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On orbit contaminant deposition measurements on Russian orbital stations and on the Russian segment of the International Space Station

A.N. Krylov, L.V. Mishina**, A. Yu. Skorovarov****
**Head of sector, Aerogasdynamics Department, RSC "Energia", Korolev, Russian Federation*
andrey.n.krylov@rsce.ru
***Leading engineer, Aerogasdynamics Department, RSC "Energia", Korolev, Russian Federation*
lubov.v.mishina@rsce.ru
****Engineer , Aerogasdynamics Department, RSC "Energia", Korolev, Russian Federation*
aleksandr.skorovarov@rsce.ru

Abstract
The contamination effect of space station induced environment to be of increasing interest for on-orbit scientific experiments. This paper describes experimental results, which have been acquired by RSC "Energia" during on-orbit contamination measurements. Experimental results demonstrate the significant influence of solar illumination and operating temperature of contamination sources on mass deposition and unregulated character of contamination deposition rate both during an orbit and during longitudinal periods. The significant increase of contaminant deposition levels have been revealed during so-called "solar" orbits, the periods when the sources of contamination to be effected by predominant Sun exposure.

1. Introduction

A spacecraft generates its own induced environment while in space. This induced environment is unique one to each spacecraft. Further, interactions between the natural space environments with the spacecraft's induced environment produce a variety of effects on space systems. These effects have direct impact on spacecraft systems and scientific equipment and a mission performance. Spacecraft' induced environment disciplines have gained considerable importance over the past forty years. On-orbit experiments are important stage of induced environment investigation as it is impossible to simulate all space condition in ground laboratories.
Some experiments have been carried out with the use of passive material samples exposed on outer surface of orbital stations [1,2] and other ones have examined contamination deposition process in real-time by using Quartz Crystal Microbalances (QCMs). QCM is a device that measures a mass per unit area by detecting the change in frequency of a quartz crystal resonator. It is useful for monitoring the rate of deposition under space conditions.
This paper summarizes experimental results, which have been acquired by S.P. Korolev Rocket and Space Corporation "Energia" (RSC "Energia") during on-orbit real-time contamination measurements on Russian orbital stations "Salut-7", "Mir" and on modules "Pirs" and "Poisk" of Russian Segment (RS) of International Space Station (ISS) using QCMs.
During the first flight experiment, named "Astra-1", induced molecular depositions on "Salut-7" orbital station have been measured in 1982. There were four QCMs installed on the external surface of station. "Astra-1" measurement results were the basis in the development of induced environments calculation methods. The next "Astra-2" flight experiment have followed from 1995 to 1997, when two QCMs were installed on the surface of "Spektr" module of "Mir" orbital station. During this flight experiment molecular deposition measurements have been recorded over two years period. In 2004 first measurements of contaminant deposition on RS ISS were started, using BKDO device supplied with two QCMs. These measurements were restarted in 2014 with upgraded QCMs and are continuing up today.

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2. “Astra-1” flight experiment on “Salut-7”

In the early 80’s, a team of investigators from RSC-”Energia”, Institute of Applied Geophysics (IPG) and Moscow Aviation Institute (MAI) developed the first flight experiment named “Astra-1” to study spacecraft induced environments [3].
The "Astra-1" apparatus was mounted on the “Salut-7” orbital station. Two QCMs (designated QCM21 and QCM24) were installed on “Salut-7” Crew Compartment and were oriented along longitudinal axis (±X) and two QCMs (designated QCM31 and QCM34) were installed on the aft of Instrumental Compartments in lateral directions. The QCMs were designed and produced by IPG and MAI with a working range from 4×10^{-8} to 1.6×10^{-4} g cm^{-2}. Unfortunately QCM31 have broken practically just after switching on, maybe due to the main thrusters effect. Initial readings of QCM21, QCM24 and QCM34 were following: 1.0×10^{-7}, 1.7×10^{-6} and 2.8×10^{-6} g cm^{-2}. QCMs locations are shown in figure 1.

