

LONG-TERM EVOLUTION OF ORBITS OF HIGH AREA-TO-MASS RATIO OBJECTS IN THE GEOSTATIONARY RING

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The Astronomical Institute of the University of Bern maintains a catalogue of objects in or near the Geostationary Ring with high area-to-mass ratios (HAMR objects). These objects have a large surface exposed to the Sun compared to their mass. Therefore, their orbits are significantly influenced by the Solar radiation pressure. The radiation pressure causes a force in the Sun-object direction which leads to a substantial change of the orbital parameters.

When determining an orbit, a scaling factor of the Solar radiation pressure is estimated as an additional parameter. Assuming that the radiation pressure varies with the distance squared between the Sun and an object, this parameter represents the area-to-mass ratio of the object.

The AIUB internal catalogue consists of about 50 objects which have an area-to-mass ratio of more than $1 \text{ m}^2 \text{ kg}^{-1}$ and which were observed in ten nights or more. Their orbits thus are quite accurate. We will present the results of the orbit determinations as well as the long-term behaviour of the orbital elements.

1. SPACE DEBRIS

In 1993, the International Academy of Astronautics (IAA) defined the term space debris [3]:

Orbital debris is herein defined as any man-made object, which is non-functional with no reasonable expectation of assuming or resuming its intended function, or any other function for which it is or can be expected to be authorized, including fragments and parts thereof.

This means that all old, non-working satellites as well as fragments caused by aging, collision or explosion count as space debris.

A category to classify space debris objects is the area-to-mass ratio (AMR), which represents the surface area of an object exposed to the Sun compared to the total mass of the object. As an example: a sheet of standard office paper has an AMR of about $10 \text{ m}^2 \text{ kg}^{-1}$, comparable to GPS satellites with an AMR of about $0.02 \text{ m}^2 \text{ kg}^{-1}$ (see [1]). Fragments of satellites, for example foil-like parts, can have AMR values up to $50 \text{ m}^2 \text{ kg}^{-1}$.

The higher the AMR value, the more the object's orbit will be perturbed by an additional acceleration along the line Sun-object and directed away from the Sun.

In the scope of this work we focused on objects with AMR values higher than $1 \text{ m}^2 \text{ kg}^{-1}$, called HAMR objects. We will show the evolution of orbits of selected objects based on orbit determinations and the development of these orbits in the future.

2. ORBIT DETERMINATION

Orbit determinations (OD) were performed with the *CeIMech* tool *SATORB*, developed by G. Beutler [1]. The orbits were determined with as much observations as possible. Also, the arcs covered by observations were chosen long as possible. A used arc does not necessarily contain all available observations but only those which results in an 'acceptable' orbit. Normally, when adding new observations, some of the the oldest ones have to be removed to get below the AIUB internal limit for a good orbit. The main criterion for an 'acceptable' orbit determination is the RMS of the residuals in right ascension and declination. In the routine process of the AIUB the upper limit of the RMS is set to $2''$.

An additionally estimated parameter was a scaling factor for the solar radiation pressure. This scaling factor was then used to derive the AMR value for each arc. In fact only the product $C_R \cdot \text{AMR}$ may be determined, where C_R is depending on the reflection properties of the object and has a value between 1 and 2. In the following we assume $C_R = 1$. The criterion to accept an orbit was that the uncertainty of the scaling factor had to be below 20 % of the value itself.

We chose six objects with area-to-mass ratios between $2.5 \text{ m}^2 \text{ kg}^{-1}$ and $45 \text{ m}^2 \text{ kg}^{-1}$. The number of nights with observations varies between 28 and 173 and the total arc length between 284 days and 1926 days. Table 1 gives an overview of the objects presented in this work, sorted by their mean AMR value. The numbers in brackets represent the $1-\sigma$ uncertainties.

