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INTEGRAL:

MODIFICATIONS TO THE RADIATION BELT ENTRY/EXIT TIMES.

prepared by/*préparé par* Mike Walker

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Updated graphs with current data	1.3	1	04/10/2011
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Updated graphs with current data, updated number of seasons used. Winter eclipse became pre-perigee eclipse, summer eclipse became post-perigee. Updated section on how FD make their changes.	All pages	

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1 INTRODUCTION

Due to seasonal variations of observed radiation levels around the Van Allen belts it is necessary to periodically change the Broadcast packet belt entry/exit times. To execute these changes, the PSF must be updated, which in general is done about a month in advance, and then the EPOS generation needs modification a few days in advance of the change taking effect. This means a prediction is necessary as to when to make these adjustments.

1.1 Time evolution of altitude of the radiation belt entry & exit

The altitude of the radiation belt entry/exit depends on the orientation and alignment of the orbit with respect to the geosphere and geotail, where ions emitted by the sun are trapped by the magnetosphere of the earth. The prediction of these entry/exit altitudes can never be an exact science, so occasional misplaced entry/exit times must be anticipated.
The following plots show the Radiation Belt Entry (Figure 1, red line) and Exit times (Figure 2, blue line) obtained from the ISDC website, defined where the IREM TC3 (soft electrons) rate reads 600 counts. The blue line in Figure 1 and the magenta line in Figure 2 are the altitudes set on board as the belt entry and exit. (See http://www.isdc.unige.ch/integral/operations/radiation).

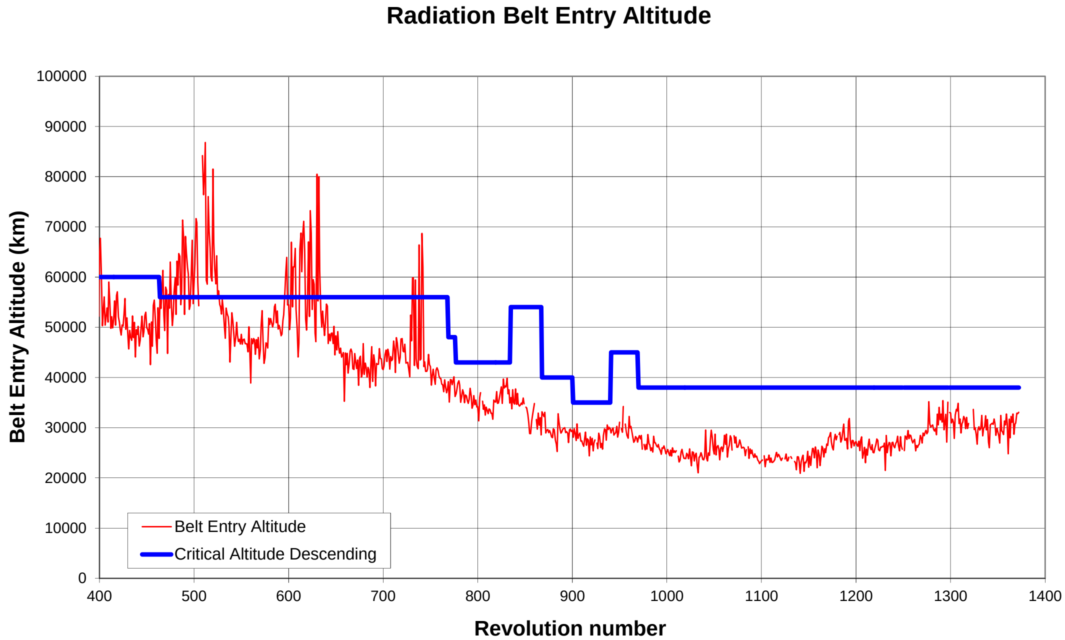

Figure 1: Radiation Belt Entry Altitude

Due to operational requirements (time to be able to react to contingencies etc.) between belt entry and LOS, it has not been possible to take advantage of the additional time. From revolution 1319 onwards, the K/LESAFE02 EDs were removed to gain observation time, however, as the belt entry altitude has been gradually increasing, it is recommended that the JEMX to SAFE EDs K/LESAFE02 be re-inserted back into the timeline from revolution 1400 (revolution of peak post-perigee eclipse period – 14 revolutions) onward, at their former locations namely CRIT_INST_ALT_DESC + 7000km – 5 seconds and CRIT_INST_ALT_DESC + 7000km respectively.

