

**RADIO OCCULTATION METHOD  
FOR REMOTE SENSING OF THE  
ATMOSPHERE AND IONOSPHERE**



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Edited by  
**Y.A. LIU**

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## Preface

This book is devoted to presentation of radio occultation (RO) remote sensing as a global method for monitoring of the earth's atmosphere and ionosphere. This technique is based on the following effect: when a spacecraft radiating radio signals moves into the shadow zone behind the earth and, afterward, appears from this zone, the radio ray produces two cuts of the atmosphere. Atmospheric and ionospheric effects arise in the most cases owing to influence of a zone near the radio ray perigee and cause significant variations of the amplitude, phase, and frequency of the radio waves. These variations enable determination of the altitude profiles of temperature, pressure, refractivity, density, humidity, and turbulence in the atmosphere, distribution of the electron density in the ionosphere, and the wave phenomena at different altitudes with a global coverage.

Aim of this book consists in a systematic description of different approaches, results of investigation, and perspectives of the RO remote sensing as a tool for investigations of the atmosphere and ionosphere. Historical stages of elaboration of RO method, its principle and technical parameters are described in chapter 1. Chapter 2 is devoted to theoretical analysis of effects of radio waves propagation in the communication links satellite-to-satellite. The RO direct problem is stated and analyzed. Variations of the amplitude, phase, and frequency of radio waves relevant to special forms of the altitude profiles of the atmospheric and ionospheric parameters are described. Sensitivity of RO method to variations of the atmospheric temperature, pressure, and electron density in the ionosphere is estimated. Inverse RO problem is discussed and scheme of determination of the altitude profiles of the atmospheric temperature, pressure, refractivity, and electron density in the ionosphere from measurements of the frequency, phase and amplitude is presented. The different radioholographic methods are described in chapter 3: (1) Radioholographic focused synthetic aperture (RHFSFA) method; (2) Fourier Integral Operators (FIO) including the Zverev's transform and General Inversion Operator (GIO), (3) Back Propagation (BP) and Canonical Transform (CT) methods; (4) Full Spectrum Inversion (FSI) technique; (5) Spectral Phase Matching Method (SPPM). These methods were elaborated with aim to improve vertical resolution and accuracy in estimation of parameters of the atmosphere and ionosphere and to avoid interfering influence of the multi-path propagation on retrieval of the atmospheric parameters. Also the eikonal acceleration/intensity method is presented and discussed in chapter 3. This technique is useful for identification of layered structures in the atmosphere and ionosphere, evaluation of the intensity of atmospheric and ionospheric irregularities, estimation of the location and parameters of inclined plasma layers in the ionosphere and for excluding of the refractive attenuation from the amplitude data with aim to measure the total atmospheric absorption. Examples of RO signals variations caused by atmospheric influence are adduced in chapter 4, and a step-by-step transfer from RO measurements to determination of the atmospheric parameters is considered. RO measurement errors and inaccuracies of data inversion algorithms influence on the accuracy of retrieved atmospheric

parameters. A short description of the basic errors sources is presented in chapter 4. Values of the atmospheric parameters, determined by the RO technique, are compared with the results, obtained by other technical means. RO sounding of the atmosphere allows obtaining information not only about the above mentioned characteristics of the atmosphere, but also about the wave, layered and turbulent structures in the atmosphere, and possibility of their research by the RO method is considered in chapter 4. Influence of the lower ionosphere on the amplitude and phase of RO signal are considered in chapter 5. Physical changes in the near-earth space environment in response to variations in solar radiation, solar plasma ejection, and the electromagnetic status of the interplanetary medium produce disturbances in the ionosphere. The disturbed ionosphere changes the amplitude and phase of RO signal. To the lowest order, changes in the total electron content (TEC) along the signal path contribute to the phase path excess. For an undisturbed ionosphere, where the electron density does not vary significantly over the short- scale lengths, this is the only effect that the ionosphere has on the RO signals. For undisturbed conditions, the tangent points in the ionosphere are absent during motion of the ray perigee in the atmosphere and the ionospheric influence may be described as a slow change (appeared as linear or parabolic trend) in the phase path excess without noticeable variations in the amplitude of RO signal. Analysis of CHAMP data indicates importance of the amplitude variations for classification of the ionospheric influence on RO signals. This classification can be mainly based on the dispersion and on the spectral form of amplitude variations. Strong regular variations in the amplitude of RO signal in the most case are connected with the inclined ionospheric layers. Regular character of the ionospheric disturbances indicates a possibility to obtain additional information about the ionospheric structure from RO measurements. This reveals usefulness of RO method for global investigation of the sporadic E- layers in the lower ionosphere which is difficult to perform by the Earth's based tools.

