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INTEGRATED PROFILING SYSTEMS AND OTHER UPPER-AIR MEASUREMENT TECHNIQUES

Operational aspects of different ground-based remote sensing observing techniques for vertical profiling of temperature, wind, humidity and cloud structure

(Submitted by E.N. Kadygrov, Russian Federation)

Summary and purpose of document

This document provides a concise overview of various techniques for ground-based remote sensing of the atmosphere on the basis of different spectral range: optical (lidar), acoustic (sodar), radio + acoustic (RASS), radiowave (microwave profilers). It briefly reviews their performance characteristics and contains a report on the status of their applications for operational and research purpose. It also provides an assessment of their advantages and limitations for operational use.

Action proposed

The meeting is invited to take information provided in the document in discussing Integrated profiling systems.

WORLD METEOROLOGICAL ORGANIZATION

INSTRUMENTS AND OBSERVING METHODS

Report No

OPERATIONAL ASPECTS OF DIFFERENT GROUND-BASED REMOTE SENSING OBSERVING TECHNIQUES FOR VERTICAL PROFILING OF TEMPERATURE, WIND, HUMIDITY AND CLOUD STRUCTURE: A REVIEW

by

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DRAFT

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FOREWORD

This review was prepared for the session 6 (Integrated Profiling systems and other upper-air measurement techniques) of the WMO expert team (ET) meeting on remote sensing upper-air technology and techniques (Geneva, Switzerland, 14-17 March 2005). Review to covers the operational aspects of different ground-based observing techniques, such as lidar, sodar, RASS, microwave radiometer, that can provide remote sensing of vertical profiles of temperature, humidity and cloud structure.

The report, prepared by Dr E.N. Kadygrov (Central Aerological Observatory, Head of Microwave Remote Sensing Laboratory, Russia), a member of ET, provides a concise overview of various techniques for ground-based remote sensing of the atmosphere on the basis of different spectral range: optical (lidar), acoustic (sodar), radio + acoustic (RASS), radiowave (microwave profilers). It briefly reviews their performance characteristics and contains a report on the status of their applications for operational and research purpose. It also provides an assessment of their advantages and limitations for operational use. In the Annex of report there are very useful information about commercially available ground-based measurement systems: sodar, RASS, lidar, microwave radiometers. The great number of reference will be very useful for those experts who would like more detailed information on specific techniques.

The information contained in this publication will assist specialists from meteorological community in their decision on modernization of present meteorological systems and may help in selecting of modern remote sensing equipment. It will be also useful for ET members for selection of projects for integration of profiling systems and other upper-air measurement techniques.

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remote sensing upper-air
technology and techniques

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1. INTRODUCTION

Remote sensing is the observation and measurement of "objects" from a distance, i.e. instruments are not in direct contact with "objects" under investigation. Remote sensing depends upon measuring some kind of energy that is emitted, transmitted, or reflected from an "object" to determine certain physical properties of the "object". Passive remote sensing is based on detecting available energy from natural resources (example - microwave radiometer). Active remote sensing, in contrast, depends on an artificial "light" source (examples - radar, lidar, sodar) to illuminate the scene. For purposes of this review, the "object" will be the Earth's atmosphere, and the remote sensors will be confined to operating from the Earth's surface. Topics to be covered include the very short description of physical principles of atmospheric remote sensing of vertical temperature profile, wind, humidity and cloud structure to only those factors that have a bearing on their operation use. Those who wish to know more about the governing theories and technical characteristics of ground-based remote sensors are referred to Clifford et al (1994), Vlaby et al, 1986; Westwater, 1993; Pampaloni and Paloscia, 2000; Kallistratova and Kon, 1985; Zuev V.E. and Zuev V.V., 1992; Krasnenko, 2001. Remote sensor measurement have characteristics that are different from those taken by in situ instruments (radiosondes, e.t.c.). Remotely sensed values are more likely to be overages over some volume that is related to a beam width or pulse length, whereas in situ measurements are usually point measurements. These differences can cause problems with comparison, interpretation and validation of data, and their use in models, and with continuity of historical records. For meteorological parameters profiling the main advantages of remote sensing measurements are in continuity in time and in low operational cost. The use of satellite and ground-based remote sensing to study atmospheric properties is revolutionizing our understanding of meteorological processes. Weather satellites view the earth from a global prospective that is unwatched by any other observing system. But ground-based remote sensing systems had source advantages too – for instance, it is impossible to measure from satellite temperature profiles in atmospheric boundary layer with sufficient accuracy. Ground-based remote sensing of the atmosphere have proven useful in a variety of geophysical application, including meteorological observations and forecasting, communications, geodesy and long-baseline interferometry, satellite validation, climate, air-sea interaction, and fundamental molecular physics. One of the reasons for the utility of these measurements is that with careful design, most of modern remote sensing systems can be operated in a long-term unattended mode in nearly all weather conditions. In this overview of recent operational aspects of different ground-based remote sensing observing techniques we confine our attention to sounding of vertical profiles of temperature, humidity, wind and cloud structure. At the Appendices are presented information about capabilities and limitation of different ground-based remote sensing observing techniques and parameters of some commercially available remote sensing systems: sodars, RASS, lidars, radars wind profilers, microwave radiometers.

2. GROUND-BASED REMOTE-SENSING PROFILERS: TYPES AND PERFORMANCE

For remote sensing providing of vertical profiles of temperature, wind, humidity and cloud structure can be used passive and active remote sensing techniques which can operate in visible, acoustic, radio-acoustic and microwave region, such are sodar, RASS, lidar, radar, and microwave radiometers.

2.1. Acoustic Sounding system

The field of acoustics is the study of the generation, transmission and reception of energy in the form of vibrational waves in matter. Acoustic frequencies are subdivided into three ranges: infrasonic (20 Hz or less); audible (20 Hz to 15,000 Hz) and ultrasonic (greater than 15.000 Hz). Audible acoustic frequency range is normally termed “sound”. The idea of probing the atmosphere with the sound has been around a century. Active acoustic remote sensing was first attempted around 1875 by Tyndal using a fog horn and an observer (more exactly listener) with ear horn to amplify the return signal. This was an attempt to get echoes from atmospheric features in the horizontal. Little progress was made with atmospheric acoustic remote sensing until the 1960’s. But in water acoustic techniques advanced remarkably during the 50 s and 60 s for submarine tracking (ASDIC in UK, SONAR – in USA, EHOLOT – in USSR). Gilman et. Al, in 1946, had measured order of magnitude larger echo return than expected, and was the first to use the term SODAR (from the acronym So‌und Detection And Ranging). They suggested that turbulent microstructure acting on a varying temperature field was responsible for enhancing the scattering. A SODAR operates on a principle similar to an active SONAR: emits pulsed acoustic energy; records the acoustic signature (or received signal) produced by the interaction of the pulsed energy with an object or refractive index changes along the propagation path. Received acoustic signal contains information about the sound energy from an object or a volume of air. The information is: intensity of the received signal; frequency of the received signal. As Neff (1986) then states, “A hiatus in SODAR development followed, until the scattering experiments of Kallistratova (1959)”, which lead to an improved calculation of scattering cross section by Monin and Obuhov (1941). Atmospheric acoustic back scattering is generally inaudible, but experience showed that the return signal is easily detectable using the electronic amplification methods and an acoustic dish. The typical 1960’s SODAR was a large speaker pointing downwards, directed at a parabolic dish to focus the transmission beam and amplify the return signal. Side lobes to the main beam are a problem, with a significant off – axis signal and the solution then, as now, was to use an acoustic wall to absorb the side lobes. In the 1960’s, this was often just a wall of straw bails around the dish.

