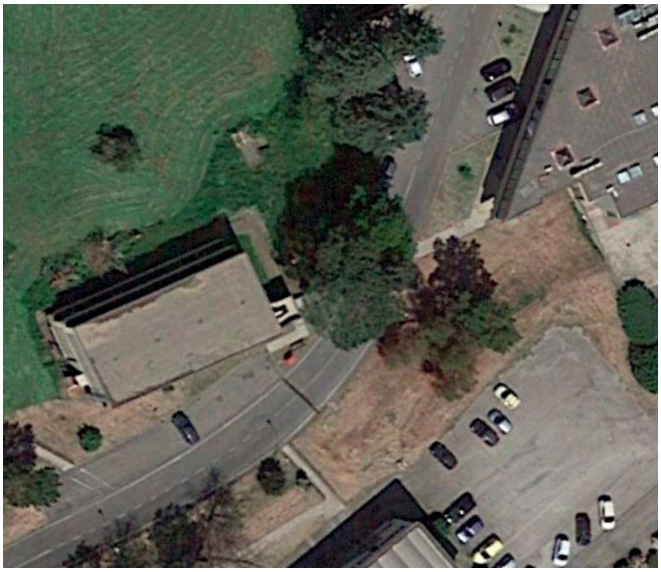

Fig. 1. Tree location.
Fig. 1. Localizzazione dell'albero.

Fig. 2. Receiver position on the tree.
Fig. 2. Posizione del ricevitore sull'albero.

used in many different applications: navigation (Branzanti et al., 2017), monitoring (Sampietro et al., 2017), seismology (Fratarcangeli et al., 2018), meteorology (Mascitelli et al., 2019; Campanelli et al., 2018), gravimetry (Capponi et al., 2018) and in each context GNSS signals are processed in order to obtain data able to integrate the information content in terms of positions, velocities and accelerations. We applied for the first time this technology to the tree motion monitoring, with the aim to investigate the applicability of GNSS receivers for detecting wind-associated tree movements.

In this study, we monitored the sway motion of the trunk of an Italian stone pine (*Pinus pinea* L.) under the wind action using, as a motion sensor, a GNSS receiver able to trace only the single frequency (Mascitelli et al., 2018). The use of the GNSS for tree monitoring could have several advantages principally because the spread application of this technology in several other monitoring contexts can assure it many improvement opportunities, but also because of competitive cost and good performances (Caldera et al., 2016).

CASE STUDY

For almost 2 months, from November 16th, 2017 to January 4th, 2018, a single-frequency GNSS receiver was used to observe the tree movements and patterns in relation to wind characteristics. These data include windy events of varying intensity and type that allow a sufficiently complete study of the impact of the wind on stone pine (*Pinus pinea L.*).

The location hosting the instrumented stone pine is the CNR-RM 1 Research Area of Montelibretti (Italy) (Figure 1). The tree is located near a building that covers part of its trunk and that could interact with its growth and consequently with its behaviour, anyway this interaction has been assessed as acceptable in view of the usefulness of this position in terms of simplifying the system's logistics. In front of the building and the tree there is a road that crosses the entire area. The other sides of the tree are substantially free and characterized by an expanse of uncultivated land Figure 1 b. The tree is about 13 meters high and has a diameter at breast height (DBH) of about 60 centimetres, the sensor is placed on trunk at a height of 11.30 m.

The period analysed (51 days) was, in general, characterized by low wind intensities. In particular, 36 days had hourly averaged wind speed less than 3 m/s for the whole day. These days were characterized by local diurnal circulation. Nine of the remaining days had hourly averaged wind speed greater than 4 m/s at least for an hour of the day. The remaining days had hourly averaged wind speed between 3 and 4 m/s for at least one hour. During the days of high wind speed (> 4 m/s, two prevalent directions were observed: Scirocco (winds coming from SE over the area) and Mistral (winds coming from NW over the area). For these days the intensity of mechanical turbulence increased.

INSTRUMENTS

Sonic Anemometer

High-frequency measurements of the three wind components were made with an ultrasonic anemometer/thermometer uSonic-3 by Metek Scientific (https://metek.de/product/usonic-3-scientific) installed at a height of ≈ 8 m, ≈ 1 m above the roof of the building, and at a distance of ≈ 15 m from the GNSS receiver. From these measurements, we computed the averaged wind speed and direction as well as the standard deviations of all wind components.