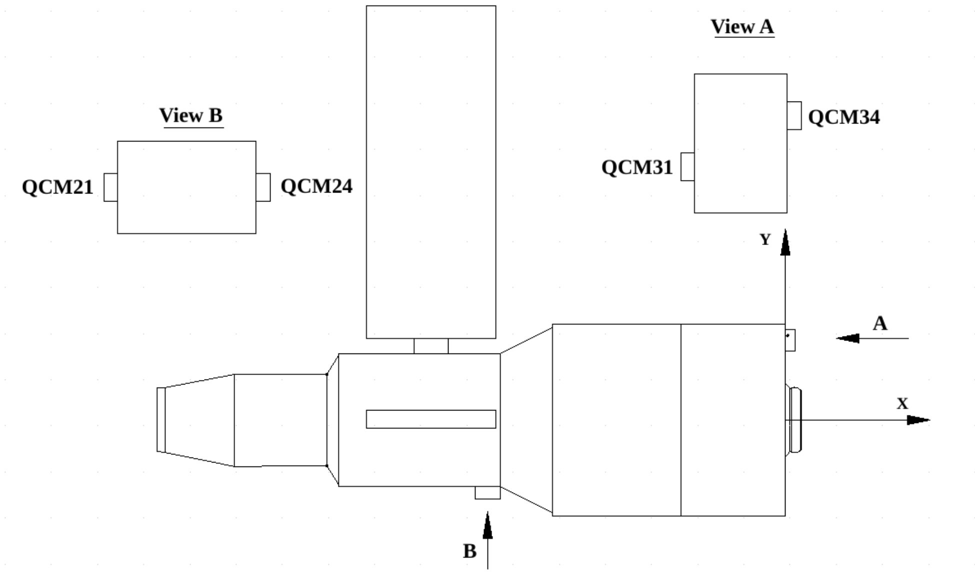

Figure 1: QCMs location on “Salut-7”

Initial measurements have been made after the launch in June 4, 1982, when sensors were isolated from the ambient environment by glass bulbs and then in June 14, 1982, just after the removal of protective bulbs. QCM21, QCM24, QCM34 recorded the following deposition levels: 2.6×10^{-6}, 2.9×10^{-6} and 4.7×10^{-6} g cm^{-2}. Later in a short period QCM34 have achieved its saturation and have not recorded mass accumulation.
In June 27, 1982 QCMs systematic switching on have been initiated but in three days QCM21 have become saturated and then 12 hours later QCM24 have also stopped recording. The saturation levels of these QCMs are assessed to be corresponded to molecular deposit about 1×10^{-5} g cm^{-2}.
This data can be used to calculate average deposition rates for two flight conditions: quiescent and non-quiescent. The non-quiescent conditions took place when “Soyuz-T6” vehicle was approaching to “Salut-7” in June 25, 1982. During the quiescent period, contaminant deposition rate ranged from 4.2×10^{-12} to 9.2×10^{-12} g cm^{-2}s^{-1}. During the non-quiescent period, deposition rate was from 5.8×10^{-11} to 7.8×10^{-11} g cm^{-2}s^{-1} when “Soyuz-T6” was approaching and 1.4×10^{-11} g cm^{-2}s^{-1} just after “Soyuz-T6” has docked.
First contamination measurement results demonstrated that contamination levels significantly depend on QCM location and orientation relatively control thrusters.

3. “Astra-2” flight experiment on “Mir”

Two QCMs were used in “Astra-2” flight experiment on “Mir” orbital station [4]. They were installed within pressurized unit mounted on 2-meter arm on “Spektr” module. The sensitivity ranges of “Astra-2” and “Astra-1” QCMs were identical ones. 1Hz of QCM’s frequency difference corresponds to 10^{-8} g cm^{-2} of mass deposition change if contaminant density to be 1g cm^{-3}.

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The “Astra-2” QCMs were not thermo-controlled and sensors’ operating temperatures were not measured. However, the temperature inside “Astra-2” pressurized unit was controlled to be above 0 °C. The location of “Astra-2” QCMs is shown in Figure 2.

