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# OPTICAL EFFECTS OF RUNNING SPACECRAFT ENGINES IN THE LOWER THERMOSPHERE

**A.V. Mikhalev**
*Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, mikhalev@iszf.irk.ru*

**A.B. Beletsky**
*Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, beletsky@iszf.irk.ru*

**V.P. Lebedev**
*Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, lebedev@iszf.irk.ru*

**V.V. Khakhinov**
*Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, khakhin@iszf.irk.ru*

**Abstract.** This paper provides a brief overview on optical effects during operation of spacecraft (SC) onboard engines in the lower thermosphere according to observational data from the ISTP SB RAS Geophyisical Observatory. We present the results of detected disturbances in the night airglow during operation of SC vernier engines in the F2-region of the ionosphere in the "Radar–Progress" space experiment. With weights of combustion products of ≤10 kg injected by SC vernier engines, the atmospheric emission of [OI] 630.0 nm atomic oxygen is enhanced. We also show optical effects from the launches and passages of heavy launch vehicles "Energiya" from the Skif-DM spacecraft on May 15, 1987 and "Proton-M" from the Yamal-601 spacecraft on May 30, 2019 from Baikonur in the zone far from the launch site. We explore the possibility of enhanced [OI] 557.7 nm atmospheric emission due to chemical modification of the ionosphere in the E-region during the flight of the Energiya space system.

**Keywords:** airglow, spacecraft launches, ionosphere, ionospheric modification.

## INTRODUCTION

Disturbances in Earth's upper atmosphere and ionosphere, which occur during the flight of a rocket with running engines, their various aspects and features have been studied for a long time. The most frequently considered issues are chemical modification of the ionosphere during spacecraft launches [Mendillo et al., 1975, 1993; Mendillo, Baumgardner, 1982] and active space experiments [Biondi, Sipler, 1984; Semeter et al., 1996; Khakhinov et al., 2013], the physical nature of the effects related to the modification of the chemical composition of the atmosphere and, in particular, those leading to an increase in the intensity of some upper atmosphere emissions [Mendillo, 1980; Dressler et al., 1991; Platov et al., 2002], classification and dynamics of ionospheric and gas-dust features in the upper atmosphere caused by fuel combustion products of rocket engines [Karlov et al., 1980; Vetchinkin et al., 1993; Platov et al., 2003], environmental problems of atmospheric pollution by rocket fuel combustion products [Krestnikov, 2018; Adushkin et al., 2000]. Artificial ionospheric features depend on many heliogeophysical conditions in which they are realized and detected (injection altitudes, composition and amount of injected matter, levels of solar and geomagnetic activity, etc.) [Shpynev et al., 2017].

This paper, based on observations at the ISTP SB RAS Geophysical Observatory (GPhO), provides a brief overview of the optical effects caused by running onboard engines of spacecraft (SC) in the lower thermosphere.

## OBSERVATIONAL RESULTS

*Optical effects observed during the operation of SC vernier engines at orbital altitudes in the F2-region*

Optical effects of this type were detected in the controlled space experiment Radar–Progress [Khakhinov et al., 2013] during the operation of approach-correcting engines of Progress cargo transportation vehicles (CTV) at orbital altitudes. During experiments with Progress M-17M on April 17, 2013 and Progress M-23M on July 30, 2014, the KEO Sentinel camera caught extended regions of enhanced brightness in the [OI] 630.0 nm bandwidth of the interference filter [Beletsky et al., 2016; Mikhalev et al., 2016]. In both experiments, the burned fuel mass was ~8–9 kg, the operation time of approaching-correcting engines was ~8–9 s, the altitude of the CTV orbits was 412–418 km, the chemical composition of exhaust gases was $H_2O$, $N_2$, CO, $H_2$, $CO_2$, H, NO, OH, $O_2$, O, N [Adushkin et al., 2000]. Recording of the enhanced brightness regions lasted for ~5–15 min. The characteristic spatial dimensions of the regions of increased intensity were estimated at ~250–350 km.

Figure 1 exemplifies the recording of an enhanced brightness region by the KEO Sentinel camera in the 630 nm emission during the experiment with Progress M-17M on April 17, 2013, 3 min after ignition of the approach-correcting engine. The bright spot at the left side of the frame is an overexposed image of the Moon.