GNSS receiver

In this study we used a single frequency receiver (LOW4), an u-blox M8T Leica Geosystems, able to track multi constellation. For this study, only GPS observations were used. The antenna was located on the top of tree, connected to a receiver positioned in the adjacent building. With the collected data an analysis of tree displacements in terms of coordinates and velocities was carried out. In order to process position data, we resorted to a differential positioning method (Leick, 2004) using a geodetic receiver located about 8 kilometres from the tree (FIAN provided by Netgeo).

DATA PROCESSING

Wind Measurements

To obtain accurate information on 3-axis wind speed and direction with high temporal resolution, the ultrasonic anemometer was used at a sample frequency of 40 Hz. After averaging over every 4 points, time series of three wind components *x*, *y*, and *z* with frequency 10 Hz were archived in a data-logger CR3000 by Campbell. The spatial resolution is determined by a distance between pairs transducer/receivers of 0.20 m.

Spikes were determined and eliminated in the data processing and the percentage of spike data were recorded for later quality control. Each [*x, y, z*] vector block was indexed to find points with abnormal deviation from the mean; that is, *current value - mean value* outside the expected range. These ranges were +/- 10 ms^{-1} for wind data. The spike elimination was made by interpolating the neighbouring data. The planar fit method (Lee et al. 2004) was used to correct the data for possible errors due to the tilt of the support and a 2D-rotation in the mean wind coordinates was applied. For analysis of correlation between wind velocity and tree motion, wind components *x* (East direction) and *y* (North direction) were averaged over one second.

Another parameter, which has been considered in these analyses, is the turbulence kinetic energy (TKE). Generally, the TKE can be quantified by the mean of the turbulence normal stresses:

$$TKE = (1/2)\,(\langle u'^2\rangle + \langle v'^2\rangle + \langle w'^2\rangle),$$

where *u', v'* and *w'* are fluctuations of the longitudinal, lateral and vertical wind components.

Tree Measurements

Velocity

The analysis in term of components of tree velocity was conducted through the use of VADASE (Variometric Approach for Displacements Analysis Stand-alone Engine). The approach is based on time single-differences of carrier phase observations collected at a high-rate (1 Hz or more) using a stand-alone receiver, and on standard GPS broadcast products (orbits and clocks), which are ancillary information routinely available (Colosimo et al., 2011).

The data stream obtained by our single frequency receiver (LOW4) was managed by RTKLIB, an open source GNSS toolkit for performing standard and precise positioning (Takasu et al., 2009), to convert the observation data from UBX protocol (specific u-blox format) to RINEX (Receiver Independent Exchange Format) format. Data were processed for days in different wind conditions.

Position

Regarding the determination of the position, also in this case we used the software RTKLIB. We have processed RINEX files via RTKPOST, an RTKLIB executable. We used the differential method and set the positioning mode both static and kinematics (Leick, 2004): the first serves to obtain a reference position, whereas the second one is finalized to the study of movement. To conduct this analysis, we also needed observation data referring to a reference station that, in this case, was a receiver located about 8 kilometres from the tree, in Fiano Romano (Rome). The receiver is the FIAN station, belonging to the Netgeo network and the ancillary data needed for the processing has been

Tab. 1. Medians geocentric coordinates.
Tab. 1. Mediane delle coordinate geocentriche.

Doy	X [m]	Y [m]	Z [m]
322	4624594.959	1036919.530	4254167.129
323	4624594.963	1036919.523	4254167.137
324	4624594.962	1036919.541	4254167.148
326	4624594.967	1036919.540	4254167.154
328	4624594.971	1036919.539	4254167.159

Tab. 2. Statics value - positioning.
Tab. 2. Valutazioni statistiche sul posizionamento.

Doy	$\bar{E}$ [m]	σ_E [m]	$RMSE_E$ [m]	$\bar{N}$ [m]	σ_N [m]	$RMSE_N$ [m]
322	0.032	0.052	0.061	0.022	0.053	0.058
323	0.011	0.071	0.071	0.016	0.066	0.068
324	-0.003	0.059	0.059	0.006	0.047	0.047
326	-0.001	0.068	0.068	0.004	0.049	0.049
328	-0.005	0.059	0.059	-0.005	0.043	0.043

Tab. 3. Statics value – velocity.
Tab. 3. Valutazioni statistiche sulle velocità.