Table 1: Objects of this work, their mean AMR value and total arc length

Object	AMR value $\text{m}^2 \text{kg}^{-1}$	Total arc length d
E06321D	2.5119(4)	1926
E07047A	4.793(5)	1162
E07308B	8.863(5)	333
E10245A	13.612(24)	318
S95300	28.576(16)	401
E09325A	45.03(3)	284

The Keplerian elements were computed for the last observation epoch. For each added night an orbit was determined. Keplerian elements were calculated for the last observation epoch in the arc and performing ODs for each night with observations, one gets an evolution of orbital elements.

The last available set of elements were then used for the long-term propagation, described in the following section. This also includes the AMR value, the last value is taken and then considered to be constant for the whole propagation period. Former studies (e. g. [2]) analysed the AMR value variation and concluded, that this assumption is not necessarily valid. There are objects, which showed variations over the analysis interval studied in that paper. Consequently, the assumption of a constant AMR value for 20 years might not be valid for all of the six objects, either.

3. LONG-TERM PROPAGATION

Propagations have been performed to analyse the evolution of the orbital elements. For this propagation a full force model was used including perturbations due to the Earth's oblateness and the gravitational attraction of Sun and Moon. Further Earth's potential coefficients up to terms of degree and order 12, the perturbations due to the Earth tides, the corrections due to general relativity, and a simple model for the direct radiation pressure were taken into account.

As an initial orbit the orbital elements of the last orbit determination have been used. During every orbit determination the AMR values are estimated. These values are used twice during the propagation of the orbital elements. On the one hand for the air drag and on the other hand for radiation pressure.

Based on these orbital elements ephemeris every ten days have been generated during a total time span of 20 years. The last epoch of an orbit determination based on observations (T_S) has been used as the first epoch for the propagation. Results are presented in the next section.

4. RESULTS OF ORBIT DETERMINATIONS AND PROPAGATIONS

The results of the orbit determinations as well as of the propagation are shown in the Fig. 1 to 6 and described in the following sections. Figures and descriptions are in ascending order of the AMR value.

4.1. E06321D

This object belong to the class of object with inclined geosynchronous orbits (IGSO).

The the propagated orbit shows that the mean semi-major axis of the orbit stays constant for 20 years after the last OD, though it might be lower than the average of the results of the orbit determinations. The shift is less than 12 km from the average value 41 425 km and can be neglected. The variations with very high frequencies may be aliasing effects.

The eccentricity shows an annual period with a sinusoidal trend of lower frequency. It never exceeds 0.08 and the orbit can be considered 'circular' for the entire interval.

The inclination will decrease for ten years after the last OD and will then rise again. This behaviour is part of the precession of the orbital pole around the pole of the ecliptic with a period of approximately 52 years (see e. g. [1]). It is a consequence mostly of the non-spherical shape of the Earth's gravitational potential and Luni-Solar perturbations. Until the end of the interval, an inclination of nearly 10° is reached.

4.2. E07047A

This object also belongs to the IGSO objects, though its orbit is eccentric.

The propagated behaviour of the semi-major axis agrees with the results of the orbit determinations and shows a constant mean semi-major axis, perturbations with lower frequencies are visible. The semi-major axis varies between 39 990 km and 40 015 km. Here again, the variations with very high frequencies and the beat wave are due to aliasing effects.

The eccentricity shows annual variations with an superposed oscillation of the average value of lower frequency. The values range from 0.08 to more than 0.2.

Like the object before, the inclination will decrease for more than 12 years after the last OD and then rises. Smaller structures with an annual period are also visible, which is a result of the influence of the Solar radiation pressure.

4.3. E07308B

This object belongs to the IGSO objects, too, with a more eccentric orbit than the previous object.

For the first 13.5 years after the last OD the mean semi-major axis stays constant with a visible annual oscil-

lation and another of lower frequency. After 13.5 years, the semi-major axis decreases by 50 m d^{-1} . The analysis interval ended before a statement could be made, whether the decrease continues, stops with a new constant mean semi-major axis or reaches an turnover point and rises again. The reason for the decrease is the influence of the Solar radiation pressure on the object and the resulting change of the orbital plane.

At the same epoch, there is nothing visible for the eccentricity. It shows an annual oscillation for the entire interval with another oscillation of lower frequency. There might also be visible a secular trend, but the analysed interval is too short to confirm the assumption.

