Experience of the Russian specialists in the area of space debris mitigation.

Flight dynamic's aspects of the communication satellite Express-AM4 flight termination from off-nominal orbit.

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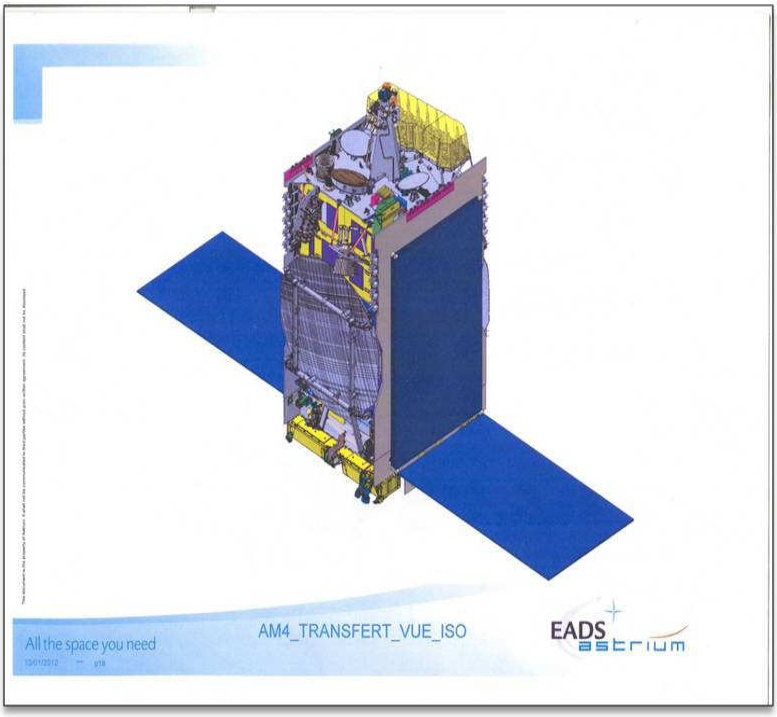
Problems of Express-AM4 organized flight termination are considered. The spacecraft was designed for telecommunication service at geostationary orbit (80˚ east longitude). Various scenarios of flight termination after reboost block malfunction are proposed. Possibility and safe of their's realization are estimated. Organization of operational work for selected scenario realization is described. Results of theoretical investigation and practical realization are shown.

As a result of off-nominal functioning of reboost block Breese-M the Express-AM4 remained at orbit with the following parameters: inclination 51.1˚, maximum altitude 20400 km, minimum altitude 650 km. At this orbit the spacecraft was in configuration "pre-insertion to geostationary orbit" (Fig. 1). Solar panels were not opened completely, onboard control system functioned nominally and the apogee engine's fuel amount was about 2800 kg.

Fig.1. Common view of Express-AM4 at off-nominal orbit.



Despite of the facts, that the onboard control system worked nominally and the fuel amount was large, the following decisions were taken: the spacecraft's using as telecommunication one at geostationary orbit is impossible, onboard resources are not enough for spacecraft's insertion to targeting orbit.

Being at off-nominal orbit, Express-AM4 begun to be dangerous for a lot of functioning spacecraft: navigational satellites of GPS and GLONASS systems (altitude 19000÷20000 km), satellites for the Earth monitoring, communication, laser location and others at altitudes diapason 700÷6000 km. Also a lot of "space debris" objects could collide with the spacecraft.

Correspondingly to EADS Astrium specialists' prediction, onboard control system could be functional not longer than to the middle of 2012 year (off-nominal mode of Sun's attitude for accumulators' recharging, off-nominal mode of onboard electronics at radiation belts and so on).

So, the task of organized flight termination having a lot of limitations for work of onboard control system and ground segment's means was formulated. MCC TSNIIMASH has a unique experience in the field of flight dynamic support of reentry and landing of both manned and unmanned spacecrafts. That is why MCC was invited for this task solution. It was a decision of Roscosmos.

As possible variants of organized flight termination were considered:

- deorbitation and splash down of unburned structure elements in safe region of ocean (preferable variant);
- spacecraft's transfer to so called "safe orbit" in order to have a minimum risk of collision with other spacecraft.

