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RADIOSONDES

W F Dabberdt and R Shellhorn, Vaisala Inc., Boulder, CO, USA

H Cole, National Center for Atmospheric Research, Boulder, CO, USA

A Paukkunen, J Hörhammer and V Antikainen, Vaisala Oyj, Helsinki, Finland

Introduction

The radiosonde is an expendable, balloon-borne device that measures the vertical profile of meteorological variables and transmits the data to a ground-based receiving and processing station. These profiles are typically obtained twice each day and are the core of the global weather observing system that provides inputs to numerical forecast models. The sensor package routinely measures the variation with altitude of temperature, humidity, and pressure as the balloon ascends from the land or ocean surface to heights up to about 30 km (a pressure altitude of about 11 hectopascals, hPa). When the device also measures winds, it is more properly called a rawinsonde, although the term radiosonde is commonly applied to both. The height profile of these meteorological variables constitutes an upper-air sounding that is known as a radiosonde observation or RAOB. In some cases, a balloon without a radiosonde is tracked by either optical or radar techniques in order to measure only winds. This type of balloon is known as a pilot balloon or simply a pibal, but it is not a radiosonde.

In 1999, there were 100 operational or synoptic radiosonde stations in the United States; they made a daily average of 182 soundings. In the continental US, an average distance of 315 km separates radiosonde stations. In 1999, there were 992 radiosonde stations worldwide (**Figure 1**) that made an average of 1209 soundings each day in support of weather forecast activities, while an additional 65 pibal stations made 576 wind soundings daily. Additional soundings are made for specialized purposes of which defense applications are the most significant. The global numbers of RAOB and pibal soundings are down considerably from their peak daily values in 1988 of 1660 and 964, respectively. The approximately half a million radiosondes used annually are manufactured by less than 10 companies worldwide. Of these, the Vaisala company headquartered in Helsinki manufactures about 70% of the global supply of radiosondes. Vaisala was founded in 1936 by Professor Vilho Vaisala, who in 1931 invented one of the world's first radiosondes (*see* Appendix).

Since 1957 all stations have made their soundings at the same times, 00.00 and 12.00 UTC, although many stations outside the US and Europe have reduced soundings to one per day because of budgetary constraints. Countries launching operational radiosondes are members of the World Meteorological Organization's World Weather Watch program; as such, they freely share their sounding data with each other. Shortly after an operational upper-air sounding is completed, a standard data message is prepared and made available to all nations using the Global Telecommunications System. These TEMP messages are transmitted in a universal format that reports meteorological conditions at various standard or so-called mandatory (pressure) levels as well as at significant levels, which represent levels where prescribed changes in meteorological conditions occur.

There are two primary purposes of upper-air soundings: to analyze and describe current weather patterns, and to provide inputs to short- and medium-range computer-based weather forecast models. One very important, specialized use of atmospheric soundings is in support of forecasting hurricane movement. Special radiosondes called dropwindsondes are launched from weather reconnaissance aircraft to observe atmospheric structure in the core of the hurricane as well as in the area downwind of the storm itself. These dropwindsonde measurements were the single most important factor in a 20% increase in hurricane forecast accuracy over the decade of the 1990s. Other uses of radiosonde data include climate studies, air pollution investigations, aviation operations, and defense applications. The radiosonde continues to be the backbone of an eclectic suite of measurement technologies (measurements both remote and *in situ* that are made from ground-based, airborne, and satellite platforms) used to provide data for input to numerical weather forecast models.

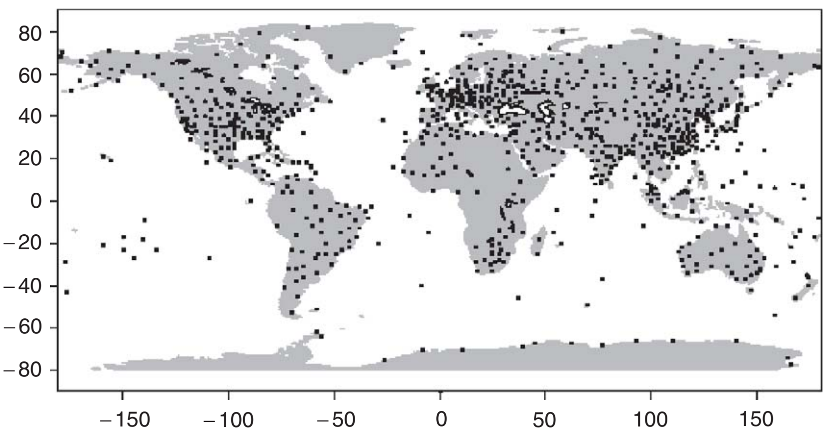

Figure 1 Global radiosonde station network.

Radiosonde Operations

The radiosonde is carried aloft by a balloon as part of a flight train (**Figure 2**). The balloon itself may be made of either natural rubber (latex) or synthetic rubber (neoprene). The mass of the flight train, the desired ascent rate, the type of gas used, and the maximum height of the sounding determine the size of the balloon. Operational radiosonde systems typically use balloons that weigh anywhere from 300 to 1200 g; they are filled to ensure an ascent rate of 300 m min^{-1}. Hydrogen is the gas most commonly used to inflate the balloon and provide its lifting capacity, although helium and natural gas are sometimes used for special applications. The flight train consists of five components: (1) the balloon; (2) a parachute to bring the radiosonde safely back to Earth after the balloon bursts; (3) 20–60 m of nylon separation line that isolates the radiosonde's sensors from water vapor and thermal contamination by the balloon; (4) a dereeler to let out the nylon line after launch; and (5) the radiosonde itself. A few countries such as the US and Switzerland actively seek to recover and then reuse their radiosondes. In the US, it is estimated that about 18% are reused after extensive refurbishment, while in Switzerland, more than 60% are recovered and reused.