The design was simple and successful, and many modern SODAR antennas are remarkably similar to these early designs, al bat with a more technical baffle. The very first SODARs detected the strength of the return echo and displayed the record on an oscilloscope; time lapse photographs of the trace then gave a permanent record of backscatter profile. By the 1960's, facsimile recorders, similar to depth sounders on ships, were used, with a time/height record being produced over a few hours. Initial SODAR research was aimed at confirming theoretical scattering theory, which in turn would validated turbulence theory. After the initial flourish of academic interest in the 1960's, the 1970's saw commercial systems being built, with bucket style antennas, whilst the academic community started work on wind profiling, using the Doppler shift in the signal return from a slightly tilted SODAR. This was also very successful, and the resulting commercial Doppler profilers of the 1980 had three bucket style antennas, two at an angle (North and West) and one pointing vertically. Each SODAR consists of three main subsystems: Antenna, Control Electronics, Display Computer. It operates by transmitting a short pulse of sound which is reflected by the small scale turbulence in the atmosphere. This turbulence is transported by the wind, and radial velocity of the air can be determined by measuring the Doppler shift in frequency being refracted from the turbulence. The range of the turbulence is determined from the delay between the transmission of the acoustic pulse, and the reception of the refracted signal. By repeated this process in three different directions, each direction having a large component being orthogonal to the other two direction the three dimensional, wind field can be calculated. The signal processing algorithm include extensive filtering and averaging, to ensure a good signal to noise measurement. The frequency of the sound pulse (from audible acoustic wave range) is chosen to provide a compromise between attenuation (which increased with frequency and limited altitude range inside atmospheric boundary layer) and environment noise. In the moderns SODAR frequency are in the range 1000÷2000 Hz (for frequency 2000 Hz altitude limitation is about 700 m, for 1000 Hz – about 700 m). The attenuate of propagating acoustic energy increases as a function of increasing frequency, decreasing temperature, decreasing humidity. For geometries of measurements SODAR may be monostatic (with one antenna for transmitter and for receiver) and bistatic - with antennas at deferent locations. SODAR also can operate with acoustic impulse emission mode or in continuous emission mode. Pulse mode ordinary used for atmospheric profiling measurement, continuous mode – for monitoring of some parameters in limited volume of the atmosphere. SODAR can have one channel for transmitting – receiving of acoustic energy, or two channel, or three channel. Some SODAR had a scanning system for antennas – for the scanning in azimut or in zenith angle, and also can have scanning in frequency (multi-frequency system) (Krasnenko, 2001). For monostatic SODAR with the scanning in frequency and in angle the Doppler shift increasing with the zenith angle and with frequency. The height resolution (ordinary 5÷20 m) is gathered by range gating, i.e. by considering the time the pulse needs to propagate from the antenna to the measured layer and back to the antenna. From the amplitude of the backscattered wave, detailed information about turbulence structure in the atmospheric boundary layer is obtained, and by evaluating the spectrum the wind speed is determined. Some modern SODAR (mini-SODAR operated at frequency range 3 kHz ÷ 6 kHz) have the phased array type of antenna. Here different beam angles are generated by phase-delayed driving and sensing of the rows and columns of acoustic transducers. Compared to three-component horn systems this results in a smaller antenna size and a more flexible use.

In general, useful information in SODAR are in backscattering acoustic signal intensity and in Doppler shift in frequency. Data product from acoustic intensity: surface based and elevated scattering layers (mixing heights, wind speed, etc.); atmospheric stability information (facsimile displays); temperature structure constant (C_T^2); and derived quantities – surface heat flux, inversion height. Data product from the Doppler shift: spectra, mean component velocities; horizontal wind speed and direction, vertical velocities; variances and co-variances of the components.

So, the SODAR technique is an effective tool for measuring of both turbulent, and wind speed parameters. Besides, in meteorological application it can be used for determination of thermal stratification type and heights of inversion edges too. The main <u>advantage</u> of the SODAR data concludes in their high spatial and temporal resolution and in a low operational cost. But as operational sensor SODAR has some <u>limitations.</u> SODARs need an acoustically quit environment free of buildings and others obstacles to the most effective. Airport environments are, in general, not quiet, so very often SODAR useful altitude is limited under 400 m even though they were set to produce data to 1 km. Strong winds blow the SODAR signal out the receiver's range when speed exceed about 15 m/s, and surface winds of about 10 m/s can cause surface noise that interference with signal processing as well (Zak, et al, 2001). Rain of moderate or greater intensity causes noise and other problems so that performance deteriorates. Hail can damage the hardware unless a hail shield is used. Even though there are heaters, snow and freezing rain caused some loss of signal strength and performance degradation (Crescenti, 1998). There are other factors affecting SODAR performance, which are not obvious as ice, strong winds, and heavy rain. Strong temperature inversion reduce the signal to noise ratios (S/N) and limit altitude coverage and general accuracy. There is less S/N in cold weather and low humidity than in warm, humid air. Light wind conditions seem to produce more spurious returned signals and questionable wind solutions than steady flows. The horizontal winds in the first few range (altitude) gates have been usually stronger than those measured by nearly meteorological towers, probably due to the integration over finite range bins extending higher in altitude than the output altitude and non linearity of wind speed with altitude (Zak et al, 2001). Some of the problems can be minimized by careful scrutiny of S/N and other parameters listed in each output file of the SODAR. As about minisodar – there advantages are in high time resolution (1 minute) and fine-scale altitude resolution (5 m), had small size and low cost. But it's maximum altitude is ordinary limited of 200 m and they emitted loud sound at frequency range about 3÷6 kHz which is not so comfortable for nearby residences (Beran, 1997). The SODAR offer an attractive cost-capability tradeoff despite their problems in some conditions. A typical SODAR cost is in the range $45,000 ÷ $100,000. Minisodar cost is about $20.000.

2.2. Radio Acoustic Sounding Systems (RASS)

The main shortcoming of SODAR, which is essential for many applications, is its incapacity for measurement of air temperature profile. Because the speed of sound in the atmosphere is a function of virtual temperature, it is possible to determine a temperature profile by tracking the speed of a vertically propagating acoustic wave (Tatarsky, 1967; Marshal et al, 1972; Kallistratova and Kon, 1985; Strauch et al, 1988; Peters et al, 1993). The ability to track these waves became feasible with the advent of the extremely sensitive receivers and high gain antennas used for wind profilers. By adding acoustic sources to wind profilers, it is possible to measure both temperature and wind. These Radio Acoustic Sounding Systems (RASS) are now an integral part of many wind profilers. They suffer the same attenuation – induced range degradation as sodars but are still capable of measuring high-resolution temperature profiles up to altitudes of a few kilometers (May et al, 1990; Clifford and Wang, 1977, Nalbandian, 1977). Virtual temperature are recovered by transmitting an acoustic signal vertically and measuring the electromagnetic energy scattered from the acoustic wavefront. The propagation speed of the acoustic wave is proportional to the square root of the virtual temperature. Enhanced scattering of the electromagnetic wave occurs at specific frequencies (Bragg scattering). The resultant Doppler shift and speed of sound can be determined. Ordinary useful range is limited at about 600 m, cold temperature significantly reduced altitude coverage in winter to about 300 m. Strong temperature inversion generally lowered altitude coverage in late night and early morning (Zak et all, 2001). RASS systems that are based on VHF radars suffer less from attenuation and under favorable conditions can measure virtual temperature up to the height of the tropopause. The retrieval of refractive index gradients and humidity profiles from RASS has also been proposed (Kallistratova and Kon, 1985; Bedard and Lataitis, 1993). Rain of even light intensity adversely affect RASS temperature and, like for the sodars, strong wind can blow the acoustic signal out of the radar beam. RASS temperature data should be corrected for vertical motion of air: vertical motion of 1 m/s can change the temperature by 1-2 degrees K (the measured acoustic speed V_{RASS} is namely sum of acoustic speed V_{ac} added to the background vertical air motion W i.e.: $V_{RASS}=(V_{ac}+W)$). For RASS output is virtual temperature which must be convert to compare with dry – bulb temperature (usually virtual temperature is 2-3 degrees C higher than dry – bulb temperature – Zak et al, 2001).