*Optical effects observed during SC launches in a zone far from the launch site*

The ISTP SB RAS Geophysical Observatory is located at a distance ~3000 km east of Baikonur Cosmodrome. After organizing optical observations of airglow, ISTP SB RAS has made several attempts to detect airglow disturbances similar to the so-called ionospheric holes, recorded during launches of large space systems [Mendillo, Baumgardner, 1982; Mendillo, 1988].

The first such attempt can be considered the observation of [OI] 557.7 nm atomic oxygen emission disturbances during the launch and flight of the Energiya space system on May 15, 1987 [Mikhalev, Ermilov, 1997]. Figure 2 shows the behavior of the [OI] 557.7 nm emission intensity during the flight of the Energiya space system. The main features of the observed airglow disturbances are as follows: 7–8 min after the launch of the Energiya space system, a short-term increase in the [OI] **557.7** nm emission intensity (up to 50 %) was observed, followed by a ~30 min decrease in the level of emission variations and an overall reduction in the emission intensity for 2.5 hrs. Later, GPhO examined the behavior of the [OI] 557.7 and 630.0 nm emissions during launches

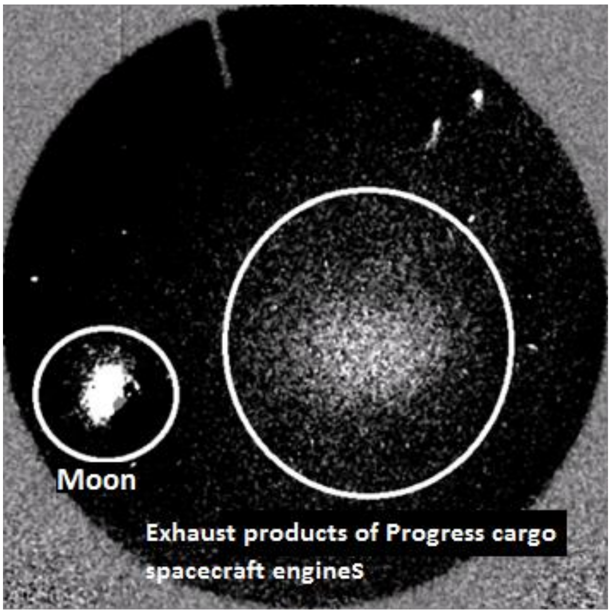


*Figure 1*. Region of enhanced brightness recorded by the KEO Sentinel camera in the experiment with Progress M-17M on April 17, 2013. Recording time is 13:27:37 UT

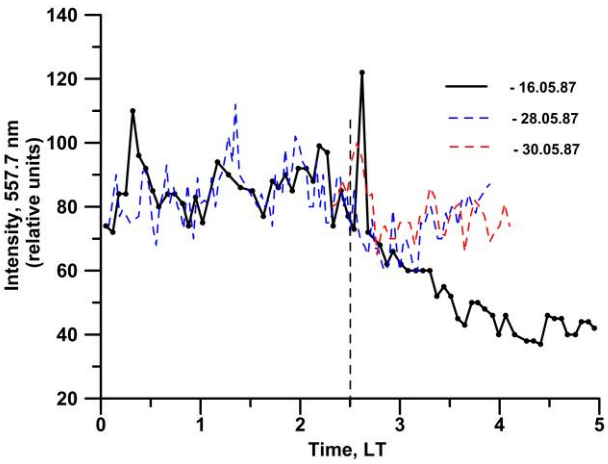


*Figure 2*. Variations in the [OI] 557.7 nm emission intensity during the flight of the Energiya space system [Mikhalev, Ermilov, 1997]. The vertical dashed line marks the launch time

of Soyuz-4TM on December 21, 1987, Progress-35 on March 23, 1988, Phobos-2 on July 12, 1988, and Soyuz-7TM on November 26, 1988. There was no effect similar in amplitude to the effect of the Energiya passage, but a change was detected in the time spectrum of optical radiation variations during post-launch periods (a time span from tens to hundreds of seconds). The characteristic time between the SC launch and the emergence of a trend toward a change in the time spectrum of the 557.7 nm emission was 7–25 min.