Within the first three years after the last OD the inclination reaches a minimum at approximately 4° and then rises again. After approximately 16.5 years a maximum at about 15° is reached. The time interval between minimum and maximum is about 13.5 years, which is smaller than the half period of the precession the orbital pole. That means, that the Solar radiation pressure causes an additional effect with a smaller period.

4.4. E10245A

This object, like the other before, belongs to the IGSO objects.

The semi-major axis shows annual oscillations with a mean value, which stays constant for approximately eleven years after the last OD. The amplitude of the oscillation rises during that interval until it gets much larger with a larger mean value than before. This phase lasts about five years, then the amplitude decreases again.

For the eccentricity no changes are visible, it shows an annual oscillation. There is also another oscillation with lower frequency visible, but it is neglectible compared to the annual oscillation.

The inclination increases for about 12 years after the last OD and reaches then a maximum at approximately 25° . This maximum does not correspond anymore to the 15° from the Earth's gravitational potential and the Luni-Solar perturbations. With increasing AMR value, the period of the oscillation decreases and the maximum inclination increases. Unfortunately in this case, there is no minimum visible to estimate a period.

4.5. S95300

The semi-major axis shows large variations with an annual period. The amplitude rises for approximately 6.5 years and then gets smaller at a higher mean value. This behaviour continues for another eleven years, then the amplitudes rises again. The analysis interval ended and the further evolution could not be investigated.

The eccentricity shows annual variation with another oscillation of lower frequency, but it is negligible compared to the annual oscillation.

The inclination shows an oscillation with a period of approximately 13.5 years. The minimum inclination is

about 1° , while the maximum is at about 31° .

4.6. E09325A

This object belongs to objects with highly eccentric orbits (HEO). At epochs of high eccentricities its perigee is about 5000 km above the Earth's surface.

The oscillation of the semi-major axis shows components of several periods. One period is approximately one year, the others are larger. Also a small secular trend is visible to larger semi-major axes.

The eccentricity shows annual oscillations with an amplitude, that gets smaller during the analysis interval. Also, another oscillation of lower frequency is visible.

Like the oscillation of the semi-major axis, the inclination shows variations with several periods. The oscillation with the highest amplitude has a period of about seven years. The inclination varies between 7° and 29° . Another oscillation has a period of one year.

5. CONCLUSIONS

In this paper, we presented the long-term evolution of high area-to-mass ratio objects in the AIUB internal catalogue. Six objects were selected, which have been observed for a long period and cover a large range of AMR values.

For each object, orbits were determined for each night with observations. Subsequently to the last orbit determination, that orbit was propagated for 20 years into the future.

We selected the semi-major axis, the eccentricity and inclination of an orbit for comparison. With increasing AMR value, the semi-major axis showed variations with a period of about one year, the changes are below 1%. Also the eccentricity showed variations with that period. For the eccentricity, other low-frequency oscillations were superposed. The inclination showed oscillations, whose period decreased and maximum value increased with increasing AMR value.

Comparing all analysed objects, we concluded that the AMR value of an object strongly influences the propagated evolution of their orbits.