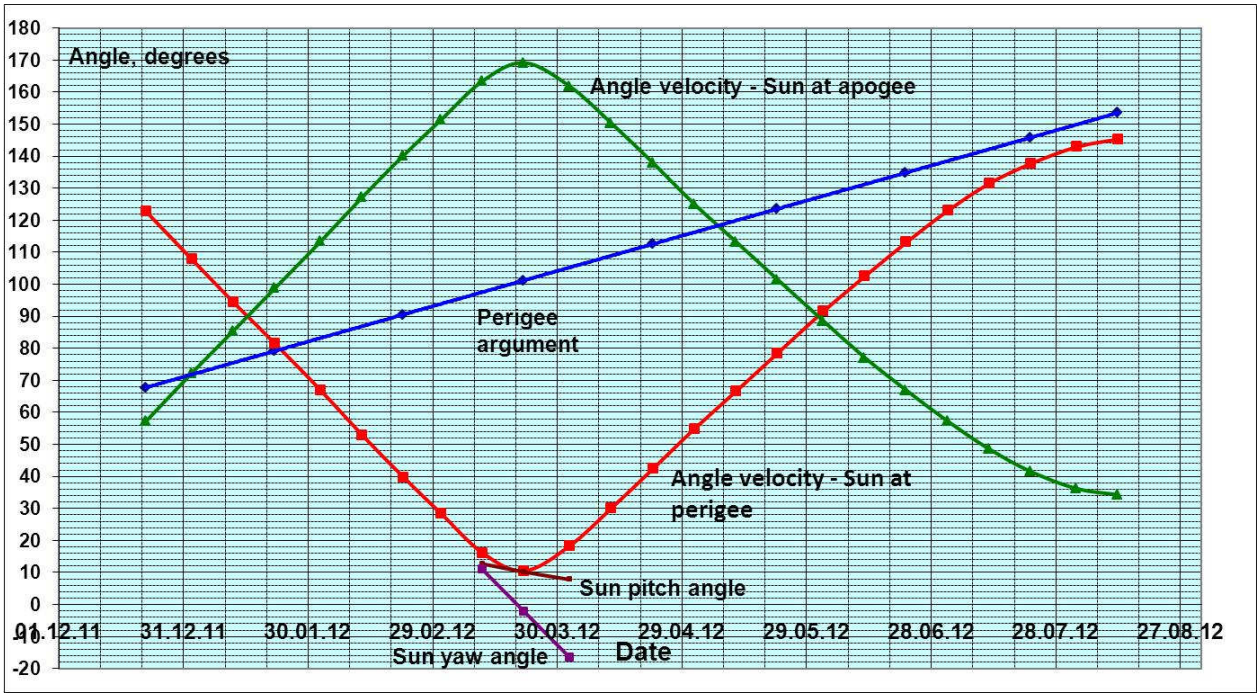
Tasks of MCC TSNIIMASH for the spacecraft's flight termination ballistic design were:

- EADS Astrium initial data analysis;
- modification of the "Progress" cargo vehicle reentry flight-dynamic support software;
- verification of EADS Astrium calculation results;
- determination of possible date's diapason for dynamic operations performance;
- the analysis of realizability's scenarios, proposed by EADS Astrium and Khrunichev space center;
- development and foundation of others ballistic scenarios;
- proposals for initial data elaboration.

As MCC TSNIIMASH deals with “Progress” cargo vehicles’ deorbitation for long time, first of all the scenario of “Express-AM4” splash down at the southern part of Pacific Ocean was considered.

But the results of calculations showed, that it is impossible. Partionally, fig.2 presents the dependence of perigee argument from date. It is easily to see, that at real dates of deorbitation performance the orbit perigee was located at Northern semi sphere. More other, at fig.2 optimum dates of dynamic operations are shown. Values of angles between spacecraft’s velocity vector and direction to the Sun at apogee and perigee were about zero at the end of 2012 year March, i.e. the Sun was at the orbit’s plane. So, dates of dynamical operations were selected.

Fig.2. Perigee argument, angles between direction to the Sun and spacecraft’s velocity vector at perigee and apogee vs date.