Doy	$\bar{E}$ [m/s]	σ_E [m/s]	$RMSE_E$ [m/s]	$\bar{N}$ [m/s]	σ_N [m/s]	$RMSE_N$ [m/s]
322	0.0006	0.0020	0.0020	-0.0001	0.0030	0.0030
323	0.0011	0.0020	0.0020	-0.0002	0.0030	0.0030
324	0.0005	0.0010	0.0020	0.0000	0.0020	0.0020
326	0.0007	0.0010	0.0020	0.0000	0.0020	0.0020
328	0.0005	0.0010	0.0010	0.0000	0.0020	0.0020

provided by CODE (Center for Orbit Determination in Europe). Data were processed for days in different wind conditions and the results of this processing were cut with a CE90 test (Circular Error with 90% probability) (Eq. 1)

$$CE90 = \frac{2.146}{\sqrt{2}}\sqrt{\sigma_E^2 + \sigma_N^2} \quad (1)$$

Where σ_E^2 is the squared standard deviation related to East coordinate and σ_N^2 is the squared standard deviation related to North coordinate. CE90 test was used to evaluate a threshold for removal of outliers. These data were compared with the velocity output and with data obtained from the sonic anemometer.

RESULTS

Non-Windy days

The first step concerned the analysis of some days characterized by absence of wind; the aim was to evaluate the behaviour of the system in quiet conditions. To perform the data analysis python language was applied. The days considered are all in the same week of November 2017, which goes from 18^{th} to 24^{th}, 322-328 day of year (doy). In these days, tree positions were obtained by static positioning for each epoch, and daily medians of the geocentric coordinates (X, Y and Z) were computed as well. The result is a set of coordinates for each day, which can be used as daily barycentric reference of the GNSS sensor on tree (Table 1).

It can be noted that there is a repeatability of the solution. In fact, the variation between the medians of all components in different days is very low, below the decimetres. It can be said that the solution is stable. Statistical analyses were carried out for all data relating to the tree, i.e. speed and positions, split in the two direction components (East and North); mean, mean squared deviation (σ) and RMSE (Root mean square error) were computed (Table 2 and 3).

As can be seen, the measurements have a good accuracy. As regards positions, there are differences to the order of some cm, as regards the velocities, the variations are relative to third decimal place (mm/s).

Windy days

To study the response of the tree to wind stresses we analysed days characterized by specific weather phenomena. First, we defined a wind speed limit above which a given day can be defined as windy, i.e. the hourly average wind speed must be greater than 4 m/s for at least one hour. The wind was recorded at a frequency of 10 Hz, whereas GPS works with a frequency of 1 Hz. In order to have comparable data, we averaged every 10 sonic values to obtain one record per second. In the months of the study campaign, we selected three days when the hourly average wind speed was > 4 m/s: 26^{th} November (Day of year 330), 12^{th} December (Day of year 346), 17^{th} December (Day of year 351).

November 26th, from this point of view, is very interesting because there is a change in the wind direction around mid-day, so the wind in the morning blows to North-West and in the afternoon to South-East (as can be seen in the upper left panel in Fig. 3). The other two days instead are characterized by winds having a prevailing direction that characterizes the entire