Because in RASS system used Bragg scattering, the maximum of scattering electromagnetic signal will be if wavelengths of acoustic signal and wavelength of electromagnetic signal will follow to the Bragg equation:

$2\lambda_e \cdot \cos\varphi = \lambda_{ac}$, where

λ_e – wavelength of electromagnetic emission,

λ_{ac} - wavelength of acoustic emission,

φ – angle between acoustic and electromagnetic wave (Tatarsky and Golitsyn, 1962). Historically at the first RASS systems were use electromagnetic waves with λ_e = 3 cm and λ_e = 8 m (Atlas, 1962; Fetter, 1961). At the former USSR first RASS system (RAZ-10) were operated at λ_e = 10 cm (Babkin, et al, 1980). Next system (RAZ – 3 and RAZ – 30) had λ_e = 3 cm and 30 cm respectively (Makarova, 1980; Bovsheverov, 1981). The Italian system RATS-MW (radio-acoustical tropospheric sounder on metric waves) had λ_e = 1,88 m and altitude range 170÷1200 m (Bonino, et al, 1979). Selection of wavelengths determine the maximum range and vertical resolution of RASS: H_{max} ~ 40 m and ΔH ~ 2 m if λ_e = 3 cm, and H_{max} ~ 3000 m and ΔH ~ 200 m if λ_e = 8 m (Kallistratova, 1985). Modern RASS had wide range of using wavelengths, more often used λ_e = 23 cm (1290 MHz); λ_e = 33 cm (915 MHz).

The cost of a RASS option with a profiler is about $30,000 - $40,000. RASS option are also available with SODARs.

2.3. Radar wind profilers

A wind profiler (or UHF profilers) is a type of Doppler radar that remotely senses vertical wind profiles from the ground (Radar means Radio Detection and Ranging). The frequencies of radars vary enormously, depending on their application. Scientist assign certain names to different frequency ranges, as described below:

Low Frequency (L.F.) – 30 to 300 kHz (wavelengths of 10 km to 1 km)

Medium Frequency (M.F.) – 0.3 to 3 MHz (wavelengths of 1000 meters to 100 meters)

High Frequency (H.F.) – 3 to 30 MHz (wavelengths of 100 to 10 meters)

Very High Frequency (V.H.F.) – 30 to 300 MHz (wavelengths of 10 meters to 1 meter)

Ultra High Frequency (U.H.F.) – 300 to 3000 MHz (wavelengths of 1 meter to 10 centimeters)

Beyond this is the microwave region – 1 to 300 GHz (wavelengths of 30 centimeters to 1 millimeter) – within the UHF band and into the microwave region, there are also some special frequencies which have extra designations. The main ones are:

L–band – 1-2 GHz (wavelengths 30 to 15 cm)

S-band – 2-4 GHz (wavelengths 15 to 7,5 cm)

C-band – 4-8 GHz (wavelengths 7,5 to 3,75 cm)

X-band – 8-12 GHz (wavelengths 3,75 to 2,5 cm)

K-I band – 12-18 GHz (wavelengths 2,5 to 1,7 cm)

K-II band – 27-40 GHz (wavelengths 1,2 to 0,75 cm)

In 2002, the International Telecommunication Union (ITU) and the World Meteorological Organization (WMO) issued a Handbook on the "Use of radio spectrum for meteorology". It describes in detail all the related application, including radar wind profilers mainly in the 400 MHz and 1300 MHz bands (UHF range). In most countries it will be essential to consult the national radiofrequency authority as to the frequencies that can be used at given wind profiler site.

The ability to detect signals from clear air was key to the development of ground-based radars that can measure winds under nearly all weather conditions. By employing various antenna configurations and beam-steering methods to project at least three beams (one vertical and two in orthogonal directions ~ 15^0 off vertical). For some 400 MHz wind profilers antenna array consists at about 144 antenna elements and even more that typically cover 100 m × 100 m (Sato, 1990). Altitude coverage to the tropopause level is achieved consistently with UHF (50 MHz) radars. Less radar sensitivity limits the range of higher frequency UHF (915 MHz) systems to around 5 km (Marther et al, 1993). Modern UHF micro-radar wind profiles has maximum range about 1500 m and minimum range about 100 m (Appendix 2 of this review).

Most wind profiling radars are Doppler radars that obtain their echoes from turbulent in homogeneities in the atmospheric radio refractive index field. In the lower troposphere the radio refractive index is dominated by water vapor and echoes are fairly strong, especially in the humid tropics. The development of wind profiler technology over the past decade or so is a direct outgrowth of several decades of radar studies of the optically clear atmosphere (Hardy and Gage, 1990). It has also benefited from the radio ionospheric research community. Much of the early work with radar wind profilers was accomplished at VHF primarily in the 40÷50 MHz frequency band and was relatively insensitive to the hydrometeors. At these lower VHF frequencies backscattered power is often very anisotropic with large enhancements from quasi-specular reflection at vertical incidence from the hydrostatically stable atmosphere. Thus VHF profilers observe over an extended height range looking vertically compared to looking obliquely. Profilers that operates at UHF frequency 405 MHz do not observe the quasi-specular echoes seen at vertical incidence at VHF. This profilers are substantially more sensitive to hydrometeors than the VHF profilers (Law, 1990). During the past 10÷15 years small, relatively inexpensive, low-powered wind profilers have been developed to operate near 915 MHz (Ecklund et al, 1990). These small profilers (mini- and micro-radar) are quite adequate for observing winds in the lower troposphere typically through the height of the atmospheric boundary layer. These profilers are very compact – antenna about 1,2÷2,5 m, and finding many commercial application and has not bad vertical resolution (about 75÷300 m). At 915 MHz the lower tropospheric wind profiler is very sensitive to the precipitation. In rain the clear air echo is often overwhelmed by the precipitation echo. Wind measurement is still possible in rain but a correction must be made for the hydrometeor fall speed that can be determined from the vertical beam. This technique works reasonably well provided the rainfall as uniform so that the fall speed is not highly variable. If the fall speed is highly variable , wind measurement will be compromised (Gage, 1990). While much progress has been made in recent years to implement radar wind profilers technology, some problem remain. For example, migraticy birds, insects, airplanes etc. can produce an unwanted contamination of profiler observations that can lead to erroneous results. One more problem-potential interference from nearly structure, radio sources, and terrain experts should be consulted when radar wind profilers are to be sited. Both VHF and UHF wind profilers are commercially available at prices ranging from less than $200.000 (mini- and micro – radars) to more than $1 million, depending on the sophistication and power of the system. There are several other radar wind profiling techniques that have been used experimentally that do not utilize the Doppler method. These techniques typically employ spaced multiple receivers. There are several related methods that use multiple spaced receivers: Spaced Antenna (SA), Radar Interferometry (RI) or Spatial Interferomentry (SI) and Imaging Doppler Interferometry (IDI). In its simplest application the spaced antenna method utilizes a vertically directed transmitter and several spaced receivers. In its simplest form the technique involves cross correlation of the receiver signal between receiver pairs. The wind is determined from the lag time for maximum correlation between receiver (Gage, 1990; Adams, 1986; Van Baclen and Richnoud, 1991). One more new method of ABL wind measurement: using of two or three 5-mm passive microwave radiometers (Kadygrov et al, 2003).

2.4. Lidar Systems

Lidar (Light Detection And Ranging) is a kind of radar using laser light instead of radio waves. It transmits pulsed laser light to the atmosphere and collects the light reflected from the atmospheric molecules, clouds and aerosol with the help of the receiving telescope. Lidars work with visible or near-infrared light and have been developed in a number of different forms (Zuev V.E. and Zuev V.V., 1992). Distribution of the atmospheric minor constituents of water vapor, temperature, aerosols, and clouds are derived from intensity of the received light and distribution of wind is derived from the Doppler shift. The rich content of optical and infrared absorption spectra has helped to make a variety of lidar systems effective tools for atmospheric research over the past few decades (Zuev, 1982; Browell, 1981; Gibson and Thomas, 1975; Zakharov and Kostko, 1977).