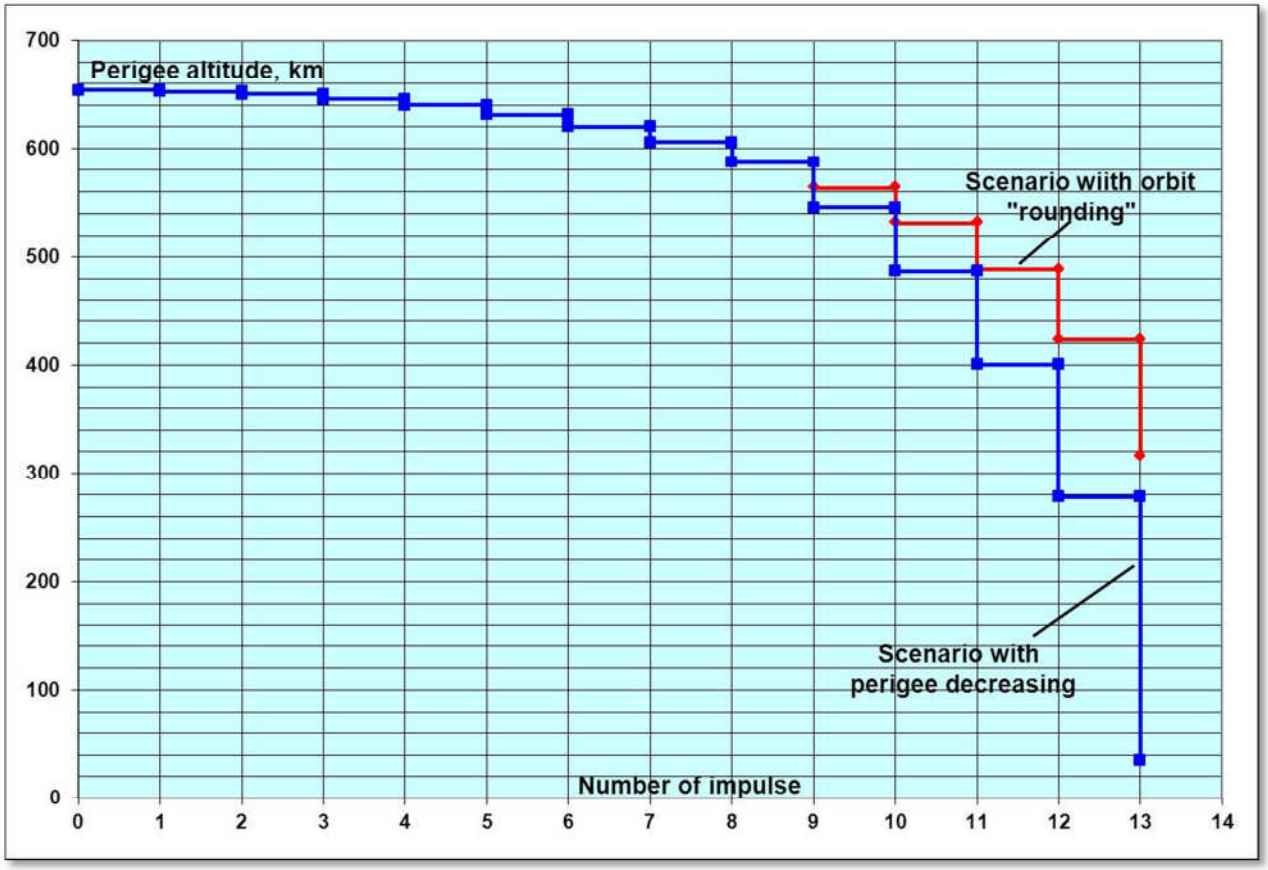
Having the results of digital simulations MCC TSNIIMASH proposed a splash down area at the northern part of Pacific Ocean.

In order to show finally, that the spacecraft’s splash down at Southern semi sphere is impossible, specialists of MCC considered variants, when the orbit is preliminary “rounded”, and later burn start time is selected for splash down at “Progress” nominal site.