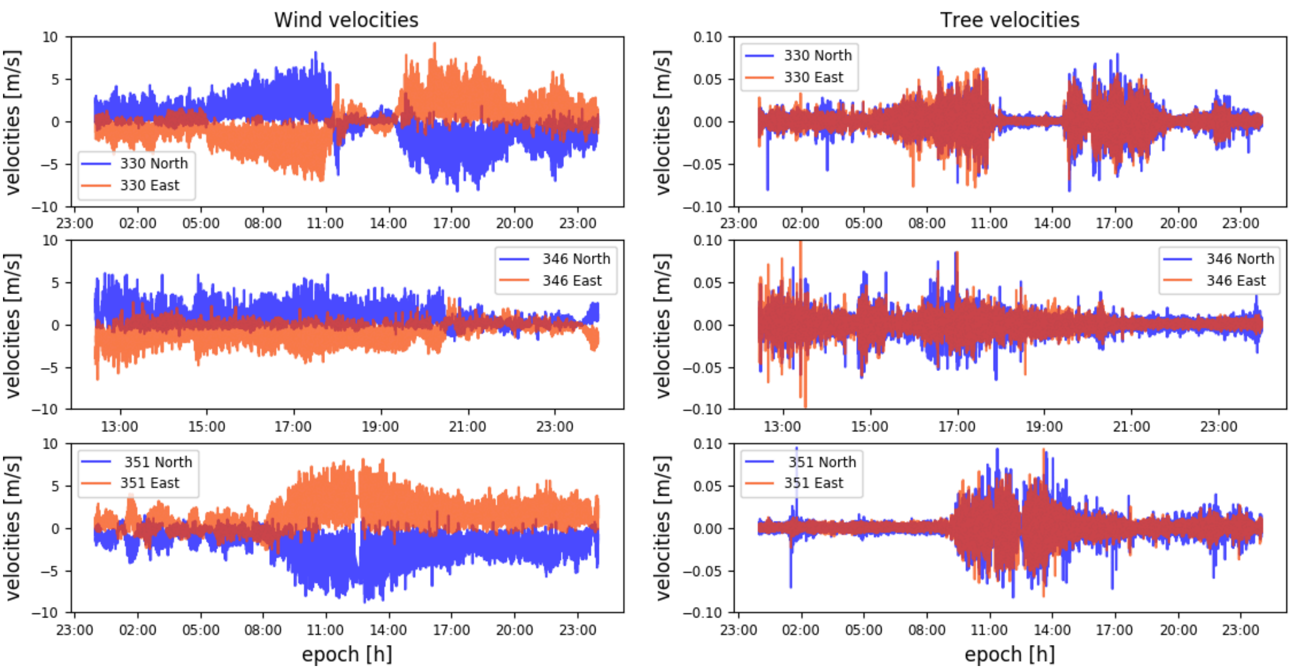

Fig. 3. Comparison between sonic anemometer data and GPS device data for 26th November (upper panels), 12th December (middle panels) and 17th December (lower panels).
Fig. 3. Confronto tra i dati da anemometro sonico e i dati da GPS per i giorni 26 Novembre (pannello in alto), 12 Dicembre (pannello centrale) e 17 Dicembre (pannello in basso).