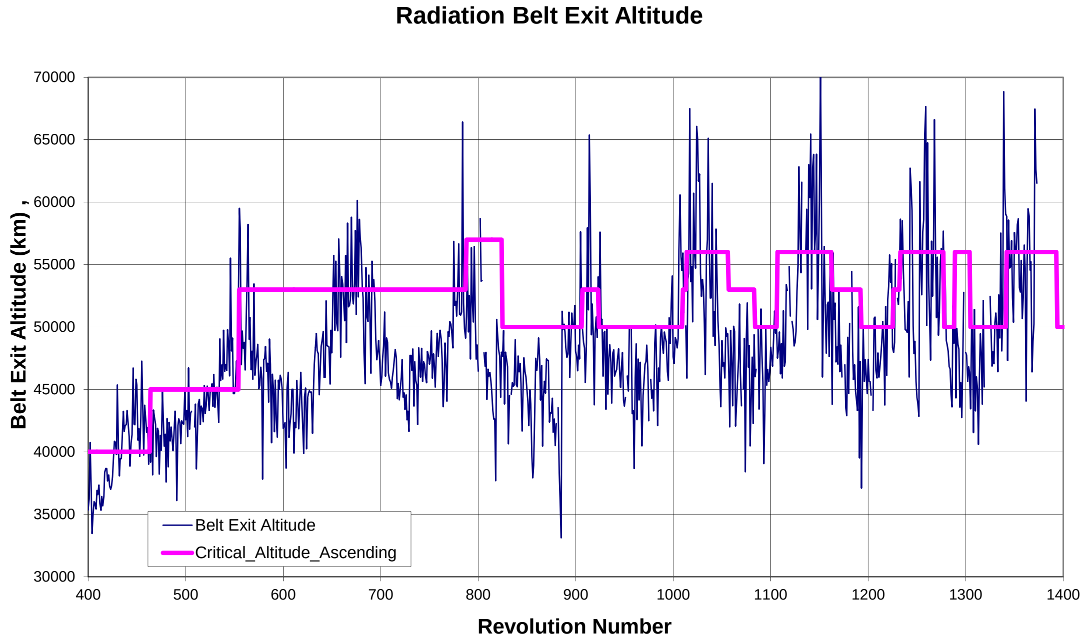

Figure 2: Radiation Belt Exit Altitude

The situation regarding the radiation belt exit is currently different and should be regularly reviewed, and action taken to optimize available science time.
Considering the past 3 high altitude belt crossing seasons, the belt exit altitude reduction performed on rev 826, the exit altitude modifications executed on revolutions 907 and 923, were not optimally performed. Also the modifications performed on revolutions 1010 & 1014, when the belt exit altitude was raised from 50000 to 53000 & 56000, were executed late, which led to problems activating IBIS on revolutions 1006 & 1007. As the integral orbit approaches the end of the season of peak belt exit altitudes, it is recommended from revolution 1393 (revolution of peak pre-perigee eclipse period + 38 revolutions) to reduce the CRIT_INST_ALT_ASC from 56000km to 50000km.

1.2 Dependency of the altitude of the radiation belt entry & exit on the sun vector

To improve understanding as to when to make adjustments of the radiation-belt exit altitude, figure 3 shows the eclipse duration. This gives an indication of where the sun vector lies relative to the orbital plane.

The peaks in the underlying near annual variation of the belt exit altitude occur when the spacecraft is flying through the geotail. This happens around the ‘Pre-Perigee’ eclipse season.