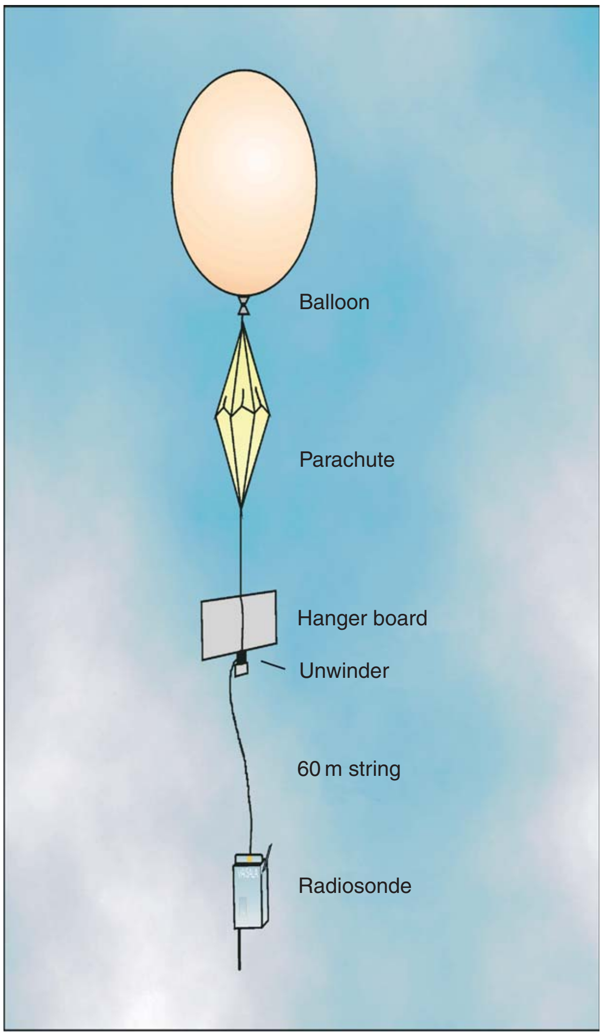

Figure 2 Typical radiosonde flight train, including balloon, parachute and hanger board, unwinder mechanism, separation line, and radiosonde.

Components of the Modern Radiosonde

The radiosonde is an electronics unit that comprises three major sections: a suite of sophisticated meteorological sensors; signal-processing electronics; and a radio transmitter to relay the measurements back to a receiver at the radiosonde launch station. The meteorological measurements are made at intervals that vary from 1 to 6 s, depending on the type and manufacturer of the radiosonde. The meteorological community has been assigned two radio frequency bands for use in transmitting meteorological data: 400–406 MHz and 1675–1700 MHz. These bands are under continuing pressure from the telecommunications industry, which seeks to use them for commercial purposes. All of the world's radiosondes are required to meet certain performance standards that have been established by the WMO (see **Table 1**). **Figure 3** illustrates four different radiosondes currently in use around the world.

Overview of Thermodynamic Sensors

Thermodynamic sensor types vary widely among radiosondes currently in use throughout the world. Temperature sensors are of four designs: capacitance sensors, thermistors, resistance wires, and bimetallic elements. The two common humidity elements are carbon hygristors and planar thin-film capacitance sensors, although gold-beater's skin is still used in Russia and China. Pressure measurements are typically made with either an aneroid cell or a piezoresistance element. There are about a dozen different radiosonde designs presently in use. As radiosondes have become more advanced, their changes have also created special challenges to climatologists seeking to piece together a consistent and homogeneous multidecadal global database to analyze and understand climate change. As a result, climate researchers must account for biases in the historical records due to changes in instrumentation and observing methods, many of which have poor or no documentation. In the

Table 1 Accuracy requirements (expressed as standard error) for upper-air measurements for synoptic meteorology

Variable	*Range*	*Accuracy requirement*
Pressure	Surface to 5 hPa	±1 hPa
Temperature	Surface to 100 hPa	±0.5 K
	100 to 5 hPa	±1 K
Relative humidity	Troposphere	±5% (RH)
Wind direction	Surface to 100 hPa	±5° for wind speed <15 m/s ±2.5° for wind speed >15 m/s
	100 to 5 hPa	±5°
Wind speed	Surface to 100 hPa	±1 m/s
	100 to 5 hPa	±2 m/s
Geopotential height of significant levels	Surface to 100 hPa	±1% near the surface decreasing to ±0.5% at 100 hPa

Source: World Meteorological Organization (1996) *Guide to Meteorological Instruments and Methods of Observation*, 6th edn. Publication No. 8. Geneva: WMO.

United States alone, these changes have been varied and significant. Four distinctly different humidity sensors have been in use since 1943. Temperature measurements have undergone major changes, including sensor type, size, and coating, exposure to the air stream, and corrections to account for radiation biases. At present, the US National Weather Service uses radiosondes from two different manufacturers, each having its own distinct set of pressure, temperature, and humidity sensors. The Vaisala company produces about 70% of the world's radiosondes, and added emphasis is given below to aspects of the design of its radiosondes and sensors.

Thermodynamic Sensors

Sensors used with Vaisala radiosondes are all of the capacitance type. Changes in pressure, temperature, and humidity result in changes in the capacitance information from each sensor, which in turn is changed to a frequency signal by using sensor transducer electronics. Sensor frequency measurements are compared with the frequencies of reference capacitance transducers, and these in turn are converted to physical measurements based on factory calibration measurements. In the case of pressure, the distance between capacitance plates changes as atmospheric

Figure 3 Examples of Radiosondes in Current Use Around the World.

pressure changes, causing a change in the measured capacitance. Older pressure sensors use an aneroid or bellows-type sensor that responds mechanically to pressure changes. Modern pressure transducers are very small silicon, micromechanical sensors. Pressure sensors also have a temperature dependence that is compensated by factory calibration of the sensor. The temperature change of capacitive sensors is measured by the change in the dielectric constant of the sensor. Older capacitive sensors consisted of a sensor that was hermetically packed inside glass. Newer capacitive temperature sensors are extremely small and fast, owing to a special twin-wire construction. Essential aspects of modern temperature and humidity sensors (and their supporting members, i.e. the sensor boom as seen in **Figure 4**) are their different coatings and treatments to minimize solar heating and improve water repellency. The approach used to measure humidity in all Vaisala radiosondes is also based on changes in the dielectric constant. The humidity-sensing technology is based on so-called thin films. The dielectric material is a very thin layer of a special proprietary polymer that has an optimum combination of measurement properties, including stability, repeatability, hysteresis, response time, and temperature dependence. Thin-film humidity sensors are calibrated to provide output in terms of percent relative humidity with respect to water; the temperature dependence is compensated by use of temperature-dependent calibration coefficients determined from factory calibration tests. Some Vaisala humidity probes incorporate two sensor elements that include heating of the sensor elements to minimize affects of water condensing on the sensors as the radiosonde moves from warm to cold layers during its ascent. The two sensors are alternately heated in sequence, and the measurement is taken from the passive sensor. The sensors are very small and designed for fast response.