6. ACKNOWLEDGEMENTS

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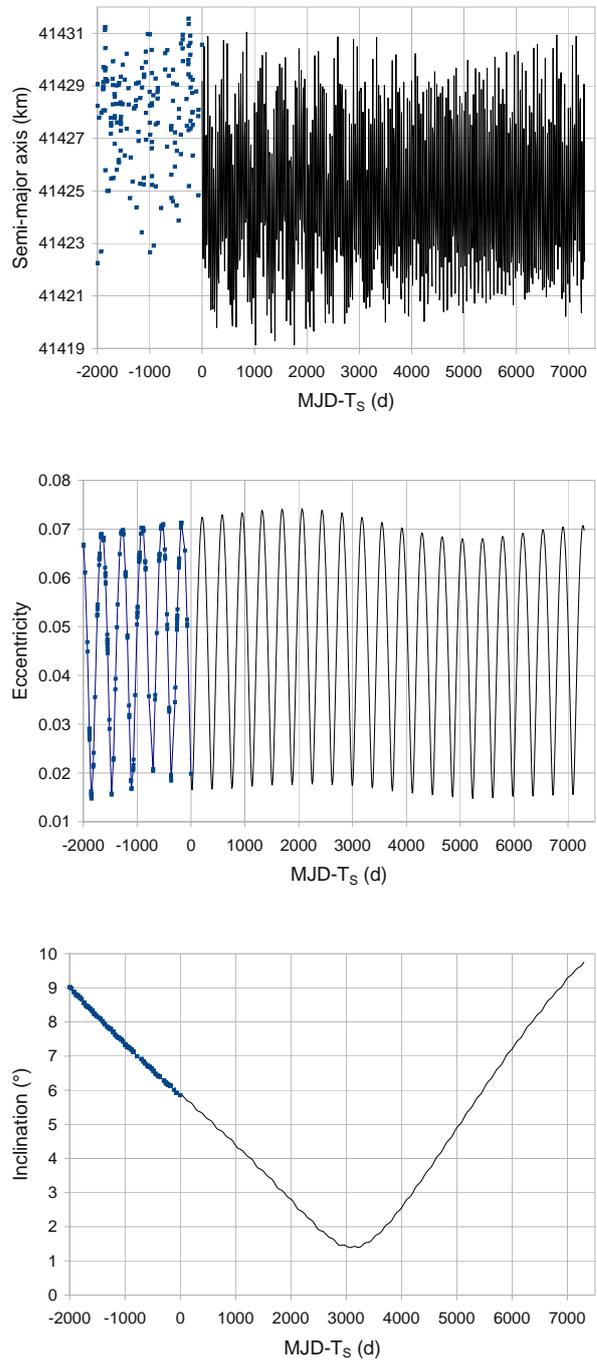


