THE ROLE OF IMPACTS AND MOMENTUM TRANSFER FOR THE EVOLUTION OF ENVISAT'S ATTITUDE STATE

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ABSTRACT

The currently proposed space debris remediation measures include the active removal of large objects and “just in time” collision avoidance by deviating the objects using, e.g., ground-based lasers. These techniques require precise knowledge of the attitude state and state changes of the target objects. In the former case, e.g. to devise methods to capture the target with a tug spacecraft, in the latter, to precisely propagate the orbits of potential collision partners, as disturbing forces like air drag and solar radiation pressure depend on the attitude of the objects.

The long-term evolution of the attitude motion is, among many other causes, depending on the effects of possible impacts of debris and meteoroid, while momentum transfer from reaction wheels or other moving internal components may contribute to the root cause of the initial attitude motion. Impacts of small particles like meteoroids and space debris pieces on compact space objects are unavoidable events, which were already observed several times, e.g., on International Space Station, or rather recently on the Sentinel-1A on August 23, 2016.

This paper will discuss a detailed analysis of the effects of momentum transfer from the reaction wheels and of debris and meteoroid impacts for the particular case of Envisat. Based on the physical model of Envisat and the MASTER environment model, the likelihood to have an impact-related attitude rate increase in ten years larger than selected threshold rates was determined.

1. INTRODUCTION

Recently the determination of attitude states, and in particular rotation rates, of space objects became a topic of interest in the space debris community. This is to be seen in the context of the multitude of techniques which are currently proposed to remove space debris from orbit or to re-orbit them into disposal orbits. The majority of the techniques to remove large objects, which are driving the evolution of the space debris population on the long term, require capturing the target with a robotic arm, a net, a harpoon, or another mechanism. The attitude motion is in all these cases a critical parameter and the maximum tolerable target rotation rate is limited.

The attitude motion of an inactive Earth orbiting object may change either due to dissipation of stored internal energy or internal momentum transfer, or because of external forces. Internal energy may be released, e.g., in form of leaking attitude control systems or pressurizes tanks, any type of breakup events, and momentum can be transferred from reaction wheels. External torques may results from the interaction with the gravity field gradients and the magnetic field of the Earth or from impulse transfer when colliding with other objects. The aim of this study is to assess the maximum angular momentum change to be expected for the defunct Envisat spacecraft, on one hand due to angular momentum transfer from its reaction wheels, and, on the other hand, from impacts with space debris objects or micrometeorites. The latter was analyzed once for a single impact event and for a statistical particle flux over a then year period. The study was in particular triggered by the sudden acceleration of Envisat's rotation observed about two months after its failure when Envisat's attitude changed from an almost stable NADIR fixed attitude to a rotation with 0.547 rpm [1], [2], [3] (inertial rotation period ~ 110s; see Figure 1).

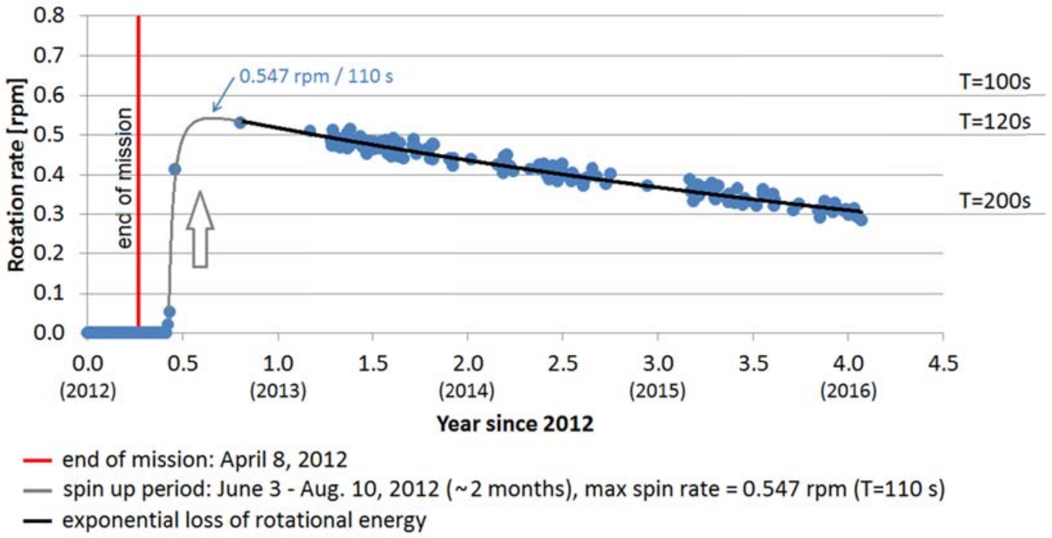

Figure 1: Inertial spin rate of Envisat measured by Satellite Laser Ranging observations (from [3]).

