Development of Compact Optical Instrumentation for Studying the Earth Upper Atmosphere Emissions on the Board of International Space Station

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Abstract – In presented work the technical pattern of Spectral Photometrical Complex (SPC) is described and the results of calculations of required energetic, spectral and temporal parameters of SPC are given. The plan of experiment "Hydroxyl" at International Space Station (ISS) with SPC instrumentation supposes carrying out the sessions of observations of Earth upper atmosphere at the night-side of the Earth. The absolute hydroxyl emission intensities will be measured with spectral resolution better then 0.5 nm in region of 830 – 1040 nm together with atomic oxygen green line emission at 577.7 nm. The measurements will be carried out in Earth limb direction. The spatial resolution of emission images is supposed to be better then 1 km.

Keywords: upper atmosphere, space experiment, hydroxyl, oxygen emission, earthquake, climate changes.

1. INTRODUCTION

In the framework of the program "Space–US" (Union State: Russia – Belarus) "The development and utilization of perspective space facilities and technologies for the sake of economical and scientific progress" the Science research institute of applied physics problems of Belarus State University (Minsk) together with Institute of Earth magnetism, ionosphere, and radio wave propagation of Russian Academy of Sciences (Moscow) have started the development of scientific instrumentation for studying spatial, temporal and spectral characteristics of upper atmosphere emissions in space experiment named "Global monitoring the atmosphere state by measuring emission intensities of hydroxyl and atomic oxygen with the purpose of creation the empirical model of mesosphere for prediction of geophysical catastrophe" ("Hydroxyl") on the board of ISS.

The need of carrying out the space experiment "Hydroxyl" was stimulated by great significance of hydroxyl emission as with relation to chemical dynamics of interaction hydroxyl with basic atmospheric constituents N_2, O_2, O, and substantiation applications of these emissions in geophysical measurements. The hydroxyl emission is applied for measuring the atmospheric temperature and concentration of minor mesospheric constituents, as well as for studying the nature of intrinsic gravity waves. Analysis of the characteristics of night atmosphere emissions in the atomic oxygen line 557.7 nm and hydroxyl bands was also fulfilled in connection with seismic activity. Despite on great practical significance and of almost fifty years history of studying the emission kinetic mechanism is so far quantitatively not clear. This fact seriously restricts the applications of OH emissions to practical purposes.

Hydroxyl molecule OH emissions dominate in nightglow spectral region of 0.52 – 4.0 µm. Emitting layer is centered near the altitude of 87 km and has thickness about 8 km regardless year season and location latitude (Baker et al. 1988). The main source of vibration excitations of radicals is the chemical reaction of hydrogen with ozone, proposed independently in the works of Bates (Bates et al. 1950) and Herzberg (Herzberg et al. 1951).

On the basis of measurements of spatial distributions of hydroxyl and oxygen emissions the following atmospheric parameters at the heights of 80 – 100 km will be received: altitude temperature distribution; altitude atomic oxygen distribution; planetary nonuniformity, permissive to reveal global planetary (gravity) waves, as well as to study the influence of underlying terrain, orographic effect; systematic measurements will allow revealing the global climate changes trends of atmospheric characteristics (global warming).

Up to now only the data from satellite UARS (Canada, USA, France) are used for determining intensity, rotational temperature of the band OH(8,3) and emission layer height. In Russia such studying is not carried out.

In the works (Nasyrov 1978, Fishkova et al. 1985, Toroshelidze et al. 1988, Fishkova et al. 1989, Korobejnikova et al. 1989) the analysis of nightglow characteristics in oxygen emission lines [OI] 557.7 and 630.0 nm, sodium Na line 589.3, and hydroxyl bands OH (8-3) were done for Central Asian seismic zone in connection with seismic activities. It was shown that during the period of preparing and evolution of earthquakes the disturbances in mentioned emissions of various temporal scales are observed. In particularly, essential increasing emission of [OI] 557.7 nm takes place for the day or two before earthquake with sharp decreasing in next day.