Two new applications of RO technique are considered in chapter 6: (1) bistatic radio location at small elevation angle and analysis of direct and reflected radio waves propagation effects conducted during MIR/GEO and GPS/MET RO missions at wavelengths 2, 32, 19, and 24 cm; (2) the absorption of centimeter and millimeter radio waves owing to influence of oxygen and water vapor in the troposphere. Experimental observation of propagation effects at low elevation angles has principal importance for fundamental theory of radio waves propagation along the earth's surface. At decimeter wavelength band, the total absorption effect in the trans-atmospheric telecommunication link orbital station MIR - geostationary satellites was measured at frequency 930 MHz. In this experiment, the refractive attenuation has been excluded by use of the phase and Doppler frequency data. Important relationships between the Doppler frequency and the refractive attenuations of the direct and reflected signals are revealed. These connections allow recalculating the Doppler shift to the refractive attenuation and open a possibility to measure the total absorption in the atmosphere by bistatic radar method. GPS/MET and CHAMP (wavelength 19 and 24 cm) RO experiments opened new perspectives for bistatic monitoring of the earth at small elevation angles. The absorption measurements are planning for the future RO missions to determine with high vertical resolution the water vapor abundance at different altitudes in the stratosphere and troposphere. Two directions discussed in chapter 6 broaden the applicable domain of the RO technique.

Y.A. Liou

# Radio Occultation Method for Remote Sensing of the Atmosphere and Ionosphere

Y.A. Liou

*Center for Space and Remote Sensing Research, National Central University,  
Chung-Li 320, Taiwan.*

A.G. Pavelyev, S.S. Matyugov, O.I. Yakovlev

*Institute of Radio Engineering and Electronics of Russian Academy of Sciences  
(IRE RAS), Fryazino, Vvedenskogo sq. 1, 141190 Moscow region, Russia*

J. Wickert

*GeoForschungsZentrum Potsdam (GFZ-Potsdam), Telegrafenberg, 14473 Potsdam  
Germany*

The remote sensing satellite radio occultation method elaborated for monitoring of the earth's atmosphere and ionosphere with a global coverage is described. Comparison of theoretical results with experimental observations of radio wave propagation effects in the earth's atmosphere and ionosphere in the communication links satellite-to-satellite is provided. Directions in application of the radio occultation method are discussed: measuring vertical gradients of the refractivity in the atmosphere and electron density in the lower ionosphere, determination of the temperature regime in the stratosphere and troposphere, investigation of the internal wave activity in the atmosphere, and study of the ionospheric disturbances on a global scale. The radio occultation technique may be applied for investigating the relationships between processes in the atmosphere and mesosphere, study of thermal regimes in the intermediate heights of the upper stratosphere-lower mesosphere, and for analysis of influence of space weather phenomena on the lower ionosphere. Radio-holographic methods are considered as a tool for determination of the altitude profiles of temperature, pressure, refractivity, internal wave activity in the atmosphere, and electron density in the ionosphere with usage of the radio links satellite-to-satellite. Results of radio occultation measurements of the atmospheric and ionospheric parameters are described. Comparative analysis of effectiveness of the radio occultation and other remote sensing methods is conducted.

## 1. Elaboration of Radio Occultation Monitoring of Atmosphere and Ionosphere

### 1.1 Stages of elaboration of radio occultation method

The RO technique relies on bistatic radio locations when a receiver is located at an extended distance relative to transmitter of radio waves [1]. In distinction with the radio tomography methods (see, for example [2], and references therein), the RO technique may be applied practically simultaneously to investigation of both the atmosphere and ionosphere. The RO technique was initially suggested for remote sensing of planetary atmospheres, ionospheres, and surfaces [1]. During the first space missions to Mars and Venus, a possibility for investigations of their atmospheres and ionospheres by RO technique was used. The RO method is based on the next effect: if a spacecraft immerses into and then egresses from a radioshadow of a planet, a radio ray perigee conducts two «sections» of the planetary atmosphere and ionosphere. According to the atmospheric and ionospheric influence, the regular and irregular variations in the amplitude, phase and frequency of radio waves take place. These variations contain important information about the atmosphere and ionosphere of a planet [1]. The first investigations of the planetary atmosphere by the RO method were conducted during 1965 Mariner-4, 6 and 1969 Mariner-7 Mars flyby's [3,4]. Before interplanetary space flights, Mars investigations were conducted by use of the earth-based spectroscopic observations, which have an inherently large measurement uncertainty in values of the Martian atmospheric pressure and other physical parameters. Information on the Martian ionosphere practically was absent. The RO sounding performed by three Mariner spacecraft has clearly shown that this method makes it possible to determine the pressure and temperature of rarefied atmosphere of Mars and the electron density of Martian ionosphere. In order to employ large informative potential of RO method, artificial satellites of planets have been used. In 1971, massive RO sounding of the rarefied atmosphere and ionosphere of Mars was performed by the first artificial satellites missions to Mars: Mars 2 and Mariner 9 spacecrafts [5, 6].