The second event during which an airglow disturbance was reliably detected in the post-launch moments is associated with the launch and passage of the Proton-M launch vehicle with the Briz-M upper stage and the Yamal-601 spacecraft on May 30, 2019 [Mikhalev et al., 2022]. The delay between the Proton-M launch from Baikonur and the time of recording of its passage over GPhO was ~11 min. Approximately 2–4 min after its passage over GPhO, an extended airglow region was formed along the SC trajectory, which persisted for ~20 min. The recording was made by the KEO Sentinel all-sky camera in the [OI] 630.0 nm emission. Figure 3 shows the images taken during the passage of Proton-M with the Briz-M upper stage over GPhO.

## DISCUSSION

At midlatitudes under quiet geomagnetic conditions, the spectral level of atomic oxygen $O(^1D)$, responsible for the [OI] 630.0 nm emission at ~200–300 km, is generally filled due to reactions of dissociative recombination of molecular oxygen ions $O_2^+$ and nitrogen oxide $NO^+$ [Shefov et al., 2006; Meneses et al., 2008].

*Optical effects observed at orbital altitudes in the ionospheric F2-region during the operation of spacecraft vernier engines*

The optical effects detected during the Radar–Progress space experiment were initially associated with the scattering of twilight sunlight and moonlight by fuel combustion products in the CTV orbit [Platov et al., 2003; Platov et al., 2011] and/or with the occurrence of additional glow in the [OI] 630 nm atomic oxygen emission as a result of chemical modification of the ionosphere [Mendillo, Baumgardner, 1982; Mendillo, 1988]. In the case of sunlight and moonlight scattering effects, the optical spectrum of the detected regions of increased intensity should better reflect the spectral composition of solar emission. In the case of ionospheric modification, increases in the [OI] 557.7 and 630.0 nm emission intensities should be observed in the night airglow spectrum. During the experiment with Progress M-23M on July 30, 2014, a slight increase in the [OI] 630.0 nm emission intensity was obtained [Beletsky et al., 2016]. Later, Mikhalev et al. [2020], when analyzing the published results of controlled experiments on injection of plasma extinguishing agents in the lower thermosphere, demonstrated the possibility of modifying the ionosphere, which leads to an increase in the [OI] 630.0 nm emission intensity, in the Radar-Progress experiments with a small amount of matter injected by SC vernier engines. In this work, we explore the contribution of the components of the matter ($H_2$, OH, $H_2$ O, CO and $CO_2$), injected during the Radar–Progress experiments, to the increase in the [OI]

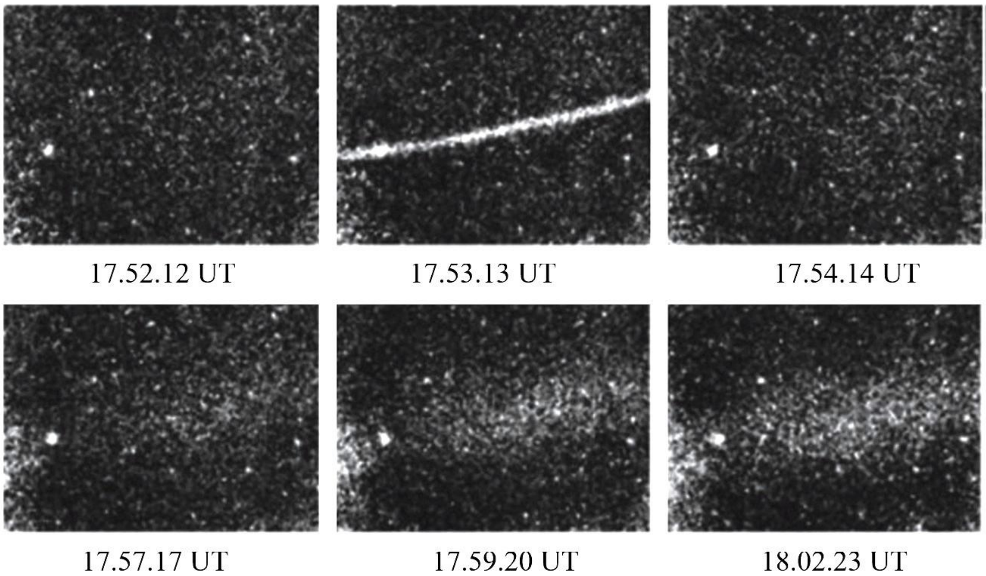


*Figure 3*. Fragments of images taken by the KEO Sentinel camera in the [OI] 630.0 nm emission on May 30, 2019

630.0 nm emission intensity. It is shown that the injection of hydrogen molecules $H_2$ and carbon dioxide $CO_2$ into the atmosphere is the most effective way to enhance the [OI] 630.0 nm emission.