The spectra of night upper atmosphere in the spectral region of 600 – 1050 nm have measured during the last several decades. The results, which differ in form and quality can be found at works (Krassovsky et al. 1962, Osterbrock et al. 1997, Piterskaya et al. 1975). In most cases only nightglow spectral structure was determined without information on intensity of spectra. In the paper (Bakanas 2002) the results of measuring the spectral distributions of various upper atmosphere emissions in absolute photometric units (Rayleigh) are presented.

2. STRUCTURE AND BASIC CHARACTERISTICS OF SPC

SPC consists of the block of optical sensors (BOS) and block of electronics (BE). BOS will be installed on a viewing port of Russian segment of ISS and is connected with BE. BOS is intended for selection and measuring emissions in given spectral regions and definite spatial parameters.

The BOS includes:

- module of spectral image (MSI) of hydroxyl emissions coupled with module of matrix array photodetector (they realized in aggregate an imagine spectrometer);
- module of recording emissions (MRE) of atomic oxygen coupled with module of linear array photodetector (filtered device, forming the one-dimensional image).

The BE is intended to control: operating of SPC, acquiring data; preliminary data processing, compressing and storage the operating and scientific information onto changeable hard disks; delivery the digital data arrays to informating-controlling system. BE supplies the control of SPC operation from the airborne equipment control system and delivery the functioning parameters of SPC into airborne telemetry information system.

BE includes of:

- data processing module;
- data storage module;
- module of communication with ISS service systems;
- power supply module.

Technical characteristics of MSI:

- spectral region: 830 – 1040 nm;
- spectral resolution: not worse than 0.5 nm;
- emission intensity of OH single line of a band at limb observation: 0.1 – 5.0 KiloRayleigh;
- spatial resolution throughout the height: 1.0 km;
- number of CCD detector array pixels in spectrum forming direction: 1024
- number of CCD detector array pixels in image forming direction: 128
- pixel size: 24×24 μm;
- field of view angle in vertical direction: 3°;
- focal length of input lens: 58.6 mm.

Technical characteristics of MRE:

- operating wavelength: 557.7 nm;
- spectral filter bandwidth: 0.5 nm;
- mean emission [OI] intensity at limb observation: 10 KiloRayleigh;
- spatial resolution throughout the height: 1.0 km;
- number of CCD linear array detector pixels: 128;
- pixel size: 24×24 μm;
- field of view angle in vertical direction: 3°;
- focal length of input lens: 58.6 mm.

When choosing optical arrangement of polychromator in module of formatting spectral image, MSI, the calculation of required energetic, spectral and spatial parameters led us to using Rowland optical schematic with replica of concave multiple-section diffraction grating, which has a number of advantages: law costs on production, simplicity in construction and optical positioning. But using the classical Rowland schematic was impossible, because of inadmissible enhancing ring radius and, correspondingly - radius of grating. For decreasing overall dimensions of optical schematic having large enough angle between optical axes "entrance slit – grating" and "grating – detector" (equaled 32.5±0.1º) the known method of 'breaking' optical axis was used. This doesn't disturb the operation of scheme and doesn't degrade the quality of forming image, but essentially decreases overall dimensions. Polychromator optical schematic of MSI is presented on Fig. 1, where its basic elements and sizes are shown.

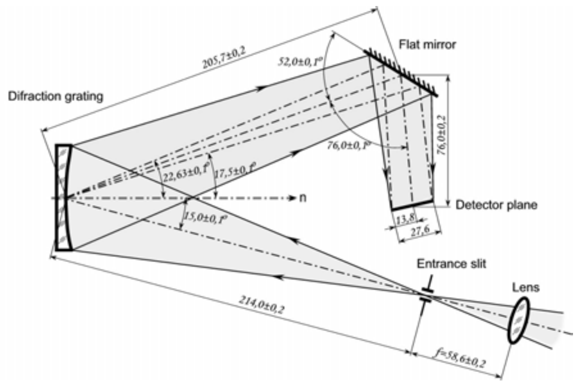

Figure 1. Polychromator optical schematic of MSI

3. SPC PARAMETERS CALCULATIONS

The height of OH emitting layer in the atmosphere is extended at the heights 80 – 93 km, and of [OI] emitting layer is about 88 – 110 km. Geometrical observation scheme in space experiment is given on Fig. 2. More detailed geometrical parameters of experiment are shown in Tab. 1. The measurements will be carried out in limb direction perpendicular to ISS velocity vector with orientation of MSI entrance slit along the Earth radius. Actually, the MSI is a type of videospectrometer which scans the emitting layer due to station orbital moving. While the MRE (for [OI] emission) is a filter device with vertical orientation of linear detector and scanning along another coordinate.