Doppler lidar operating at 0.3 to 10 μm wave lengths receive signals scattered from airborne particulates such as sea salt, dust, smoke and water droplets (Beran, 1997). These particulates remain suspended for days and move with the wind, marking them useful targets for lidar wind measurements (Eberhard et al, 1989, Zuev V.E. and Zuev V.V., 1992). Systems using wavelengths nearer 600 nm, and relying on Raman scattering, which occurs when laser radiation is scattered from atmospheric constituents such as H_2O, N_2, O_2, have been used for measure temperature and moisture during nighttime (Melfi and Whiteman, 1985; Alpers et al, 2004).

Differential absorption lidar (DIAL) systems using the difference in attenuation of the backscattered signal at two wavelengths have been employed to infer range – resolved value of atmospheric temperature and water vapor (Mason, 1975). Early DIAL systems operated at wavelengths between 700 and 800 nm and the technique has been demonstrated using a coherent CO_2 lidar (Hardesty, 1984). More often modern DIAL system are favored technique for airborne lidars. For this review more important systems for temperature and water vapor profiling, so lidar using Raman scattering. Typical Raman lidar had following subcomponents (Zuev V.E. and Zuev V.V., 1991):

- System enclosure (including optical mounting system, window/hatch assembly, climate control, and utilities);
- Laser: ordinary it is frequency – tripled Nd: YAG laser;
- Laser – beam expander;
- Receiving telescope;
- Dichroic beam splitters and narrow band interference filters;
- Photo multipliers;
- Amplifiers;
- Discriminators;
- Multichannel scalers;
- Data acquisition environment.

Ordinary Raman lidar systems detect selected spices by monitoring the wavelength – shifted molecular return produced by vibrational Raman scattering from chosen molecule or molecules. But in the modern Rayleigh /Mie/ Raman lidar system the altitude range of temperature profile measurement was extended from the atmospheric boundary layer up to the upper mesosphere using three different temperature measurement methods (Medaglia et al, 2003; Alpers et al. 2004). This methods were optimazed for three altitude ranges:

1. Probing the spectral Doppler broadering of the potassium D_1 resonance lines with a tunable narrow – band laser emitter allows the determination of atmospheric temperature profiles at the metal layer (free metal atoms as e.g. Fe, Ca, Na and K) altitudes (80-105 km).

2. Between about 20 and 90 km temperatures were calculated from Rayleigh backscattering on air molecules, where the upper start values for the calculation algorithm were taken from potassium lidar results. Correction method have been applied to account for, e.g. Rayleigh extinction or Mie scattering of aerosol below 3 km.
3. Rotational Raman lines is strong enough to obtain temperatures by measuring the temperature dependent spectral shape of the Rotational Raman spectrum. This method works well down to about 1 km (ABL).

The three described temperature lidar methods on their own are experimentally well established and are utilized in various lidar systems all over the world. Beside the fact that they are the most expensive and delicate of all types of atmospheric profilers, it seems that due to their characteristics they will probably be used mainly for probing higher atmospheric levels including the stratosphere. A lidar systems dedicated to wind and turbulence profile measurements is an alternative to SODAR in all weather conditions except dense fog, moderate precipitation, and low clouds which limited operational systems capable of observing the basic meteorological parameters of wind, temperature and moisture. A significant drawback to the use of lidar technology for operational weather observations has been their size, complexity and relatively high cost (from $200.000 up to $ 1 mln and even more). Thanks to space laser technology development, these limitations are becoming less important during last decade.

2.5.Passive microwave remote sensing profilers

Passive microwave remote sensing is similar in concept to thermal remote sensing. All physical objects emits microwave energy of some magnitude, but the amounts are generally very small compared to optical wavelengths (Basharinov et al, 1974). The microwave energy recorded by a passive sensor (microwave radiometer) can be emitted by the atmosphere, reflected from the surface, emitted from the surface, or transmitted from the subsurface. Microwave radiometers measure brightness temperature whose values and variations at different frequencies can correlated with some atmosphere parameters (Vlaby et al, 1986). The atmosphere contains gaseous molecules, liquid and ice cloud particles. Microwave radiation from the atmosphere is due to the absorption and scattering of gaseous molecules of oxygen (with the absorption complex of resonance lines near 60 GHz or 5 mm and one line at 118 GHz) and water vapor (with resonance line at 22,235 GHz and at 183 GHz) and from liquid water, and depends on their temperature and concentration (Basharinov, 1974; Westwater, 1993).

For a well-mixed gas such as oxygen, whose fractional concentration is independent of altitude below 80 km, the radiation contains information primarily on atmospheric temperature (Gevakin and Naumov, 1967; Westwater and Strand, 1970, Waters, 1976; Rodgers, 1976). As an important tool of atmospheric remote sensing, microwave radiometers are used for temperature profiling, and vapor and liquid column measurement (Vlaby et al, 1986; Basharinov et al, 1974; Askne and Westwater, 1986; Gorelik et al, 1973; Troitsky, 1986; Toong and Staelin, 1970; Basharinov and Kutuza, 1968; Rabinovich and Shukin, 1968). Radiometer measurements are inexpensive compared to the cost of radar and lidar, and it can provide all-time observations in both cloudy and clear air situations. However, using radiometer measurements can have specific difficulties:

1) the measured brightness temperature is proportional to cumulative emission from various layers;
2) both scattering and absorption contribute to the measured radiation, which is governed by an integral – differential Radiative transfer equation;
3) the relation between brightness temperature and the atmospheric parameters is non-linear.

The measurements also enable the continued development of absorption and radiative transfer models in both clear and cloudy atmospheres. This development has been greatly aided by long-term, carefully calibrated radiometer measurements, supplemented by frequent radiosonde release using active sensors for cloud identification (Westwater et al, 2004). Last, but not least, is the development of retrieval and data assimilation algorithms. To take advantage of continued improvements in radiometric techniques, it is important to provide such quality measurements with algorithms to calculate brightness temperature given the state of the atmosphere. In the clear atmosphere, this requires calculating absorption as a function of frequency from given vertical profile of pressure, temperature and water vapor density. Currently, there are three main absorption models that are widely used in the propagation and remote-sensing communities. H. Liebe developed and distributed of the computer code of this Microwave Propagation Model (MPM) (Liebe, 1989). More recently, Rosenkranz developed an improved absorption model that also is frequently used in the microwave propagation community (Rosenkranz, 1998 and 2004). Another model that is used extensively in the US climate research community is the Line by Line Radiative Transfer Model (Clough and Iacono, 1995). Techniques to derive meteorological information from radiation measurements are generally based on numerically solving the radiative transfer equation (Tikhonov and Arsenin, 1977; Twomey, 1977; Chahine, 1970). For mildly nonlinear problems, a perturbation form of the radiative transfer equation (RTE) is frequently used as the basis of subsequent iteration. An excellent review article discussing optimal estimation technique for solving RTE was written by Rodgers, 1976. Others more modern frequently used method in radiometry include neural network inversion (Del Frate and Schiavon, 1998) and Kalman filtering (Han et al, 1997). Operational aspects of ground based remote sensing of temperature, water vapor and cloud liquid will be described in separate topics of the present report.