Figure 1: E06321D, AMR = 2.5119 m² kg⁻¹, T_s = 54 063

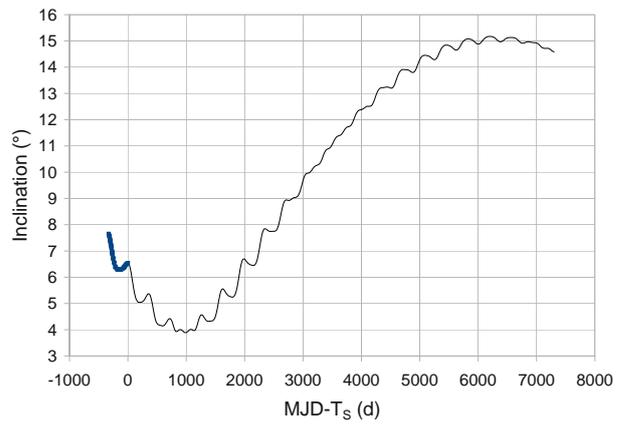
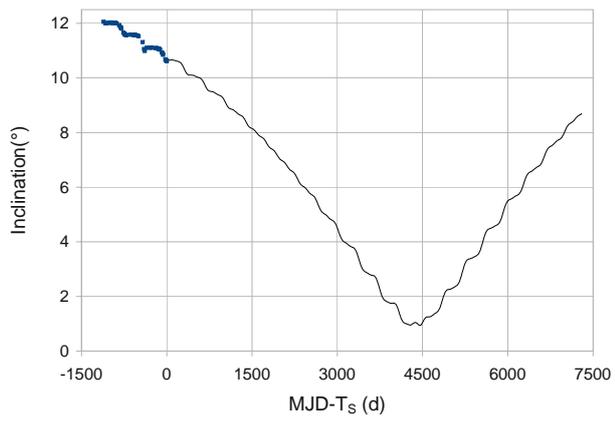
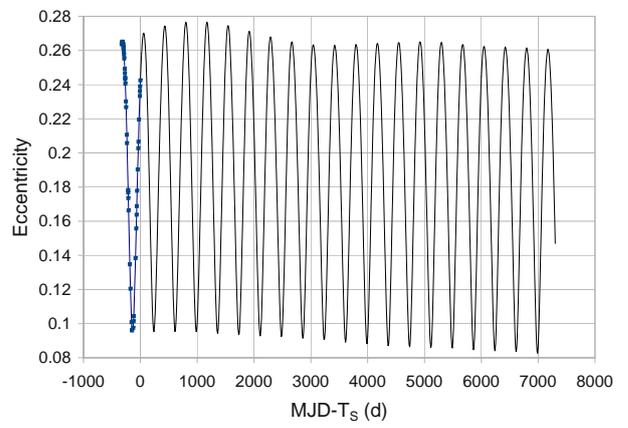
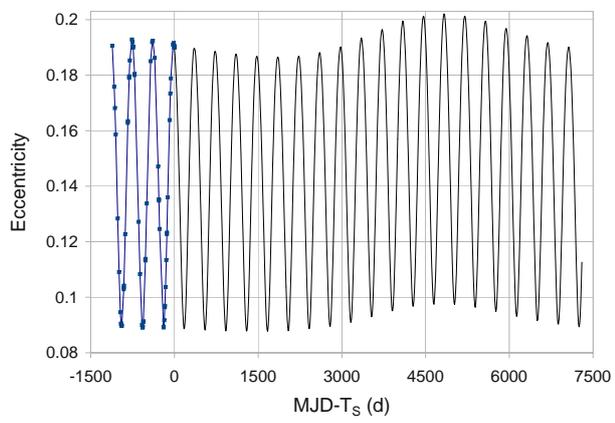
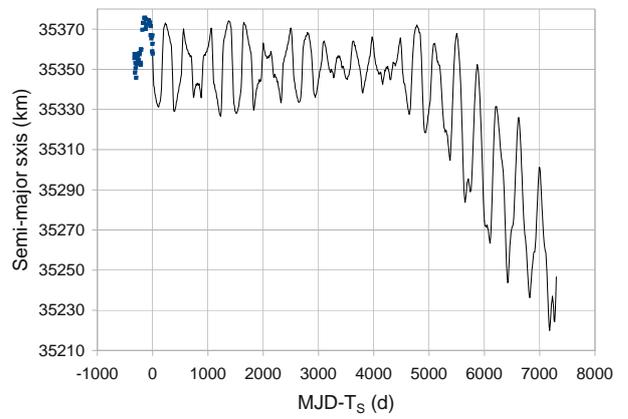
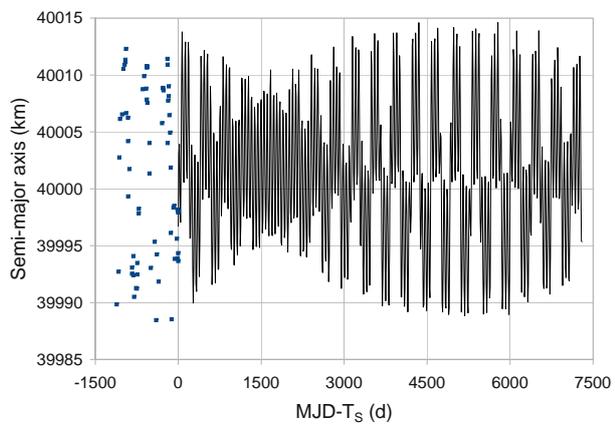