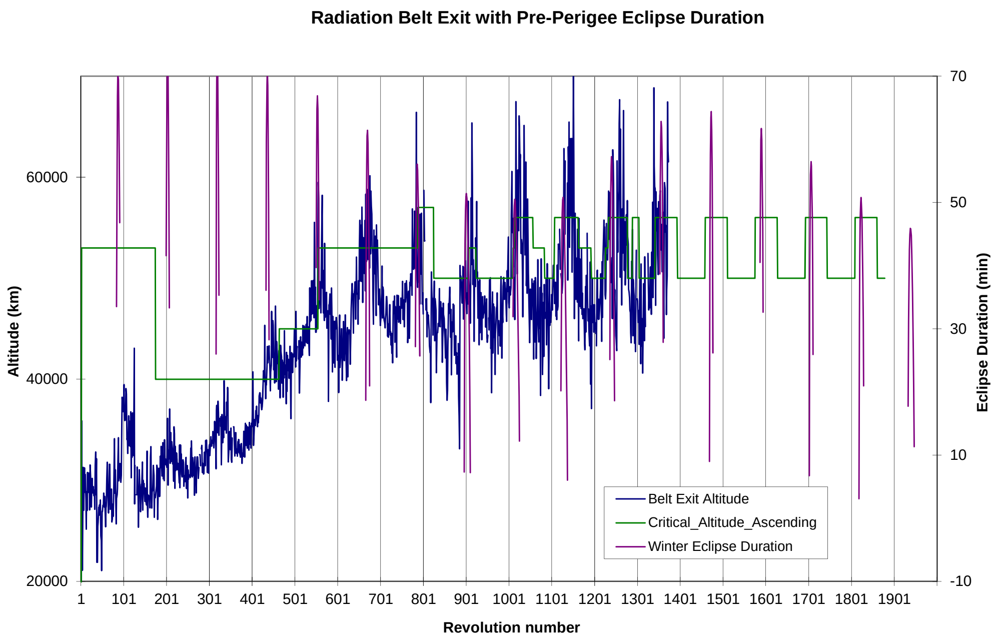

Figure 3: Radiation Belt Exit with Pre-Perigee Eclipse Duration & Critical Altitude Ascending

Examining the belt exit reduction performed on Rev 924 (08/05/2010) would indicate that it was done a little too early. Using the revolution with the maximum eclipse duration, (which occurred on Rev 901) as a reference, an offset of a further 8 revolutions (3 revs plus margin of 5) would be more appropriate. Thus a better time to have performed this change would have been on revolution 932.