2. MOMENTUM AND IMPULSE TRANSFER ANALYSIS

The interaction between compact space objects, such as spacecraft and upper stages on a geocentric orbit, and small particles like meteoroids and space debris pieces (hereafter collectively called MMOD) is unavoidable and has been observed many times. In case that the impact particle will not cause a catastrophic collision, meaning that the target body is not completely disrupted, the impulse of the impacting particle will be partially transferred to the angular momentum of the impacted body and partially to its linear momentum. Such an event will cause, among other effects, a sudden change of the attitude state of the impacted body. The size and direction of the resulting angular momentum change will strongly depend on the impact particle mass, the impact velocity, and on the impact geometry, i.e. the location and impact angle with respect to the target body center of mass. In our investigation we used a simple model for the Envisat satellite consisting of a bus (a rectangular cube with dimensions 4m x 4m x 10m, 7512 kg) and solar panel (a thin plate with dimensions 14m x 5m x 0m, 388 kg) (see Figure 2). By using the parallel axis theorem, we determined the momenta of inertia for this model. The values obtained for $I_{\hat{x}}$, $I_{\hat{y}}$, and $I_{\hat{z}}$ for the given principal axis of inertia are listed in the Table 1.

$I_{\hat{x}}$ [kg.m^2]	**$I_{\hat{y}}$ [kg.m^2]**	**$I_{\hat{z}}$ [kg.m^2]**
135284.9	21163.7	134476.5

Table 1: Momenta of inertia for the Envisat model consisting of a solid rectangular cube (satellite bus) and a thin plate (solar panel).

3. SINGLE IMPACT EVENT

In this case we investigated the probability for a collision between Envisat and a particle with a mass within the interval 0.0016 g to 1 kg. In addition we derived the resulting angular momenta that particle would transfer to the satellite model during the collision by assuming given scenario. A representative synthetic population has been generated by using ESA MASTER tool [5] and the orbital elements of Envisat from October 2014. For every generated particle which was defined by the mass, impact velocity, and impact angle we calculated the resulting received angular momentum $\vec{L}_j$, and consequently for a given case also the angular velocity change $\omega_{particle}$ and the resulting spin period P. Three different cases a, b or c, corresponding to a rotation around the principal axes $\hat{x}$, $\hat{y}$ or $\hat{z}$, respectively, were analyzed. These cases are shown in Figure 2. The impacting particle hits the target at four different locations (green points defined by position vector $\vec{r}_i$ displayed as blue arrow) to achieve that the target would start rotating either around the principal axis $\hat{x}$ (Figure 2 a), $\hat{y}$ (Figure 2 b) or $\hat{z}$ (Figure 2 c and Figure 2 d). 1,000 synthetic particles per mass interval were generated and the angular momentum that these particles would transfer to Envisat was computed. The resulting probability for different angular momentum changes around the three principal axes over a period of ten years are given in Figure 3. The corresponding angular velocities are provided in Figure 4.