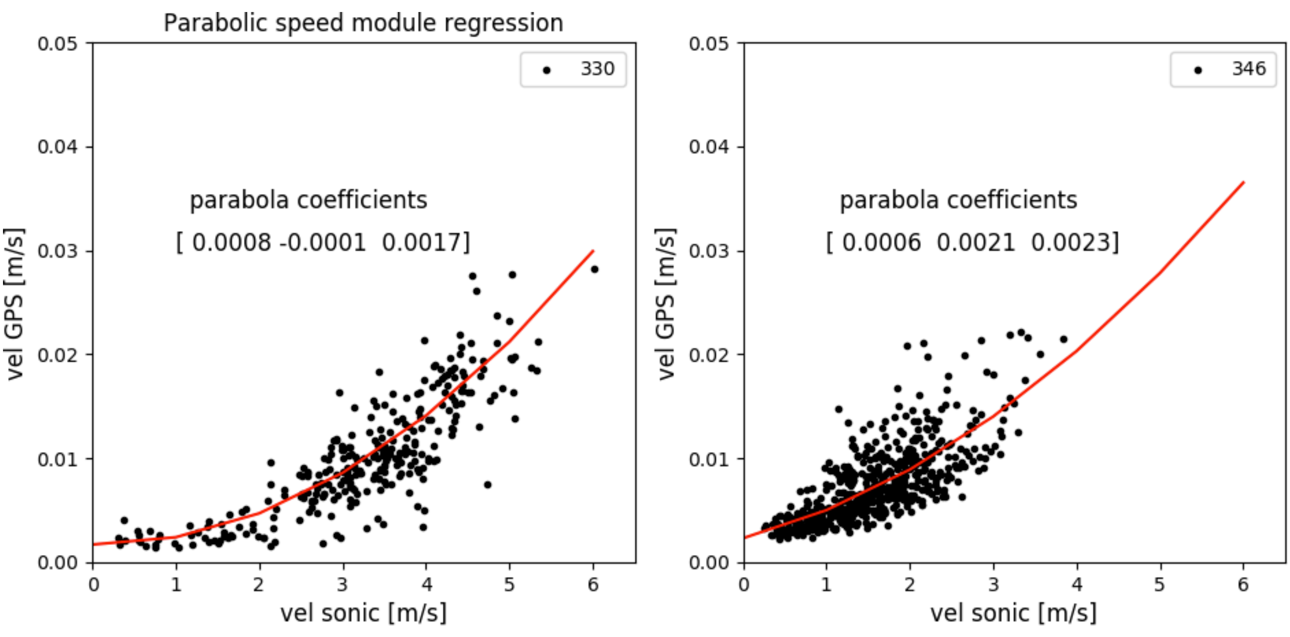

Fig. 4. Parabolic correlation between velocities averaged every 60 seconds – 26th November morning (doy: 330) and 12th December (doy: 346).
Fig. 4. Correlazione parabolica tra velocità mediate ogni 60 secondi - 26 Novembre mattina (doy: 330) e 12 Dicembre (doy: 346).

day. Particularly on December 12th, the wind blows to North-West (Scirocco, as in the morning of the 26th), instead, during the 17th goes to South-East (Mistral, as in the afternoon of the 26th).

Trends of velocities registered by sonic anemometer and by GPS device are coherent (Fig. 3), confirming that the receiver located on the trunk is effectively able to register the tree response to the wind. Sonic anemom-

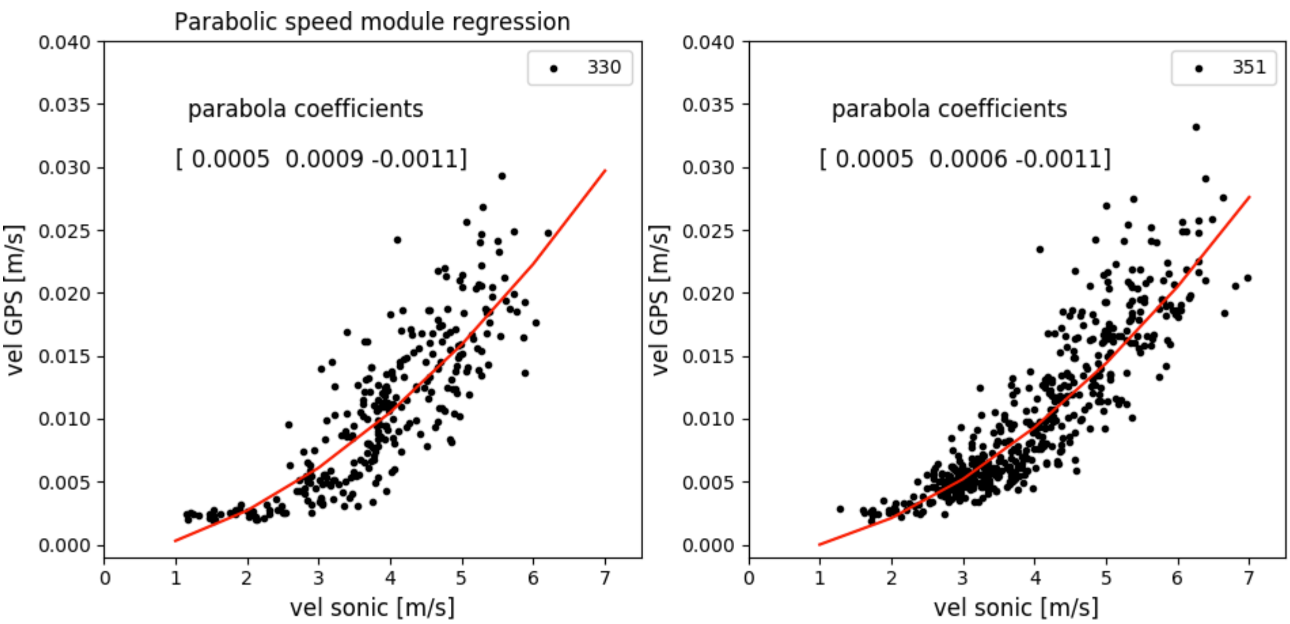

Fig. 5. Parabolic correlation between velocities averaged every 60 seconds – 26th November afternoon (doy: 330) and 17th December (doy: 351).
Fig. 5. Correlazione parabolica tra velocità mediate ogni 60 secondi - 26 Novembre pomeriggio (doy: 330) e 17 Dicembre (doy: 351).

