IONOSPHERE AND UPPER ATMOSPHERE RESEARCH WITH RADARS

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Keywords: Ionosphere, middle atmosphere, thermosphere, ionosonde, MST radar, incoherent scatter radar, meteor radar, MF and HF radar, coherent scatter, interferometry, plasma irregularities, D-, E-, and F-region, turbulence, gravity waves, traveling ionospheric disturbances, ionospheric heating, plasma drift.

Contents

Summary

This chapter describes the use of radars for studies of the Earth’s ionosphere and atmosphere. In particular, these techniques are most useful for continuous observation in certain regions, which is not possible with other techniques such as rockets or satellites.

The combination of radar observations and in-situ and remote sensing methods aboard spacecraft, combined with models and simulations, yield an almost complete view of our Earth’s middle and upper atmosphere and ionosphere environment.

1. Introduction

Electromagnetic waves of frequencies between a few kHz and some GHz are used with radio and radar methods for scientific studies of the Earth's atmosphere-ionosphere environment. The reasons for these studies are at least twofold, namely basic research to understand complex phenomena in our environment and communication-oriented applications. A major contribution to our knowledge of the ionosphere stems from contributions of radar application. These will be briefly summarized in this chapter, particularly taking into account the most recent developments of systems, methods and their capabilities for atmosphere-ionosphere research.

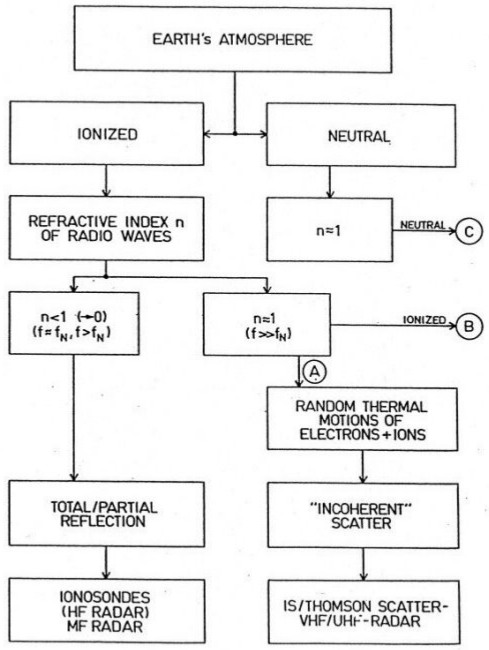

Figure1. Schematics of the Earth’s atmosphere with respect to radar observations, given by the refractive index n of its neutral and ionized partitions

RADAR stands for Radio Detection and Ranging. The method involves transmitting a pulsed electromagnetic wave, which is scattered or reflected from irregularities in the refractive index. The transmission is focused into a particular direction of interest by means of a high-gain antenna. A small fraction of the backscattered or reflected electromagnetic wave reaches the receiving antenna, where it is detected and analyzed. Measuring the time delay between the transmitted and received signals allows the determination of the range from the radar location to the irregularity region. The range resolution is given by the duration of the transmitted electromagnetic pulse. The direction is given by the antenna beam bearing; the angular resolution is given by the antenna beam width. Many parameters, such as radar cross-section and velocity can be deduced from analyzing the received signal spectra. These are then used to deduce atmospheric and ionospheric parameters. Radars apply most modern analog and digital techniques, which are described in more detail in the referenced publications.

The Earth’s atmosphere and its ionized part, the ionosphere, are dispersive media determined by their refractive indices *n* (Figure 1). Radar and radio methods are applied on certain frequencies *f* in the electromagnetic frequency spectrum. The wave undergoes total or partial reflection in the ionospheric plasma when its frequency is equal to the critical or plasma frequency f_N which is used with ionosondes or HF-radars. When the wave frequency is much larger than the plasma frequency, incoherent scatter from thermal motions of free electrons in the ionosphere takes place. This is called incoherent or Thomson-scatter. Instabilities in the ionosphere generate plasma turbulence, i.e. a direct perturbation of the ionization structure, which cause coherent scatter on HF, VHF and UHF and is used to study the E- and F-region irregularities. Clear air turbulence in the neutral atmosphere causes small deviations of the refractive index *n* due to density, temperature and humidity variations, which result in tropospheric and stratospheric irregularities leading to coherent-scatter as well. At mesospheric altitudes neutral air turbulence causes an indirect perturbation of the ionization (mesosphere and D-region irregularities), which in turn results in coherent scatter. This is used with the mesosphere-stratosphere-troposphere radars, operating in the VHF and HF bands.