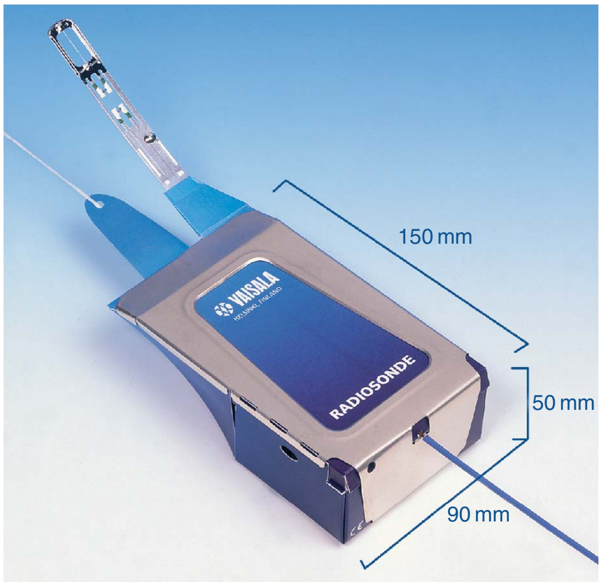

Figure 4 Vaisala RS90 Radiosonde with sensor boom.

The accuracy of radiosonde data is a combination of multiple factors: sensor performance; related transducer electronics; mechanical construction of the sonde and sensor housing; sensor and sensor-boom coatings and treatments; calibration technology; and calibration and correction algorithms. In addition to issues of radiosonde performance, the uncertainty of upper-air measurements includes sampling considerations, such as the density of the observation network, time interval between observations, and the homogeneity of the atmosphere. Together, these instrumental and environmental factors govern the accuracy and representativity of the observations.

Specialized Radiosonde Sensors

Some radiosonde manufacturers offer optional sensors to make supplemental environmental measurements. Additional electronics are used to interface the supplemental sensors to the radiosonde. Measurements of ozone concentration and radioactivity are the two most common supplemental measurements. Radiosonde measurements of ozone are made worldwide, although at fewer stations and typically only once per day or less often. The most common radiosonde ozone sensor is the electrochemical type, while radioactivity is typically measured with Geiger–Müller tubes. Other supplemental measurements in use today include dew point, optical backscattering by fine particles, electric field, and video imaging of particles and hydrometeors. Most advanced radiosonde ground systems effectively support both synoptic and research users, and offer options for post-ascent data calculation and analysis of supplemental measurements.

The Vaisala ozonesonde consists of an electrochemical ozone sensor connected to an interface unit and a modified radiosonde. Consequently, humidity, pressure, temperature, and geopotential height can be measured simultaneously with ozone sampling. Upper-air winds are also measured. This lightweight, balloon-borne instrument is capable of measuring the vertical distribution of atmospheric ozone up to 3 hPa. The uncertainty of the ozone measurement is of order 5–10% of the local values. The electrochemical concentration cell (ECC) ozone sensor detects ozone on the basis of an iodine–iodide oxidation-reduction or redox electrode reaction in neutral buffered solution. The sensor consists of an electrochemical concentration cell that contains two platinum electrodes immersed in separate potassium iodide solutions of different concentrations, which are separate anode and cathode chambers. The chambers are linked with an ion bridge. As air containing ozone flows into the cathode solution, a chemical reaction occurs and the platinum electrodes carry electrons between the cells of the sensor. An electrical current is generated in proportion to the rate at which ozone enters the cell. The ozone concentration is determined from the electric current measurement using an equation that considers the airflow rate, air pressure, and pump temperature. The interface can also be used with other sensor types, such as the Brewer–Mast sensor. The Brewer–Mast sensor uses similar ozone detection reaction, but instead of a reference chamber, the driving potential for the measurement circuit is an electrical circuit. The ECC-type sensor is more accurate and is more widely used.

The Vaisala radioactivity sonde is a combination of a radioactivity sensor and a modified radiosonde. The radioactivity sonde can measure the vertical profile of radioactivity in the troposphere and in the lower stratosphere, up to altitudes of 40 km. The radioactivity sensor measures radiation with two Geiger–Müller detectors – ionization chambers filled with special gas mixtures. One detector is sensitive only to gamma radiation, while the other measures both gamma and beta radiation. This way it is possible to make measurements of both gamma and beta radiation. The detectors have pulse outputs; the count rate is proportional to the radiation intensity and is read at fixed time intervals. The measurement accuracy is about $\pm 10\%$.

Overview of Windfinding

There are several techniques for measuring winds with only a balloon or with a combination balloon and radiosonde. When a radiosonde measures winds it is called a radio-wind-sonde or rawinsonde. Rawinsonde windfinding methods vary widely. In all cases, the winds are determined by observing the drift of the balloon. One class of wind measurement techniques tracks the balloon externally using one of three methods: (1) optical systems use a theodolite to visually track the balloon's azimuth and elevation; (2) radio theodolites track a radio signal sent from a transmitter on the radiosonde, again to obtain azimuth and elevation information; and (3) radar systems track a radar retroreflector suspended from the balloon to obtain slant range, azimuth, and elevation. The second class of wind measurement techniques uses various navigation systems. Two such systems currently in use employ the LORAN-C navigation system and various VLF systems, such as the Russian ALPHA system and the US Navy's VLF system. A new navigation-based windfinding technique is now coming into widespread usage. A receiver inside the radiosonde accurately measures the horizontal and vertical Doppler velocity of the radiosonde with respect to those Global Positioning System (GPS) satellites that can be observed at any given time (typically, four to eight satellites). Other types of GPS receivers also observe the latitude, longitude, and altitude of the radiosonde. In both cases, the GPS receiver measures directly the drift velocity of the balloon and hence the wind. Two major advantages of the GPS-based techniques are the high accuracy and precision of the wind measurements, and the worldwide coverage of GPS.