Figure 2: E07047A, $AMR = 4.793 \text{ m}^2 \text{ kg}^{-1}$, $T_S = 54\,897$

Figure 3: E07308B, $AMR = 8.863 \text{ m}^2 \text{ kg}^{-1}$, $T_S = 54\,413$

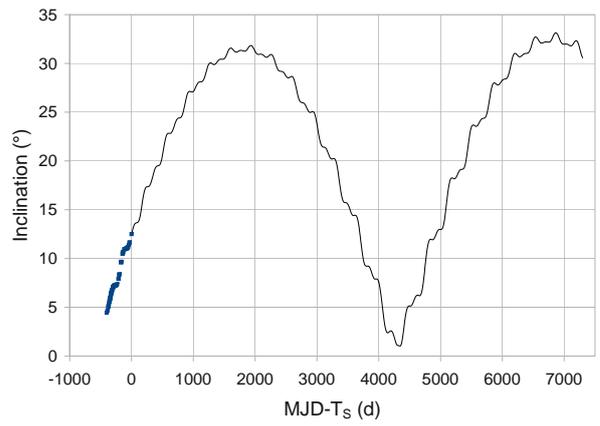
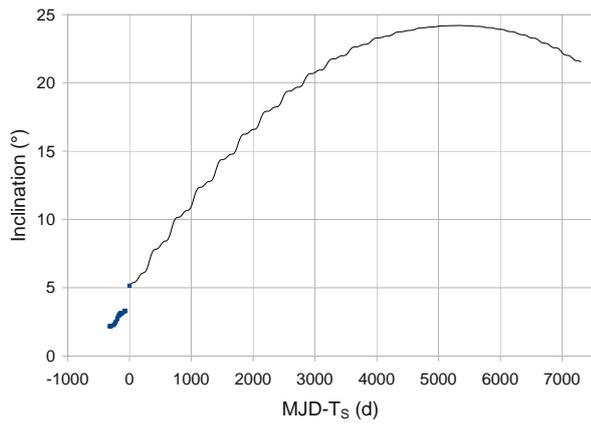
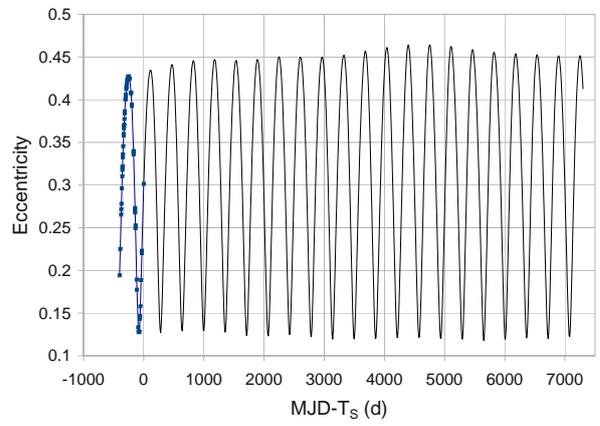
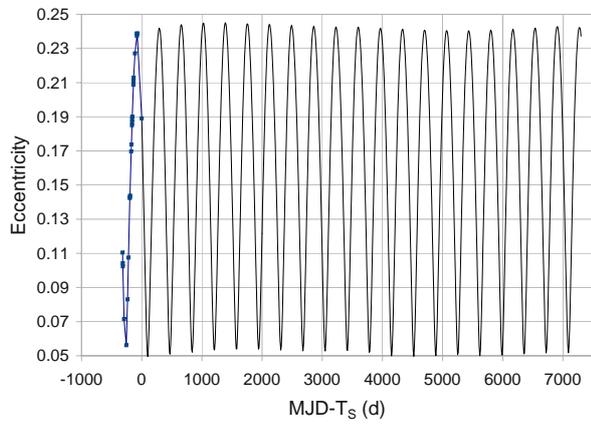
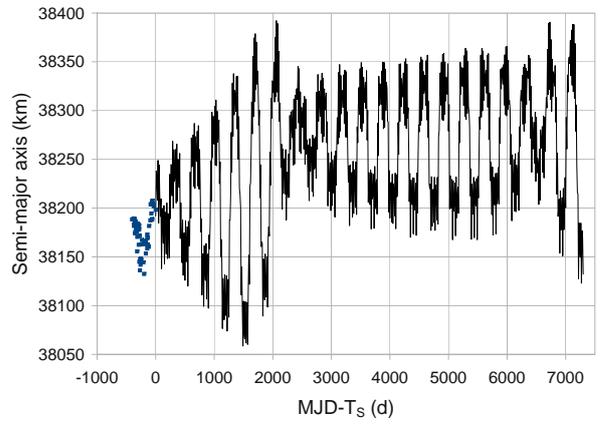
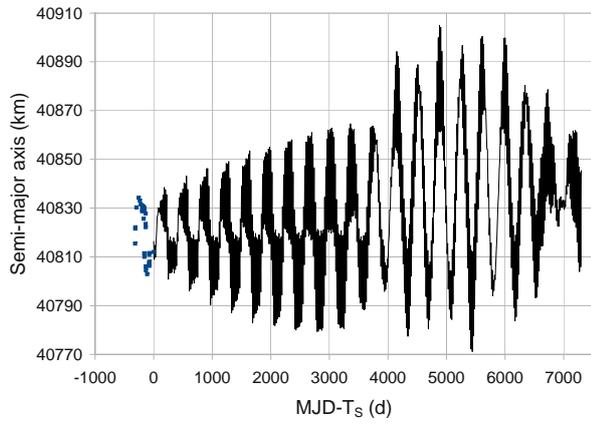