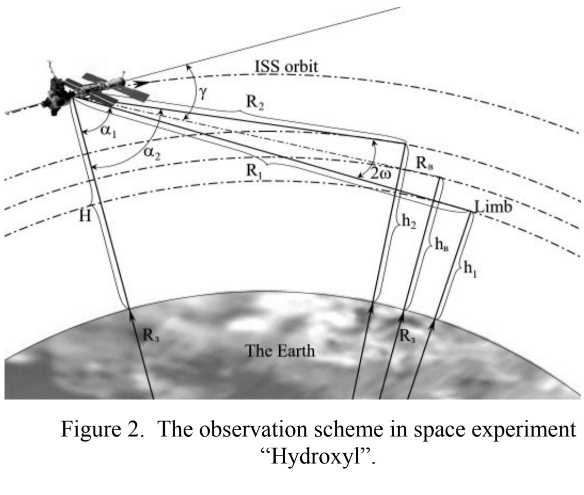

Figure 2. The observation scheme in space experiment "Hydroxyl".

For formulation of basic energy equation of any optical channel (MSI or MRE) we will consider a single detector pixel. Realizing this we will take into account three basic

Table 1. GEOMETRICAL PARAMETERS OF SPACE EXPERIMENT "HYDROXYL"

Parameter	Value	Formular
Radius of the Earth R_E, км	6400	
ISS orbit height H, км	400	
The lower boundary height of observed layer h_1, km	80	
The upper boundary height of observed layer h_2, km	110	
The angle from nadir α_1, corresponding to h_1, grad.	72,35	$\alpha_1 = \arcsin\left[\left(R_E + h_1\right)/\left(R_E + H\right)\right]$
The angle from nadir α_2, corresponding to h_2, grad.	73,21	$\alpha_2 = \arcsin\left[\left(R_E + h_2\right)/\left(R_E + H\right)\right]$
Linear angle of vertical FOV 2ω, grad.	0,86	$2\omega = \alpha_2 - \alpha_1$
Uncertainty of ISS axes orientation Δ, grad.	0,1-1,0	
Angle of obliguity of device axis downward from local horizon γ, grad.	17,2	$\gamma = 90^\circ - \alpha_1 - \omega$
Angle of obliguity at FOV deviation downward on 0,1°, α_-, grad.	72,25	$\alpha_- = \alpha_1 - \Delta$
The lower boundary height at axis deviation downward on 0,1° h, km	76,39	$h_- = \left(R_E + H\right)\sin\alpha_- - R_E$
Angle of obliguity at FOV deviation upward on 0,1°, α_+, grad.	73,31	$\alpha_+ = \alpha_2 + \Delta$
The upper boundary height at axis deviation upward on 0,1° h_+, km	113,42	$h_+ = \left(R_E + H\right)\sin\alpha_+ - R_E$
Distance to the center of observed layer (limb) R, km	2013	$R = \sqrt{\left(R_E + H\right)^2 - \left(R_E + h_в\right)^2}$

contributions into pixel noise charge (the number of noise electrons): photon (or radiative) noise of registered radiation, dark current (thermal) noise, and readout noise. Let write-down known signal-to-noise merit (*S/N*):

$$S/N = \frac{F_\lambda Q_\lambda T}{\left[\left(F_\lambda + F_\lambda^b\right)Q_\lambda T + I_d T + N_r^2\right]^{1/2}}, \qquad (1)$$

where F_λ - radiation flux at the detector pixel (friendly signal, measured in photons/(pixel·s))

F_λ^b - atmospheric background noise flux

$Q_\lambda \equiv \sigma S(\lambda)$ - spectral sensitivity (or quantum efficiency) σ - quantum efficiency of CCD emitter, $S(\lambda)$ - relative spectral sensitivity of CCD

N_r^2 - readout noise component

I_d - dark current (in electron/(pixel·s))

T - time of exposure

λ - radiation wavelength

Index λ refers to spectral dependence of corresponding quantity. In this connection mentioned quantity either refers to monochromatic radiation or to integrated radiation over the very narrow spectral range (about 0.5 nm for 557.7 nm line and corresponding to one rotational line of OH rotational-vibrational bands).