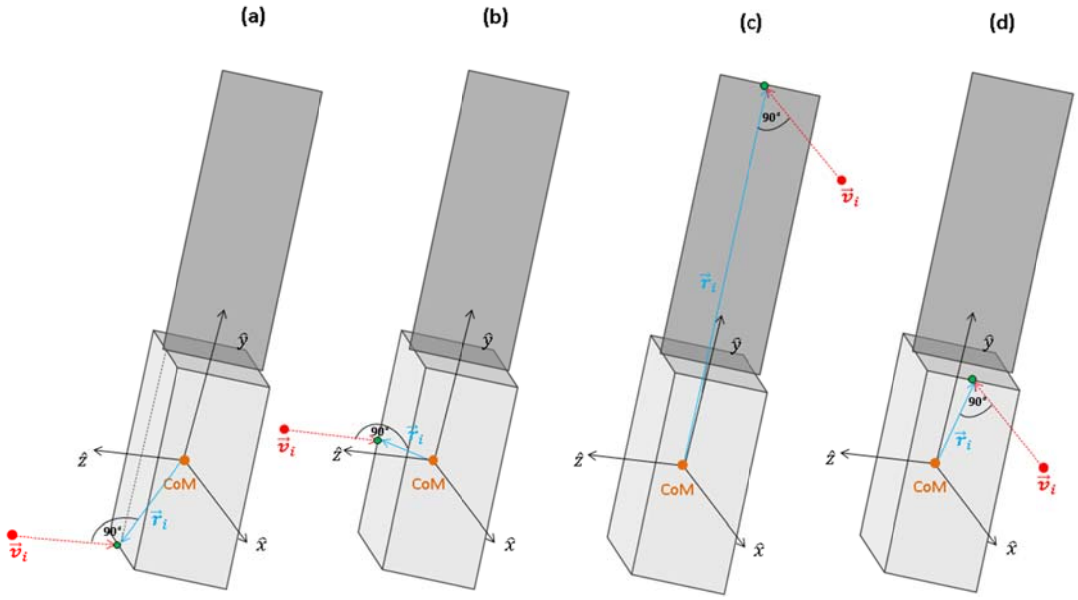

Figure 2: Visualization of four different collision scenarios to determine the transferred angular momentum and the resulting angular velocity change of the target after a collision. The impactor is showed as a red point colliding with target in the position marked by the green point and blue position vector.

These results clearly show that there is an very small probability for an impact which would result in a substantial change of the angular momentum and thus in a substantial change of the spin rate around any axis of Envisat. There is, e.g., only a 0.9% probability that the bus would be hit by a particle of 6.31 g which in the worst case (case (a) Figure 2) would change the angular velocity by 0.15 deg/s, corresponding to spin period of ~40 min. An impact of an object with a mass of ~100 g is required to spin up Envisat from a stable attitude to about 0.4 rpm, which would be comparable to the angular momentum change observed two months after the contact with the spacecraft has been lost (Figure 1). Such an event is predicted with a probability of 0.24% over a time span of 10 years or with a probability of 0.004% over a period of two months. As a conclusion we may clearly excluded an impact event for the explanation of the observed spin rate change of Envisat as a collision with an object of this mass would have damaged the spacecraft severely but remote sensing observation show no evidence of any damage on Envisat.

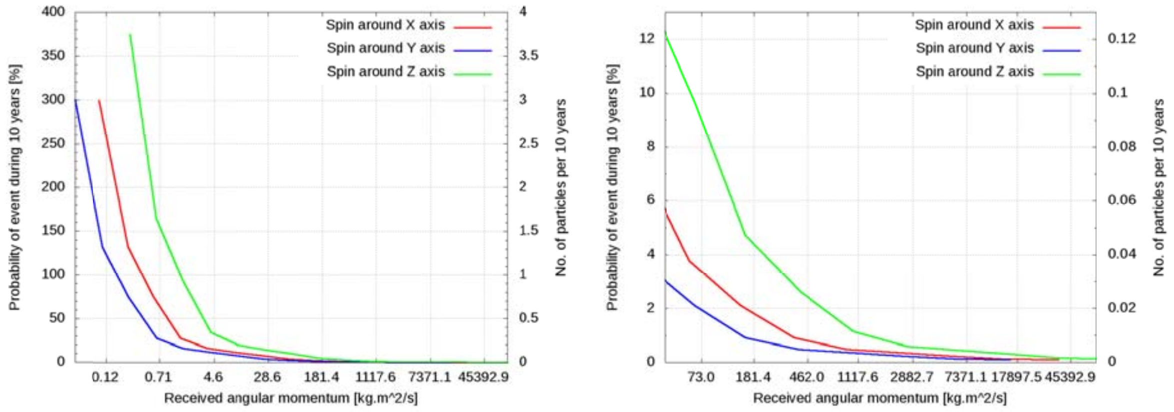

Figure 3: Probability of collision during ten years of exposure (vertical axis) versus received angular momentum assuming a perfect inelastic collision for three different cases causing maximum rotation around the principal axes $\hat{x}$ (red), $\hat{y}$ (blue) and $\hat{z}$ (green). The figures show the result of 1,000 simulations using the MASTER MMOD population (mass and impact velocity distributions) generated by the MASTER program assuming Envisat orbit and 10 years of exposure.