The first reliable direct measurements of composition, pressure, and temperature in the upper and middle atmosphere of Venus were obtained from USSR entry probe missions. Investigation of Venusian atmosphere via the RO method was started during Mariner 5 and 10 Venus flyby's [7, 8]. Detailed investigations of the atmosphere and ionosphere of Venus started in 1975 with usage of the first Venus artificial satellites Venera 9 and 10. By means of these spacecrafts, the RO experiments at three frequencies were conducted in 50 regions of Venus [9–13]. During these experiments effects of radio waves propagation through the ionosphere and dense Venusian atmosphere were studied. Vertical profiles of temperature  $T(h)$  and pressure  $P_A(h)$  were obtained independently from measurements of the amplitude and frequency of radio waves. The second series of RO investigations were performed in 1978 by the Pioneer Venus spacecraft [14], and third series of experiments were conducted in 1984 by use of Venera 15 and Venera 16 satellites [15–17]. Investigations of the Venus atmosphere and ionosphere were conducted at the decimeter ( $\lambda = 32$  cm and 13 cm) and centimeter wavelength bands ( $\lambda = 8$  cm, 5 cm, and 3.6 cm). These multi-frequency measurements allow effective conducting RO investigations of thin atmospheric structures, determining the altitude profiles of temperature, the latitude and longitude distributions of the wind velocities at different altitudes in the atmosphere, detecting the atmospheric turbulence, measuring the altitude profile of sulfuric acid density responsible



for the radio waves absorption, and providing detailed study of the ionosphere under different condition of solar illumination. It is important that the RO investigations of the atmosphere and ionosphere were provided in mass scale with global coverage. The first stage of development of the RO method was completed with detailed investigations of the atmospheres and ionospheres of Mars and Venus. A more comprehensive description of this stage is given in [16].

The RO investigations of the earth's atmosphere are possible with usage of two satellites, one of which radiates signals, while the other spacecraft receives them. During motion of the satellites, the radio ray perigee passes through the medium conducting nearly vertical section of the earth's atmosphere at different altitudes. A possibility of RO method application to study the atmosphere and ionosphere of the earth has been considered at the initial stages of investigations. Theoretical estimations of the atmospheric and ionospheric influence on radio waves propagation in the communication link satellite-to-satellite have been provided for revealing a sensitivity of radio waves to features in vertical structures of the atmosphere and ionosphere. Arguments on behalf of RO method in the case of investigation of unknown atmospheres of planets are different from the arguments in the case of investigation of the well-known atmosphere of the earth. In the first case, acquisition of any additional information is justified, while, in the second case, this method should have advantages over the other traditionally ground-based and remote sensing methods for collection of meteorological and ionospheric data. In publications [18–26], problem of the RO remote sensing of the atmosphere and ionosphere of the earth is considered; general relationships for the changes of the frequency, phase, amplitude, bending angle and absorption of radio waves were obtained; estimations of the expected atmospheric and ionospheric effects on radio wave propagation were evaluated for three cases *a*) two satellites are moving at the same orbit supporting nearly the same distance, *b*) geostationary satellite – satellite moving along a low earth orbit (LEO) and *c*) LEO satellite – a satellite of the Global Positioning System (GPS). For these cases, the theoretical dependences of the refractive attenuation, bending angle, variations of the amplitude, frequency and absorption of radio waves were obtained as functions of the altitude of the radio ray perigee. The authors of these publications estimated the necessary accuracies in measurements of the amplitude, frequency, and phase of radio waves with aim to achieve the required precision in determination of the ionospheric and atmospheric parameters including the atmospheric pressure and temperature.

The first RO experiments were made in two satellite-to-satellite links: that of a geostationary satellite and LEO satellite [25] and that of the Apollo–Soyuz Test Project [26]. The RO experiments have shown that the atmosphere and ionosphere change the frequency and amplitude of radio waves in a complex way. Therefore, systematic investigations of the properties of radio wave propagation along the RO satellite-to-satellite paths are required. These investigations were started in Russia in 1990 with the use of the orbital station MIR and two geostationary satellites [27–31]. Radio links of the Ku band ( $\lambda = 2$  cm) and the UHF radio band ( $\lambda = 32$  cm) with transmitters of increased power and antennas with high directivity were used. The detailed investigations of the atmospheric and ionospheric influence on the radio waves propagation and estimations of real possibilities of studying the earth's atmosphere and ionosphere by the RO method have been provided by use of these tools in 1990–1998 years. It became evident that the RO system of investigation of atmosphere and ionosphere will be effective when high-stable signals are used. The first

studies proposing the usage of highly stable signals of navigational satellites of the GPS and GLONASS systems for sounding the earth's atmosphere and ionosphere appeared in the late 1980-th [23, 24]. A testing RO system was realized in USA in 1995 year with using a LEO satellite Microlab having a receiving device for registration of signals of the navigational satellites GPS, emitting the radio waves in two wavelength bands  $\lambda_1 \approx 19$  cm and  $\lambda_2 \approx 24$  cm [32–39]. Microlab mission functioned during period 1995 – 1998 years and performed nearly 11 000 measurement sessions. The obtained vertical profiles of the atmospheric temperature and the electron density in the ionosphere were compared with the data of ground-based measurements, and it has been demonstrated that the RO measurements provide a high level of accuracy [32–39].