Tracking Techniques

Optical tracking methods One of the earliest methods for determining the winds aloft was to visually or optically track small balloons, called pilot balloons (pibals). This method was developed in the mid-1870s using a small expendable balloon tracked with a small telescope. The small optical device, similar to a surveyor's transit, is called a theodolite and can accurately measure elevation and azimuth angles. If the balloon's height can be determined then its position can be found by trigonometry. There are basically two pilot balloon techniques still in use: (1) single-theodolite and (2) double-theodolite. In the former, the elevation and azimuth angles of the balloon are measured at regular intervals (typically once per minute). Balloon altitude is determined by assuming a constant ascent rate that is determined from the size and free lift of the balloon. Balloon position is then calculated from the height and the azimuth and elevation measurements. Tracking the balloon during a nighttime observation is accomplished by attaching a light stick or small battery-powered light. In the double-theodolite technique two theodolites are located a known distance apart (the baseline) and simultaneous observations taken of the balloon at given time intervals. By measuring the azimuth and elevation angles to the balloon from the two known positions, the three-dimensional balloon position can be determined by the law of sines. The double-theodolite method enables accurate measurements of the balloon position without assuming a constant rate of ascent for the balloon, which can be a source of error. In this method the baseline distance needs to be accurately measured and should be at least one-fifth of the maximum range to the balloon. The baseline should also be perpendicular to the prevailing winds. The method is not routinely used because of baseline restrictions and the cost and difficulty of coordinating two sets of observers.

Radiotheodolite and radar methods Another tracking technique used for determining winds is called radio direction finding or RDF. During World War II the US Army Signal Corps developed the first RDF system, called the SCR-658. This system operated at 400 MHz and used two separate operators to steer a large antenna array to determine the direction of the radiosonde transmitter. A more modern radio direction finding antenna automatically tracks the 1680 MHz telemetry signal transmitted from the radiosonde. The antenna azimuth and elevation data are sent to a computer at the ground station along with the pressure height data from the radiosonde to determine the change in radiosonde position (winds) during flight. The RDF technique (**Figure 5**) is the radio frequency equivalent of the optical theodolite method, and the tracking system is called a radiotheodolite. There are different types of RDF antennas, including 2–3 m diameter dish antennas and phased-array flat-plate antennas. RDF systems can resolve the azimuth and elevation angles to within 0.05°. If the upper-level winds are high then the radiosonde will be a long distance away, resulting in the antenna elevation angle being near the horizon. At stations that experience high winds, the radiosondes can be equipped with a transponder to measure slant range or distance to the radiosonde. Winds can then be determined using azimuth, elevation, slant range, and height of the radiosonde. A similar method for tracking the radiosonde uses a radar reflector on the balloon flight train so that it can be tracked by windfinding radar. Slant range to the radiosonde is measured by the radar as well as azimuth and elevation angles. Radar windfinding is a common method used in many countries around the world; in 1998 about 45% of the stations used radar, as tallied in Oakley (1998).

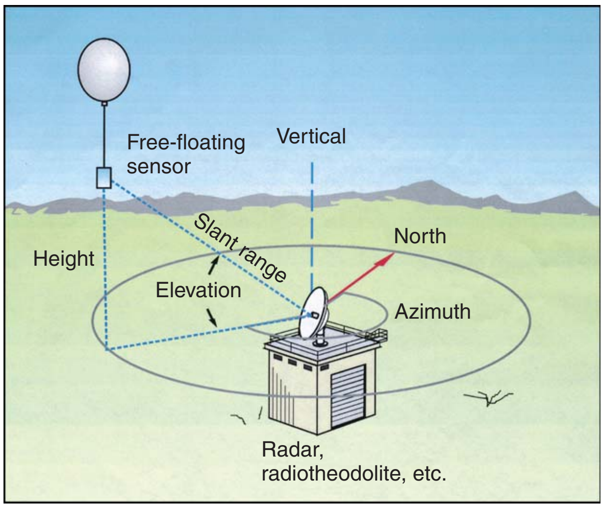

Figure 5 Angle-dependent tracking system.

In the Russian and Chinese upper-air networks a combination RDF-transponder method is used, called secondary radar. Some 200 such systems are deployed worldwide. The parabolic or array-type RDF antenna transmits a short pulse that is received by the radiosonde. The radiosonde then 'wakes up' and retransmits the pulse by transmitting the temperature and humidity data, which are received by the ground-based RDF antenna. The RDF antenna azimuth and elevation angles are measured and the slant range is determined from the travel time of the pulse. Secondary radar systems use radiosondes that do not have a pressure sensor; pressure is calculated from the hydrostatic equation.

Navigation aids (NAVAIDS) The use of navigation aids for obtaining upper-air winds from radiosondes began in the early 1960s. The US Weather Bureau (now the National Weather Service of the National Oceanic and Atmospheric Administration, an agency of the US Department of Commerce) sought to find a way to measure winds at sea for the Ships of Opportunity Program. At that time the only way to measure winds aloft at sea was with a radar or RDF system; both systems were costly and required a mechanical stabilization system for the tracking antenna. In 1964, the bureau awarded a contract to Beuker's Laboratory Inc. (BLI) of New York to develop a windfinding system using retransmitted Loran-C navigation signals to track the radiosonde. The technique proved successful. Owing to the limited coverage of Loran-C, two years later the worldwide Omega navigation system was proposed as an alternative for windfinding. Radiosondes that use these NAVAID signals to determine winds contain a small, inexpensive radio receiver to receive the navigation signals from fixed ground stations. The radiosonde then retransmits (**Figure 6**, usually at 400 MHz) the signals to the data processing system at the ground station. There are at present three types of NAVAID signals in use: (1) Loran-C, (2) very low-frequency (VLF) systems, and the (3) Global Positioning System (GPS).

Loran-C coverage has increased since 1964, but because its primary use is for coastal navigation it does not provide worldwide coverage. Loran-C stations transmit a unique series of pulses at 100 kHz that identify each station. If the radiosonde receives and retransmits signals from at least three stations, then

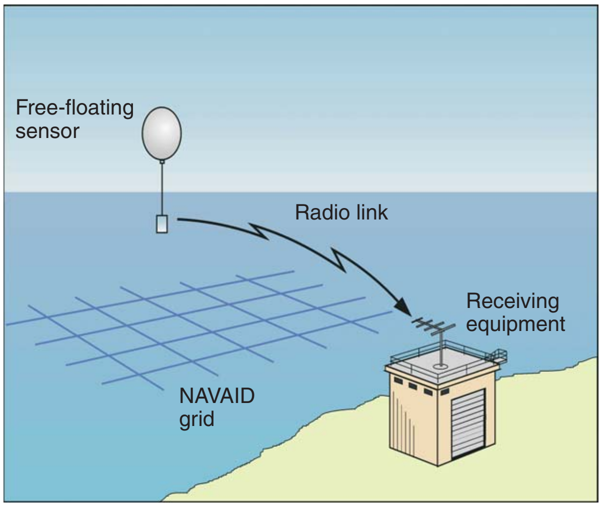

Figure 6 NAVAID retransmission system.

the data processing system at the ground station can determine the time of arrival of those signals at the radiosonde and its distance from each ground station. Winds are determined from the change in position of the radiosonde.

