Aspects of remote detection of ionospheric disturbances caused by spacecraft engine exhaust jets

***V. Khakhinov*, S. Alsatkin, D. Kushnarev, V. Lebedev**

Institute of Solar-Terrestrial Physics Siberian Branch of Russian Academy of Sciences
(ISTP SB RAS)
664033, Lermontov st. 126a, p/o Box 291, Irkutsk, Russia

Abstract

Since 2007, we have carried out active space experiments using the 'Progress' transport spacecraft (TSC) and the Irkutsk Incoherent Scatter Radar (IISR). Engine burns of orbital maneuvering subsystem were a source of ionospheric disturbances at a height of 340 km. The amount of used fuel varied from 2 to 11 kg. The flow directions relative to IISR and amount of injected exhaust products varied from flyby to flyby. The flows directed to IISR were almost parallel to the geomagnetic field line. In these cases, the observed effects were most pronounced. The electron density depletion reached 20-40%. According to our estimations, life-time of the ionospheric 'hole' was about 10-15 minutes. The experiment sessions in 2011-2013 showed rather weak effects of engine exhaust jet on ionospheric plasma. The difference between electron density profiles obtained before and after burning does not exceed statistical uncertainty, and the engine exhaust jet effect is undistinguishable. The most important factor affecting the 'Radar-Progress' experiment is the TSC 'Progress' orbit altitude.

1. Introduction

Active space experiments (SEs) play a major role in investigating near-Earth space (NES). To study some geophysical events (e.g., formation, evolution, and dynamics of small- and medium-scale irregularities in the ionosphere), we can use the controllable influence of spacecraft's liquid propellant engines (LPEs) on space plasma.

Artificial ionospheric disturbances induced by LPE exhausts were observed by incoherent scatter radars (ISRs). Such SEs were conducted during launches of Space Shuttle [1-3]. The amount of exhaust products varied from 87 kg (the experiment over the Jicamarca ISR) to 830 kg (the experiment over the Millstone Hill ISR). These experiments resulted in formation of extended regions with low electron density in the ionosphere; the regions existed for more than 1 hour.

The distinctive feature of our SE is the insignificant influence that exhausts (the mass of exhaust products is from 2 to 11 kg) have on the ionosphere. The examination of ionospheric plasma response to ejection of small amounts of exhausts is of great interest. We study formation, evolution, and dynamic behaviour of the ionospheric disturbances created artificially at a given time and place. SE results play a major role in developing theoretical and mathematical models of the LPE exhaust jets, in its interaction processes with the ionosphere, and in checking the ionospheric models themselves. SE sessions were conducted under certain external orbital conditions such as helio-geophysical conditions, and location and orientation of cargo spacecraft (CS) in orbit.

2. Space experiment

Since 2007, Central Research Institute of Machine Building, Moscow (TsNIIMash) and Institute of Solar-Terrestrial Physics of Siberian Branch of the Russian Academy of Sciences, Irkutsk (ISTP SB RAS) have been conducting SEs 'Radar-Progress' (prior to 2010, the experiment was called 'Plasma-Progress') aimed at studying space-time characteristics of ionospheric disturbances arising during operation of LPEs on board 'Progress' cargo spacecraft. Cargo spacecraft are involved in SE in the free flight mode at an altitude of about 350 km, after the cargo delivery mission to the International Space Station is completed. The main facility for the diagnostics of these disturbances is Irkutsk Incoherent Scatter Radar (IISR). IISR is owned by ISTP SB RAS and located at a distance of 100 km from Irkutsk (Russia). IISR is a monostatic pulse radar station with frequency scanning of antenna pattern. Frequency range is 154—162 MHz, pulse power is 2.5 MW, pulse repetition frequency is 24 Hz, pulse duration ranges from 100 to 1000 μs. Radar digital control and acquisition system allows us to control antenna pattern and record the full form of received signal on electronic media in real time during each cycle of sounding. IISR software allows us to get the height profile of electron density (*Ne(h)*) of ionospheric plasma at heights from 120 to 1200 km.

Figure 1 presents location and ground projection of IISR fields of view. The rectangles denote the boundaries of the field of view at a height of 2000 km. During the passage through the main IISR beam, one of two propulsion devices (PDs) is being activated aboard the cargo spacecraft: 8 orientation and mooring engines (OMEs) or 1 approach and correction engine (ACE). The total fuel consumption rate for OME is 376 g/s; that for ACE, 1 kg/s.

