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Wind field parameters determination in the lower layer of the atmosphere based on remote sensing measurements

Wyznaczanie parametrów pola wiatru w dolnej warstwie atmosfery na podstawie pomiarów teledetekcyjnych

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Key words: meteorological radar, Doppler phenomenon, components of wind vector, upper air sounding

Abstract

Safety of various human activities depends to a significant extent on weather conditions which are the result of physical processes in the lower layer of the atmosphere. In numerous cases, the wind field information is required in the form of vector field. Complete description of the wind field is not feasible using only the results of standard direct wind measurements even if they are made in a fairly dense measurement network.

The paper presents remote sensing measurement systems which provide data for determining the horizontal and vertical components of the wind vector at variety of levels in real time. The remote sensing methods of wind measurements use the Doppler phenomenon, i.e. the relation between the meteorological object movement velocity and the difference in frequency of the original signal and the backscattered one. Results obtained using data from meteorological Doppler radars, including the E700XD mobile radars in Polish Air Bases and radiotheodolite sounding systems are presented.

The processed results of measurements are presented in the form of the wind vector fields at selected levels, profiles of the vertical component of the wind vector in a defined layer of the atmosphere and vertical profiles of the wind speed changes.

Słowa kluczowe: radar meteorologiczny, zjawisko Dopplera, składowe wektora wiatru, sondaż aerologiczny

Abstrakt

Bezpieczeństwo różnych form działalności ludzkiej w znacznej części zależne jest od warunków atmosferycznych, które są wynikiem procesów fizycznych przebiegających w dolnej warstwie atmosfery. W wielu przypadkach niezbędna jest wiedza o polu wiatru przedstawianym jako pole wektorowe. Pełnego opisu pola wiatru nie można dokonać na podstawie tylko wyników standardowych bezpośrednich pomiarów wiatru, nawet wtedy, gdy wykonywane są w dość gęstej sieci pomiarowej.

W pracy przedstawiono teledetekcyjne systemy pomiarowe, które w czasie rzeczywistym dostarczają danych do wyznaczenia składowych horyzontalnych i pionowych wektora wiatru na różnych poziomach. Metody teledetekcyjnego pomiaru wiatru wykorzystują zjawisko Dopplera, tzn. zależność różnicy pomiędzy częstotliwością echosygnału rozproszonego przez obiekt meteorologiczny a częstotliwością emitowanego impulsu od prędkości ruchu obiektu. Przedstawiono wyniki uzyskane na podstawie danych z dopplerowskich radarów meteorologicznych, w tym mobilnego radaru E700XD działającego w polskich bazach lotniczych oraz z radioteodolitowego systemu sondażowego.

Opracowane wyniki pomiarów przedstawiane są w postaci pól wektora wiatru na wybranym poziomie, rozkładu pionowych składowych wektora wiatru w zdefiniowanej warstwie atmosfery oraz pionowych profili zmian prędkości wiatru.

Introduction

The Earth atmosphere is a non-linear dynamic environment full of local centers of thermodynamic instabilities which means that it continuously changes in time and space. Knowing the spatial and temporal structure of the measurable meteorological parameters enables to determine their fields for any horizontal and vertical cross-sections of the atmosphere.

Wind is the air particles movement caused by numerous factors. In meteorology the term wind is considered for a wide class of horizontal and vertical air movements which occur both in the boundary layer and in upper atmosphere. The air particles movement, like in other fluids, is subject to the hydrodynamic rules. It is laminar, i.e. air particles move along straight lines parallel to the stream direction only up to a certain value of the movement velocity. It is adopted that the movement becomes turbulent with dynamic mixing of air particles when the stream speed exceeds 4 ms^{-1}. Turbulent movement of air particles causes wind gusts, i.e. sudden short changes of wind speed and direction.

In the lower part of the atmosphere, especially in the boundary layer, the ground surface impact on air particles movement is significant. Results of measurement experiments indicate a firm diurnal cycle of turbulent processes. At day, heated ground surface intensifies vertical mixing of air. At night, when the energy flux to convective movements is stopped, the boundary layer is characteristically and distinctly layered.