Since the ionosphere is directly coupled to the neutral atmosphere and the magnetosphere, some radar systems, such as the incoherent scatter (IS) radars, are designed or optimized for such studies. Those radars and their descents are also used for studies of the neutral atmosphere, such as the mesosphere, stratosphere and troposphere (MST). The main categories of ionospheric radars are summarized in Table 1. Both the ionosphere and the atmosphere are studied with both techniques in the region where the ionosphere is strongly coupled to the neutral atmosphere, namely the D region and the mesosphere (see *Aeronomic Phenomena*).

Systems	**Frequency bands**						**Altitude Region**
	VLF	LF	MF	HF	VHF	UHF	
Sprite detection	x						(Mesosphere)
LF drift		x					Mesosphere, lower thermosphere
MLT/MF radar			x				Mesosphere, lower thermosphere
Meteor radar				x	x	x	Mesosphere, lower thermosphere
HF radar			(x)	x			D- / E- / F-region
Doppler sounder				x			D- / E- / F-region
Heating API				x			D- / E- / F-region
Heating diagnostic	x			x	x	x	D- / E- / F-region
MST radar					x		Mesosphere (strato-troposphere)
Coherent scatter				x	x	x	D- / E- / F-region
Incoherent scatter					x	x	D- / E- / F-region

Table1. Radar techniques for ionospheric research

The Mesosphere-Lower-Thermosphere (MLT) radars, also called MF radars, encompass partial reflection, and wind-wave-turbulence measuring methods. They cover the altitude region of about 60 km to 100 km. The LF drift method can be regarded as passive radar; it measures the drifting pattern of lower ionospheric reflection of LF radio transmitters. Meteor radars, covering 70 km to 120 km altitude, include techniques for studies of atmospheric/ionospheric as well as astrophysical parameters. HF radars include the wide variety of the ionosondes and their progressive digital evolutions to determine high-resolution ionospheric profiles and drift velocities. They are operated from the ground for studies of the D-, E- and bottomside F-region, and from satellites to observe the topside of the ionosphere. The term HF radar encompasses also backscatter radars for distant observations of the ionospheric profile and irregularities, imaging of ionospheric structure and dynamics and its coupling to the magnetosphere as well as the over-the-horizon radars for detection and tracking of remote targets. HF radars, such as digital ionosondes and backscatter radars for profiling, are the only systems sweeping over a large portion of the frequency spectrum, encompassing typical ranges of ionospheric critical frequencies up to some 20 MHz. The HFCW (continuous wave)-Doppler sounding systems, are essentially applied for studies of ionosphere and atmosphere dynamics by measuring ionospheric reflection height variations at several distant locations. Ionospheric modifications, also called ionospheric heating, are done in ranges of ionospheric critical frequencies. It highly relies on radar methods for diagnostic purposes, operating in the HF, UHF and VHF bands. They include the investigations of the modification of ionospheric background parameters as well as the development of field-aligned and artificial periodic irregularities and plasma turbulence. Heating facilities are also applied as radars for ionospheric, mesospheric and thermospheric observations. Mesosphere-Stratosphere-Troposphere (MST) radars detect echoes from turbulence induced ionization irregularities and dusty plasma layers in the D-region/mesosphere. The studies of the stratosphere and troposphere with MST radars are not subject of this article.

The term coherent scatter radars is used for radars observing backscatter from ionospheric irregularities, which are aligned with Earth's magnetic field and for studies of the corresponding plasma instabilities. The term ionospheric irregularity is frequently used, whereas most of them result from a spectrum of plasma waves, created by the instabilities. Incoherent scatter radars, detecting backscatter from the ionospheric plasma, are the most powerful tools for studying the full profile of many ionospheric parameters, such as electron density, electron temperature, ion temperature and plasma velocity. Also incoherent scatter is basically coherent, since it results from the radar wavenumber component of the spatial spectrum of ion-acoustic waves existent in the ionospheric plasma.

Transmitters used in radar applications are almost exclusively operated in pulsed-coded (binary phase or frequency) modulations, operate at peak power levels up to a few hundred Watts, such as the MLT radars, vertically beaming HF-radars and CW-Doppler systems. Meteor radars and coherent scatter radars have transmitter powers up to some ten kilowatts, whereas some trans- horizon and high-power MST radars apply up to some hundred kilowatts and incoherent scatter radars produce some megawatts. Antennas are ranging from simple dipoles to multi-Yagi phased arrays and large dishes. The optimum frequencies of radars are given by typical scales of the governing scattering and reflection processes. As Table 1 shows, the applied frequencies range from a few MHz (MF) to some GHz (UHF).