Type and duration of the PD operation vary in each session (from 5 to 11 s), as well as the local start time and direction of exhaust jets. The duration of passage of the cargo spacecraft in the radar beam is 15-20 s. To conduct the experiment, we selected the following options of the direction of exhaust jets:

– towards the IISR beam ('towards IISR') (Figure 2a);

– along the cargo spacecraft motion ('braking') (Figure 2b);
– against the cargo spacecraft ('acceleration');
– northward, in the plane of the local horizon of the cargo spacecraft ('northward').

Note that the 'towards IISR' direction is practically along the geomagnetic field (GF) lines, whereas other directions are across GF.

To obtain *Ne(h)* profile in the series of 'Radar-Progress' experiments, we used the 5-bit Barker code of 200 µs pulse, sample rate of 4 µs, height resolution of about 6 km, and integration time of 120 s. The ionospheric measurements were performed at two sounding frequencies corresponding to the two IISR beams (lines of sight). We selected the observation direction so that it was possible to study *Ne(h)* profiles in the area of the TSC flyby.

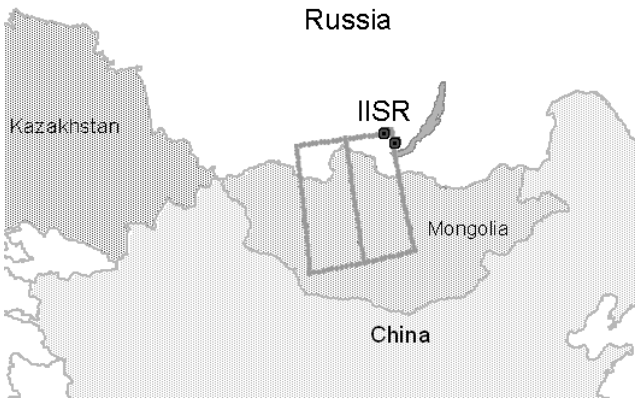

Fig. 1 IISR location and ground projection of field of view (rectangle) at a height of 2000 km

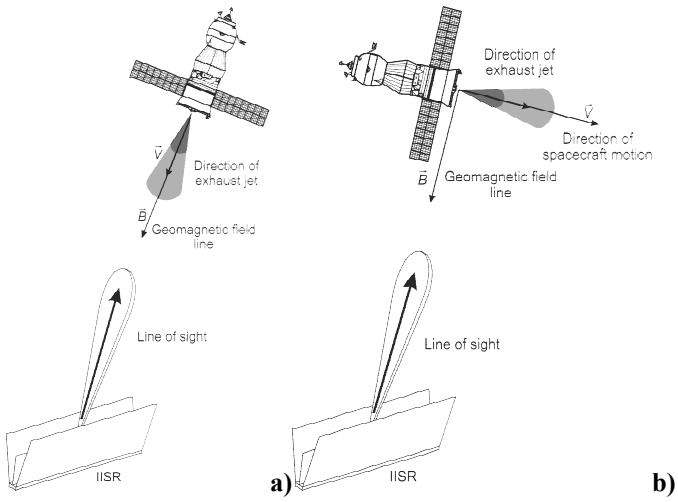

Fig. 2 Geometry of the experiment: a) 'towards IISR', b) 'braking'

3. Observation results

The first SE session (September 2007) revealed dramatic effects of exhaust jets on ionospheric plasma. Figure 3 presents the electron density height profiles *Ne(h)* before and after LPE burns. When the exhaust jet was directed 'towards IISR' and the burned fuel consumption was 5.1 kg, a region of decreased (down to 40%) electron density was formed (a 'hole' extending from the cargo spacecraft orbital altitude down to 250 km) [4-6]. The following years 2008 and 2009 were the years of the prolonged solar minimum. This led to the decrease in the background electron density, and the detection of weak ionospheric disturbances was limited by the IISR technical capabilities. Later experiments in 2010 were carried out at higher solar-activity level, and, consequently, at higher background *Ne*. These experiments confirm the previous conclusion that detectability of artificial irregularities depends on background *Ne*. Figure 3 shows *Ne(h)* profiles for the experiment of 1 September 2010 when ACE exhaust stream was directed northward. Dashed curve corresponds to the conditions observed 5 min before burning, thick solid curve is *Ne(h)* ~5 min after, and thin solid curve is *Ne(h)* ~10 min after. The largest depletion was ~28%, about 10 min after burning. Figure 4 presents the results of the experiment of 4 September 2010 (the largest depletion was ~12%, about 10 min after burning) in the same way. Thin solid horizontal line corresponds to the TSC 'Progress' orbit altitude.