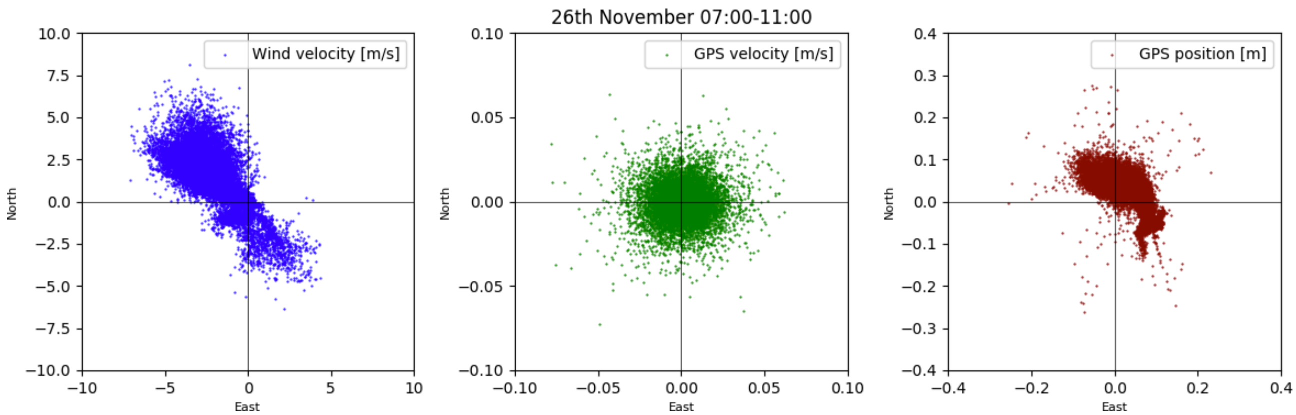

Fig. 6 Example of components comparison for days characterized by north-west wind.
Fig. 6. Esempio di confronto tra componenti per i giorni caratterizzati da vento di nord-ovest.

eter clearly discerns the two directional components, whereas the GPS located on the tree reveals an oscillating motion (Gardiner et al., 2016; De Langre, 2008) that causes the almost completely overlapping of the two components.

As can be deduced from the previous graphs, it is possible to analyse separately the windy event characterising the morning of 26th November and the one characterising the afternoon. It is also evident the similarity in directional terms of the two events, belonging to the same day, with those highlighted in the following dates, respectively 12th and 17th December.

To analyse the relation between the two velocities (the wind speed registered by the anemometer and the tree swaying speed registered by the GPS), a scatterplot of the speed modules, averaged every 60 seconds, was made obtaining a parabolic correlation. The comparison carried out between different events highlights the similarity of system response to similar stresses, i.e. parabola coefficients (Figure 4 and Figure 5).

Figure 6 shows plans of components (wind velocity, tree velocity and tree positions) for the wind event on the morning of 26th November. There is an excellent coherence as regards the response recorded by the sen-