During of the development of orbit’s “rounding” scenarios the following fact was the main: when deboost impulse value is low, it’s effectively is large. But in this case it is necessary to perform a lot of impulses. When impulse value is large, it’s effectively is low due to large angle between velocity vector and direction to the Sun.

At fig. 3 the two variants of impulses' implementation are shown. The firsts 9 impulses were optimized for apogee altitude's decreasing. By red color the variant than apogee altitude decreasing was optimized using all the onboard fuel amount is marked. As a result, final orbit shall have the following parameters: maximum altitude 2000 km, minimum altitude 300 km. So, this scenario's realization is impossible. By blue color another scenario of maneuvering is marked. A possibility of reentry is shown, but the splash down point is steel allocated at Northern semi sphere. So, this scenario is also wrong.

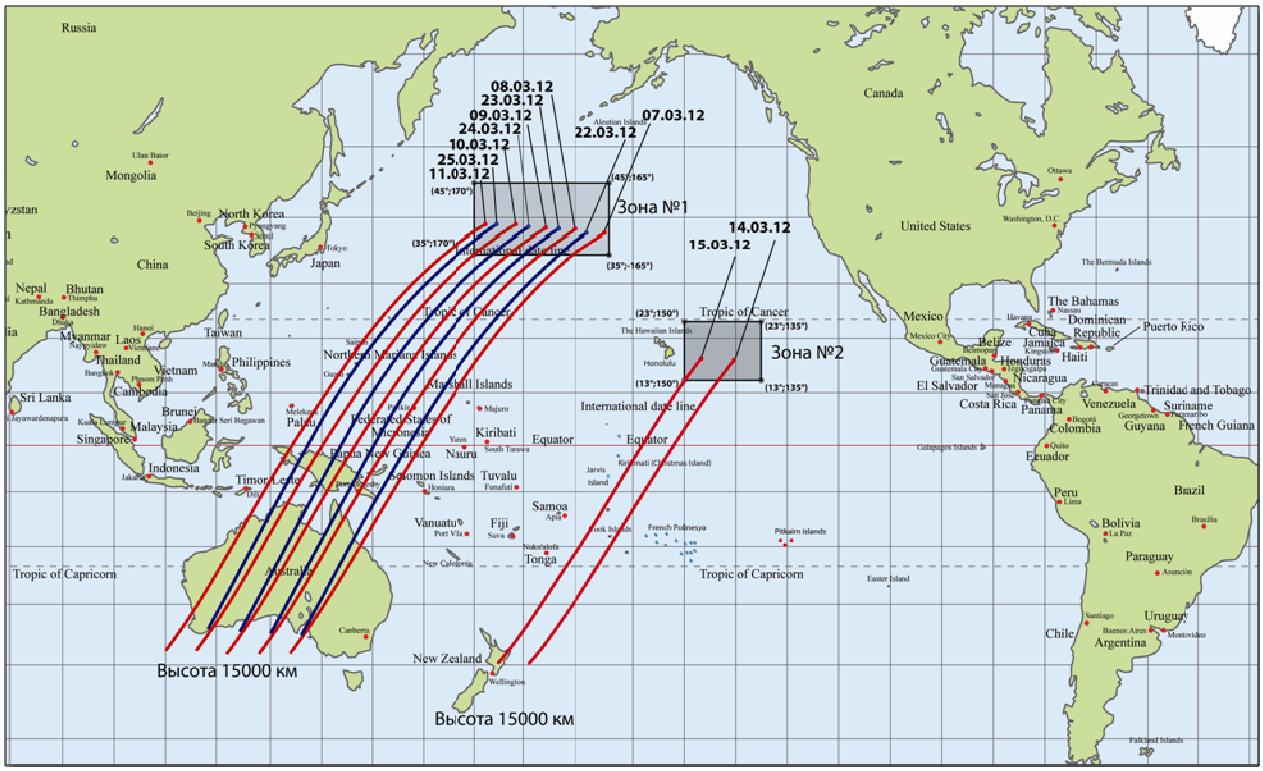
Fig. 3. Multiipulse splashdown scenario's analysis.