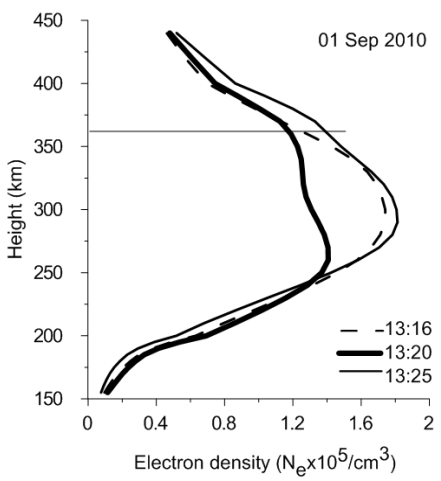

Fig. 3 *Ne(h)* during the experiment on 1 Sep 2010. ACE runs northward at 13:20:02 UT. Amount of fuel was 7.5 kg, TSC orbit altitude 364 km

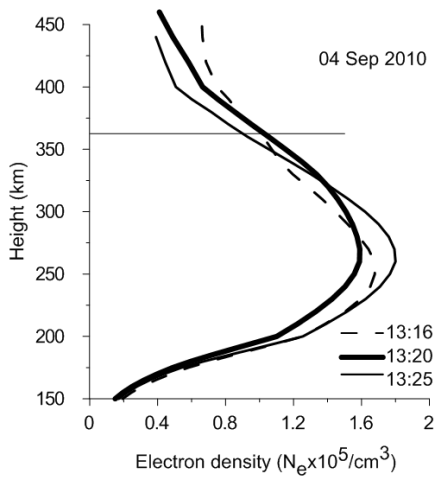

Fig. 4 *Ne(h)* during the experiment on 4 Sep 2010. ACE runs northward at 12:59:30 UT. Amount of fuel was 7.44 kg, TSC orbit altitude 363 km

The sessions conducted in April and September 2010 confirmed the dependence of the disturbance detectability not only on background *Ne(h)*, but also on the LPE power. That is why only ACE was used during the last SE sessions.

In 2011-2013, we conducted 6 SE sessions, including 17 measurement cases. Directions of LPE injection jets, time and duration of ACE burns varied. Sounding pulse parameters and IISR acquisition system settings were not changed. Figures 5-7 exemplify the measurement results obtained in 2011-2013. The difference between *Ne(h)* profiles obtained before and after burning does not exceed statistical uncertainty, and, hence, the engine exhaust jet effect is undistinguishable [7-10].

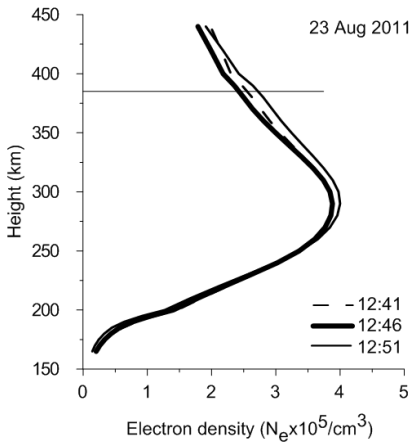

Fig. 5 *Ne(h)* during the experiment on 23 Aug 2011. ACE runs 'braking' at 11:46:17 UT. Amount of fuel was 9.0 kg, TSC orbit altitude 384 km

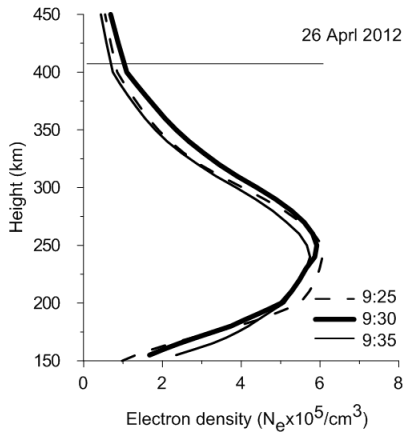

Fig. 6 *Ne(h)* during the experiment on 26 April 2012. ACE runs 'towards IISR' at 09:27:52 UT. Amount of fuel was 9.0 kg, TSC orbit altitude 407 km