The second stage of the RO investigations included elaboration of algorithms for the data analysis and practical validation of these algorithms during mission of MIR – geostationary satellites and Microlab – GPS. The second stage was completed with a detailed study of characteristic properties of propagation of decimeter and centimeter radio waves along the satellite-to-satellite paths. As a result of this stage, efficiency of the RO method for exploration of the earth's atmosphere and ionosphere has been demonstrated. It became evident that, in order to provide efficient investigation and monitoring of the atmosphere and ionosphere via the RO method, it is necessary to construct a system that uses several satellite-to-satellite paths simultaneously and to develop new methods for analysis of RO measurements. During the third stage of RO investigation, an international system for global monitoring of the atmosphere and ionosphere was developed (see Table 1.1.1). This system currently included several satellites, which can receive signals from the navigational satellites of GPS system and conduct more than 3000 sessions of RO measurements per day [40–49]. The international RO system uses the satellites – receivers of GPS signals CHAMP (2000), SAC-C (2000), GRACE-A (2002), FORMOSAT-3/COSMIC (2006), METOP (2006), TerraSAR/TanDEM-X (2007), and other, having nearly circular orbits with inclination  $75^\circ - 85^\circ$  at altitudes 500 – 800 km.

Stage	Satellite	Number of satellites	Years of experiments	Country
I	MARS 2 MARINER 9 VENERA 9 and 10	2	1971 – 1972	Russia USA
	PIONER VENUS VENERA 15 and 16	5	1975 – 1984	Russia USA
II	MIR– GEOSTATIONAR	2	1990 – 1998	Russia
	MICROLAB 1	1	1995 – 1998	USA
III	CHAMP	1	2001	Germany
	GRACE	2	2002	Germany – USA
	FORMOSAT-3/COSMIC	6	2006	Taiwan –USA
	Metop-A	1	2006	ESA
	TerraSAR-X	1	2007	Germany

Table 1.1.1. Stages of elaborating of RO method for remote sensing of the atmosphere and ionosphere

## 1.2. RO system for monitoring the atmosphere

To obtain information about the atmosphere and ionosphere for meteorology, climatology, and geophysics, it is required (1) a global coverage of the earth's surface by the RO measurements; (2) high accuracy of measurements and usage of radio signals in different frequency bands. Global sounding may be fulfilled only by use of many satellites, transmitting radio waves, and satellites - receivers of signals. The time period required for sounding of the atmosphere in a given region should be essentially shorter than the time scale corresponding to the changes in the atmospheric state, and the frequency of measurements in any region should correspond to the frequency of observations usual for standard meteorological practice, i.e. one time per six hours. A system consisting of high orbital satellites with long orbital period and satellites installed in low orbits satisfies these requirements because difference in orbital periods the low orbital satellites will periodically immerse into or egress from the earth's limb relative to the high orbital satellites, providing RO sounding of the atmosphere above different regions. The scheme of RO sounding of the atmosphere is shown in Fig. 1.2.1. In Fig. 1.2.1 the satellites, transmitting the radio waves, are located in points  $G_j, j=1, \dots, n+2$ , and the satellite-receiver of signals is disposed at point L, point T corresponds to the radio ray perigee and is disposed at the minimal altitude above the earth surface. For supporting this system of remote sounding of the atmosphere, the navigational satellites are used as emitters of radio waves. This solves the problem of global coverage of the earth and assures high accuracy in measurements of atmospheric parameters owing to high stability of signals, emitted by navigational satellites.