After that, the monoimpulse scenario of Express-AM4 flight termination was concidered. At fig. 4 the results of digital simulation of monoimpulse scenario of Express-AM4 for various dates of the apogee engine's burn start are shown. Preliminarily the two splash down sites (nominal and back-up) at the northern part of Pacific Ocean were selected. Optimum intervals for dynamic operations performance were determined and the possibility of spacecraft's splash down in given sites was proved.

Having the results of all variants of the spacecraft flight termination's calculations the monoimpulse scenario of splash down was finally selected.

Fig. 4. On the analysis of monoimpulse splash down scenario.



The second variant of Express-AM4 flight termination was a transfer to so-called “safe” orbit. In this case “safe” orbit means a minimum probability of collisions to other spacecraft.

For this task’s solution the following two variants were considered:

- “safe” orbit with parameters: maximum altitude 18000 km, minimum altitude 2000 km (variant of Khrunichev space center);
- “safe” orbit with parameters: maximum altitude 15500 km, minimum altitude 12000 km (variant of MCC TSNIIMASH).

Digital simulation of the first variant shown, that three burn starts of apogee engine are needed. It was caused by onboard control system’s features at shadows phases near perigee. After final forming of orbit about 2 tons of fuel could remain in onboard tanks.The analysis of simulation’s results shown, that this orbit is not quite safe. It could cross to a lot of others spacecraft’s orbits. Moreover, having so high residuals of fuel, a probability of fuel tanks explosion could be high. In this case quantity of space debris objects could increase.

The results of the second variant’s simulation shown, that for the spacecraft’s transfer to given orbit too three burn starts of apogee engine are needed (perigee increasing, apogee decreasing and final forming of orbit). The last burn start’s parameters were selected in order to

have zero residuals of fuel. This orbit could be really “safe” because it practically hasn’t crosses with other spacecraft’s orbits.

The results of Express-AM4 flight termination’s flight-dynamic design are in the following:

- jointly with EADS Astrium and Russian space communication company (RSCC) the receiving and analysis of initial data were performed;
- modification of the cargo vehicles “Progress” reentry flight-dynamic support was made;
- the analysis of Express-AM4 transfer to “safe” orbit’s realizability was performed;
- optimum scenarios of the spacecraft’s transfer to “safe” orbit were determined;
- the results of investigations were used for selection of Express-AM4 flight termination scenario.

After consideration of all the scenarios of the spacecraft’s flight termination the variant with monoimpulse deorbitation and splash down at the given region on Pacific Ocean was selected.

The second part of works for organized flight termination was devoted to operational flight-dynamic support of dynamic operations’ realization. The MCC tasks were:

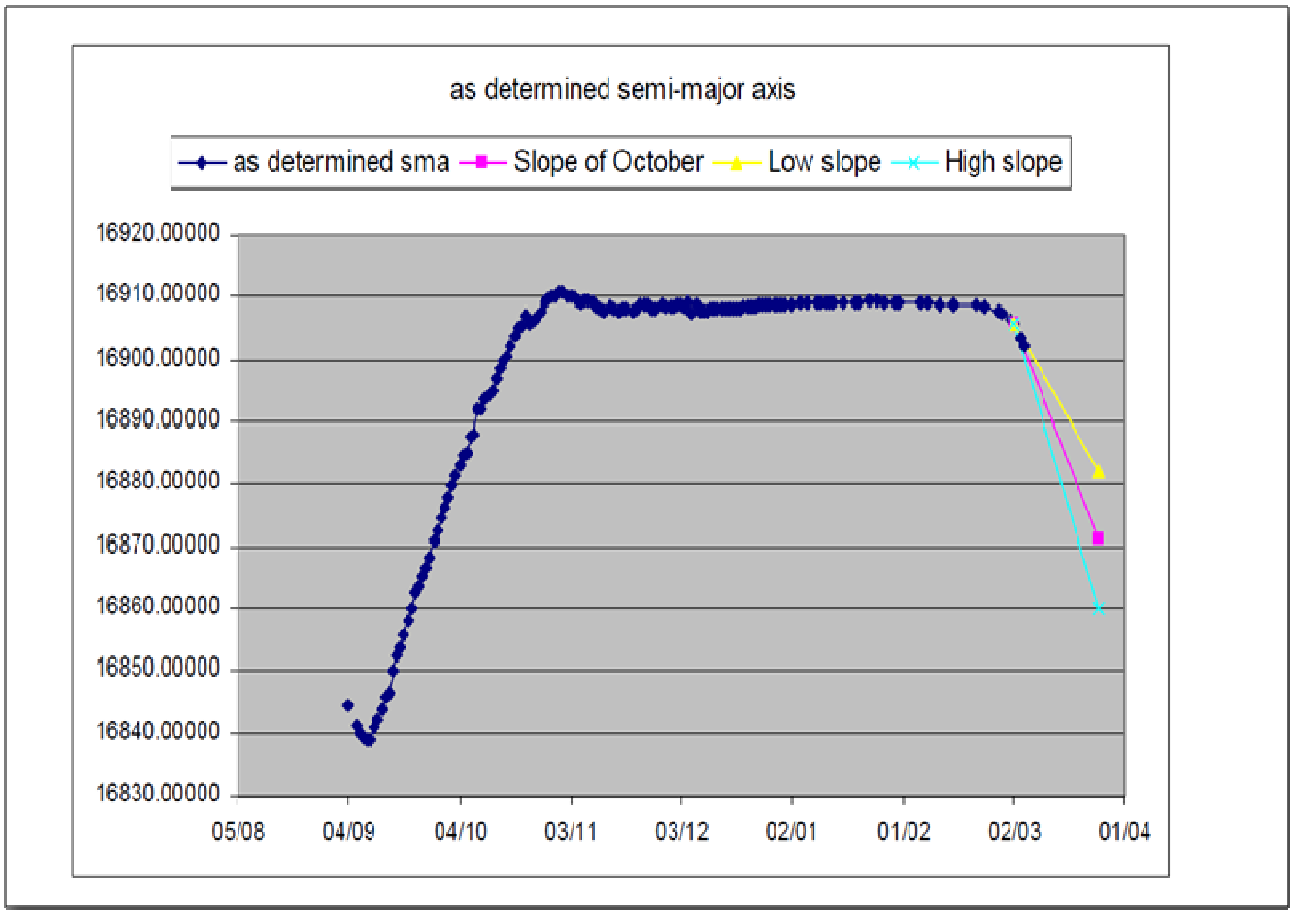
- to take part in organization of operational interaction to EADS Astrium and RSCC;
- to take part in work of RSCC working group and Roscosmos operational group;
- regular receiving of the spacecraft’s current orbital parameters and analysis of targeting conditions at selected reentry dates;
- verification of EADS Astrium’s calculations for final reentry’s preparations;
- operational on-duty during operations at the reentry date, monitoring of real operation’s for the possible cases of off-nominal situations;
- operational estimation of real geographic coordinates of the possible splash down center using measurements from ground stations Uralla (Australia) and Beijing (China) after the apogee engine cut-off;
- preparation and passing of MCC’s official conclusion to RSCC about results of the spacecraft’s flight termination.

After the beginning of operational flight monitoring very serious problem was detected. If the spacecraft provided the attitude control to the Sun direction only, after every shadow phase

of orbit control engines started to work for spacecraft re-attitude to the Sun. It was necessary for accumulators recharging. So, to predict the orbit evolution was very difficult.