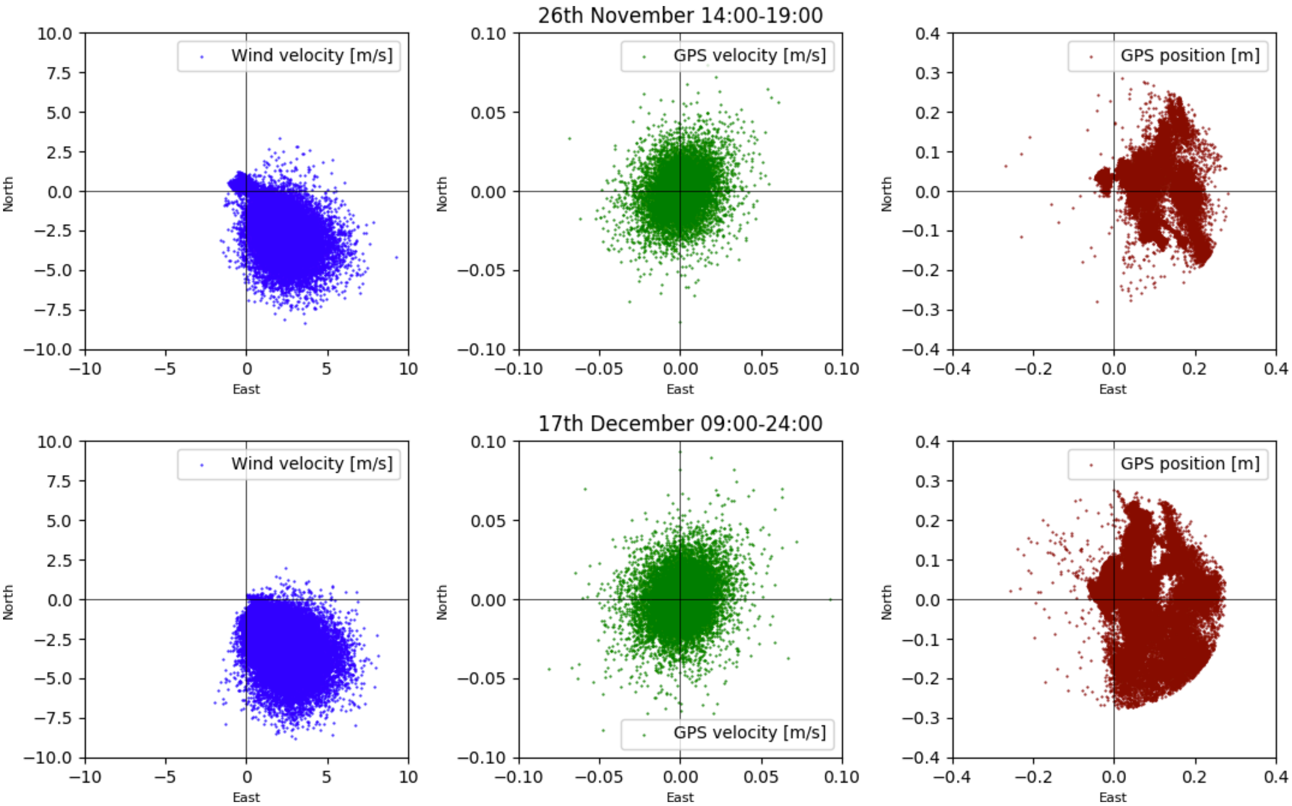

Fig. 7. Example of components comparison for days characterized with south-east wind.
Fig. 7. Esempio di confronto tra componenti per i giorni caratterizzati da vento di sud-est.

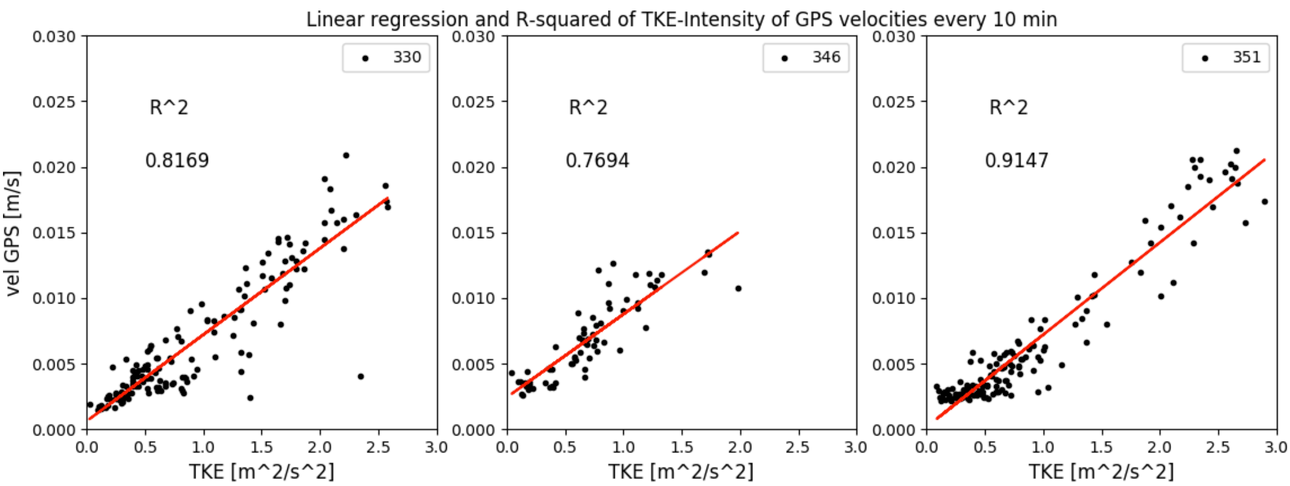

Fig. 8. Scatterplot of TKE and velocity registered by GPS receiver.
Fig. 8. Scatterplot di TKE e velocità registrate dal ricevitore GPS.

sor on the tree also on positions, in fact, it moves in the direction in accordance with the wind (third graph on the right, Fig. 6).