The complexity of air particles movement requires measuring the horizontal and vertical components of the wind vector at selected levels for complete description of the wind field. Standard direct wind measurements made at the height of 10 m above ground are a source of reliable wind data only for a limited area at the measurement site. These direct measurement results are considered to be representative for areas which sizes are determined using certain adopted assumptions. However, in majority of cases, even for a dense measurement network, the area size cannot be objectively and unambiguously determined.

Making measurements in real time for vast areas requires remote sensing methods which have some limitations related with the applied technology and conditions of radiation or sound propagation in the atmosphere. Remote sensing results interpretation requires comprehensive knowledge concerning the character and impact of the limitations. This inconvenience is fully compensated by high frequency or even continuous measurements.

Wind field data, apart from direct application to support of miscellaneous forms of human activities, constitute input data for numerical models providing among others specialized weather forecasts, including sea surface state and wave.

Methods of remote sensing of wind field

Wind field parameters are measured by means of remote sensing methods using Doppler radars (RAdio Detection And Ranging), sodars (SOund Detection And Ranging) and lidars (LIght Detection And Ranging). The change of the received signal frequency (echo) with respect to the emitted signal frequency (electromagnetic or acoustic wave) depends on the scale of movement of areas of cloud particles or heterogeneity caused by wind.

For mono-static sounding (the measurement device's transmitter and receiver are in the same place), the Doppler frequency shift is proportional to the radial component of wind velocity, i.e. to the component along the antenna beam.

Determining the horizontal and vertical components of wind vector in a defined layer of atmosphere requires a series of the radial component measurements for various angles of the antenna beam elevation.

In geographically oriented systems the horizontal components of the wind vector yield data for determining the meteorological wind direction, i.e. the direction from which the wind blows [1, 2].

Investigating wind field by means of meteorological Doppler radars

Measurements made by means of meteorological radars are based on the effects of electromagnetic radiation interaction with atmosphere and meteorological objects (clouds and hydrometeors) which are spatial targets composed of water droplets and/or ice crystals of diameters from a few to several micrometers and of the concentration of the order of a million per 1 dm^3. The power of the signal received at the radar receiver is the sum of powers of signals reflected by the components of the object. The receiver system of classic meteorological radar records so called radiolocation reflectivity of the object which value depends on the spectrum of particles of the object (e.g. a cloud) and their concentration.

In atmospheric research by means of radiolocation, electromagnetic radiation from the range of 1 GHz through 30 GHz is used. The range is divided in a few bands recommended for specific measurements (Table 1) [3].

Table 1. Frequency ranges of electromagnetic radiation used in meteorological radars
Tabela 1. Pasma częstotliwości fal elektromagnetycznych stosowanych w radarach meteorologicznych

Band symbol	Frequency range [GHz]	Wave length [cm]	Application
K	18 ÷ 27	1.11 ÷ 1.67	Research of clouds without precipitation
X	8 ÷ 12	2.50 ÷ 3.75	Short range observations and polar regions observations
C	4 ÷ 8	3.75 ÷ 7.50	Long range observations in mid latitudes climates
S	2 ÷ 4	7.5 ÷ 15	Long range observations in tropics and hazardous weather phenomena observations
L	1 ÷ 2	15 ÷ 30	Weather channel in air traffic control radars

The national meteorological support system includes two independent meteorological radar systems: the POLRAD system managed by the Institute of Meteorology and Water Management and the system of E700XD mobile radars installed at military airbases and developed since autumn 2011. The location of the radars and their technical capabilities enable in practice observation over the entire territory of Poland and the South Baltic Sea. The radars in both systems are equipped with Doppler channel for wind field measurements (Table 2). The Doppler channel provides results of the radial wind component measurements and the width of the spectrum of the measured velocities [3, 4, 5].

Table 2. Basic technical data of radars in the systems of meteorological support for Poland [3, 5]
Tabela 2. Podstawowe dane techniczne radarów pracujących w systemach meteorologicznej osłony obszaru Polski [3, 5]

Radar parameter	Unit	POLRAD system radars	E700XD radars
Frequency band		C	X
Operation frequency	GHz	5.65	9.345 (user tunable within ±20 MHz range)
Emitted pulse duration (pulse width)	μs	3.3; 0.4	1; 10; 40; 70
Repetition frequency	Hz	1200/900	50 ÷ 2500
Doppler channel range	km	125	100
Antenna horizontal rotation time	s	20	18
Antenna beam width at the half power level	deg	1	3.6

The velocity spectrum width is defined for the spectrum of velocities measured during one radar session. Each radar scan (measurement results obtained for one rotation of the antenna at a constant angle of elevation) includes data concerning approaching or departing water droplets, ice crystals or hail, and each of these moves with its own speed and in its own direction. If the atmosphere is turbulent then each particle may move with velocity differing to some extent from other particles. The radial component is an average of all these velocities while the spectrum width is a measure of the values, the velocities differ from one another. The velocity spectrum width is proportional to turbulence intensity and wind speed.