2.5.1. Temperature profiling

Microwave temperature profiling radiometers have been designed primarily for downward viewing from a satellite. At present time one of the well known satellite-born instrument is Advanced Microwave Sounding Unit which can to determine temperature profiles from about 3 km above Earth's surface up to about 50 km (Poulsen et al, 2000). However, upward-looking instruments can provide useful high-temporal-resolution information about temperature structure at the low troposphere and atmospheric boundary layer (ABL) (Hogg et al, 1983; Troitsky, 1986; Kadygrov and Pick, 1998; Solheim et al, 1998; Grewell et al, 2001). In principle, temperature can be measured at any wavelength of the electromagnetic spectrum. In the case of atmospheric temperature profiling, advantage is taken of several properties of oxygen molecules, which comprise 23% of the mass of the Earth's atmosphere. First, O_2 molecules radiate (and absorb) at a number of discrete frequencies between 50 and 70 GHz. These spectral lines are a consequence of rules of quantum mechanics which only allow oxygen molecules to have particular rotational energy states. Furthermore, since the O_2 molecules are in thermodynamic equilibrium with the local environment, this means that if we can measure the strength of the thermal emission from the oxygen molecules, then we can deduce the physical temperature of the molecules that produced this emission. Second, the oxygen absorption is strong enough that the effective distance that emission is "seen" from is of the order of a few kilometers, depending on the frequency. On the ground level the O_2 absorption is a single broad feature because individual oxygen emission line have been blended together by pressure broadening. Third, oxygen molecules are a well-mixed component of the atmosphere at all heights, which is to say that the number of emitting molecules at any altitudes depends only on the pressure altitude (Basharinov et al, 1974). Water vapor, for example, could not be used as a temperature surrogate because it's distribution (or mixing ratio) compared to its surroundings varies erratically. 60 GHz microwave radiometers are very portable and can provide reliable automated continuous profiling from a variety of sites; these feature are not available with the other technique (Kadygrov et al, 2003). Two technique mostly used for microwave temperature profiling (Shider, 1972). First is well-known method used a zenith-viewing multichannel radiometer with frequencies of 53-58 GHz in the wings of the O_2 absorption band (Hogg et al, 1983; Lebsky et al, 1976; Troitsky, 1986; Solheim, 1998; Crewell, 2001; Liljegren, 2004). It can measure temperature profile of the lower troposphere (up to about 5 km) (Troitsky, 1986). For good accuracy it is needed to have additional measurement channels for measurement of water vapor and cloud liquid (ordinary it is channels with the frequencies 23,8 GHz and 30 or 35 GHz) (Solheim, 1998). As was shown in (Liljegreen, 2004), multichannel method without scanning had a low vertical resolution at the lowest part of the ABL (about 300 m). Second method is based on using an angular-scanning single-channel radiometer with the central frequency of 60 GHz. This method and the new instrument were proposed by Troitsky et al, 1993; and discussed in detail by Kadygrov and Pick, 1998; Westwater et al, 1999. Due to the large atmospheric absorption by molecular oxygen at 60 GHz, angular-scanning method has some advantages for ABL temperature profiling over the multichannel method (Cadeddu et al, 2002; Kadygrov et al, 2003):

1) the measurements do not depends on changes of water vapor density or on the presence of fog or low clouds; so it can really to operate in all weather conditions;
2) there is no need for calibration in the artificial microwave farget (it is possible to use atmospheric emission in horizontal direction);
3) better vertical resolution in the lower 100 m;
4) the bandwidth of the receiver is very wide (4 GHz) which provides a high sensitivity of the receiver (about 0,02 K at 1 s integration time);
5) instrument has a small sizes and relatively small cost;

But the single-channel angular-scanning method has its limitations in altitude measurement because it measures only from the ground level and up to 1000 m. The cost of commercially available multichannel instruments is about \$200.000 ÷ \$250.000, and scanning single channel instruments about \$60.000 - \$90.000.

2.5.2. Microwave radiometric measurements of water vapor

In contrast with absolute temperature, whose percentage variability is only 10 to 20%, water vapor exhibits a large variability in space and in time. This is a huge different in total water content between the equator and the poles, and for a fixed location, the total content can vary by a factor of 30 during the year. In the troposphere, where most of the vapor is present, vapor concentration generally decreases with altitude, but a high degree of spatial structure is frequently evident. Microwave radiometry alone will not resolve this structure (Westwater, 1993). Consequently, most of the work in the field has concentrated on providing accurate measurements of integrated quantities, such as integral water vapor path (WVP), or outside the cloud physics community it can be called precipitable water vapor (PWV) or integrated water vapor content (IWV) (Rogers, and Yan, 1989). Microwave radiometers can provide instantaneous and continuous measurement of WVP. Such measurements can be also provided by the using of the Global Positioning System (GPS) (Ware, 1992). The GPS consists of a constellation of 24 satellites that are capable of providing very precise location for specialized receivers. If the position of a GPS receiver is fixed at a pricisily known location, small errors in the perceived location of the receivers are attributable to, among other thing, the total amount of water vapor between the receiver and the satellites. It has been demonstrated that this error in position can be separated from other error sources and converted into the total amount of atmospheric moisture along the path between the receiver and the satellite. But this method in not a pure ground-based because microwave radio signals transmitted from satellite and so is out of this review line.

Measurements of microwave thermal emission and its variation with atmospheric moisture were first reported in Dicke et al, 1946. Although most of their measurements were taken during clear conditions, they mentioned that some cumulus clouds were quite absorbing at centimeter wavelengths. Subsequently, Barret and Chung, 1962; Stailin, 1966; Rabinovich and Shukin, 1968, discussed the determination of profile information from multispectral emission or extinction observations. In addition, Staelin, 1966, discussed the possibilities of simultaneous vapor and cloud liquid determination. These possibility were experimentally demonstrated in Toong and Staelin, 1970, where vapor and cloud liquid were derived from emission observations at five frequencies. In addition, the Russian scientific literature contains many descriptions of experimental determinations of vapor and liquid (Plechkov, 1968; Gorelik et al, 1973, Basharinov and Kutuza, 1968; Hrulev et al, 1978). For total water vapor measurement (WVP) in a clear atmospheric condition it is possible to use even one-channel radiometer which can measure the absolute signal at frequency, for instants, 23,8 GHz. But such radiometer need in very careful absolute calibration with expensive microwave target. Rassadovsky and Troitsky, 1984, proposed to use for such measurement dual-channel differential radiometer with frequencies ν_1 = 22,238 GHz (in the center of H_2O line) and ν_2 = 20,73 GHz (in the wings of H_2O line) Such system can measure WVP even in cloudy atmosphere because influence from clouds to the measured brightness temperature is about the same for both channels. But more common is the dual-channel systems with frequencies ν_1 = 23,8 GHz and ν_2 = 36,5 GHz (Westwater, 1998). In operation with such instrument ordinary ν_1 informations is used for WVP determination, and ν_2 – for cloud liquid determination and also for limitation of ν_1 channel data in the presents of clouds (Gorelik et al, 1973). The dual-channel water vapor weighting function are quite smooth, exhibiting a roughly linear dependence on height. Consequently, it is not at all obvions that profile can be retrieved from such measurement (Westwater, 1993). But in Aleshin, et al, 1977 described method of water vapor profile determination on the basis of statistical regularization method and with the using of measured near-by surface humidity and measured total water vapor. More often for water vapor profile recovery used data from several channel at the wings of 22,235 GHz spectral line (Solheim et al, 1998; Crewell et al, 2001). But the optical depth of this line is small and more of the channel had information only about integral water vapor path, and influence of water vapor profile even for the central frequency 22,235 GHz is less than 3K only (Aleshin, 1977). Some authors proposed to improve this method by combining the MWRP retrieval with those from the GOES-8 sounder (instead neural network retrieval) and by incorporating brightness temperature measurement at off-zenith angles (Liljegren, 2004) – as about the same that is using in single-channel an angular-scanning radiometer for ABL temperature profiling (Kadygrov and Pick, 1998). A new and promising method of measuring water vapor profiles was proposed by Uttal et al, 1990. This method used the combination of data measured by a dual-channel microwave radiometers and wind profiles, measured by a 8,6 mm Doppler radar, to derive the fluxes. The radiometer-radar method yields significant small-scale structure in the moisture-flux field that was smoothed by the radiosonde measurement (Stankov et al, 1996, Bianco et al, 2004). This combined remote sensing method has some advantages over radiosonde (or rawinsonde) sampling (Westwater, 1993):

1) the profile from the radar and the radiometer are instantaneous (the air mass can change significantly as the rawinsonde travels between the surface and the top of the measurement level);
2) the remote sensing profile is a true vertical measurement (in contrast rawinsonde drifts horizontally as it rises);
3) the remote sensing method can sample the air mass quasi-continuously whereas rawinsondes can obtain only one sample per launch.