To evaluate constant reaction of tree to similar stresses we performed a comparison analysis, in velocities and positions, between wind events having the same direction. Planimetric graphs in Figure 7 were made to better understand the relation between quantities and depict the results.

In Figure 7 two events characterized by Mistral wind, respectively 26th November afternoon and 17th December, were considered. In the left panels of Figure 7 are reported the wind speeds related to the wind intense events; as shown these two cases are similar in terms of direction and they have also the same intensity. In the middle panels of Figure 7 are reported the tree velocities registered by the GPS device, which clearly illustrate the range of the speed values of the system when we refer to comparable events; whereas in the right panels of figure 7, the positions are shown.

By this picture it is possible to notice that tree reacts univocally to similar wind stresses both in terms of velocity and position. It is also interesting to note that, in both the above figures (Fig. 6 and Fig. 7), the positions taken by the sensor have a shifted barycentre with respect to the rest position of the tree. This behaviour is in line with what can be observed in relation to the oscillations of tree individuals.

The turbulence kinetic energy (TKE) is strictly correlated, in a linear way, with GPS velocity in all the three days (i.e. 26th November, 12th December and 17th December) (Fig. 8).

DISCUSSION

The study was conducted on days that were not windy and on days that were characterized by winds with speeds greater than 4 m/s (value based on Beaufort wind force scale). As far as non-windy days are concerned, statistical analyses have been carried out to understand the accuracy of measurements and their relative errors, which are some cm for positions and some mm/s for speeds. So from these analyses, it can be said that accuracy is good and error is acceptable. This condition has been achieved also because of an accurate positioning of the sensor on the upper part of the tree, which has minimised the impact of multipath and cycle slip (Leick, 2004). The solution robustness was confirmed by the repeatability of daily medians of geocentric coordinates (Table 1). During windy days absolute values of tree and wind speeds, averaged every 60 seconds, have been put in relation and a parabolic correlation has been observed, therefore as wind speed increases tree starts to move increasing its speed. Another interesting point to consider is the scale factor between the two measures; this is caused by the fact that the forcing wind is setting in motion a body that is far from the concept of ideal rigid body.

Observing the positions recorded by GNSS sensor it can be seen that tree moves coherently with wind direction and that the tree has chartered patterns of movement coherent with those observed by trees studied by other technologies (Hassinen et al., 1998; Mayer, 1985; Mayer, 1987; Mayer, 1989; Amtmann, 1986). In addition, it has been noted, through comparisons between different days, that tree has a constant response to events of similar wind (Fig. 7); a confirmation in this way is provided by parabolic coefficients, indeed for days with comparable winds they are very close to each other. Different comparisons have also been made with turbulent kinetic energy (TKE) which, coherently with results previously obtained, has an excellent linear correlation with tree speed (Fig. 8).

CONCLUSION AND FUTURE RESEARCH

Increasing the intensity and frequency of extreme weather events exposes trees more than ever to conditions that could compromise their stability. This leads to serious risk for people, objects, structures and infrastructures, especially in urban settings where the fall of a tree is more likely to have serious consequences. However, by studying the effects of wind on arboreal individuals, it is possible to understand, and then eventually monitor the extent of the risk of falling in order to provide reliable alerts.

The preliminary study shown in this paper focuses on a tree belonging to the species Pinus Pinea L., located in the CNR-RM1 research area of Montelibretti (Italy). It was decided to study this specific species because it is very common in cities, where the instability of trees can cause more damage. The aim of this study is to test the applicability of GNSS receivers for monitoring wind-associated tree movements, so in order to study the movements of the tree, a single-frequency GNSS sensor has been placed at the top of the trunk and wind speed was recorded by a sonic anemometer located about 20 m from the tree. This study evidenced that accuracy of measurements and their relative errors are enough for the purposes of the measurements made. Statistic outputs evaluation provided very promising results, showing the capability of this instrumental solution in the analysis of movement patterns.

Future investigations will focus on automating the system and further tests will be carried out on different tree species (monocormic and polycormic trees) to assess their behaviour in response to intense weather events. This instrument will be very useful in order to evaluate the criteria that have been applied up to this point and to attempt an implementation in view of an early warning system.

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