Fig. 1. E700XD Mobile Doppler radar antenna [4]
Rys. 1. Antena mobilnego radaru dopplerowskiego E700XD [4]

Proper interpretation of wind measurements by means of radars requires quantitative analysis of limitations of the remote sensing method based on the radar technical parameters. During initial atmospheric research using the E700XD radar, the following parameters were analyzed: the scanned volume of the atmosphere, the defined “radar silence zone”, the volume of the atmosphere to which the measurement results are assigned, the sounding pulses repetition frequency and the received signal sampling frequency.

For assumed standard atmospheric refraction of the electromagnetic radiation, the so called “effective Earth radius” used in radiolocation has the value of $R_e \approx 8493$ km [3]. For these conditions, the volume of the atmosphere scanned by radar may be defined according to figure 2. It indicates also the volume below the “radar horizon” from which no radar data is acquired, either in the Doppler, or the classic channels.

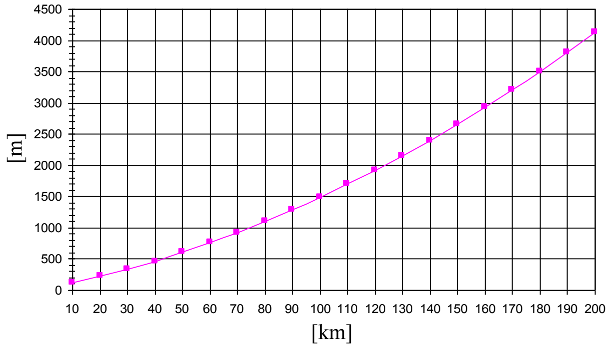

Fig. 2. Minimum altitudes at the radar beam elevation angle of 0.5° at which the radar may detect a meteorological object as a function of distance from the radar

Rys. 2. Minimalne wysokości, od jakich radar może wykryć obiekt meteorologiczny w funkcji odległości od radaru, przy kącie elewacji osi wiązki antenowej 0,5°

The E700XD radar provides a selection of the sounding pulse time lengths which enables to control the radar sensitivity. In case of meteorological radars, this feature defines the capability to detect various phenomena (atmospheric precipitation, cloud type etc.). Since this is a mono-static mode radar, its receiver circuitry is closed for the time of emitting the sounding pulse which means that no data are received. The volume around the radar from where no data are received is called "radar silence zone" and its radius depends on the sounding pulse time length. For example, for a pulse of time length of $\tau = 1$ µs, the radius of the "radar silence zone" is $R_{ms} \approx 150$ m, for $\tau = 40$ µs – $R_{ms} \approx 6$ km, and for $\tau = 70$ µs – $R_{ms} \approx 11$ km.

The volume of the atmosphere to which the measurement result is assigned has dimensions and shape dependent on the technical parameters of the radar. It is assumed that the volume from which the signal is received at any specific moment is a cylinder (or more precisely frustum of cone) limited by the external surface of the antenna beam. The height of the cylinder depends on the sounding pulse width and its diameter – on the distance from radar and on the antenna beam width. For example, for the E700XD radar for the sounding pulse time length $\tau = 1$ µs the cylinder height is about 150 m and its diameter increases with the distance from the radar: for 10 km it is about 600 m, for 50 km – about 3.2 km, and for 100 km – about 6.3 km.

Selection of pulse repetition frequency which impacts the radar maximum range and accuracy of the measured wind velocity is important for research conducted by means of the E700XD radar. For smaller values of the pulse repetition frequency, the detection range is greater but the accuracy of the wind velocity values is lower. For higher values of the pulse repetition frequency the accuracy is higher but the range is smaller.