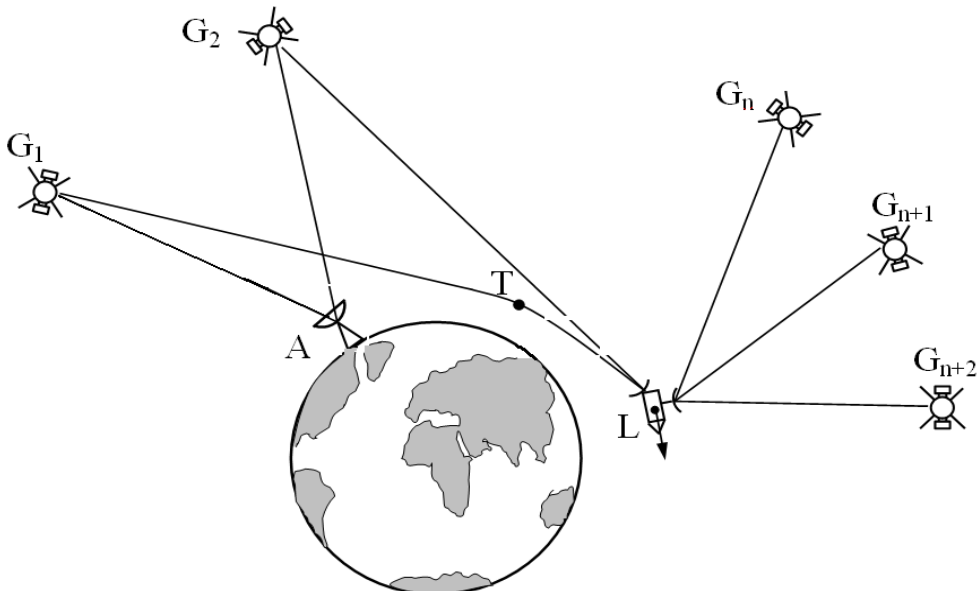


Fig. 1.2.1. Scheme of RO remote sensing,  $G_1$  is the occulted navigational satellite,  $G_2$  is the reference satellite, L is the low orbital satellite-receiver,  $G_n \dots G_{n+2}$  are satellites for measuring the orbital parameters of the low orbital satellites, and A is the ground-based station for receiving RO information and data analysis.

A detailed description of the stages of elaboration and designing of navigational systems, basic principles, and structure of emitted signals and usage for RO investigations are published in [50–52]. Navigational satellite systems are destined for solution of navigational problems, i.e. for determination of the coordinates and velocities of different objects on the surface of land and sea, in the atmosphere and in the earth's environmental space. Coordinates and velocity of any object may be determined from the results of measurements of its distance from any three navigational satellites, and velocity – from the changes of these distances, i.e. from the radial velocity. In the radio-technical systems, the distances, as a rule, are determined from the signal delay, and the radial velocity – from the Doppler shift of its frequency. To increase the accuracy of measurements of the signal delay, it is necessary to broaden its spectrum. To increase the accuracy of measurements of the Doppler shift, it is necessary, vice versa, to increase the signal duration. This contradiction may be avoided under a condition of joint estimation of the delay and Doppler shift in the case of application of signals with large base. The signal base is equal to the product of its duration and effective spectral width. Application of the noise-like signals with large base is necessary for functioning of the navigational system. In the navigational satellite systems GLONASS and GPS for achieving the high resolution and stability relative to the noise and interferences, the noise-like signals with phase-manipulation are applied. These signals consist of the impulse sequences with initial phases having discrete values 0 and  $\pi$ . The initial impulse signal with duration  $\tau$  is divided to  $N$  elements. Each of these elements has duration  $\tau_N = \tau/N$ . In this case, the equivalent spectral width of the noise-like signal is by a factor  $B = \tau / \tau_N$  greater, than the same one of the initial signal.

Navigational system GPS consists of ~29 satellites (canonically 24 plus a few spares) that are distributed in six circular orbital planes, having inclination  $55^\circ$  to the equatorial plane. The angle between the orbital planes is equal to  $60^\circ$ . The altitude of satellites is equal to 20,180 km, orbital period is about 11 h 58 m. Distribution of the satellite on the orbits assures observing five or more satellites above any region of the earth's surface. Each GPS satellite continuously broadcasts signals in two frequency bands L1 and L2. All GPS satellites transmit signals at the same carrier frequencies, which are formed from the frequency  $f_0=10.23$  MHz. The carrier frequency  $f_1$  (band L1) is equal to  $154 f_0$ , and the carrier frequency  $f_2$  (band L2) –  $120 f_0$ , i.e.  $f_1=1575.42$  MHz, and  $f_2=1227.6$  MHz. The ratio of the carrier frequencies is equal to  $f_2/f_1=60/77$ . Signals in bands L1 and L2 are coherent and modulated by the two pseudo-random codes: the basic P-code with the speed of transmission 10.23 Mb/s and open C/A code with the speed of transmission 1.023 Mb/s. Diagrams of transmitting antenna illuminate practically uniformly the earth's hemisphere, as seen from the satellite. The power of the GPS signal at the output of a linearly polarized ground based antenna having the gain coefficient +3 dB, is greater than -163 dBW for channel L1 when using P-code, or -160 dBW for C/A code, and -166 dBW for channel L2. It is planning from 2014 year, that system GPS will have satellites of new generation with increased values of the signal power.