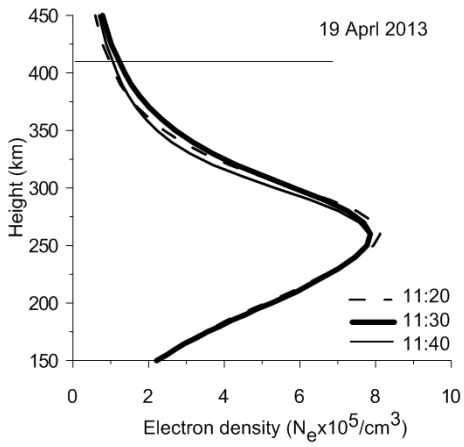

Fig. 7 *Ne(h)* during the experiment on 19 April 2013. ACE runs 'towards IISR' at 11:29:24 UT. Amount of fuel was 9.0 kg, TSC orbit altitude 410 km

4. Discussion

Experiments conducted in 2011-2013 allowed us to analyse most factors affecting the conditions of the 'Radar-Progress' experiment. We found a parameter which varied throughout the experiment series and which has never been taken into account before. This factor is the TSC 'Progress' orbit altitude. Over the last 3 years, the ISS altitude was lifted in order to reduce the delivery time of crews and cargoes. Together with the ISS orbit, the 'Progress' orbit was also lifted and, the height of the engine exhaust jets was increased, respectively. Thin solid horizontal line in Figures 3—7 shows the TSC orbit altitude. Figure 8 shows the lift of the average TSC 'Progress' orbit altitude (from 340 km (2007) to 410.5 km (June 2013)) over the past 6 years. At the same time, the peak height of *Ne* varied from 250 to 350 km (315 km during the session on 20 September 2007 and 300 km during the session on 16 June 2013). During the latest experiment series, ACE thus burned at heights where the electron density was 1.5 - 2 times lower than at the peak height of *Ne*.

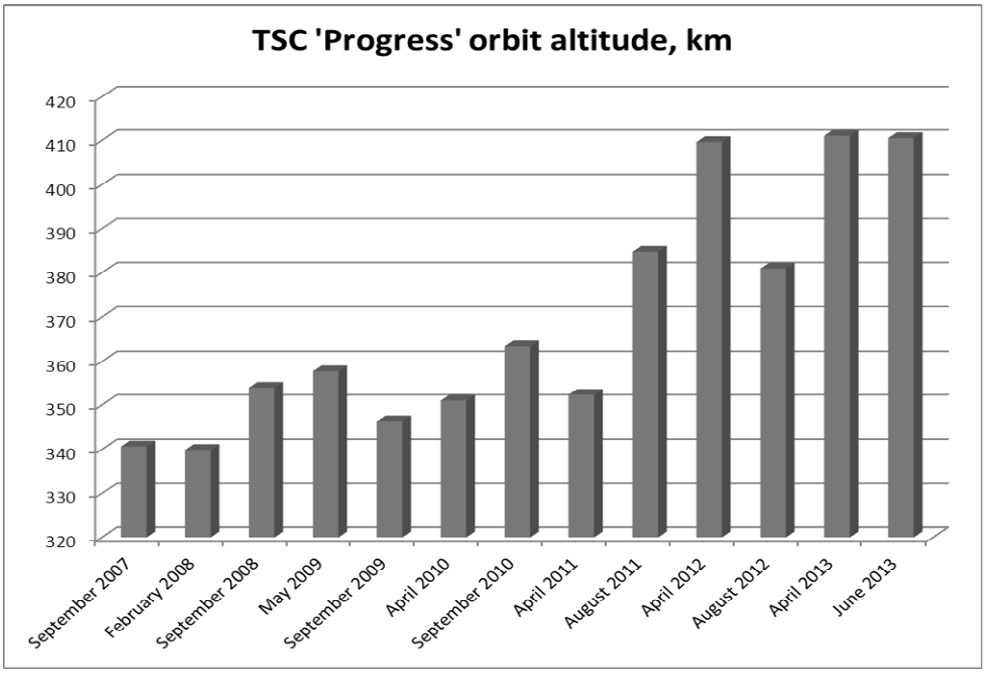

Fig. 8 TSC 'Progress' orbit altitude (2007—2013)

It should also be noted that only a part of IISR beam can be filled with TSC emission products, since the TSC 'Progress' trajectory does not usually coincide with the ground IISR beam projection. Under these conditions, the TSC emission effect is weakened. Therefore, the electron density depletion was insignificant despite the relatively large burned fuel consumption.