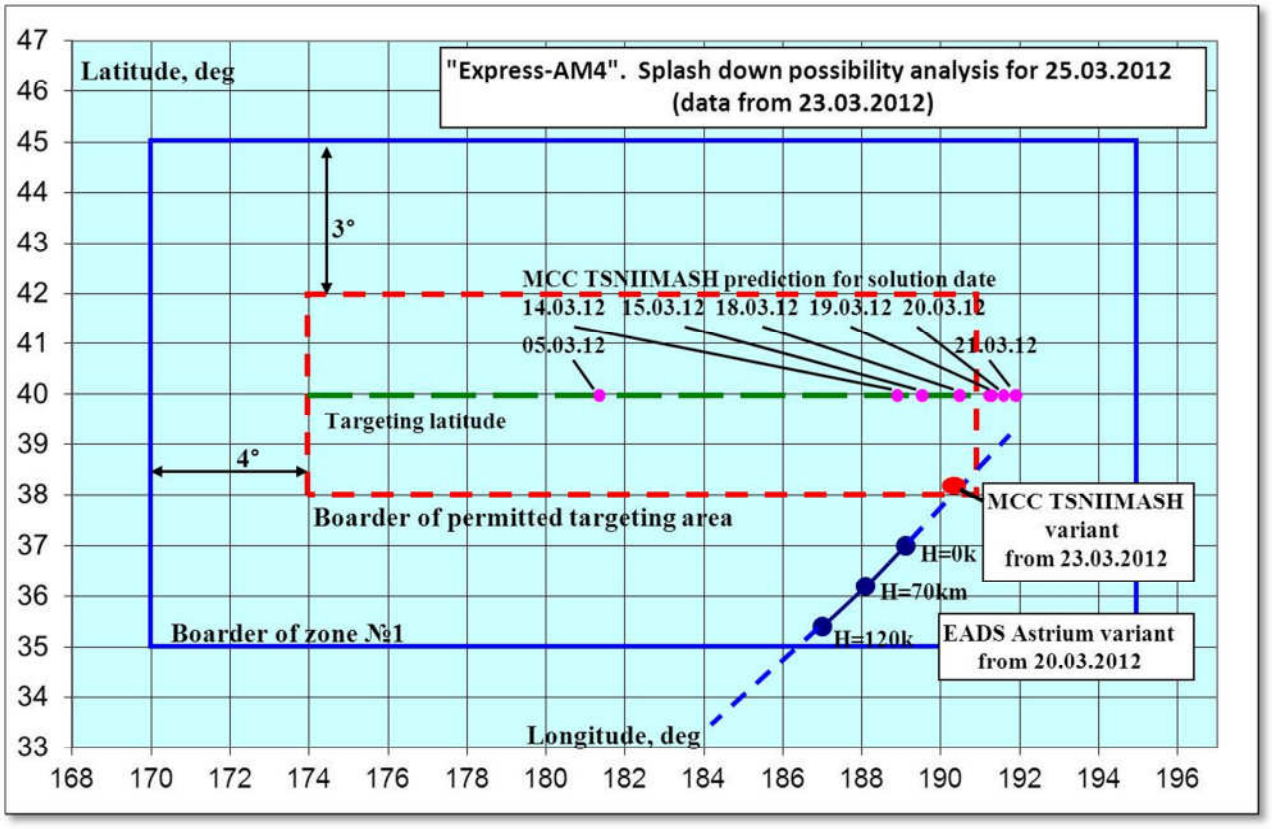
French colleagues proposed the method of prediction based on analysis of orbit parameters' behavior at autumn 2011when shadow phases of orbit still took place. Three variants of possible orbit's evolution were proposed (fig. 5).

Fig. 5.Various hypothesis of orbit evolution.



In order to guarantee the splash down of the spacecraft structure unburned elements' at given site, MCC TSNIIMASH estimated possible size of dispersion area. Then, the targeting area inside of given site was determined (fig. 6).

Fig. 6. Variants of targeting for 25.03.2012.



It is easy to see (fig. 6), that beginning from 05.03.2012 predictioned center of splash down points moved to the right boarder of permitted targeting area. 20.03.2012 the predicted center was already out of permitted area. Having this solution, MCC operationally informed RSCC and EADS Astrium that targeting to the center of permitted area (by latitude) for 25.03.2012 is impossible.

After that together with french colleagues the variant of targeting for 25.03.2012 (fig. 6, at the boarder of targeting area) was developed and approved as final one.

Works during last two days of Express-AM4 flight:

<u>24.03.2012:</u>

- EADS Astrium calibrated onboard gyroscopes, after this, performed the orbit determination using trajectory measurements from 3 orbits;
- EADS Astrium calculated the parameters of deorbitation impulse taking into account targeting conditions for 25.03.2012, recommended by MCC TSNIIMASH (targeting latitude inside of permitted splash down site's boarders). The results were operationally transmitted to MCC TANIIMASH;

- MCC TSNIIMASH performed calculations for verification of EADS Astrium's results. Confirmation of the data was operationally transmitted to RSCC.