The other class of ground-transmitting navigation systems is the VLF systems. These operate in the 10–30 kHz frequency range and their long-wavelength signals are characterized by low attenuation and the ability to propagate long distances; this allows worldwide coverage with a minimum number of ground transmitters. The Omega navigation system was the most widely used VLF system for both navigation and windfinding until it was closed down on 30 September 1997 because of cost considerations and the emergence of more accurate GPS windfinding systems. However, other VLF stations operated by US and Russian defense agencies continue to operate. VLF windfinding is similar to Loran-C, except for the difference in radio frequency and the corresponding decreased windfinding accuracy of VLF.

The third type of NAVAID windfinding system uses signals from the so-called Global Positioning System (GPS) satellites. GPS was conceived in the early 1970s for the US Department of Defense (DOD), and is operated by the US Air Force. The GPS system became fully operational in late 1995. There are 24 satellites in six orbital planes spaced 60 degrees apart. The satellites are in a 20 200 km circular orbit, with an inclination angle of 55° and a periodicity of 12 hours. At any time or place in the world, there are 6 to 11 GPS satellites 5° or more above the horizon and hence usable for GPS windfinding. There are two primary GPS techniques for determining winds from radiosondes. The GPS signals cannot be retransmitted from the radiosonde back to the ground because the bandwidth of the 1575 MHz (called the L1 band) GPS carrier signal is too wide (~2.0 MHz). The worldwide civilian use of GPS has become so great that many manufacturers produce inexpensive, small GPS receivers each the size of a credit card that can decode the navigation message every second and produce accurate three-dimensional position coordinates, as well as speed and heading. A second, less expensive method uses a codeless receiver in the radiosonde that measures only the Doppler shift of the carrier frequency. The Doppler shift has two components: (1) the Doppler shift due to the satellite motion (i.e., the largest component), and (2) the Doppler shift due to radiosonde movement. The radiosonde receiver sends the Doppler information back to the ground data system. The ground data system must have a local GPS receiver that can decode the GPS message and independently measure the Doppler shift from each satellite. The satellite Doppler shift is subtracted from the radiosonde Doppler shift and the difference yields the radiosonde motion.

Specialized Types of Radiosonde Systems

Dropsonde

The dropsonde is the airborne counterpart to the conventional radiosonde (sometimes also called an upsonde). Dropsondes are ejected from research aircraft and float to earth on a special balloon-like parachute. Current state-of-the-art dropsonde sensors include capacitance fine-wire sensors to measure temperature, capacitance silicon pressure sensors, and GPS receivers to measure winds. Humidity is measured with a pair of thin-film capacitance sensors that are heated alternately to avoid condensation on descent from colder to warmer air. All measurements are made twice every second, while the 400 g dropsonde falls at an initial rate of about 25 m s^{-1} at 15 km altitude, decreasing to about 10 m s^{-1} at sea level. Dropsonde data are transmitted by radio from the sonde to a data system in the aircraft. Atmospheric soundings from dropsondes provide the ability to measure conditions over remote areas such as the oceans, polar regions, and sparsely inhabited landmasses; they also provide a means to obtain soundings in and around severe weather systems, such as hurricanes. Atmospheric soundings obtained from dropsondes during hurricane reconnaissance flights have improved the accuracy of forecasts of hurricane landfall by about 20% over the decade of the 1990s.

Dropsondes were first developed in the 1960s for the US Navy and Air Force for hurricane reconnaissance and were an adaptation of radiosonde technology. These early dropsondes were heavy – about 2.5 kg – and did not have inherent windfinding capability; windfinding at that time still used only radar or RDF. With the development of Omega NAVAID windfinding technique for the radiosonde it became possible to incorporate that technology into the dropsonde. This occurred in 1974 when the National Center for Atmospheric Research (NCAR) developed an Omega Dropwinsonde (ODW) for use in the Global Atmospheric Research Program's Atlantic Tropical Experiment. In 1982, the Air Force adopted the ODW system for hurricane reconnaissance and this system was used until the early 1990s.

In 1985 NCAR began development of a smart (i.e. microprocessor-based), lightweight digital dropsonde that incorporated Loran and Omega windfinding. The Omega version of this dropwinsonde was adopted by the US Air Force in the early 1990s for its hurricane reconnaissance mission (**Figure 7**). The next major improvement in dropsonde technology occurred in 1995 when NCAR completed development and testing of a new GPS dropsonde with codeless GPS windfinding capability and an advanced aircraft data system (AVAPS). In 1996 NCAR licensed Vaisala Inc. of Woburn, Massachusetts, to commercialize production and sales of the GPS dropsonde (**Figure 8**) and AVAPS. In the relatively short time the GPS dropsonde has been in use it has found research applications in the determination of hurricane structure and motion, the study of clear-air turbulence associated with upper-level jet stream structure, and observing strategies for midlatitude weather forecasting. Current adaptations of the GPS dropsonde technology are focusing on launches at higher altitudes – including the lower stratosphere – as well as autonomous launches that eliminate the need for operators to launch the sonde and record the data, and offer the promise that it will be possible one day to obtain operational dropwinsonde profiles from commercial aircraft. **Figure 9** shows a test dropsonde launcher mounted on the underside of an ER-2 high-altitude weather research aircraft.