For supporting the global navigational radio field the navigational system GLONASS will have 24 satellites, orbiting around the Earth in three planes. The orbits of the GLONASS satellites are near circular with the altitude about 19,100 km, orbital period 11 h 15 m 44 s and inclination  $64.8^\circ$ . Orbital planes are displaced by  $120^\circ$  on longitude of the ascending node. In each orbital plane, eight satellites are disposed with  $45^\circ$  latitude shifting, the satellites in the neighboring orbital planes are displaced by  $15^\circ$ . This structure of the

GLONASS constellation assures observation in any region of the earth. Four or more GLONASS satellites are continuously transmitting the coherent signals in the two bands L1 and L2. The carrier frequencies in the bands L1 and L2 are formed coherently from the reference frequency 5 MHz. The ratio of carrier frequencies, emitted by a separate satellite GLONASS in the bands L2 and L1, is equal to  $f_2/f_1=7/9$ . The GLONASS satellites are transmitting the navigational signals of the standard and heighten accuracy. The signals of the standard accuracy are formed by modulation of the carriers  $f_1$  and  $f_2$  with the frequency 0.511 MHz, the heighten accuracy signals are modulated by a special code with a chip rate 5.11 MHz. The power of the GLONASS signals at the output of a linearly polarized ground based receiving antenna having the gain coefficient +3 dB, is greater than -161 dBW for the frequency band L1, and -167 dBW for the frequency band L2

The spaceborne and ground-based segments constitute the system of RO monitoring of the atmosphere. The spaceborne segment includes the navigational satellites (point G in Fig. 1.2.1) and several satellites - receivers in the low orbits (point L), having qual-frequency receiver and antenna for the navigational and RO measurements. A key element of the satellite L is a measuring receiver, conducting registration of the amplitude, phase path excess of radio waves, and coordinates for navigation. Navigational measurements are conducted with the sampling frequency 0.1 Hz by use of antenna with zenith orientation. One or two directional antennae are installed for the RO measurements on the satellite L. If one directional antenna is installed on a satellite L, the axis of its diagram is located in the orbital plane of the satellite and oriented to the earth's limb in the direction, opposite to vector of orbital velocity. This antenna assures sounding the atmosphere during setting of the receiving satellite behind the earth's atmosphere relative to a navigational satellite. Antenna, oriented in direction of the orbital motion of the receiving satellite, is destined for observation of the rising navigational satellites. Installation of two antennae increases by about two times a number of regions, sounded at one orbital turn of a satellite.

For supporting necessary altitude resolution in determination of the atmospheric and ionospheric characteristics measurements of the signal parameters should be conducted with a high sampling frequency, this requires a special onboard memory device for storage of the results of measurements before their transmission to an earth-based receiver station. To diminish the required volume of memory, the sounding of the upper ionosphere is provided with the small sampling frequency (10 Hz), and when the minimal altitude of radio ray  $G_1L$  is achieved 130 km measurements with the large sampling frequency (50 or 100 Hz) are provided. The results of measurements, concentrated in the onboard memory device, are periodically transmitted to an earth-based receiving stations, and then to the Center of Guidance and Data Analysis. The structure of the ground based part of the system contains a net of the stations for receiving of the satellite information, the measuring centers that control the orbits and the time onboard the navigational satellites, and the Center for Guidance and Data Analysis. The scheme shown in Fig. 1.2.1 demonstrates the different variants of RO sounding: «autonomous», when measurements are conducted only in one communication link  $G_1L$ , «differential» for measurements with usage of two communication links  $G_1L$  and  $G_2L$ , and the technique double differencing measurements, that used an ground-based center (point A).

The Center for Guidance and Data Analysis provides analysis of all information for supporting high accuracy in the retrieved parameters of a sounded medium and forms the data bank having several levels and comparison of the onboard clocks of all navigational (G)

and measuring satellites- receivers (L) and their correction to the precise atomic clock. Also determination of the coordinates and vectors of the satellites velocities, estimations of the quality of the primary data, the data analysis with usage of different methods for obtaining the altitude profiles of the parameters of the sounded medium are conducted in the Center for Guidance and Data Analysis. The results of measurements and data analysis are retained, as a rule, in three-level format. The first level contains detailed information describing measurement conditions. The second level, accessible for customers, contains the date and time of beginning of measurement session, session number, number of a navigational satellite, taking part in RO sounding, number of channel of measuring receiver, the time interval between the sequential samples, value of signal-to-noise ratio in the band L1 and L2, coordinates and component of velocities of the navigational and LEO satellites, and values of the phase path excess of the signals L1 and L2, caused by influence of a medium. Analysis of these data allows one to determine the parameters of a medium in different region of the earth. Values of the physical parameters of a medium, determined from the results of analysis of the RO signals, are listed in the data of the third level. These data contains date, time and number of measurement session, altitude in the atmosphere, latitude and longitude of the investigated region, refractivity, air density, pressure and temperature in the atmosphere, the bending angle, and other parameters.

In the present time, the satellites GRACE-A, GRACE-B, METOP-A, FORMOSAT-3/COSMIC, and TerraSAR - X are used for the RO sounding of the atmosphere and ionosphere. These satellites provide more than 3000 measurement sessions per day. Experimental information received from these satellites is analyzed in real time in the centers of data analysis in USA, Germany, and Taiwan. This system provides the global control of the current state of the atmosphere and ionosphere and allows one to solve the next problems:

- monitoring the altitude distribution of temperature, density, and pressure with high accuracy and high vertical resolution for improvement of weather prediction and studying the climate changes;
- providing control of the geopotential altitude;
- monitoring of the distribution of water vapor for better understanding the role of the global water vapor circulation in the meteorological and climatological problems;
- control of the turbulence and internal atmospheric waves distribution;
- monitoring the ionosphere and revealing connection of the ionosphere and upper atmosphere with the solar activity and antropogenic influence.