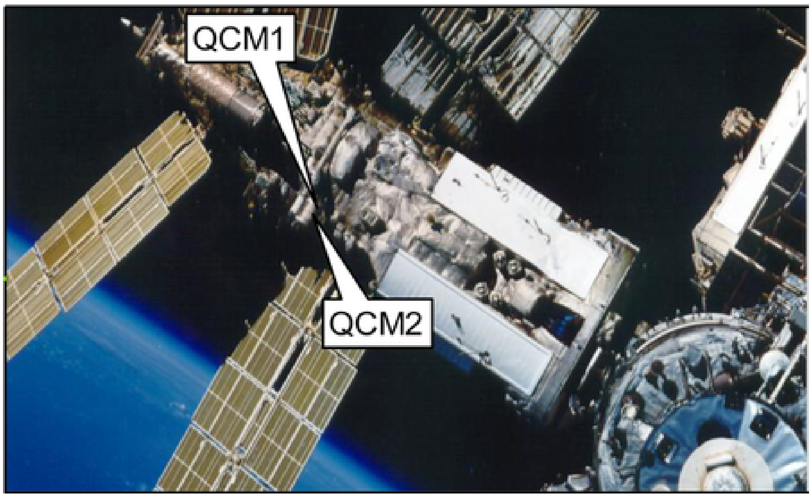

Figure 2: “Astra-2” QCM locations on the “Mir” orbital station

“Astra-2” experiment has started in May 22, 1995, 48 hours after “Spektr” launch. Contaminant deposition measurements have been made during two years. QCM1 protective cover was removed in June 15, 1995. Before the protective covers removal, QCM readings were 1.13×10^{-5} for QCM1 and 3.1×10^{-6} g cm^{-2} for QCM2. Average deposition rate on QCM1 was about 4×10^{-13}g cm^{-2}s^{-1} taking into account time period from 28.06.95 (just after its cover removal) to 15.11.95. First case of QCM1 abnormal behavior (out-of-range readings) has been recorded in August 15, 1995 during so-called “solar” orbit. “Solar” orbit means that shadow duration on orbit is equal to zero or practically equal to zero in a contrast with standard half-an-hour shadow duration. In November 15, 1995 QCM1’ readings were once more out-of- range and then its readings had been giving zero deposition.
QCM2 have operated more reliably and have showed slow mass deposition increase. No significant changes in contaminant deposition rates have been recorded during Space Shuttle, “Soyuz” and ‘Progress” docking and during PIC [5] flight experiment. The average recorded contaminant deposition rate was approximately 5×10^{-11} g cm^{-2}s^{-1} in the initial experimental period until September 8, 1995. Beginning that date average contaminant deposition rate became approximately 1×10^{-12} g cm$^{-2}\cdot$s^{-1} until December 26, 1996. At the end of the experiment, a small mass loss was recorded. “Astra-2” QCM2 measurement results are shown in Figure 3. At the same picture fuel consumption and shadow duration are presented for the same time period.

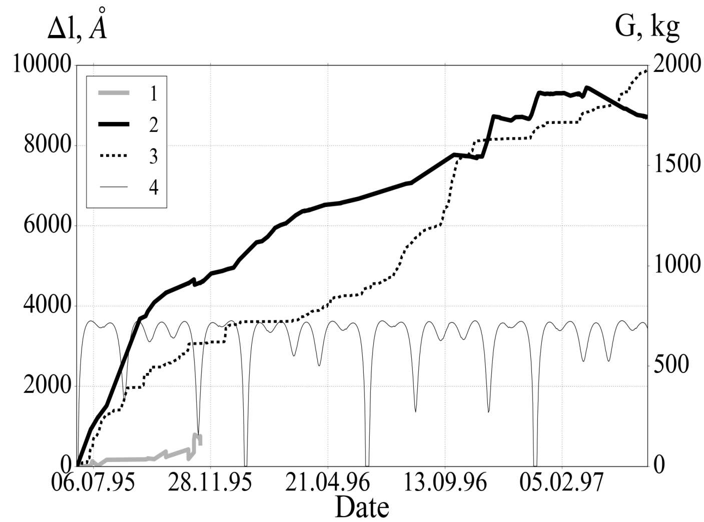

Figure 3: “Astra-2” QCMs readings; 1-QCM1; 2- QCM2; 3- fuel consumption; 4- shadow duration

“Astra-2” measurements show periods with significant increases in contaminant deposition rate. To better understand the reasons of this behavior, the influence of solar illumination was analyzed. These periods with significant

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increases in contaminant deposition rate were found to correlate with so-called “solar orbits” – the orbits without shadow part. this effect is illustrated in Figure 4.
One hypothesis is that heating of external surfaces during solar orbits produces more intensive evaporation of contaminants previously absorbed by porous materials. Conversely, during a period from March through June of 1997, a loss of accumulated mass on QCM2 was recorded when surfaces within its field-of-view were predominantly in a shadow.

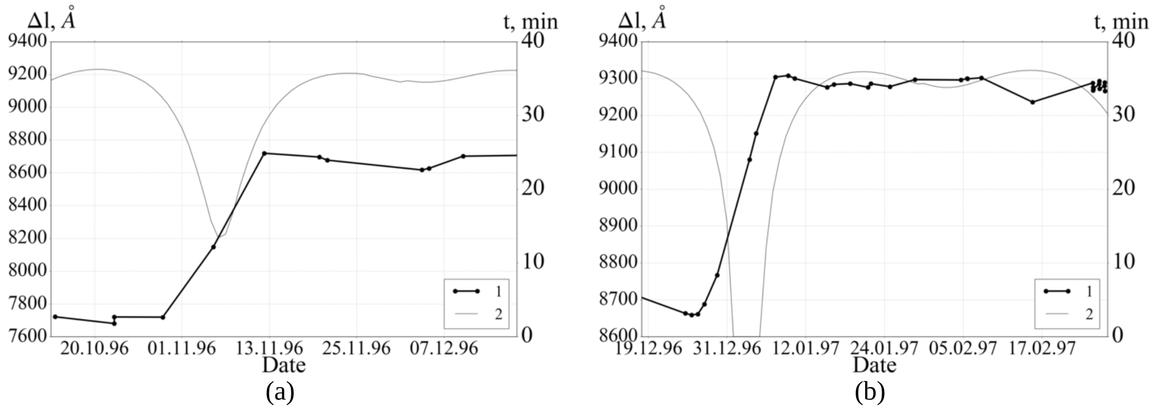

Figure 4: “Astra-2” QCM2 readings on “solar” orbits, 1- QCM2 readings; 2- shadow

At the end of “Astra-2” flight experiment, QCM2 data with good resolution was recorded onto an on-board laptop. A plot of this data is shown in Figure 5, displaying interesting features. During the shadow orbital period, contaminant deposition levels increase, but during Sun exposure periods, while overall contaminant deposition levels decrease, significant jumps in readings were also recorded.