Driftsonde System

Improvements in short- and medium-range synoptic-scale weather forecasts will depend on improved upper-air soundings over the data-sparse regions of the Northern and Southern Hemispheres. Progress towards this objective will require the optimal use of existing data sources, creative new observing methods, and improved numerical methods for data assimilation. The driftsonde system is being developed as a cost-effective sounding system that could fill these critical gaps in data coverage over oceanic and remote arctic and continental regions. The driftsonde concept seeks to obtain a large number of high-vertical-resolution GPS dropsonde profiles through the lower stratosphere and the entire troposphere by autonomous launching of dropsondes from specially designed balloon platforms. The driftsonde system includes a polyethylene carrier balloon with an attached gondola (**Figure 10**) that carries a payload of up to 24 GPS dropsondes. The carrier balloon ascends to between 50 and 100 hPa (20 and 16 km) and then drifts in the prevailing stratospheric westerlies for up to five days, deploying dropsondes at prescribed and special times over data-sparse regions of interest. The first

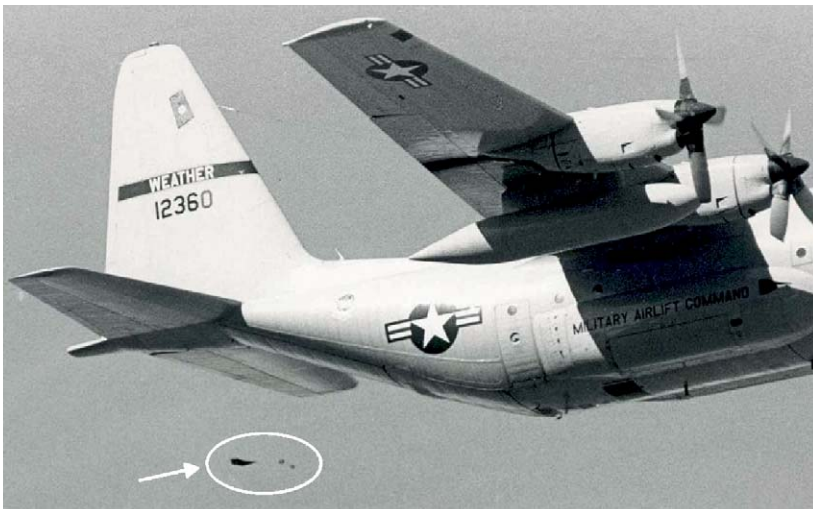

Figure 7 USAF C-130 Hurricane Hunter launching a GPS dropsonde.

Figure 8 GPS dropsonde descending on its parachute.

application of the driftsonde system will be in support of The Hemispheric Observing System Research and Predictability Experiment (THORPEX), a five-to-ten-year international program of atmospheric observing system research and development, and experimentation with numerical forecast systems that will be conducted in the 2002–2010 time frame.

Automated Shipboard Aerological Program (ASAP)

The Automated Shipboard Aerological Program (ASAP) is a multinational effort initiated by Canada in 1982 to obtain upper-air soundings over the oceans. Omega NAVAID radiosondes are launched from commercial ships of opportunity using a specially designed launch system (**Figure 11**) that permits flight trains to be launched in high-wind conditions. The upper-air sounding data from the radiosonde are sent back to the shipboard ASAP system where the data are processed in near real time to create a TEMP SHIP message. This message is the ocean equivalent of the TEMP message generated for land-based RAOB systems. The ASAP system sends the message to a GOES geostationary satellite that relays the information to the Global Telecommunications System (GTS), which then transmits it to the numerical weather prediction centers around the world.

The ASAP program had its beginning in June of 1981, when Canada decided to discontinue its weather ship program owing to the high costs of operating and maintaining the ocean weather ship *PAPA* located in the Gulf of Alaska at 50° N, 145° W. The original intent was to replace the weather ship data with satellite observations; however, persistent cloudiness in areas such as the Gulf of Alaska and the North Atlantic, coupled with the lack of surface weather data, made this goal impossible to attain. To remedy this problem, the Atmospheric Environment Service (AES) of Environment Canada, the National Weather

Figure 9 Remote-controlled GPS dropsonde launcher system installed on the NASA ER-2 high-altitude weather research aircraft.

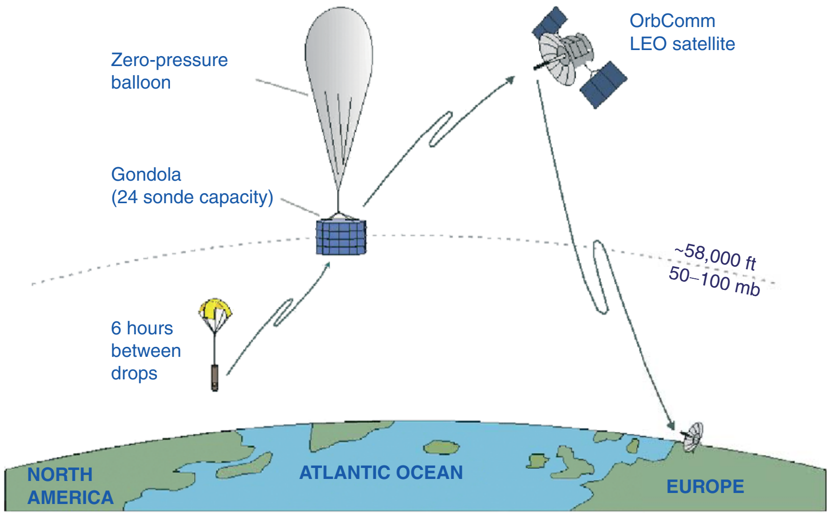

Figure 10 The driftsonde system concept.

Service (NWS) of NOAA, and NCAR established a joint ASAP project to develop a modular, mobile, moderately priced, upper-air sounding system. This system, when placed on commercial vessels (ships-of-opportunity) routinely crossing the Pacific and Atlantic oceans, provides real-time upper-air soundings that complement those of the global land-based upper-air network.

The ASAP program operated by AES Canada started in the spring of 1982 with one commercial ship (a Japanese automobile carrier) that operated from Vancouver, British Columbia, to Japan. By 2001, it had evolved into an international program with 11 countries operating 22 ASAP units – see **Table 2**. Since 1994, the ASAP program has made about 5300 upper-air soundings per year. In 2001 a lengthy Southern Hemisphere route was inaugurated with port calls in Germany, the UK, South Africa, Australia (both east and west coasts), New Zealand, and South America.