Another argument in favor of ionospheric modification in the Radar–Progress experiments can be the ~10–20 min electron density decreases observed in individual sessions (Figure 4) [Khakhinov et al., 2013, Shpynev et al., 2017], which coincide with the characteristic lifetimes of disturbances in the 630 nm emission intensity (~5–15 min) [Beletsky et al., 2016].

*Optical effects observed during SC launches in a zone far from the launch site*

Mikhalev, Ermilov [1997] did not discuss in detail the results of observation of a short-term increase in the [OI] 557.7 nm emission intensity because of the absence of Energiya trajectory characteristics at that time. It was only noted that the optical effects associated with an increase in intensities of prohibited atomic oxygen emissions [OI] 557.7 and 630.0 nm were previously observed during launches of Atlas-Centaur launch vehicles and others at altitudes above 200 km [Rycroft, 1982]. The increase in the [OI] 557.7 and 630.0 nm emission intensities is attributed to chemical reactions of combustion products — molecules $H_2$, $H_2O$, $CO_2$, etc. —

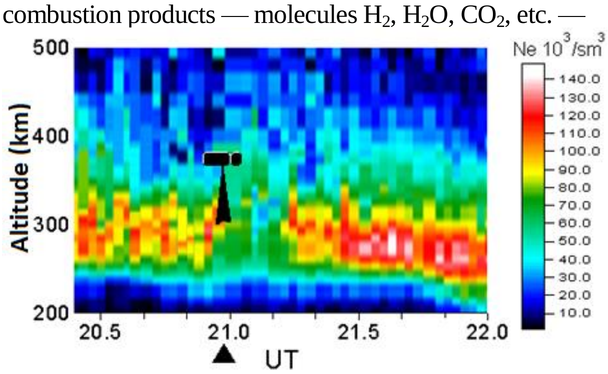


*Figure 4*. Dynamics of the formation of a region of decreased electron density $N_e$ after ignition of SC engines (▲)

with $O_2^+$, which cause dissociative recombination to accelerate 100–1000 times (ionospheric modification) with the formation of atomic oxygen in excited states.By now we know that the Energiya space system carried a test model of the Skif-DM spacecraft weighing 80 t. The main engines of the Energiya launch vehicle were turned off 467.8 s after its launch, and 15 s later Skif-DM separated. Skif-DM after separating from the second stage of the Energiya space system was supposed to make a rotation of 180° in the direction of flight by its own engines to launch it into a circular near-Earth orbit. However, due to improper operation of the onboard systems, the subsequent automatic activation of Skif-DM's main propulsion system was performed on a rotating spacecraft, which did not allow it to be deployed to the circular near-Earth orbit [Gubanov, 1998].

The short-term increase in the [OI] 557.7 nm emission intensity observed by GPhO on May 15, 1987 7–8 min (420–480 s) after the launch of Energiya can be attributed to the last seconds ($T$~467.8 s) of the operation of the Energiya second-stage engines. This allows us to assume that Energiya passed in a zone close to GPhO, presumably at E-region altitudes ~100–120 km.

The Energiya space station was equipped with an oxygen-kerosene engine using ~350 t kerosene fuel ($C_{10}H_{22}$) and ~1500 t liquid oxygen as an oxidizer. When kerosene is oxidized with oxygen, water vapor ($H_2O$) and carbon dioxide ($CO_2$) are released according to the stoichiometric formula [Portola et al., 2012]

$$2C_{10}H_{22}+31O_2 \rightarrow 20CO_2+22H_2O. \quad (1)$$

When the Yamal-601 spacecraft was launched, the fuel components of the Briz upper stage consisted of nitrogen tetraoxide $N_2O_4$ (oxidizer) and fuel asymmetric dimethylhydrazine $C_2H_8N_2$ (ADMH) [https://www.roscosmos.ru/450].

In nitrogen tetraoxide oxidation of fuel ADMH

$$C_2H_8N_2+2N_2O_4 \rightarrow 3N_2+2CO_2+4H_2O, \quad (2)$$

as in oxygen oxidation of kerosene, carbon dioxide $CO_2$ and water $H_2O$ molecules are formed.