## 2. Direct and Inverse Problems of Radio Occultation Remote Sensing

### 2.1. Refractivity, rays, and bending angle

A direct problems of RO investigation of the atmosphere or ionosphere is resolved to determine the changes of the amplitude, phase or frequency of radio waves in the communication link satellite-to-satellite, if vertical profile of the refractivity  $N(h)$  is known. This problem was investigated in detail in the publications [16, 21, 22, 28, 29, 37, 48, 52-59]. We will follow these publications during analysis of the RO direct problem. Geometry of the RO direct problem is shown in Fig. 2.1.1. The satellites are disposed in the points L and G at the altitudes  $H_l$  and  $H_g$ , the earth's center is located at point O, the radio ray LTG has in the

point T a minimal altitude  $H$  above the earth surface. The radio ray in the free space, in the segments  $LL_1$  and  $GG_1$ , is a straight line, in the segment  $L_1G_1$  the ray is curved because of the medium influence. Change in the ray direction is described by the bending angle  $\xi$ . Let us assume that the atmosphere or ionosphere is a locally spherical symmetric medium. Hence, on the ray segment  $L_1G_1$  near the point T, one may neglect influence of the horizontal gradients of medium and the refractivity index  $n(r)$  depends only on the distance  $OC = r = a + h$ . Let us introduce the altitude  $h$  of the arbitrary point C on the ray trajectory and designate  $a$  is the earth's radius,  $\theta$  is the central angle  $LOG$ ,  $r_g = a + H_g$ ,  $r_l = a + H_l$ , and  $r_t = a + H$  are, correspondingly, the distances  $OG$ ,  $OL$ , and  $OT$ . The decimeter and centimeter radio waves are used for the RO sounding so that the medium parameters insignificantly change at a distance equal to the wavelength. Therefore, one may apply the geometric optics for the analysis of the direct problem. For a spherically symmetric medium, the following relationships are valid

$$n(r) r \sin \gamma = \text{const} , \tag{2.1.1}$$

$$P \Delta S = \text{const} , \tag{2.1.2}$$

where  $\gamma$  is the angle between the radius-vector  $\mathbf{r}$  and the unit vector of a radio ray  $\mathbf{I}_0$ .

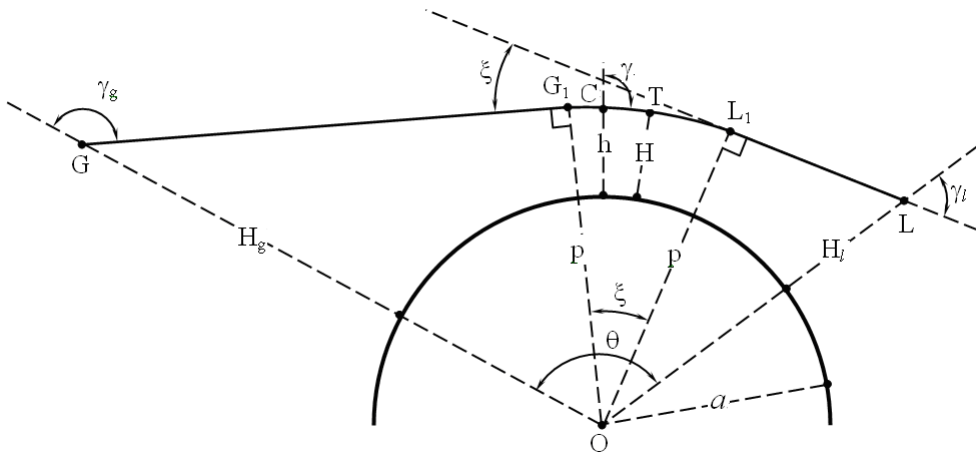


Fig. 2.1.1. Geometry of the RO direct problem.

Equation (2.1.2) connects the density of the power flow  $P$  and the cross section of a ray tube  $\Delta S$ . Eq. (2.1.2) allows determining the changes in value  $P$ , caused by refraction of radio waves. Derivation of the relationships (2.1.1) and (2.1.2) is described in many monographs on radio waves propagation (see for example, [59]). It follows from (2.1.1) that the altitude dependence of the refractive index  $n(r)$  determines the main features of radio waves propagation.