Selection of the analyzed sample width is important for frequency analysis of the received signal. The E700XD radar data processing system enables selection of 8 values from the range of 125 m through 1000 m with 125 m increments [5].

The influence of the analyzed sample width for a defined sounding pulse time length on the resolution and accuracy of the wind velocity measurement results requires further investigation.

Wind products in Doppler channel radar data processing systems

Radar data acquired from subsequent scans of the atmosphere, so called Doppler scans, at different antenna beam elevation angles are processed by the radar information systems. Products of the systems are graphical presentations of wind field in the form of maps, diagrams and cross-sections of the atmosphere tailored to the requirements of the users. For specific wind products, appropriate color palettes were defined to which the values of radar measurements and computation results were assigned.

Wind products available for users include data used for meteorological support of aviation, sea navigation, natural disaster and catastrophes recovery operations and other human activities. The set of products includes the following imagery [6]:

- conical cross-sections of the distribution of the radial velocity and the radial velocity spectrum width;
- distribution of the radial velocity and the radial velocity spectrum width at constant altitudes;
- distribution of the maximum radial velocity and the radial velocity spectrum width;
- distribution of the radial velocity and the radial velocity spectrum width at cross-sections along selected routes (Fig. 3);
- wind vertical profile;
- horizontal wind as an image of horizontal wind vectors at constant altitudes at nodes of a regular grid described by longitude and latitude values (Fig. 4);
- radial wind velocity as a function of azimuth for a defined elevation angle within a defined range of distance along the radar beam;
- wind shear products presented as gradients of the radial velocity for a defined elevation angle;
- horizontal gradient of wind velocity as an image of the radial velocity change in a horizontal plane in a located meteorological object at a defined altitude taking the Earth curvature into consideration;

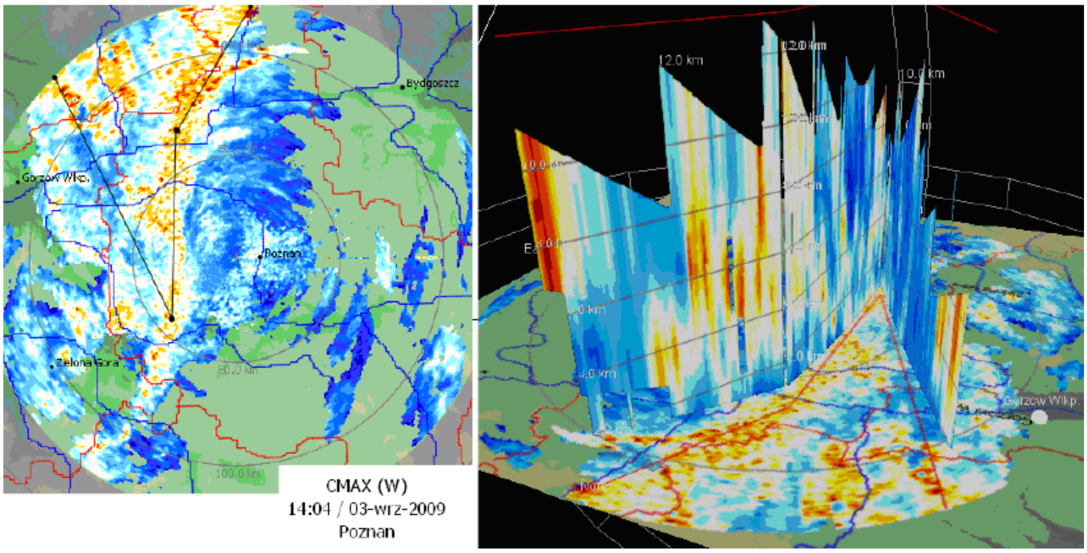

Fig. 3. Vertical profile of radial velocities along a defined route (polyline) in a meteorological object [6]
Rys. 3. Pionowy rozkład prędkości radialnych wzdłuż określonej trasy (linia łamana) w obiekcie meteorologicznym [6]