For each impact geometry (related also to given moment of inertia, see **Error! Reference source not found.**) and total angular momentum we can calculate the obtained rotation velocity of the model. In Figure 4 can be seen received angular velocity (lower horizontal axis) and resulting spin period (upper horizontal axis) as a function of probability of event (left vertical axis).

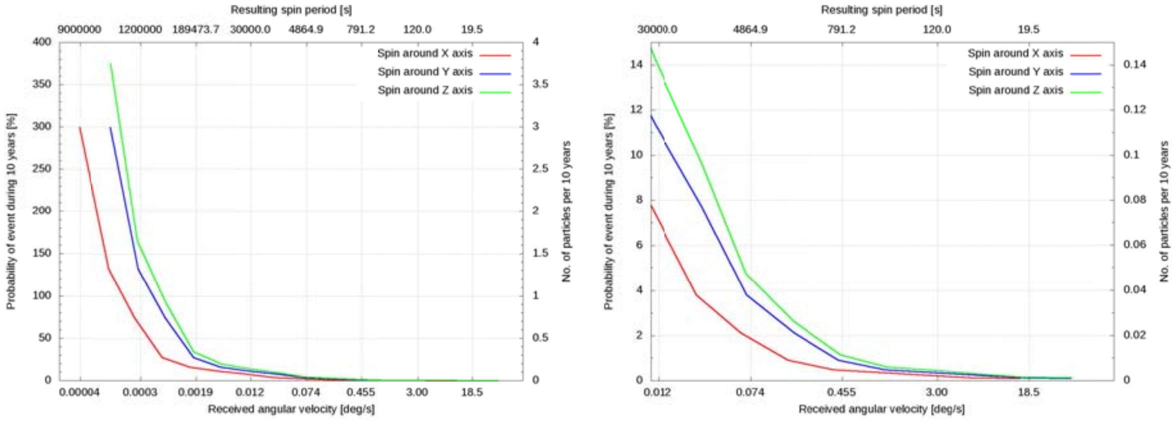

Figure 4: Probability of collision during ten years of exposure (left vertical axis) versus received angular velocity (lower horizontal axis) and resulting spin period (upper horizontal axis) assuming a perfect inelastic collision for three different cases causing maximum rotation around the principal axes $\hat{x}$ (red), $\hat{y}$ (blue) and $\hat{z}$ (green). The figures show the result of 1,000 simulations using the MASTER MMOD population (mass and impact velocity distributions) generated by the MASTER program assuming Envisat orbit and 10 years of exposure.

4. STATISTICAL PARTICLE FLUX IMPACTS

To investigate the effect that would be caused by a flux of particles impacting Envisat during ten years of exposure, the ESA MASTER model MMOD population of particles heavier than 10^{-15} kg was used. The properties of this population are given in Figure 5. The MASTER tool was then used to predict impacts of this MMOD population with Envisat over a 10 year period. In total about 5 10^{6} particles were impacting Envisat. We may now again consider a worst case situation and assume that all impacts occurred at one of the positions (a), (b), or (c) defined in Figure 2. The total amount of angular momentum received from this flux of particles over 10 years is relatively small, namely 29.4 kg m^2s^{-1} for case *(a)*, 12.2 kg m^2s^{-1} for case *(b)*, and 97.6 kg m^2s^{-1} for case *(c)*, respectively. Some characteristics of these impacts are given in Figure 6.The results of these cumulative momentum transfers are equivalent to an impact of a single particle with a mass equal to ~0.45 g, ~0.45g and ~0.55g, respectively, resulting in angular velocity changes of 0.013 deg/s, 0.033 deg/s, and 0.042 deg/s for the three cases.