2.5.3. Microwave radiometric measurements of cloud liquid

Liquid water in cloud it is possible to measure by any frequency from microwave region outside the resonance gaseous absorption lines (first of all from O_2 and H_2O). Such frequencies range called “absorption window region” are 30÷35 GHz and 85÷90 GHz (Basharinov, 1974). In a sense, cloud liquid is a contaminant on the microwave radiometric determination of temperature and water vapor (Westwater, 1993). However, measurement of liquid are valuable in their own right. Important application are aircraft-icing detection, weather modification, and climate. For non-precipitating clouds, microwave emission and absorption come principally from cloud liquid, with contributions from ice being negligibly small. Weather radar can not detect clouds zones containing small water drops, and the only tool for remote sensing as applied to the problem of aircraft-icing detection is microwave passive radiometry. Scientific methods for weather modifications and aircraft-icing detection depends on understanding the physical processes associated with the formation and evolution of super cooled liquid water (SLW). The first paper reporting microwave radiometric observation of SLW that were simultaneously accompanied by aircraft reports of icing conditions was by Hogg et al, 1980. About the same results were reported by Koldaev et al, 1996. Special microwave instrument for “real-time” retrieval of cloud parameters such as Liquid Water Path (LWP) and the average temperature of the liquid water layer was described by Koldaev et al, 2000. These parameters are very important for diagnosing winter clouds. Microwave system consists of two microwave radiometers operating at 85 GHz and 37 GHz. The main feature of this system is that it can operate in an unattended mode within a very wide range of weather conditions such as heavy rain, freezing rain, freezing drizzle and heavy snowfall. The theoretical RMS accuracy of the dual-channel system in deriving cloud liquid amount is about 0,003 cm, which corresponds to a cloud liquid density of 0,03 g/m^3 for a 1-km thick cloud. With the increasing sensitivity of the 85 GHz channel, the threshold is lowered to 0,005 mm. This sensitivity may allow the observation of liquid in cirrus clouds, if it exists (Westwater, 1993).

The contribution of cloud liquid water to the microwave signal increases roughly with the frequency squared. It depends on temperature and is proportional to the third power of the particle radius. In the last years approaches to further improve the LWP retrieval were directed towards the inclusion of additional microwave channels and the combination of microwave radiometer measurements with other ground-based instrumentation. The potential of deriving cloud liquid water profiles from multi-channel radiometer measurements has been suggested by Solheim et al, 1998: “low resolution cloud liquid profiles can be determined by observing radiated power at selected frequencies from 22 to 59 GHz, together with a cloud base height measurement”. More realistic way for cloud liquid remote sensing profiling looks the using of combined active and passive microwave measurements (Shupe et al, 2003). During NASA CRYSTAL-FACE Program were used vertically pointing 35 GHz Doppler radar, dual-channel microwave system (20,6 GHz and 31,65 GHz) and micro-pulse lidar for identifications of the base of the cloud liquid layer. Such combinations gave the possibility of determination not only LWP, but also liquid water content (LWC). As conclusions for microwave remote sensing of clouds structure it is possible to indicate, that there are two levels of instruments:

1) simple and low cost instruments for measurement of integral parameters (total water vapor and integral liquid) such are single or dual-channels microwave radiometer;
2) multichannel and combined system for determination of water vapor profile and liquid water profiles in clouds.

The first level looks to be optimal for routine meteorological and air-pollution observation, second – for research in atmospheric physics.

3. APPLICATIONS OF GROUND-BASED REMOTE SENSING INSTRUMENTS DATA

Ground-based remote sensors can be effective for a wide range of operational applications. However, it is important to consider the overall observing system before making a deployment decision. A satisfactory answer to the question of where and when ground-based profilers should be used must be given in the context of a total observing system, where validated requirements are met by a combination of platforms and sensors (Berau, 1997). A clear understanding of meteorological requirements is fundamentally important, and often difficult to achieve. The list of potential needs for data is long and ranges in scale from initialization of global numerical models to the monitoring of very small-scale events such as wind shear at airports. An equally long list can be generated for the desired parameters and constituents to be measured, the required resolution (temporal and spatial), and specification of accuracy. The challenge faced by observing system designers is to match these requirements with the available sensors and platforms. Last two decades it was some additional support for improving of meteorological instruments and methods of observation from European Community in the form of COST Program (COST – European Cooperation in the field of Scientific and Technical Research, http://cost.cordis.lu) special actions. Some of actions were (and is) directly connected with ground-based remote sensing:

- COST-73 – Weather radar networking (complete 24.09.1991);
- COST-74 – Utilization of VHF/UHF radar wind profiler networks for improving weather forecasting in Europe (complete 16.09.1991);
- COST-75 – Advanced Weather Radar Systems (complete 28.10.1997);
- COST-76 – Development of VHF/UHF Wind profilers and Vertical Sounders for Use in European Observing Systems (complete 23.03.2000);
- COST-712 – Microwave Radiometry (complete 28.11.2000);
- COST-720 – Integrated ground-based remote sensing stations for atmospheric profiling (running 03.10.2005);
- COST-722 – Short range forecasting methods of fog, visibility and low clouds (running 29.11.2006);
- COST-727 – Measuring and foresting atmospheric icing structures (running 26.04.2009).

The improving reliability of automated ground-based remote sensors makes it feasible to place them in uninhabited locations where they need only to be visited every few months or even years. This can result in significant savings over more traditional observing systems that require people on-site continually. For future development of integrated remote sensing profiling system for upper-air measurement it is needed also to know in details the possible applications from different remote sensing instruments.

3.1. SODAR

Measured and calculated parameters in atmospheric boundary layer:

- Horizontal wind speed and direction;
- Vertical wind speed;
- Standard deviations of all wind speed components;
- Temperature structure parameters;
- Reflectivity to derive boundary layer height and height of nocturnal inversions;
- Indication of temperature inversions and it’s low border height;

- Determination of atmospheric stability.

Typical SODAR applications include:

- Micrometeorological studies;
- Local climate analysis;
- Regional weather forecast;
- Pollution flow monitoring;
- Supplement of network weather stations;
- Measurement of optical propagation conditions.

3.2. RASS

In addition for a SODAR function it may to measure virtual temperature with a high vertical resolution. It gave additional possibilities for pollution flow monitoring and regional weather forecasting.

3.3. Radar wind profilers

Measured and calculated parameters are (in the altitude range 100 m÷15 km for different radar frequencies):

- Horizontal wind speed;
- Vertical wind speed;
- Indications on temperature inversion;
- Refractive index fluctuations.

Typical radar wind profiler data applications:

- Weather forecasting (particularly if using radar wind profilers network as in USA and UK);
- Forecasting of precipitation;
- Forecasting of air pollution and air quality monitoring systems;
- Using at airports to monitor low-level winds in the vicinity of runways used for takeoff and landings;
- Research studying of ionosphere and middle atmosphere.

3.4. Lidar

Measured and calculated parameters are in the altitude range 100 m ÷ 105 km for different wavelengths and using laser types:

- Aerosol scattering ratio;
- Backscatter depolarization ratio;
- Vertical profiles of water-vapor mixing ratio;
- Vertical profiles of temperature;

- Stratospheric ozone vertical profiles of mixing ratio;
- Cloud bourder altitude;
- Vertical profiles of horizontal wind.