Rocketsonde

The rocketsonde is similar to a dropsonde except that a rocket is used to carry the sonde to the desired deployment altitude where the sonde is ejected and floats to Earth on a small parachute. Two types of rocketsondes are in use today, and are classified according to their maximum altitude. High-altitude rocketsondes are used primarily by the military and use a large rocket to carry the sensor package to altitudes in excess of 70 km. The Super Loki solid-fuel rocket motor is typically the launch vehicle for high-altitude rocketsonde deployments. Two meters long, it accelerates to 1500 m per second, and delivers its meteorological payload above the stratosphere into the mesosphere. The typical payload package, called a dart, is approximately 1.1 m long with an inside tube diameter of less than 5 cm, and contains the meteorological sonde. After the rocket motor burns out, the dart continues to coast to an altitude ranging from 70 to 110 km. At apogee, a timed detonation of a small explosive charge located in the tail of the dart ejects the meteorological payload, which then begins its parachute-aided descent. The payload consists of either a meteorological sensor package – the rocketsonde – or an inflatable sphere. The high-altitude rocketsondes often contain a transponder, a miniature receiver–transmitter that can be tracked by a radio direction finding and ranging system to determine winds and altitude. The inflatable sphere provides atmospheric density data, obtained from its fall velocity as determined by a precision tracking radar.

The second type of rocketsonde is smaller and less expensive, and is used to measure only thermodynamic variables in the lower 1–3 km of the atmosphere above earth. The Vaisala RK91 low-altitude rocketsonde (**Figure 12**) is primarily designed for naval shipboard operations that require observations of the refractive index profile near the ocean surface, but can also be used over land where only thermodynamic data are required. The RK91 can be prepared for launch in less than 10 min; it reaches apogee in less than 20 s, and provides a detailed thermodynamic profile with 1 s resolution. After ejection of the sonde payload, the sonde drifts on a parachute to the surface from an altitude of 1 km in less than 6 min. Vertical resolution is dependent on the rate of descent (typically 3 m s^{-1}), rate of data transmission (1 Hz) and sensor response time. At temperatures above freezing, vertical resolution is about 3 m.

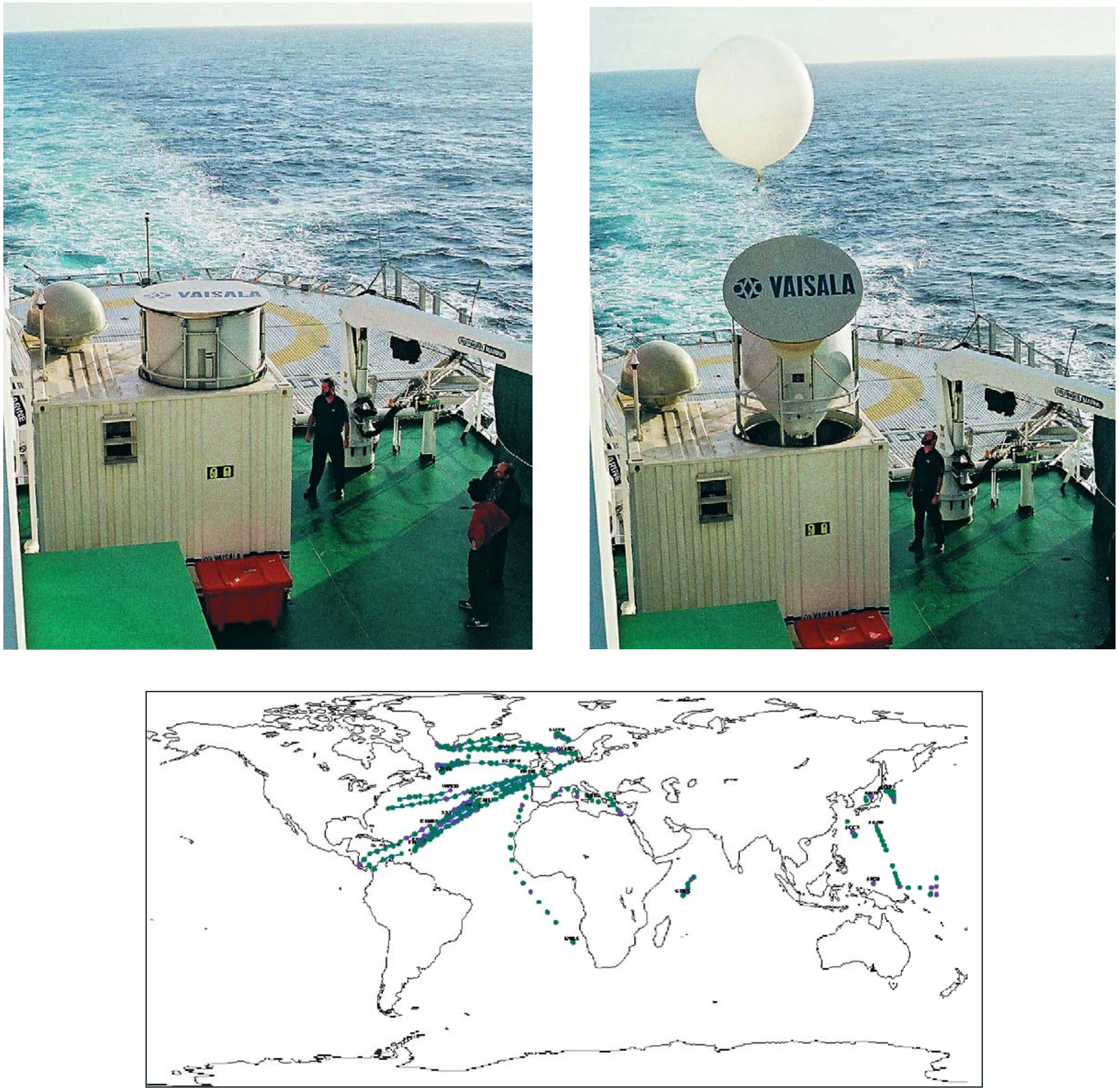

Figure 11 The ASAP system is housed in either a standard 3 m (shown above) or 6 m sea container with a specially designed hatch to enable routine radiosonde launches in sustained winds up to 25 m s^{-1} (gusts up to 35 m s^{-1}). (Bottom part) Worldwide ASAP radio soundings for November 2001.