2. Radar Observation Principles

Figure 2 shows a schematic diagram representing the main observation concepts applied in MLT-, meteor-, some HF-, MST- and coherent scatter radar systems. This Figure explains the concepts for overhead scattering and reflection; in principal it applies also to all other radar applications, operating in the forward scatter, backscatter or total reflection oblique modes. To cover larger areas and to measure velocity vectors, the Doppler method (Figure 2a) is utilized, where a narrow antenna beam is steered into different directions. It is also known as the Doppler beam swinging (DBS) method. This method is always applied by the incoherent scatter radar, where the full spectrum information is measured at different, horizontally separated positions in the ionosphere.

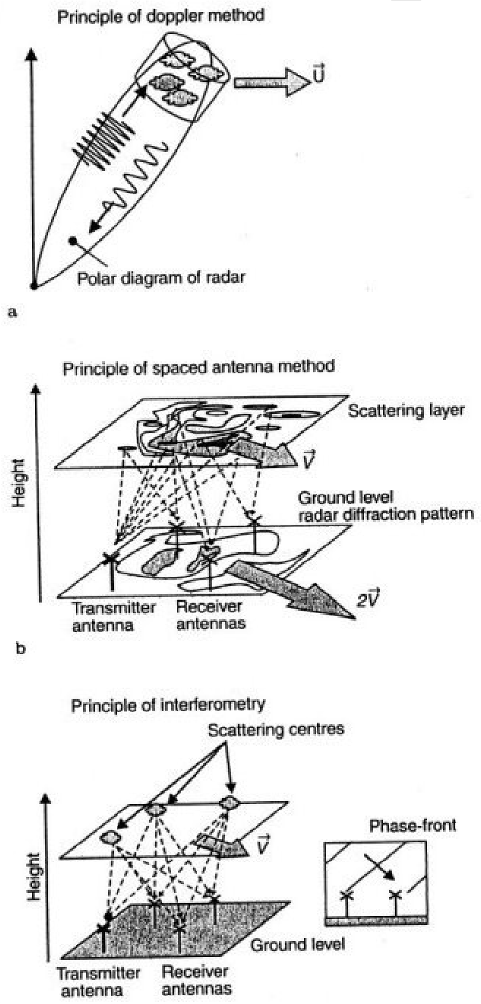

Figure 2. The three basic methods used by coherent scatter radars to observe the atmosphere and ionosphere: Doppler beam swinging (upper), spaced antenna drift (center) and interferometer technique (from Hocking, 1997). MST radars mostly use phased array antennas. Ionosondes apply dipole, rhombic or loop antennas, and incoherent scatter radars mostly apply large high-gain dish antennas.

The spaced antenna method (Figure 2b), where the changing diffraction pattern on the ground caused by backscattering from aloft is measured, is applied to deduce the horizontal velocity, shape and coherence of the scattering layers by analyzing the cross correlation or cross spectra analysis of signals received at spaced antennas. This method is used with the MLT radars and becomes standard also in MST radars.

The interferometer method (Figure 2c) is a natural extension of the spaced antenna method. It utilizes the fact that the modern radar systems are phase-coherent and the amplitude and phase (or the quadrature signal components) are measured. Phase information at separated antennas allows the determination of the angle of arrival. It yields, with better accuracy, similar parameters as the diffraction pattern method and the Doppler beam swinging method. It also allows digital beam forming and high-resolution radar imaging by employing a larger number of receiving antennas. The advantages of this method are becoming more widely known and are accepted to constitute the features of contemporary radar systems for ionospheric and atmospheric research. The interferometer method is applied in many varieties in all radar systems, covered in this article. Such mutations are radar imaging to deduce the visibility and brightness functions of scattering regions, digital beam formed using spaced antennas (SDI). Interferometry in the frequency domain (FDI) is often used to overcome limitations in using very short pulses to detect thin layering.

The exceptions are the incoherent scatter radars where the scattering process itself prevents the required coherency of the diffraction pattern at the receiving site. Here the Doppler method (Figure 2a) with different antenna beam pointing angles is used. Another possibility of measuring velocity and anisotropy is to apply multi-static observations using transmitting and receiving antennas at separated locations, such as the EISCAT tri-static UHF incoherent scatter radar system.

3. Mesosphere, Lower Thermosphere and Meteor Observations

The mesosphere-lower-thermosphere MLT radars, also called MF radars, have their origin in the early applications of LF, MF and low HF radars to analyze partial reflections from the D region by means of the differential phase and amplitude methods to deduce the electron density profile. The partial reflection of the radar waves was assumed to be from irregularities in the ionization, and it was soon recognized that this technique could be extended by measuring the mean drift and variability of these irregularities, mostly using the spaced antenna method (Figure 2b). Since the irregularities are strongly coupled to the neutral atmosphere due to the high collision frequency between neutrals and ions, this opened a possibility to study neutral winds in the mesosphere and lower thermosphere. A multitude of MF radars is used all over the globe, in particular to measure the mesospheric and lower thermospheric wind field.