Typically lidar data application are:

- Research studying in the middle atmosphere;
- Investigations of atmospheric boundary layer including atmospheric radiations;
- Urban meteorology (for instants, investigations of city heat island).

3.5. Passive microwave remote sensing systems

Measured and calculated parameters are (for different altitude range for different frequencies):

- Temperature profiles (from the ground up to 5 km);
- Total water vapor content;
- Total liquid water content in clouds;
- For combined system: water vapor and liquid profiles;
- Wind profiles (for the lowest part of atmospheric boundary layer).

Typical applications of microwave radiometers data are:

- Regional weather forecast;
- Local climate analysis;
- Pollution flow monitoring;
- Urban meteorology;
- Forecasting of radio wave propagation;
- Validation of satellite data;
- Supplement of network weather (in Russia there is network of ABL temperature profile monitoring on the basic of microwave scanning single channel radiometers);
- Remote detection of aircraft-icing conditions;
- Weather modifications;
- Research studying of atmospheric radiation.

4. SUMMARY

Ground-based remote sensing can be effective for a wide range of meteorological operational applications. The main advantages of remote sensors are its low operational cost and continuity in time which allows time series and time-height cross section to be delivered. Most of modern remote sensing systems are very portable and can provide reliable automated continuous profiling from a variety of sites.

5.1. APPENDIX 1. Table 1. Summary of capabilities and limitations of different ground-based observing techniques that can provide remote sensing of temperature, humidity and cloud structure

Instruments	Strengths	Limitation
1	2	3
1. SODAR	- Continuous sampling of lower atmospheric boundary layer; - Finer vertical resolution; - Smaller time of integration; - Can sample below 100 m; - Relatively low cost	- Interference from precipitations; - Interference from acoustic noise sources; - Height (>15 m/s) winds limit altitude coverage; - Negative effect of externally generated acoustic noise to nearby residences; - Altitude coverage limited during temperature inversion; - Performance degrades in low humidities, cold.
2. RASS	- Can measure victual temperature profiles in ABL; - Can work with SODARs; - Low to moderate cost	- Output is virtual temperature, need in convertation; - Adversely affected by precipitation; - Should correct for vertical motion; - Altitude coverage limited during temperature inversion; - High (>15 m/s) winds limit altitude coverage; - Interference from ground clutter.
3. Radar wind profilers	- Data not as sensitive to high winds; - Not sensitive to acoustic noise; - Continuous sampling of ABL; - Better operates in turbulent atmosphere; - Moderate cost	- Interference from bird, aircrafts; - Interference from precipitation; - Lowest altitude sampled ~ 50 m; - Possible interference with ground radio transmitted sources (EM noise); - Performance degrades in low humidities;

1	2	3
		- Large sample volumes coarser resolution.
4. Lidar	- Continues sampling of the middle atmosphere; - High temporal and spatial resolution; - Not sensitive to acoustic or EM noise; - (Doppler lidar) continuous sampling of ABL parameters	- Limited range in fog, clouds, high aerosol concentration conditions; - Limited range in precipitations; - Operation in unattended mode needs more demonstration; - Relatively high cost.
5. Microwave temperature profilers for ABL (single channel)	- Continues unattended measurement practically in all weather conditions; - Can operate in urban area; - Automatic calibration without special external microwave target; - Relatively high vertical resolution in contrast with multichannel microwave profilers; - High temporal resolution; - Relatively low cost	- Altitude range limited at 1 km; - Relatively low vertical resolution in contrast with active instruments (lidar, RASS)
6. Microwave temperature profilers for troposphere (multichannel)	- Continuous unattended measurements; - Can operate in urban area; - High temporal resolution; - Not sensitive to fog and high aerosol concentration	- Interference from precipitable clouds; - Interference from water vapor; - Interference from heavy rain; - Low vertical resolution; - Need in external microwave target with liquid nitrogen for calibration; - Relatively high cost
7. Microwave passive systems for water vapor and cloud liquid measurements	- Continuous unattended measurement practically in all weather conditions excluding heavy rain; - High temporal resolution; - Can operate in urban area	- Need in external microwave target for calibration; - For profiling need in combined measurement with additional instruments (Doppler radar); - Influence from liquid precipitations

5.2. APPENDIX 2. Commercially – available ground-based remote sensing systems

At this appendix are presented some examples of commercially – available ground-based remote sensing systems as additional information for the review. It is not a catalog of modern instruments, but only examples of technical parameters. All information – from manufacturer flyers.

5.2.1. SODAR

1. MODOS – Mobile 3 – component SODAR (**www.metek.de**)

   Measuring Ranges:
   - wind velocity: 0÷35 m/s;
   - wind direction: 0÷360^o;
   - minimum measuring height: 10÷30 m;
   - maximum measuring height: 200÷500 m;
   - finest height resolution: > 10 m.

   Measuring accuracy:
   - wind velocity: 0,5 m/s;
   - wind direction: 5 degree;
   - radial wined component 0,1 m/s.

   From same manufacturer also available Phase Array SODAR: DSDPA. 90-24; DSDPA.90.64

   RASS extension is also available.

2. Aero Vironment mobile 3 component SODAR Model 2000 (**www.aerovironment.com**):
   - height range: 50÷750 m;
   - height resolution: 20 m;
   - frequency: 1400÷2500 Hz.

3. 3 – component SODAR "Volna-3" (Institute of Atmospheric Optics, Russian Academy of Science, Tomsk, Russia, **odintsov@iao.ru**):
   - height range: 25÷750 m;
   - height resolution: 12÷25 m

   Measured ranges:
   - wind speed: 0,3÷30 m/c with the accuracy ±0,2 m/c for wind speed and ±3 degree in wind direction;
   - antennas dimensions: 2×2×3 m.

4. 3 – component SODAR "LATAN-3" (Institute of Atmospheric Physics, Russian Academy of Science, **margo@omega.ifaran.ru**):
   - altitude range: 30÷500 m;

- height resolution: 8-17 m.

Measured ranges:

- horizontal wind speed: 0,2÷30 m/s;
- vertical wind speed: ± 2 m/c.

Measured accuracy:

- C_1^2: 40%;
- vertical wind speed: ± 0,1 m/c;
- horizontal wind speed: ± 0,5 m/c.

5.2.2. Mini-SODAR

1. Mini-SODAR Model 400 Aero Vironment (**www.aerovironment.com**)

Technical specifications:

- maximum altitude: 200 m;
- minimum altitude: 15 m;
- height resolution: 5 m;
- transmit frequency: 4500 Hz;
- averaging interval: 1 to 60 minutes;
- wind speed range: 0÷45 m/s;
- wind speed accuracy: ≤ 0,5 m/s;
- wind direction accuracy: ± 5 degree;
- weight: 116 kg;
- antenna dimension: 1,2×1,2×1,5 m.

2. Mini-SODAR with Phased Array Antenna (**www.remtechinc.com**).

Different type with different altitude range: PA1, PA2, PA5. A smallest one is PAO with following parameters:

- Number of elements in antenna: 52;
- Central frequency: 3500 Hz;
- Antenna size: 0,4×0,4 m;
- Antenna weight: 12 kg;
- Acoustic Power: 1 W;
- Maximum range: 1000 m;
- Average range typical conditions: 600 m

RASS function are also available.

5.2.3. RASS

1. Vaisala LAP-3000 system (**www.vaisala.com**)
   - Maximum height: 1,0÷1,5 km;
   - Minimum height: 75÷150 m;
   - Range resolution: 60, 100, 200, 400 m;
   - Temperature measurement accuracy: 1°C;
   - Operated radio frequency: 915 MHz, 1290 MHz.
2. REMTECH RASS Extension system (can operate with REMTECH SODARS)

   Radar part technical parameters:

   - Frequency: 915 MHz or 1290 MHz.