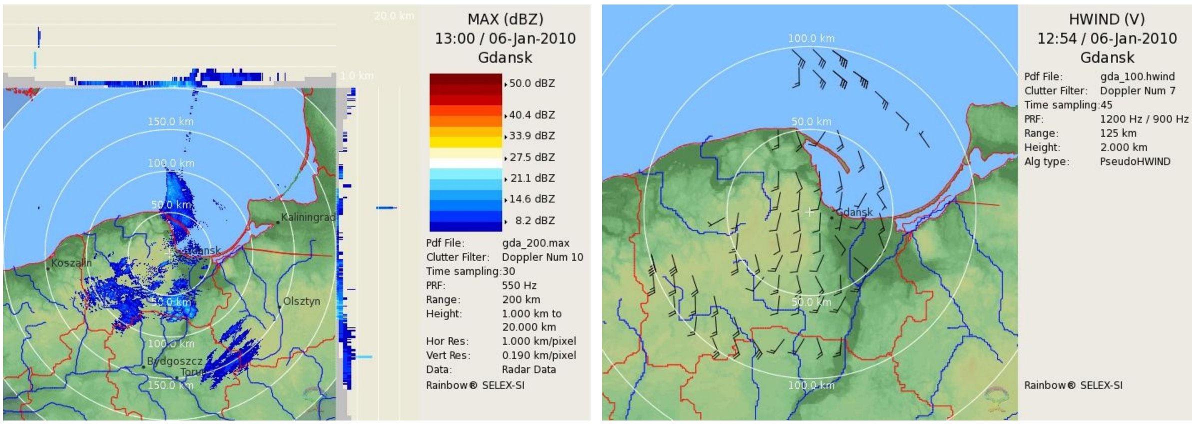

Fig. 4. Maximum reflectivity of meteorological objects (left). Horizontal wind at 2 km altitude in grid nodes (right) [7]
Rys. 4. Odbiciowość maksymalna od obiektów meteorologicznych (po lewej). Wiatr horyzontalny na wysokości 2 km w punktach regularnej siatki (po prawej) [7]

- vertical wind gradient (wind shear) as an image of the radial velocity change between two firmly indicated layers of the atmosphere;
- turbulence as an image of velocity change between two indicated layers of the atmosphere.

Wind field investigation using upper air sounding results

BAR mobile upper air sounding system composed of Vaisala RT20A radiotheodolite and Aviomet AGAT20A surface weather station was used for wind field investigation. The system configuration enables autonomous (independent of external radio-navigation and power supply systems) sounding of the troposphere and lower stratosphere (up to the altitude of 30 km) providing measurements at every 1.5 s in 10 m thick layers of the atmosphere.

The system uses Vaisala 1680 MHz RS92-DD digital radiosondes designed for RT20A radiotheodolites. The radiosondes are suspended under latex or synthetic meteorological balloons inflated with helium or hydrogen. Sensors onboard the radiosondes measure: air temperature with 0.2°C accuracy in the range of $-90 \div +60$°C, relative humidity with 2% accuracy in the range of $0 \div 100$% and atmospheric pressure with 0.5 hPa accuracy in the range of $1080 \div 3$ hPa.

Wind speed and direction are computed using the movement vector of the radiosonde between consecutive measurement instances. Radiosonde location at any moment is determined by the radiotheodolite system which continuously observes the moving radiosonde using its 4-panel antenna system (Fig. 5). Wind is measured with 0.15 ms^{-1} accuracy for speed and with 2° accuracy for direction.

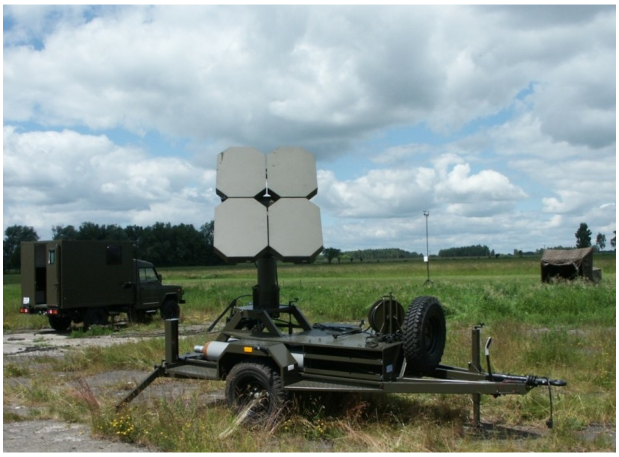

Fig. 5. BAR upper air sounding system at measurement site. The RT20A radiotheodolite antenna at foreground, AGAT20A surface weather station and system operator shelter in the background