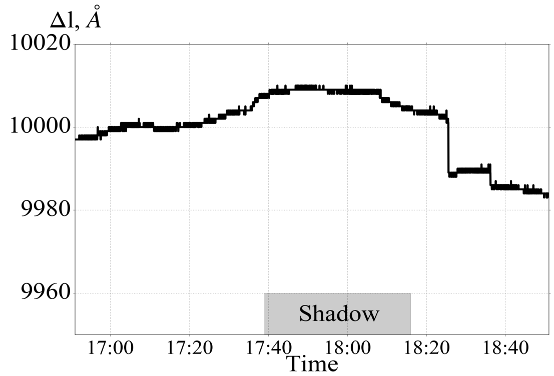

Figure 5: “Astra-2” QCM readings on total orbit

“Astra-2” results demonstrate complex and sometimes ambiguous character of on-orbit contamination processes. Deep understanding of these processes requires detailed knowledge of spacecraft construction, orientation, solar illumination and dynamics of thermal environment of spacecrafts and sensors.

4. BKDO measurements on “Pirs” module of RS ISS

On-orbit contamination measurements on RS ISS were started in July 2004, using BKDO device. BKDO was equipped with two QCMs similar to “Astra-2” ones, but with built-in quartz temperature control. BKDO was located on the “Pirs” module of RS ISS. QCM sensors are oriented in ± Y RS direction.
In July 1, 2004, RS crew has installed BKDO unit on external surface of “Pirs” module. Initial QCM readings after installation were 2.8×10^{-5} g cm^{-2} for QCM1 and 2.7×10^{-5} g cm^{-2} for QCM2. The location and photo of BKDO are shown in Figures 6 and 7.

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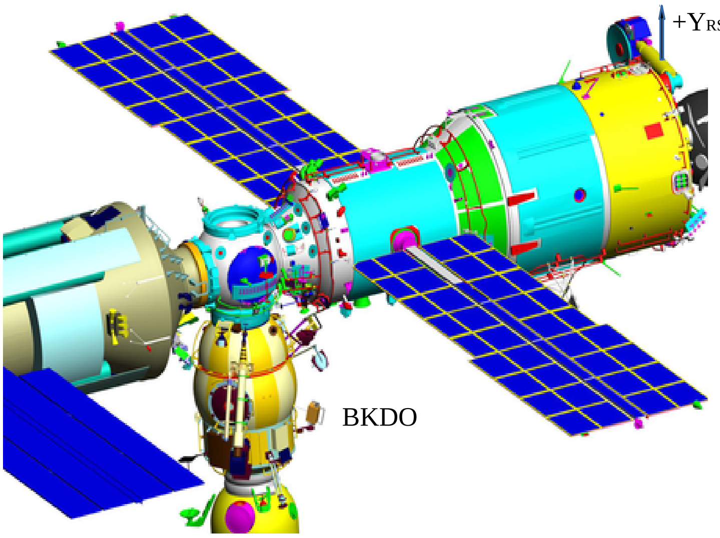

Figure 6: BKDO location on the “Pirs” module

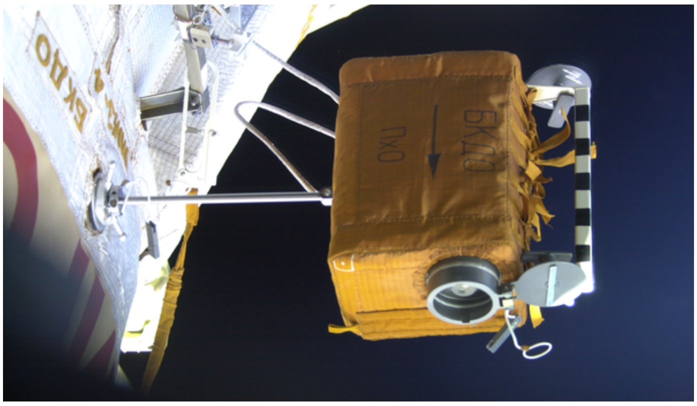

Figure 7: BKDO photo on the “Pirs” module. An arrow points to QCM1

BKDO QCM1 had unstable operation similar to “Astra-2” QCMs. Some recording were out-of-range and to the end of July its recording have become unreasonable. BKDO QCM2 readings were more stable and have recorded 3.25×10^{-5} g cm^{-2} deposition to July 11, 2006. However, QCM2 readings dropped to 1×10^{5}g cm^{-2} on July 20, 2006 and shortly after that became equal to zero. The average contaminant deposition rate recorded during the stable operation periods was 9×10^{-12} g cm^{-2}s^{-1} for QCM1 and 5×10^{-12} g cm^{-2}s^{-1} for QCM2. Some averaged results for QCM2 are shown in Figure 8.