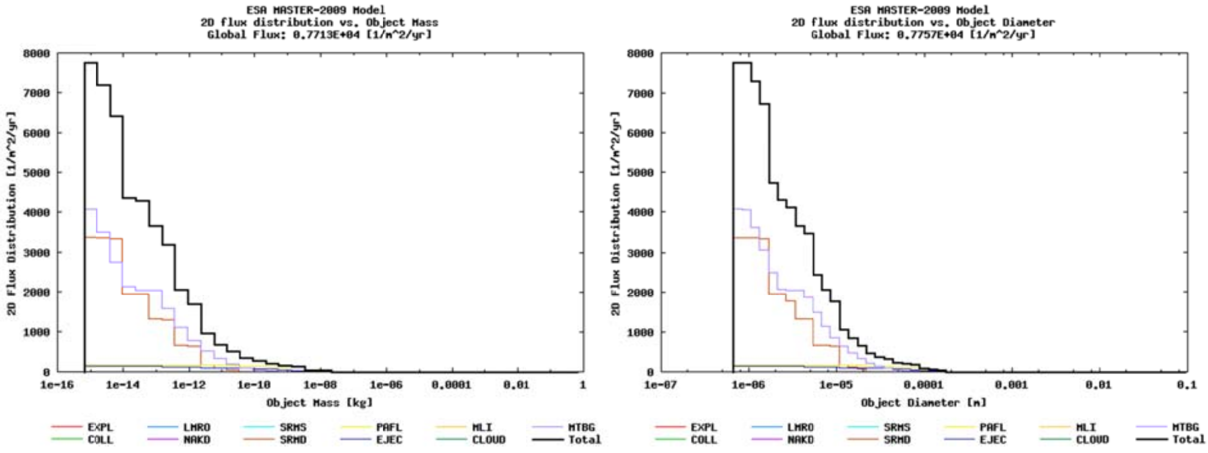

Figure 5: Cumulative distributions for the mass (on the left) and size (on the right) of the MMOD particles. The flux was generated by MASTER for the Envisat orbit (reference to 21102014). The simulation covered 10 years from 01-11-2014 to 01-11-2024 using the MASTER MMOD population in the mass range 10^{-15} g - 1 kg.

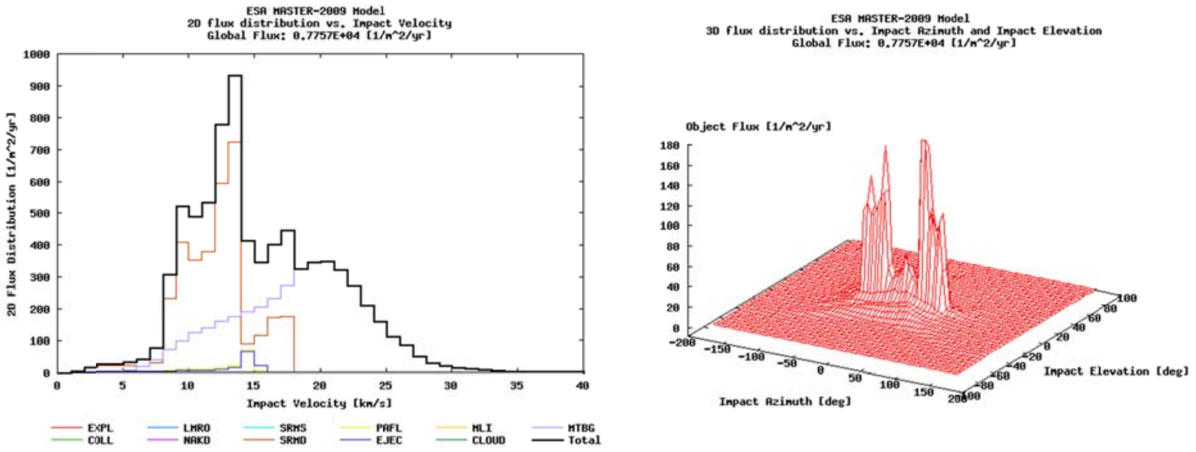

Figure 6: Impact velocity distribution (left) and impact azimuth and elevation distribution (right) of the MMOD particles. The flux was generated by MASTER for the Envisat orbit (reference to 21102014). The simulation covered 10 years from 01-11-2014 to 01-11-2024 using the MASTER MMOD population in the mass range 10^{-15} g - 1 kg.