Rys. 5. System sondażowy BAR podczas pomiarów. Na pierwszym planie antena radioteodolitu RT20A, w głębi stacja pomiarów AGAT20A oraz stanowisko operatora systemu

Vaisala DigiCORA III and Aviomet MetNet information systems are used for the measurements results processing in the BAR upper air sounding system. The products of these systems include data concerning over thirty parameters characterizing the state and properties of the atmosphere along the track of the radiosonde carried by the meteorological balloon. The processed measurement results are available in the form of matrices including meteorological data for further specialized processing and in the form of coded messages used in meteorological support of military operations (NATO standard messages) and in the national meteorological support (the World Meteorological Organization standard messages and the International Civil Aviation Organization standard messages).

Data concerning vertical profile of wind speed and direction and horizontal components of the wind vector (Fig. 6) were used to investigate the structure of the wind field in the sounded layer of the atmosphere. Special filtering procedures smoothing the recorded data concerning the radiosonde location were applied for wind data processing. The filtration is necessary because the radiosonde is suspended under the balloon on a 30 m long suspension strand to prevent the balloon from having impact on the results of air temperature and humidity measurements. This causes that the radiosonde location at any moment is subject to the balloon free ascent, its drift with the wind and radiosonde movement caused by the inertial force. The measurement results are assigned to appropriate locations in the atmosphere using the track of the radiosonde (Fig. 7).

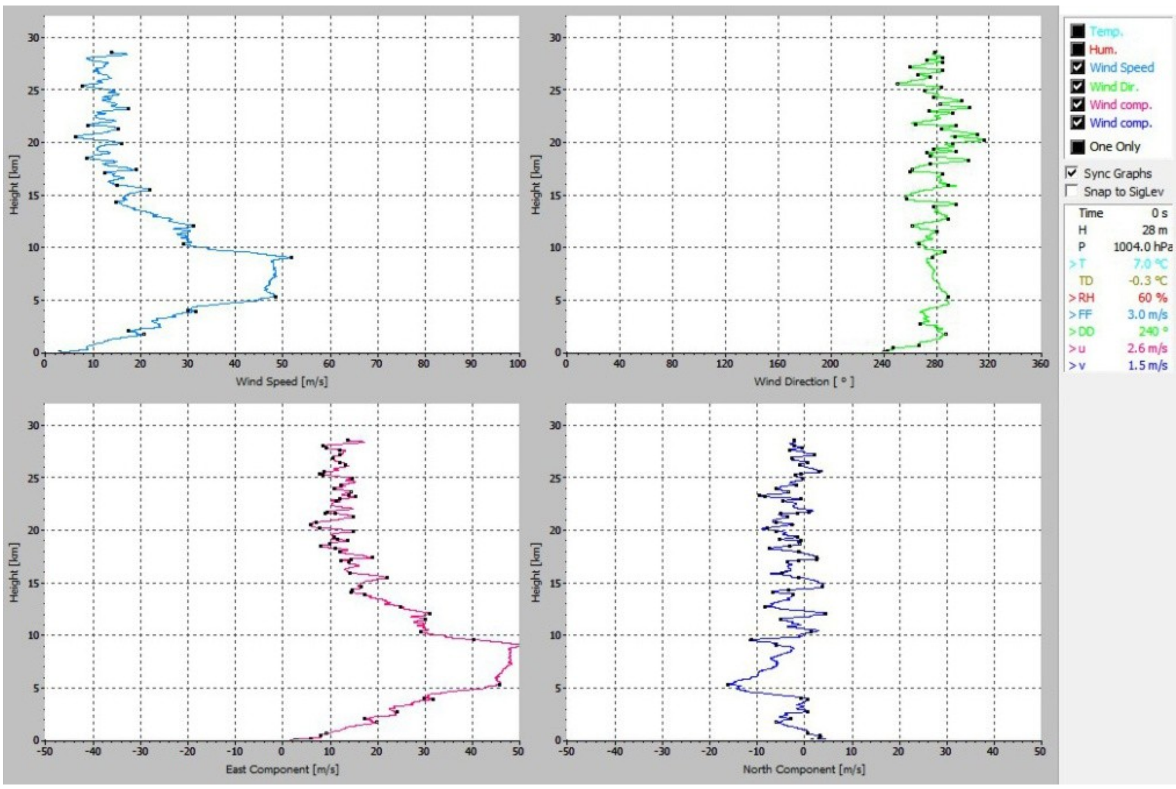

Fig. 6. Vertical profiles of wind speed and direction, and horizontal components (East and North) of the wind vector acquired during an upper air sounding