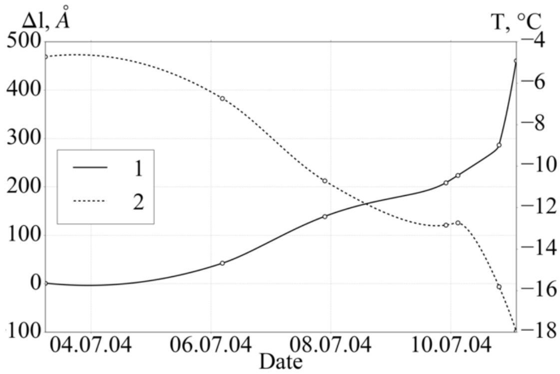

Figure 8: 1-BKDO QCM2 averaged readings, 2 – sensor temperature

One of QCMs has been returned by Space Shuttle STS-115 for the analysis. Photo of this QCM sensor is in Figure 9.

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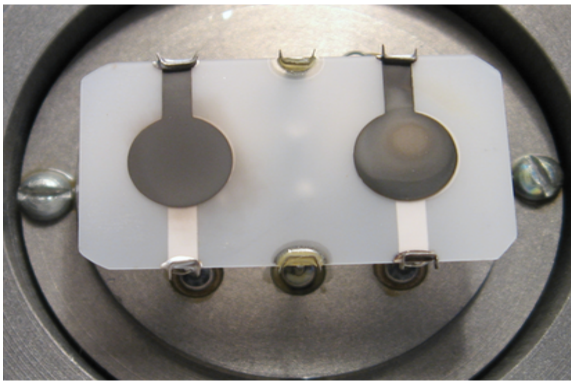

Figure 9: Silver degradation on QCM

By results of checks of the returned sensor, it was concluded that the main reason of the nullification of its readings was the degradation of sensitive silver coating element due to atomic oxygen influence. The electronics of QCM sensor was in working condition. Repairing a spare set of QCMs sensors were implemented by replacing the quartz plate on mass sensor to a gold coating one.

5. BKDO measurements on "Poisk" module of RS ISS

Modified BKDO device was delivered to RS ISS by "Progress M-23M" in April 10, 2014. In August 18, 2014 RS crew have installed BKDO on "Poisk" module of RS ISS during extravehicular activity (EVA-39). QCMs sensors were oriented in Zenith – Nadir direction. The location and photo of BKDO are shown in Figures 10 and 11.

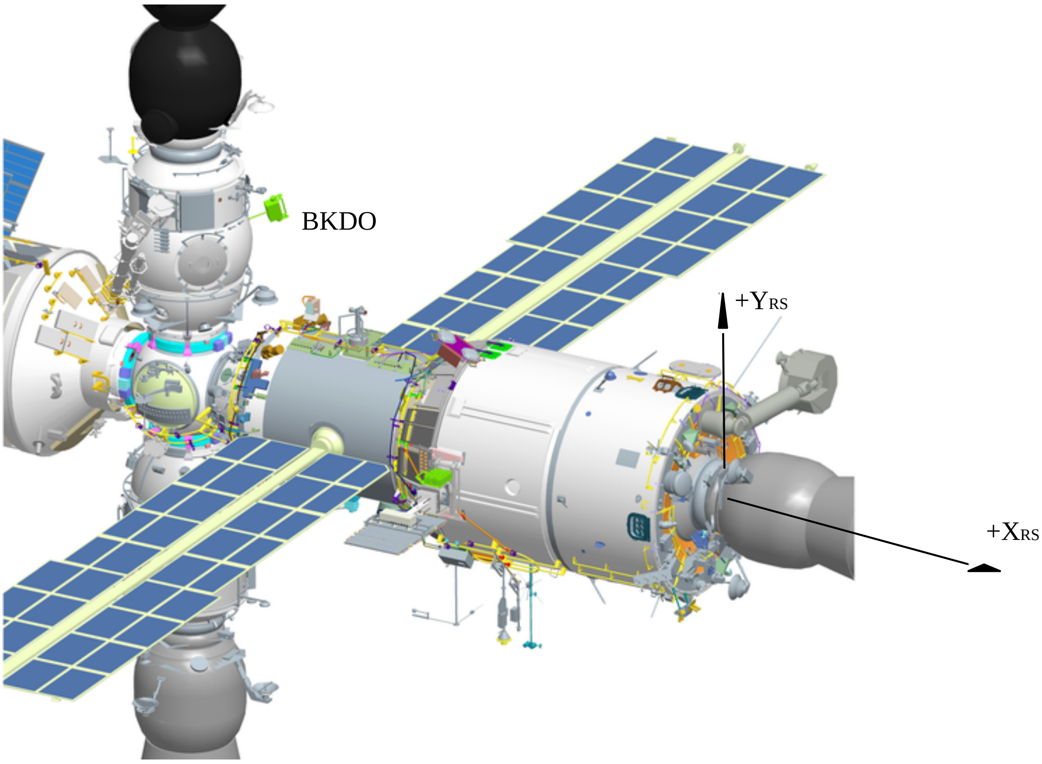

Figure 10: BKDO location on "Poisk" module

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Figure 11: BKDO photo, initial position on “Poisk” module