25.03.2012:

- specialists of MCC's ballistic service were at operational shift;
- information about nominal apogee engine's burn start and cut-off was received (fig. 7);

Fig. 7. Final phase of Express-AM4 flight.

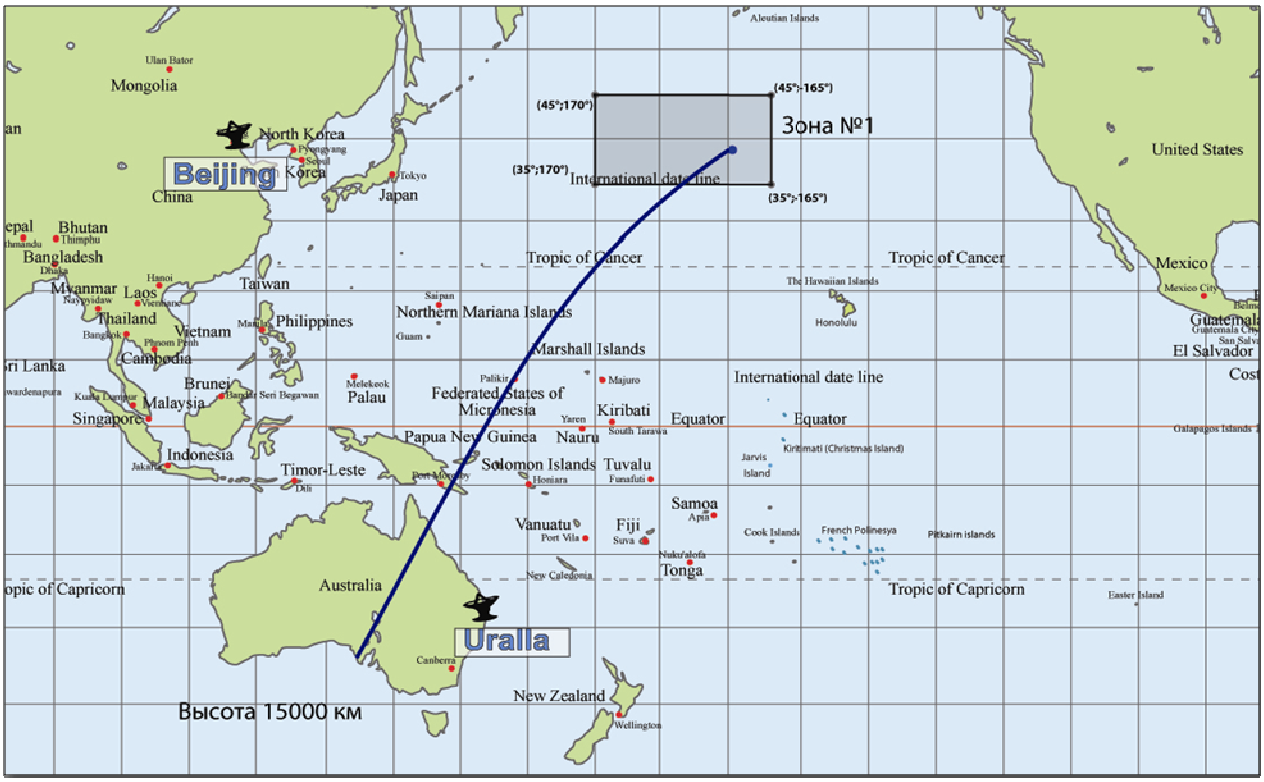
- EADS Astrium has operationally determined the parameters of real trajectory after deorbitation and estimated the possible coordinates of splash down area. The results were operationally transmitted to MCC TSNIIMASH;
- MCC TSNIIMASH performed an estimation of EADS Astrium's results and confirmed them. The results were operationally transmitted to RSCC.

26.05.2012:

- official conclusion of MCC TSNIIMASH was transmitted to RSCC.

Final phase of the spacecraft's flight was tracked by two ground stations: Uralla (Australia) and Beijing (China) –fig. 8.

Fig. 8. Realization of Express-AM4 splash down.



So, having the tracking data of realized deorbitation trajectory, it was possible to estimate the splash down site coordinates. The results confirmed that the spacecraft's flight termination took place at targeting area.