The most essential background radiation on observations at the night side of the Earth is the Moon light scattered by atmosphere, Earth surface and the clouds. The brightness of this background is maximum at zero phase of Moon (full moon) and decreases three order of magnitude on 14-th day after full moon (new moon). For the most bright object (a cloud) at full moon and at average Moon zenith angle of 45° estimated value of this brightness is about $4 \cdot 10^{-8}$ W/cm^2·sr·µm. But if underlying surface is out of FOV we can neglect the scattered Moon light for evaluative calculations. Then the registered background intensity (continuum) defined by atmospheric gases can come to 300 – 400 Rayleigh within the interval of 1 nm near wavelength 800 nm.

The equation (1) can be resolved relatively to exposure time *T*, if the other parameters are consider given. Then we receive:

$$T = \frac{(S/N)^2}{2I_S}\left[1 + I_d/I_S + \sqrt{\left(1 + I_d/I_S\right)^2 + \frac{4N_r^2}{(S/N)^2}}\right] \qquad (2)$$

where I_S - the useful signal current (e^-/ (pixel·s)), which is calculated in the following expression:

$$I_S = (\pi/4) B_\lambda \left(D/f\right)^2 \eta_\lambda \left(\Delta a\right)^2 Q_\lambda, \qquad (3)$$

where B_λ - spectral brightness of useful signal,

D, f - diameter of entrance lens and its focal distance,

η_λ - efficiency of spectrometer optical chain at wavelength λ,

$(\Delta a)^2$ - area of CCD array single pixel.

For the Rowland optical schematic, shown on Fig. 1, efficiency of spectrometer optical chain is given by following formular:

$$\eta_\lambda = \tau \frac{r_a^2}{r_b^2} \rho_\lambda , \quad (4)$$

where τ - transmittance of entrance lens, пропускание входного объектива;

ρ_λ - grating reflection coefficient, which depends on wavelength, angles of radiation incidence and reflection on grating and profile of grating grooves;

r_a , r_b - distances, shown on Fig. 1 ($r_b = r_{1b} + r_{2b}$)

After substituting the all values into equations (2), (3) (namely, average dark current at - 25°C of 1 e^-/ (pixel·s); average readout noise of 6 e^-/pixel; average quantum efficiency of CCD Q_λ = 0.2; average brightness of single line in the bands of OH at limb observation - 1000 Rayleigh) for signal-to-noise ratio S/N = 3 we obtain that exposure time in MSI for hydroxyl emission has to be 13 s and more. In another hand, at the same conditions and even if signal-to-noise ratio S/N = 10 the corresponding exposure time for green line of oxygen 577.7 nm registration (in MRE channel) will be equal 0.6 s. Besides all optical parameters for MSI and MRE were calculated and they were found to be acceptable (customary): for example, $D \approx 2.5$ cm, $f \approx 5$ cm.

For accuracy verification of insuring required energetic and spectral parameters the prototype of MSI polychromator was developed and created. The outward appearance of workable SPC optical block is presented on Fig. 3.

Figure 3. The outward appearance of SPC optical block

4. CONCLUSION

Initial test and calibration of MSI prototype on laboratory metrological complex have shown, that optical schematic is well-behaved and allows to insure spectral resolution less than 0.5 nm in spectral region of 830 – 1040 nm.

Conducting the space experiment "Hydroxyl" will result in obtaining new information about atmosphere physical parameters at the altitudes of 80 – 110 km and in ability of forecasting earthquakes and some types of man-caused disasters.

Space studying the kinetic mechanisms of hydroxyl and atomic oxygen emissions and received data base will become the basis for checking, reasoning and modifying the empirical models of these emissions. It will make the models to be suitable for forecasting emissions intensities at given sun and geophysical conditions.

5. REFERENCES

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