Figure 4: E10245A, $AMR = 13.612 \text{ m}^2 \text{ kg}^{-1}$, $T_S = 55\,443$

Figure 5: S95300, $AMR = 28.576 \text{ m}^2 \text{ kg}^{-1}$, $T_S = 55\,307$

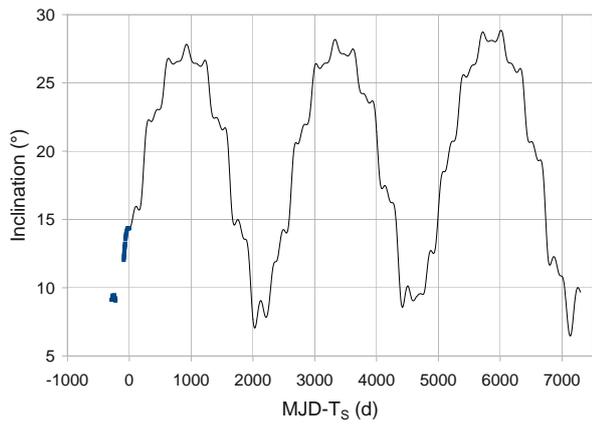
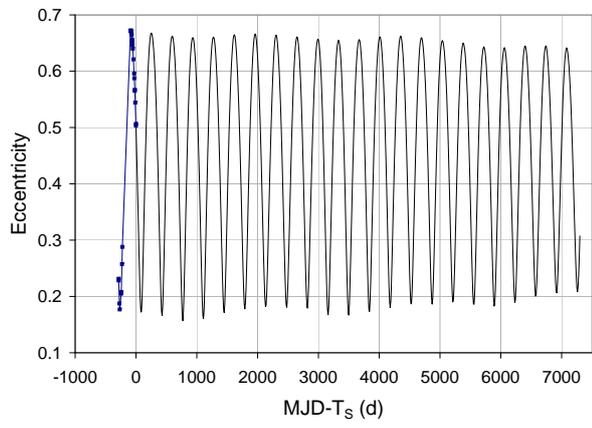
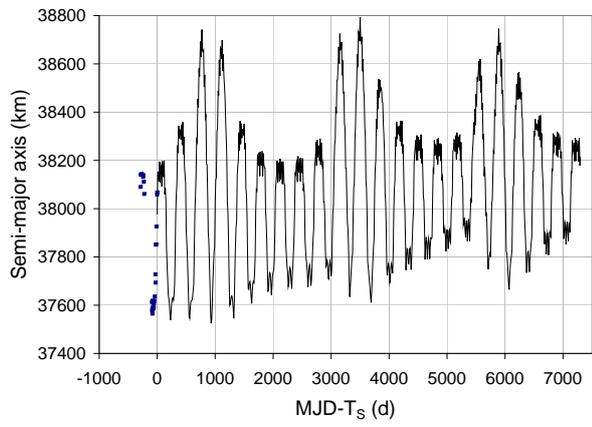


Figure 6: E09325A, $AMR = 45.03 \text{ m}^2 \text{ kg}^{-1}$, $T_s = 55157$