QCMs measure contaminant mass deposition within the range from 4.42×10^{-9} to 2.84×10^{-4} g. Sensors’ field-of-view cone angle is 120 º. During transportation and storage sensors’ contamination levels were 79 Å for QCM1 and 16 Å for QCM2 (taken into account that deposition density to be 1 g×cm^{-3}).
Regular measurements sessions have started in August 25, 2014. Measurement sessions are performed from one to four times a week in quiescent conditions and in non-quiescent conditions during ISS thruster operation, venting, EVA, docking and undocking of visiting vehicles, etc. During “solar” orbits daily measurements are planned.
To assess the effect of the sensor orientation on the contaminant deposition, BKDO orientation was changed by rotation around the rod axis by 90º. As a result, QCM1 became to be directed towards American Segment (AS) of ISS in ram direction, and QCM2 became to be directed in wake direction. BKDO rotation has been carried out during EVA-41 August 10, 2015. BKDO position after first rotation is shown in Figure 12.

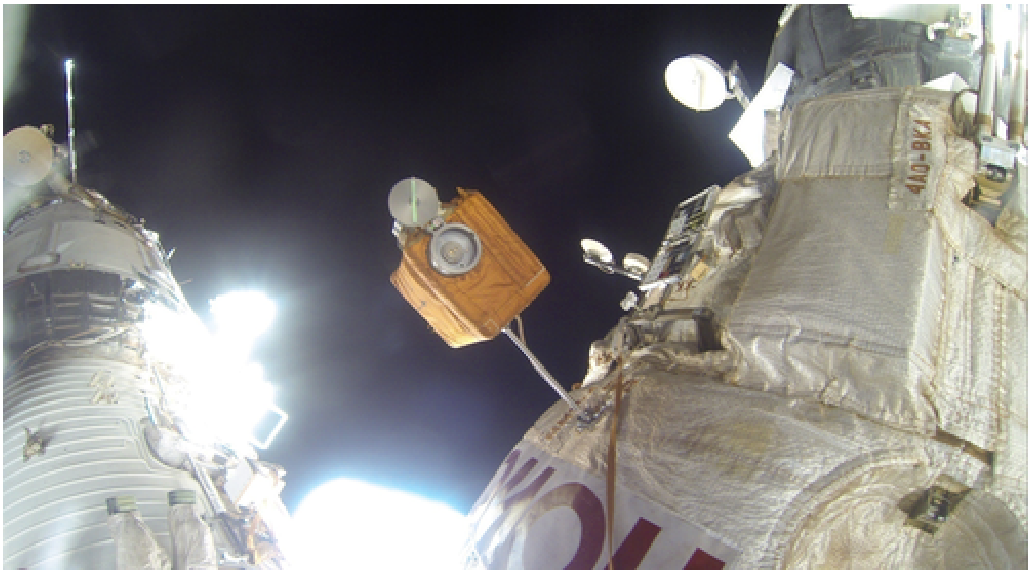

Figure 12: BKDO position after first rotation, August 10, 2015

Next orientation change of BKDO has been carried out during EVA-42 February 3, 2016. BKDO longitudinal axis has been directed perpendicular to “Poisk” module surface as presented in Figure 13.