   Radar antennas (2 at 5 meters separation):

   - Diameter: 2000 mm;
   - Focal length: 658 mm;
   - Source type: circular polarization;
   - Power consumption: 200 W.

5.2.4. Radar wind profilers

1. Vaisala LAP-3000 Doppler Lower Atmosphere Radar (**www.vaisala.com**)

   Technical parameters:

   - Maximum height: 2÷5 km;
   - Minimum height: 75÷150 m;
   - Range resolution: 60, 100, 200, 400 m;
   - Wind speed accuracy: ≤ 1 m/s;
   - Wind direction accuracy: ≤ 10 degree;
   - Averaging time: 3÷60 minutes;
   - RF power output: 600 W peak;
   - Antenna: electrically steerable;
   - Aperture: 2,7 m^2;
   - Power requirements: about 2 kW.
2. Mini-Radar wind Profiler (**www.apptech.com**)

   System specifications:

   - Operating frequency: 915 MHz;
   - Peak transmitter power output: 1000 W;
   - Minimum range: 100 m;
   - Maximum range: 3000 m;

- Range resolution: 75, 150, 300 m;
- Doppler radial velocity: ± 0,5 m/s;
- Antenna: planar array (2,4 m × 2,4 m);
- Incoherent data average: 60 sec.

3. Mini-Radar wind profiler (Moscow State Academy of Instrument Engineering and Information Science, Moscow, Russia, **info@attex.ru**)

Technical parameters:

- Altitude range: 10÷3000 m;
- Altitude resolution: 20÷50 m;
- Wind velocity range: 1÷30 m/c;
- Accuracy of wind velocity measurement: 0,5 m/s;
- Accuracy of wind direction measurement: 8 degree;
- Wavelength: 1,8 cm;
- Average emitted power: 1 W;
- Weight: 35 kg;
- Power requirements: about 200 W.

5.2.5. Lidars

Ordinary lidar is expensive instrument and can be manufacturing by different companies or University by a special order. For atmospheric investigations are using different techniques: Raleigh, Mie and Raman scattering, differential absorption, Doppler and resonance scattering. In continuous base lidars for atmospheric investigations are using in University of Bonn, Germany (temperature profile measurement in troposphere and stratosphere); Pennsylvania state University, USA (Raman lidar); Institute of Atmospheric Optics SB RAS, Tomsk, Russia (stratospheric ozone, stratospheric aerosol; temperature profiling, water vapor); Leibniz Institute of Atmospheric Physics, Germany (potassium lidar and Rayleigh/Mie/Raman lidar); Sandia National Laboratory, USA (Raman lidar); National Institute of Environmental Studies; Tsukuba, Japan (Mie scattering aerosol lidar), Meteorological Research Institute, Tsukuba, Japan (Raman lidar for measuring of water vapor and aerosol), etc.

5.2.6. Passive Microwave Remote Sensing Systems

1. MTP-5HE-single-channel scanning radiometer for atmospheric boundary layer temperature profiling (**www.kippzonen.com**).

Technical parameters:

- Altitude range: 0÷1000 m;

- Altitude resolution: 50÷200 m;
- Measurement cycle: 150 s minimum.

Accuracy of temperature:

- profile retrieval: 0,3÷0,8^{o}C;
- Receiver sensitivity: 0,08^{o}C;
- Power consumption: 60 W;
- Ambient temperature range: -40^{o}C ÷ +50^{o}C;
- Calibration: self-calibrating;
- Dimensional: 25 cm diameter, 60 cm length;
- Total weight: 20 kg.

Also available modifications of the instrument: MTP-5H – with amplitude range 0÷600 m but with improved accuracy, and MTP-5P-specially designed for Antarctica conditions and with vertical resolution 10÷20 m at the lowest 100 m; MTP-5M – mobile system.

2. TP/WVP – 3000 – Temperature and water vapor profiler (**www.radiometrics.com**).

Continuously profiles water vapor to 10 km height by observing 5 frequency channels from 22 to 30 GHz, and 7 channel from 51 to 59 GHz for temperature profiling, also provides a liquid water profile.

Technical parameters:

- Number of channels: 12;
- Cycle time: 20 s;
- Operating temperature: -50^{o}C to +50^{o}C;
- Receiver resolution: 0,25^{o}C;
- Accuracy: 0,5^{o}C;
- Weight: 32;
- Power: 120W maximum.

Some modifications are also available: WVP-1500-water vapor profiler with 5 frequency channels from 22 to 30 GHz; TP-2500 – temperature profilers (7 channels from 51 to 59 GHz).

3. MICCY (microwave radiometer for cloud cartography) – a 22-channel instrument for measurement of cloud liquid water path (LWP), integral water vapor (IWV), vertical profiles of temperature, vertical profiles of humidity (**www.radiometer-physics.de**).

Technical features:

22 channels located in three frequency bands:

Band A: 10 channels from 22,235 GHz to 28,235 GHz, dual polarization at 25,535 GHz;

Band B: 10 channels from 50,8 GHz to 58,8 GHz, dual polarization at 54,8 GHz;

Band C: 2 channels at 90 GHz, dual polarization.

Antrenna: 95 cm Cassegrain system;

Absolute radiometric accuracy: 1,0K.

Calibration procedures:

- Automatic gain calibration and sky tipping;
- Four point noise calibration;
- Build-in cold target (can be filled with liquid nitrogen).

Three – stage thermal stabilization of all receiver components;

Automatic rain shutter system, dew blower;

Weight: approx. 2500 kg (including the trailer);

Size: 3,2 m/1,5 m/2,7 m.

Also available dual profiler RPG-HATPRO; RPG-LWP liquid water path radiometer.

4. DHS (Dangerous Height Sensor) – dual-channel system for retrieval of cloud parameters (LWP) and the average temperature of liquid water lager in clouds (**www.kippzonen.com**). Main application – aircraft icing detection.

Technical parameters:

- working frequencies:	85 GHz and 37 GHz;
- calibration:	two internal microwave targets and “clear sky” technique;
- antenna beam width:	6^o;
- power consumption:	maximum 200 W average 60 W;
- ambient temperature rang:	$-50^oC \div +50^oC$ (in all weather conditions);
- total weight:	40 kg.

5. ASMUWARA – All sky Multi-Wavelength Radiometer (designed and built at Institute of Applied Physics at the University of Bern, **www.unibe.ch**)

This instrument consists 9 channel in the frequency range from 18 to 151 GHz, a broad-band thermal infrared radiometer (wavelength band 8 to 14 µm), meteorological sensors, and optional camera. The radiometers are housed in a temperature – controlled cylinder with all beams aligned in a horizontal direction pointing to a rotating mirror scans the sky and two calibration loads. All channels have the same view and a common full beam width of 9^o, formed by corrugated horns. Radiometer can provide instantaneous and continuous measurements of vertically integrated water vapor and liquid water.

6. GSR – Ground-based Scanning Radiometer of the NOAA/Environmental Technology Laboratory (ETL) (**www.etl.noaa.gov**).

GSR is a multi-frequency scanning radiometer operating from 50 to 380 GHz. The radiometers are installed into a scanning drum or scan head. The GSR uses a sub-millimeter scan head with 11-channels in the 50-56 GHz region, a dual-polarization measurement at 89 GHz, 7 – channels around the 183,31 GHz water vapor absorption line, a dual-polarized channel at 340 GHz, and three channels near 380,2 GHz. It also has a 10,6 micrometer infrared radiometer within the same scan head. All of the radiometers use lens antennas and view two external reference targets during the calibration cycle. In addition, each of the radiometers design included two internal reference points for more frequent calibration cycle. The primary use of the instrument is to measure temperature, water vapor, and clouds at cold and dry conditions.

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