Rys. 6. Pionowe profile prędkości i kierunku wiatru oraz składowych horyzontalnych (wschodniej i północnej) wektora wiatru otrzymane w czasie sondażu aerologicznego atmosfery

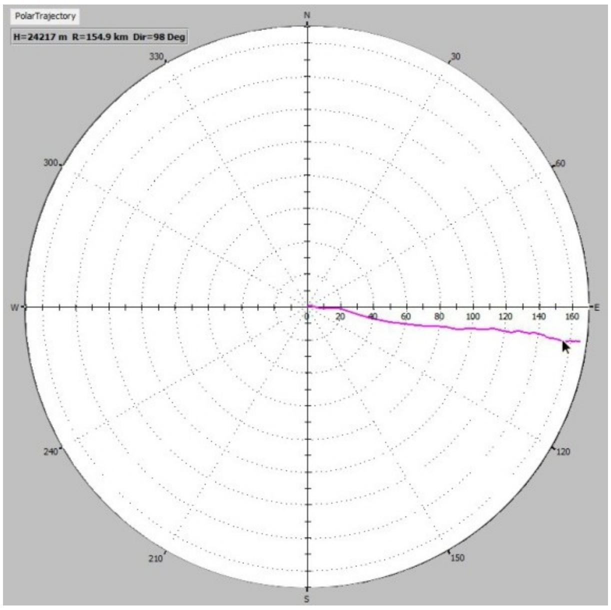

Fig. 7. Track of radiosonde during an upper air sounding
Rys. 7. Zapis toru lotu balonu z sondą w czasie sondażu aerologicznego atmosfery

Conclusions

Remote sensing systems are reliable sources of information about the state of the atmosphere. The information is acquired with high frequency from a fairly vast area which is of special importance for regions with thin network of direct measurements. Modern technologies in the systems enable both full automation of standard remote sensing measurements, and application of adjustable measurement scenarios appropriately to the scope of atmospheric research.

Data processing procedures play an important role in the radiolocation systems for atmospheric research. Only basic products, e.g. conical cross-sections of the distribution of the radial velocity and the radial velocity spectrum width, are prepared using exclusively the measurement results. Other products are prepared using computational procedures which utilize relations, mainly empirical, describing atmospheric processes. The accuracy of the computed results depends significantly on taking into account the impact of environmental conditions on the processes. In case of the E700XD radars introduced to the military hydro-meteorological service, it is necessary to verify the products generated by the WeatherScout® information system over a long multi-season period of time.

Wind field measurements in the boundary layer of the atmosphere by means of the meteorological Doppler radar have limitations related with electromagnetic radiation refraction and the sounding pulse width which for the mono-static sounding geometry defines the range of the “radar silence zone”. The depth of the atmospheric layer from which no wind data may be acquired increases with increasing distance from the radar and the antenna beam elevation angle.

Measurement results from upper air soundings significantly fill the lack of wind data in the boundary layer of the atmosphere. However, these measurements results concern a few or several meters thick layers of air at a defined location. Approximately, it may be assumed that in comparison with the radar measurements these are point source measurements.

Defining the area of the atmosphere for which the measurements are representative is important from the point of view of interpretation of wind field and other meteorological parameters measurements by means of upper air sounding. Usually, there are no unambiguous and objective prerequisites concerning indication of such areas. In numerous cases, especially in the boundary layer of the atmosphere, the variability of the parameters is considerable and the question of the measurements representativeness is practically unresolved.

In authors’ opinion, it is legitimate taking effort to create an upper air sounding network and develop a system for the measurement data processing. Computational procedures concerning the properties of non-linear media should be applied for interpolation and extrapolation of the measurement results. It would result in the capability to monitor local changes of meteorological parameters at any altitude or pressure levels. The proposed project would use a meso-scale computational grid with 2 ÷ 3 km resolution in the horizontal plane and not more than 100 m in the vertical one.

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