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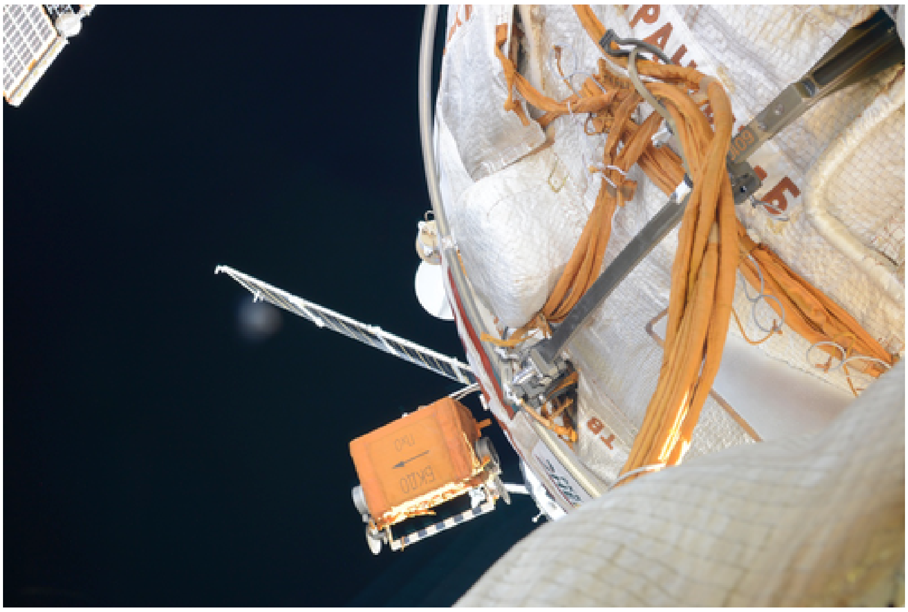
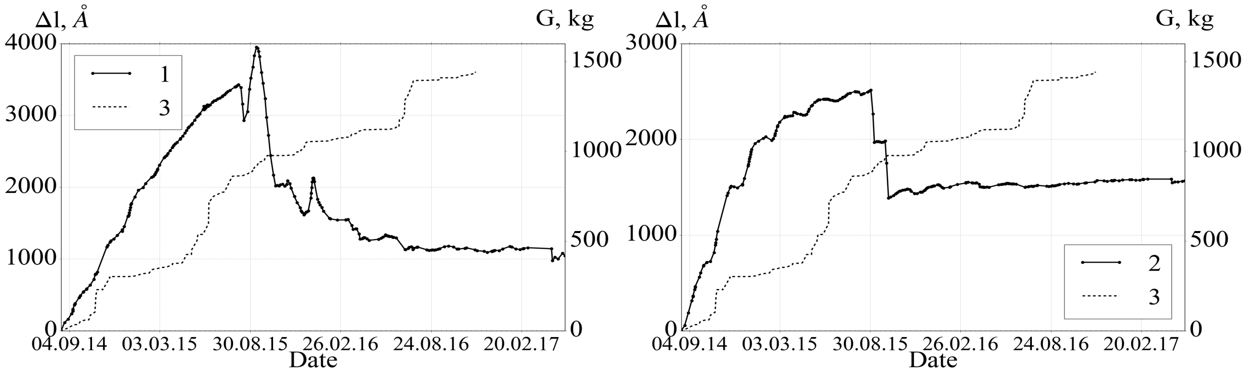


Figure 13: BKDO position after second rotation, February 3, 2015

QCM1 regularly shows unstable operation at the beginning of the measurement period, QCM2 works more stable. Generalized contamination data over entire period of measurements are shown in Figure 14. Fuel consumption expended for ISS orientation control support and orbit corrections are also in Figure 14. Each point on this graph represents the average value of contamination level during each measurement session. Unstable operation data QCM1 are filtered.



(a) (b)

Figure 14: QCM contamination data, 1- QCM1; 2- QCM2; 3- fuel consumption

Direct correlations between thruster operation intensity and QCMs readings are not observed. There is some temporal delay of contamination increase relatively periods of intensive fuel consumption. This fact is possible to indicate following contamination process: during intensive thrusters operation unburned fuel products are accumulated in leaky cavities and on multi-layer insulation (MLI) and then under Sun heating they evaporate and cause contamination. In favor of this hypothesis is the significant increase of contamination deposition during “solar” cycles. The similar effect was observed in "Astra-2" experiment.

Contamination accumulation processes on QCM1 and QCM2 are different and essentially depend on BKDO orientation. After first rotation of BKDO the contamination deposition processes on QCMs have significantly changed. After initial fluctuations QCM1 contamination deposition have decreased about three times while QCM2 readings have initially fallen two times and then have stabilized as presented in Figure 14. After second rotation of BKDO unit QCM1 shows smooth deposited mass decrease as there are no ISS elements in its field-of-view, while QCM2 demonstrates gradual slow mass increase as there are MLI surfaces of “Poisk” module in its field-of-view.

Figure 15 demonstrate measurements data in quiescent conditions at the initial orientation. During one orbit you can observe cyclic change of contamination level depending on QCM sensor temperature and the illumination of surfaces in its field-of-view. Similarly "Astra-2" experiment results on shadow part of an orbit there is slow mass