5. MOMENTUM TRANSFER FROM REACTION WHEELS

There are in total five reaction wheels installed on Envisat [1]. The configuration of the reaction wheels is shown in Figure 7. One reaction wheel is aligned along the x_{esa} axis (ESA reference system) or along the $\hat{y}$ axis (reference system used in this paper). Two reaction wheels are aligned along the y_{esa} axis (along the $\hat{z}$ axis) and two reaction wheels are aligned along the z_{esa} (along the $\hat{x}$ axis)

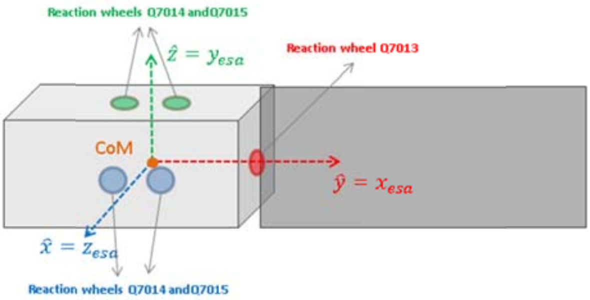

Figure 7: Distribution and direction of the reaction wheels installed on Envisat in the satellite body coordinate system and in the ESA satellite body coordinate system.

Each of the five reaction wheels has a capacity of 40 N m s (40 kg m^{-2}/s) with a torque range of ±0.45 Nm. The maximum angular momentum L_{max} which can be transferred from the wheels to the body amounts thus to $L_{y_{esa}max}$ = $L_{z_{esa}max}$ = 80 N m s and for x_{esa} it is $L_{x_{esa}max}$ = 40 N m s.

For this analysis we used slightly different values for moment of inertia of the principal axes of inertia of Envisat which were determined by ESA (Table 2).

$\boldsymbol{I_{x_{esa}}}$ [kg m^2]	$\boldsymbol{I_{y_{esa}}}$ [kg m^2]	$\boldsymbol{I_{z_{esa}}}$ [kg.m^2]
17023.3	124825.7	129112.2

Table 2: Momenta of inertia for the Envisat spacecraft determined by ESA.

The maximum change in angular velocity for the three axes, if the momentum from fully loaded reaction wheel would be transferred to the body, is given in Table 3.

Principal axis	**No. of reaction wheels aligned with axis**	**Reaction wheel capacity [kg m^2 s^{-1}]**	**ENVISAT moment of inertia [kg m^2]**	**Maximum angular velocity change [deg s^{-1}]**	**Corresponding rotational period [hour]**
$\boldsymbol{x_{esa}}$	1	40	17023.3	0.1346	0.743
$\boldsymbol{y_{esa}}$	2	40 + 40	124825.7	0.0367	2.723
$\boldsymbol{z_{esa}}$	2	40 + 40	129112.2	0.0355	2.817

Table 3: The maximum angular velocities and corresponding rotational periods of Envisat which can be obtained from reaction wheel(s) assuming different principal axis of inertia.

These results show that a momentum transfer from the reaction wheels cannot explain the observed spin-up of Envisat as the maximum change in angular velocity from this transfer is almost two orders of magnitudes smaller than the observed one (period of ~120s).

6. SUMMARY

Effects of debris and meteoroid impacts and of momentum transfer from the reaction wheels for the particular case of Envisat were analyzed. Based on the physical model of Envisat and the MASTER environment model, the likelihood to have an impact-related spin rate change in ten years was determined.

There is an very small probability for a single impact which would result in a substantial change of the angular momentum and thus in a substantial change of the spin rate around any axis of Envisat over a ten year time period. A particle of ~100 g is required to spin up Envisat from a stable attitude to about 0.4 rpm, which would be comparable to the angular velocity change observed two months after the contact with the spacecraft has been lost. The probability for such an event is less than 0.25%. Simulations showed that the accumulated momentum transfer from the entire MASTER MMOD population is also minor and would in with worst case assumption result in angular velocity change of 0.04 deg/s.

The maximum momentum which could be transfer from the Envisat's reaction wheels to its body, assuming that the wheels were fully loaded, would result in an angular velocity change of 0.14 deg/s, 0.037 deg/s, and 0.036 deg/s, respectively, for the three main axes of inertia. Again, this is by far not sufficient to explain the observed spin-up of Envisat after its failure.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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