5. Conclusions

The experiment sessions in 2011-2013 showed rather weak effects of engine exhaust jet on ionospheric plasma. The difference between electron density profiles obtained before and after burning does not exceed statistical uncertainty, and the engine exhaust jet effect is undistinguishable. Detectability and disturbance parameters depend on the TSC 'Progress' orbit altitude, burned fuel consumption, IISR beam direction, helio-geophysical conditions, and exhaust jet direction relative to the TSC velocity and the geomagnetic field.

The most important factor affecting the 'Radar-Progress' experiment is the TSC 'Progress' orbit altitude. To confirm this hypothesis, it is necessary to reduce the altitude down to peak heights of electron density (250—350 km) in further experiments.

Acknowledgments

The work was supported by RFBR Grants 13-05-00456, 13-02-00957, 13-05-00979.

References

1. Bernhardt, P., Huba, J., Swartz, W., Kelly, M. "Incoherent scatter from space shuttle and rocket engine plumps in the ionosphere." *Journal of Geophysical Research, V. 103*, № A2, 2239–2251, 1998.

2. Bernhardt, P., Huba, J., Kudeki, E., Woodman, R., Condori, L., Villanueva, F. "Lifetime of a depression in the plasma density over Jicamarca produced by space shuttle exhaust in the ionosphere." *Radio Science, V. 36*, № 5, 1209–1220, 2001.

3. Foster, J., Holt, J., Lanzerotti, L. "Mid-Latitude Ionospheric Perturbation associated with the Spacelab-2 Plasma Depletion Experiment at Millstone Hill." *Ann. Geophys, 18* , 111-119, 2000.

4. Shpynev B. G., Khakhinov V. V., Medvedev A. V., Potekhin A. P., Lebedev V. P., Tverdokhlebova E. M., Manzheley A. I., "Ionospheric perturbation associated with the "Plasma-Progress" experiment at Irkutsk." *Proc. XXIX URSI GA*, GP2-05.3, 2008.

5. Lebedev V. P., Khakhinov V. V., Gabdullin F. F., Korsun A. G., Tverdokhlebova E. M., Laletina E. A., Manzhaley A. I., "Studying the characteristics of the plasma environment at low-orbiting space vehicles by radar methods". *Cosmonautics and Rocket Engineering, v.50 (1)*, pp. 51-60, 2008.

6. Potekhin A.P., Khakhinov V.V., Medvedev A.V., Kushnarev D.S., Lebedev V.P., Shpynev B.G., "Active space experiments with the use of the transport spacecraft "Progress" and Irkutsk IS Radar." *PIERS Proc*., pp.223-227, 2009.

7. Potekhin A., Shpynev B., Alsatkin S., Ratovsky K., Lebedev V., Kushnarev D., "Results of Complex Radiosounding of Ionospheric Disturbances Generated by the Transport Spacecraft "PROGRESS" Onboard Thrusters." Proc. XXX URSI GA. 2011. HP2.15.

8. Khakhinov V.V., Shpynev B.G., Lebedev V.P., Kushnarev D.S., Alsatkin S.S., Khabituev D.S., "Radiosounding of ionospheric disturbances generated by exhaust streams of the transport spacecraft "Progress" engines." *PIERS Proc*., pp.1162-1166, 2012.

9. Khakhinov V.V., Potekhin A.P., Lebedev V.P., Shpynev B.G., Alsatkin S.S., Tverdokhlebova E.M., Kurshakov M.Yu., Manzheley A.I., Timofeyeva N.I., "Remote sensing of ionospheric disturbances generated spacecraft engines exhaust jets." *Electromagnetic Methods of Environmental Studies*, pp. 99-101, 2012

10. Borisov B.S., Gabdullin F.F., Garkusha V.I., Korsun A.G., Kurshakov M.Yu., Strashinskiy V.A., Tverdokhlebova E.M., Khakhinov V.V., " Radiophysical characteristics of low-orbit spacecraft plasma environment revealed by space experiments." *Nelineinyi mir (Nonlinear World), V. 10*, pp. 700-709.