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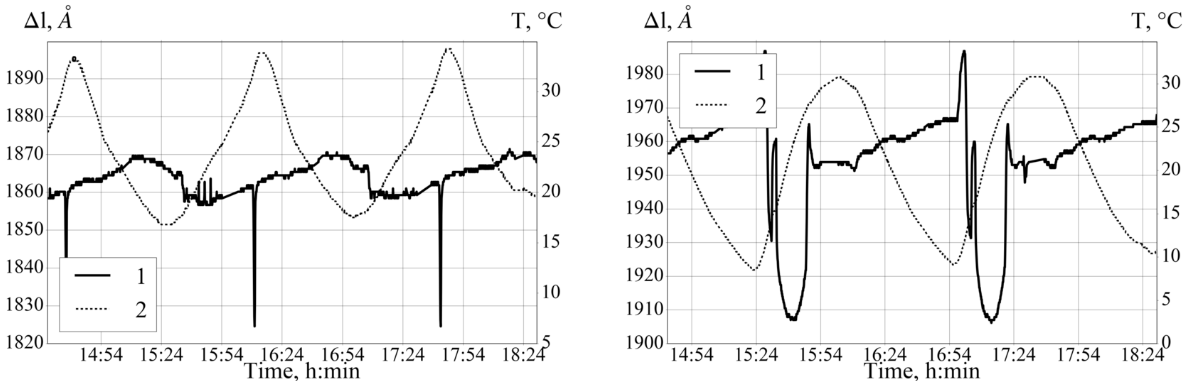
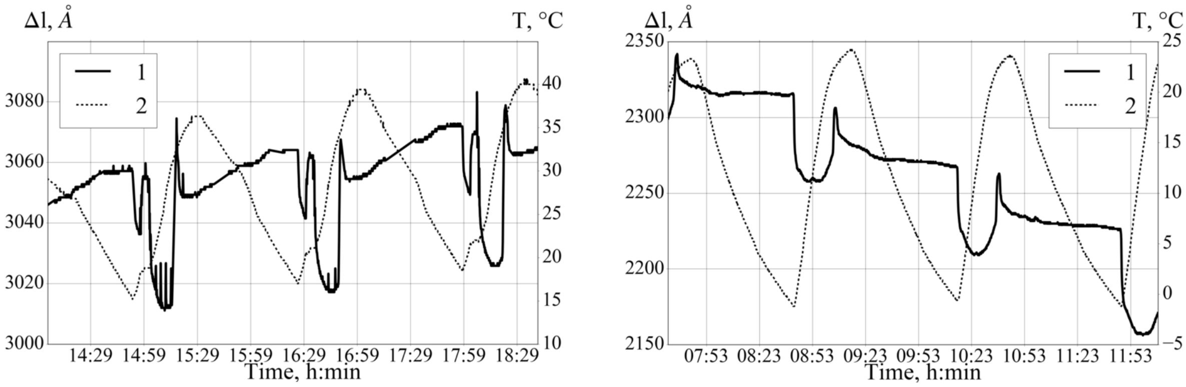
accumulation and at the exit from the shadow an abrupt change of readings is observed. Such behavior is assumed to be associated with rapid uneven heating of reference and sensitive elements of QCMs at the shadow exit.



(a) (b)

Figure 15: A typical QCM contamination data in the initial orientation, (a) - QCM1; (b) - QCM2

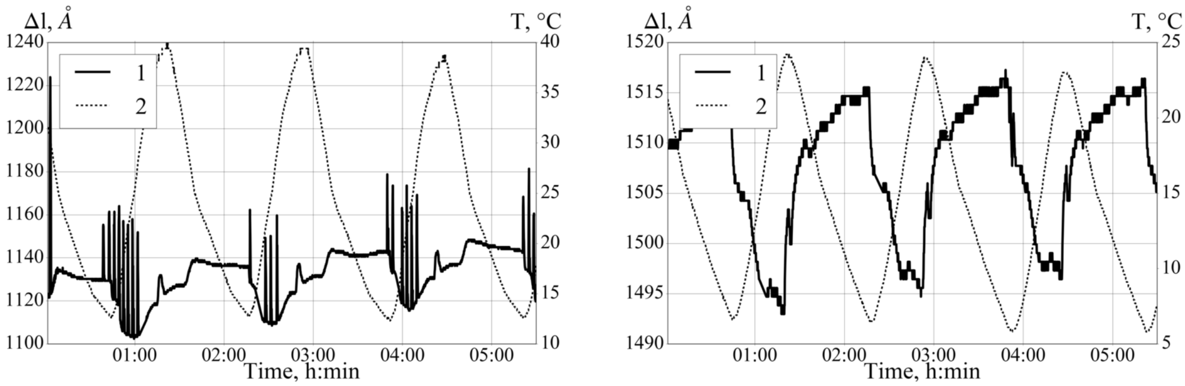
After first orientation the contamination deposition character during an orbit has changed. Examples of typical QCM readings are shown in Figure 16.



(a) (b)

Figure 16: Typical QCM contamination data after first rotation, (a) - QCM1; (b) - QCM2

Examples of typical sensor readings after second rotation are shown in Figure 17.



(a) (b)

Figure 17: Typical QCM contamination data after second rotation, (a): QCM1; (b): QCM2

In non-quiescent conditions it was possible that unburned combustion products of docking/undocking vehicles “Soyuz” and “Progress” could reach QCM2 sensor. However perceptible correlation between thruster firings and mass deposition on QCMs sensors were not observed due to insufficient sensitivity and far distance from the contamination source to sensors.

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6. Conclusion

QCMs have been used to characterize induced environment contamination on Russian orbital stations and RS ISS. These measurements were crucial in understanding actual induced molecular deposition levels and effects of solar exposure on QCM measurements and spacecraft contaminant sources, as well as the importance of contamination control to ensure successful science operations. A long observation of the impurities deposition dynamics while "Astra-2" experiment and measurements by BKDO unit on RS ISS allowed to record a significant increase in impurities deposition rate during solar orbits, when hot external surface of the RS ISS to be in field-of-view of sensors. Significant anisotropy of contamination fluxes was discovered. The contamination flux intensity is higher in Zenith direction and less in Nadir direction, when the outgassing sources to be in ISS shaded zones.

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