Appendix

Historical milestones leading to the development of the modern meteorological radiosonde

Year	*Milestone*
1643	Evangelista Torricelli invents the barometer in Florence, Italy.
1648	French mathematician Blaise Pascal observes the decrease of atmospheric pressure with altitude.
1749	Alexander Wilson, Glasgow, Scotland, uses kites to study the variation of temperature with altitude.
1783	The French Montgolfier brothers, Joseph-Michel, and Jacques-Étienne invent the hot-air balloon.
1783	Jacques Alexandre Césare Charles, Paris, France, uses a manned balloon to make the first measurements of variations of pressure and temperature with altitude.
1784	Englishman John Jeffries, London, and Frenchman Jean-Pierre Blanchard begin the systematic study of the atmosphere using manned balloons.
1804	French physicists Louis Gay-Lussac and Jean Baptiste Biot ascend to 7 km in a

Table 2 Number of ASAP units operating in 1989 and 2001

Country	*Number of ASAP units*	
Year	*1989*	*2001*
Australia/UK/USA (Southern Hemisphere)		1
Canada	5[a]	
Denmark	2	2
EUMETNET		2
Finland	1	
France	4	4
Germany	4	3
Iceland/Sweden		1
Japan		5
Russia		1
Spain	1	1
United Kingdom	2	1
United States of America	5[a]	1

[a]Jointly supported by Canada and US.

balloon and discover that water vapor decreases with altitude.

1822 Englishmen Sir Edward Parry and the Rev. George Fisher use kites with recording thermometers to study the Arctic atmosphere.

1847 William Radcliff Birt is the first to measure winds aloft (and temperature) with a kite flown from Kew Observatory, London.

1892 Frenchmen H. Hermite and G. Besançon launch the first free-flying weather balloon with mechanical recording system (the 'meteorograph').

1893 Lawrence Hargrave, Sydney, Australia, invents the box kite; by end of decade, many major observatories are using box kites routinely to measure the atmosphere; they include: Blue Hill (near Boston, Massachusetts), the Central Physical Observatory (Moscow), Trappes (near Paris), Kew (London), Lindenberg (Germany), and Ilmala (Helsinki).

~1900 British scientist W. H. Dines invents the mechanical meteorograph design that is widely used until 1939.

1901 Richard Assmann, Germany, is first to use 'extensible' rubber balloons for free-flying soundings with meteorographs.

1917 Germans F. Herath and M. Robizsch use the 'telemeteorograph' to transmit meteorological data from a kite using the steel kite cable as the signal cable.

1920 US Weather Bureau and Army Air Corps establish a program of daily upper-air soundings using airplanes at 20 locations nationwide.

1921 US Weather Bureau establishes a kite network for routine upper-air observations; this remains in operation until 1933.

1927 M. R. Bureau and M. Idrac (France) invent the 'shortwave' (RF) tube-type transmitter and publish a paper describing the flight of their first balloon-borne sonde (although it is unclear whether any meteorological variables were actualy measured). Their paper is the first documented use of the

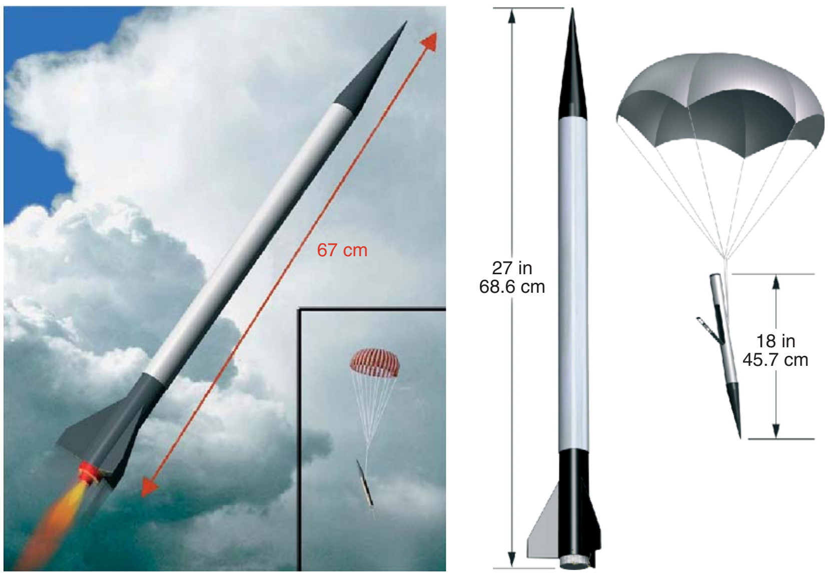

Figure 12 Low-altitude rocketsonde unit with detached sonde descending on parachute (insert).

term 'radiosonde,' which they attribute to H. Hergesell (president of the international aerological commission).

1929 January 17: M. Idrac and M. R. Bureau test the first free-flying radiosonde, called the 'Thermoradio', with a bi-metallic temperature sensing element to transmit temperature data to a ground station.

1930 January 30: P. A. Moltchanov (Russia) uses a radiosonde to measure temperature and pressure to a height of 10,000 m from Slutzk. From 1930 to 1936 several thousand soundings were made in the USSR with the Moltchanov radiosonde.

May 8: M.R. Bureau launches a radiosonde measuring temperature and pressure from Trappes, France, reaching an altitude of 14,400 m.

May 22: P. Duckert (Germany) flies the first radiosonde measuring pressure, temperature and humidity to a height of 15 000 m from the Aerological Observatory at Lindenberg.

1931 December 30: Prof. Vilho Väisälä (Finland) flies a radiosonde from Helsinki telemetering temperature to the ground up to a height of 7 km; like Duckert, Väisälä used the measuring elements to control the capacitance of the radio oscillator circuit.

1936 July 30: Prof. Väisälä establishes the Väisälä Company and delivers the first commercial order for 20 radiosondes, delivered to Prof. Carl Gustav Rossby at the Massachusetts Institute of Technology.

1974 The National Center for Atmospheric Research (Boulder, Colorado) develops the dropsonde, a special radiosonde that is launched from research aircraft and measures winds, pressure, temperature, and humidity while descending on a parachute.

1976 The Vaisala Oy company (Helsinki) introduces the first computer-controlled upper-air sounding systems.

1982 The US National Oceanographic and Atmospheric Administration begins routine use of dropsondes for hurricane research; one year later, the US Air Force initiates its hurricane reconnaissance program.

1995 The first commercial radiosonde systems using the satellite Global Positioning System to measure winds are introduced by the Atmospheric Instrumentation Research company (Boulder, Colorado) and the Vaisala Oy company (Helsinki).

See also

Observation Platforms: Kites; Rockets. **Observations for Chemistry (Remote Sensing):** Microwave. **Satellite Remote Sensing:** GPS Meteorology.

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RAINBOWS

See **OPTICS, ATMOSPHERIC**: **Optical Phenomena**