Echoes from meteors, ablating in the atmosphere between about 70 km and 120 km, provide a means to deduce orbital information of the originating meteoroids as well as studying the atmosphere. Radars had been applied for these purposes including more detailed studies of the interactions of the meteor with the atmosphere and ionosphere, as well as for the modification of the ambient ionosphere by the meteors, such as plasma wave excitation and effects on the incoherent scatter process in the D-region. Meteor trails are called overdense when their plasma frequency is equal to or larger than the radar frequency. Here specular reflection-type echoes result. Specular type reflection echoes occur when the radar wave vector is perpendicular to the trail. Trails are called underdense when their plasma frequency is smaller than the radar frequency. The echo strength is dominantly given by the electron density and the radius of the trail. The Doppler shift of the meteor radar echo is caused by the motion of the trail. Since the trail is carried by the neutral background wind, the Doppler shift is used to determine the wind velocity.

After the trail has fully developed, it begins to dissipate, essentially by ambipolar diffusion, eddy diffusion and recombination. The trail then becomes underdense resulting in non-specular echoes. The backscattered amplitude from an underdense trail decreases exponentially with time mainly by ambipolar diffusion. The decay times are used to measure the ambipolar diffusion coefficient. It has been shown that the diffusion coefficient D is proportional to the ratio of the square of temperature T and pressure P. Thus, if either T or P is known, the other parameter can be deduced. When taking P from atmospheric models, the temperature T can be inferred from the meteor radar measurements of the diffusion coefficient.

4. Studies of the Mesosphere with MST Radars

The technique of using sensitive clear air radars to investigate the upper atmosphere at altitudes from the troposphere to the mesosphere owes much of its success to the early days of ionospheric incoherent scatter observations. The lowest mesospheric height, from where MST radar echoes are returned, is given by the D-region electron density and is usually around 60-70 km. At radar wavelengths of a few meters corresponding to Bragg wavelengths of radars in the low VHF band, variations of the refractive index become very small due to viscous damping of neutral turbulence in the upper mesosphere. The largest height is around 90 km, where meter-scale irregularities, induced by neutral turbulence at the scales of a few meters, cease to exist. Above 80-90 km the incoherent scatter process would become dominant, provided that the radar is sensitive enough to detect such signals. The condition that sufficient electron density as well as neutral variations at the Bragg scales have to be present, cause the MST radar echoes from the mesosphere to be fairly variable and intermittent. Whereas these echoes are usually called "turbulence echoes" a new brand of echoes had attracted wide attention in the last decade, namely the Polar Mesosphere Summer Echoes, which are discussed in section 4.1.

The basic parameters measured with MST radar are deduced from the Doppler spectrum, such as the signal power, the Doppler shift and the spectral width, and spaced antenna methods are also used for this purpose. Furthermore the anisotropy of turbulence scattering layers can be determined. These parameters are used to study turbulence itself, where two methods are applied. One relies on the dependence of the scatter cross section on turbulence intensity and the background gradient of electron density, the other on the spectral width. From these measurements the eddy diffusion coefficients can be deduced. Doppler shift or spaced antenna analysis yield estimates of the three dimensional wind-vector, which allows studies of mean winds, long-period waves, tides and gravity waves. Of particular importance is the deposition of momentum and energy by waves into the mesosphere, which strongly affect the mean mesospheric circulation.

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Biographical Sketch

Dr. Jürgen Röttger, is senior scientist emeritus at the Max-Planck-Institut für Aeronomie in Germany, and is professor adjunct at the Institute of Space Science of the National Central University in Taiwan. He received his Ph.D. from Göttingen University and started ionospheric research in the early 1960s at the Max-Planck-Institut, working on sub-polar and transequatorial radio propagation, equatorial spread-F and traveling ionospheric disturbances. In 1974 he became involved in the development of the new generation of MST radars, namely the SOUSY VHF radar for studies of the structure and dynamics of the middle and lower atmosphere. In 1982 he became assistant director science of the EISCAT Scientific Association. In 1985 he was heading the atmospheric science division of the Arecibo Observatory, and was director of the EISCAT Scientific Association from 1986 to 1997. During that period he was in charge of the new EISCAT Svalbard Radar project. The years 1998-2002 were devoted to establishing and using the SOUSY Svalbard Radar for polar middle and lower atmosphere research. He has been associate editor and guest-editor of several scientific journals, is chairing international workshop and working group activities of SCOSTEP and URSI, and conducting international schools on atmospheric radar. His research interest is in radar meteorology and coupling between the lower middle and upper atmosphere using radar methods.