When the ionosphere is modified as a result of injection of fuel combustion products into the upper atmosphere, water vapor $H_2O$ and carbon dioxide $CO_2$ are usually considered as one of the main components in the dissociative recombination reactions accompanied by a decrease in electron density and a simultaneous increase in [OI] 557.7 and 630.0 nm emission intensities [Mendillo et al., 1975, 1993; Dressler et al., 1991]:

$$H_2O+O^+\rightarrow H_2O^++O, \quad (3)$$

$$H_2O+O^+\rightarrow H_2O^++O(^1D), \quad (4)$$

$$H_2O^++e^-\rightarrow OH+H, \quad (5)$$

$$CO_2+O^+\rightarrow O_2^++CO. \quad (6)$$

It is not unlikely that reactions (3)–(5) involving water vapor $H_2O$ make the main contribution to the electron density decrease in their region, and reaction (6) involving carbon dioxide $CO_2$, in which the molecular oxygen ion can subsequently participate in the dissociative recombination reaction, is one of the main reactions providing an enhancement in the [OI] 557.7 and 630.0 nm emission intensities [Mikhalev et al., 2020].

It is natural that the enhancement in the [OI] 557.7 and 630.0 nm emission intensities will depend on the altitude distribution of electron density, atomic and molecular ions $O_2^+$, $O^+$, and other atmospheric components at altitudes of injection of the SC combustion products. Thus, the electron density having a maximum at 270–350 km (F2 layer) can have significant values (~$10^3$–$10^4$ cm$^{-3}$) at certain nighttime hours at ~110 km (E, $E_s$ layers) [Mirtov, Starkova, 1976; Encyclopedia ..., 2008]. This also applies to atomic and molecular ions $O_2^+$, $O^+$ [Danilov, Vlasov, 1973; Mishin et al., 1989]. Probably, when interpreting the optical effects of the Energiya flight we should not rule out the occurrence of shock waves and modulation of the 557.7 nm emission layer, taking into account the orbital speeds and record weights (2400 t) of the Energiya space system and the weight of the Skif-DM test model (80 t) [Gubanov, 1998]. For example, a similar effect of modulation and curvature of the 557.7 nm emission layer, presumably associated with the impact of a large meteoroid [Avakyan et al., 1991], was seen from the International Space Station Mir.

## CONCLUSIONS

Dmitriyev et al. [1991] have quantitatively estimated the [OI] 630.0 nm emission enhancement caused by injection of carbon dioxide $CO_2$, oxygen $O_2$, and hydrogen $H_2$, formed during the operation of rocket engines, into the upper atmosphere (F2-layer altitudes). It has been found that in order for the [OI] 630.0 nm emission to increase 10 times there should be 100 t $CO_2$, 100 t $O_2$, and 0.063 t $H_2$ injected. The analysis of the optical effects observed in the Radar–Progress active space experiment during the operation of CTV vernier engines at F2-layer altitudes enabled correction of the minimum mass (≤10 kg) of injected fuel combustion products at which their detection and recording in ground-based optical observations become possible. In this case, the expected increase in the [OI] 630.0 nm emission intensity above the background value can be as large as ~10–50 R; the characteristic scales of the glowing areas are tens and hundreds of kilometers, and the lifetimes of these features are from tens to hundreds of seconds depending on the mass of the injected matter.

We have described the features and conditions of the flight of the Energiya space system with the Skif-DM spacecraft during which a short-term increase in the [OI] 557.7 nm emission intensity was observed in a zone far from the launch site. We have explored the possibility of increasing the [OI] 557.7 nm emission through chemical modification of the ionosphere in the E-region during the Energiya flight. With reference to the recording of the optical effects caused by the flight of the Yamal-601 spacecraft with a useful mass of 20 t, we can assume that the geographical location of GPhO is likely to provide reliable detection of the optical effects of launches and flights of heavy-lift launch vehicles from Baikonur in a zone far from the launch site.

The results presented in this paper can be used to develop an empirical model of variations in the [OI] 557.7 and 630.0 nm atmospheric emissions during chemical modification of the ionosphere by rocket fuel combustion products, which will complement the list of existing empirical models of variations in atmospheric emissions of the upper atmosphere [Shefov et al., 2006].

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