Let us consider the features of the altitude profile  $n(h)$ . The distinction of the refractive index  $n(h)$  from unity is very small. Therefore, it is convenient to introduce the refractivity  $N$  equal to  $N = n - 1$ . The refractivity  $N$  depends on the pressure  $P_a$ , temperature  $T_a$ , and humidity  $w_a$

$$N = \frac{77.6}{T_a} \left( P_a + \frac{4810 w_a}{T_a} \right) \cdot 10^{-6}, \quad (2.1.3)$$

where the pressure and humidity are expressed in millibars, and the temperature is measured in Kelvin. The hydrometeors in the troposphere (rain, snow, mist, ... etc) introduce a small addition  $\Delta N$ , determined by an approximate relationship  $\Delta N \approx 1.4 w_w$ , where  $w_w$  is the water content expressed in  $\text{g}/\text{m}^3$ . It is important that  $N$  in the atmosphere does not depend on the frequency. In the troposphere, the pressure and humidity are diminishing when the altitude  $h$  is increasing according to an exponential dependence, and the temperature has a nearly linear change as function of height. Hence, the altitude profile of the refractivity may be approximated by an exponential law

$$N \approx N_0 \exp(-b_1 h), \quad (2.1.4)$$

where  $N_0$  is the refractivity near the earth surface. Values  $N_0$  may be determined by use of Eq. (2.1.3) from measurements of  $P_a$ ,  $T_a$ , and  $w_a$ . In the moderate latitudes,  $N_0$  on average is equal to  $3.06 \cdot 10^{-4}$  in winter, in summer this value is near to  $3.3 \cdot 10^{-4}$ ; the parameter  $b_1$  is equal to  $0.13 \text{ km}^{-1}$ , it changes in  $0.12 - 0.14 \text{ km}^{-1}$  interval. Value  $b_1$  may be determined from the magnitude of  $N_0$  if one accounts for insignificant changes of  $N$  at the altitude 10 km, where  $N$  is equal to  $9.2 \cdot 10^{-5}$ . Therefore, with accounting for expression (2.1.4), one may obtain

$$b_1 = -\frac{1}{10} \ln \left( \frac{9.2 \cdot 10^{-5}}{N_0} \right). \quad (2.1.5)$$

It follows from the relationships (2.1.3), (2.1.4), and (2.1.5), that the approximated dependence  $N(h)$  may be found from the near surface values of pressure, temperature, and humidity. The real profiles  $N(h)$  may differ from the exponential dependence. The more accurate form of vertical profile  $N(h)$  may be described by the relationship

$$N(h) = N_0 \exp(-a_1 h^2 - b_1 h). \quad (2.1.6)$$

Approximation (2.1.6) corresponds in average good to the actual dependence  $N(h)$ , however it does not account for the features of  $N(h)$  at the tropopause and in the troposphere, where temperature inversions and clouds permanently exist. More detailed information on the altitude distribution of  $N$  in the troposphere is given in [60-62].



Let us consider dependence of the refractive index on the frequency and altitude in the ionosphere. It is known that the plasma's refractivity is determined at high frequencies by a simple relationship

$$N = -\chi N_e f^{-2}, \quad (2.1.7)$$

where  $\chi = 40.3$ , the electron density  $N_e$  is expressed in  $\text{m}^{-3}$ , and  $f$  is the frequency in Hz. Derivation of this formula is given, for example, in [59]. It follows from (2.1.7) that  $N$  is negative and dependence  $N(h)$  repeats the altitude profile of the electron density of ionosphere  $N_e(h)$ . The refractivity diminishes as  $f^2$  when the frequency  $f$  increases. Vertical profile  $N_e(h)$  may be described by different ways in the area, located above the main ionospheric maximum, when  $h > h_m$ , and in the lower part of the ionosphere when  $h < h_m$ . In the upper part of the ionosphere  $N_e(h)$  may be satisfactorily described by an exponential dependence

$$N_e = N_m \exp[-b_2(h - h_m)], \quad (2.1.8)$$

where  $N_m$  is the electron density in the main ionospheric maximum,  $h_m$  is the altitude of the main maximum of the electron density,  $b_2$  is the parameter, characterizing the speed of diminishing of the electron density when the altitude increases. For the part of the ionosphere, located below the main ionospheric maximum, it is difficult to find the appropriate approximation, describing dependence  $N_e(h)$ . As a rough approximation in this region, one may use a formula

$$N_e \approx N_m \left[ 1 - \left( \frac{h_m - h}{d_2} \right)^2 \right]. \quad (2.1.9)$$

This approximation corresponds to abatement of the electron density up to zero at the altitude  $h = h_m - d_2$  where  $d_2$  is the approximated width of the lower part of the ionosphere. Vertical profiles  $N_e(h)$  depends on the daytime, season, latitude, and solar activity. If  $h < h_m$ , dependence  $N_e(h)$  has a complex form: in this area the regular ionospheric layers  $F_1$  and  $E$  are located, irregularly additional sporadic plasma  $E_s$  layers appear in this area. The rough approximation (2.1.9) does not account for these features. There are numerous publications with detailed description of the distribution of electron density. The International Reference Model of the Ionosphere (IRI) [63, 64] has been designed for presentation of the standard altitude dependences  $N_e(h)$  in the Internet.

Let us analyze the refraction of radio waves in situation shown in Fig. 2.1.1. It follows from formula (2.1.1)

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