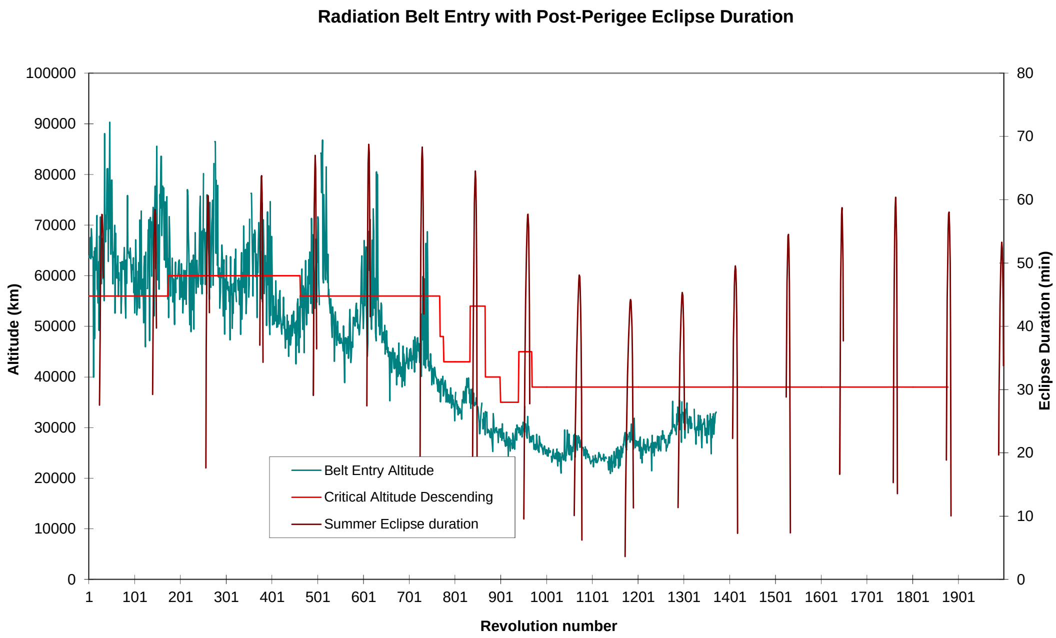

Figure 4: Radiation Belt Entry with Post-Perigee Eclipse Duration & Critical Altitude Descending

Figure 5 shows an overlaid plot of the observed radiation belt exit altitude against a relative revolution number for the last 5 'Pre-Perigee' eclipses. These were chosen, to be representative of the current situation with their high Belt exit altitudes. They have been overlaid in figure 5, and have been aligned using the maximum eclipse duration as a reference.

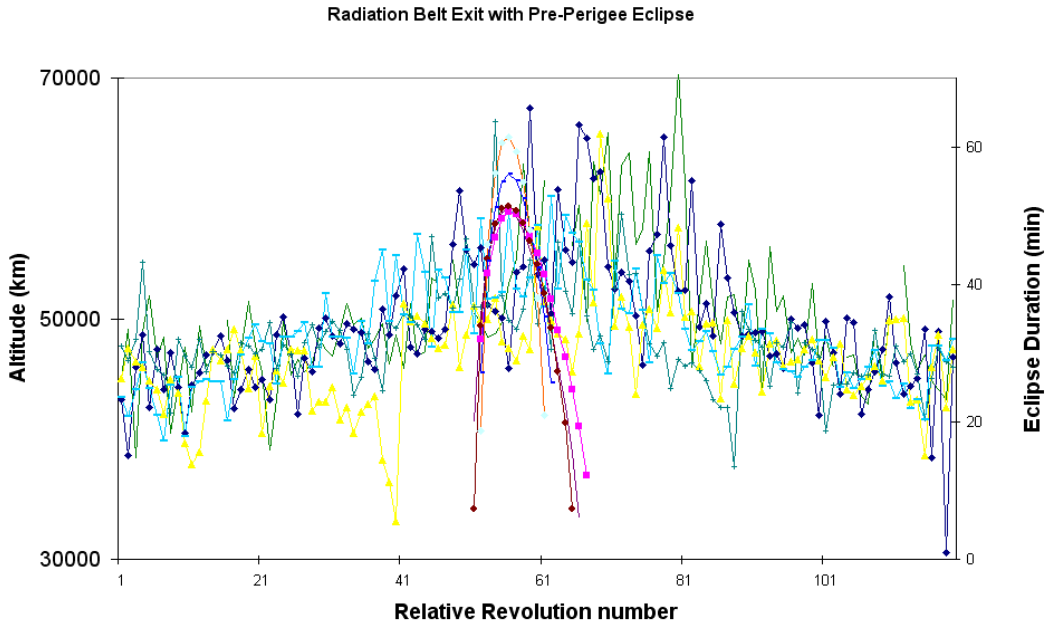

Figure 5: Overlaid Radiation Belt Exit Altitudes for last 5 seasons

By taking the mean and standard deviation of these last 5 seasons, an attempt was made to take an average season as a reference, see figure 6. Examination shows that due to the noisy nature of these seasons, the mean value shows only a slight trend; however the standard deviation shows a sharp rise 14 revolutions before the peak eclipse duration (rev 56 on this graph) and a sharp drop 38 revolutions after.

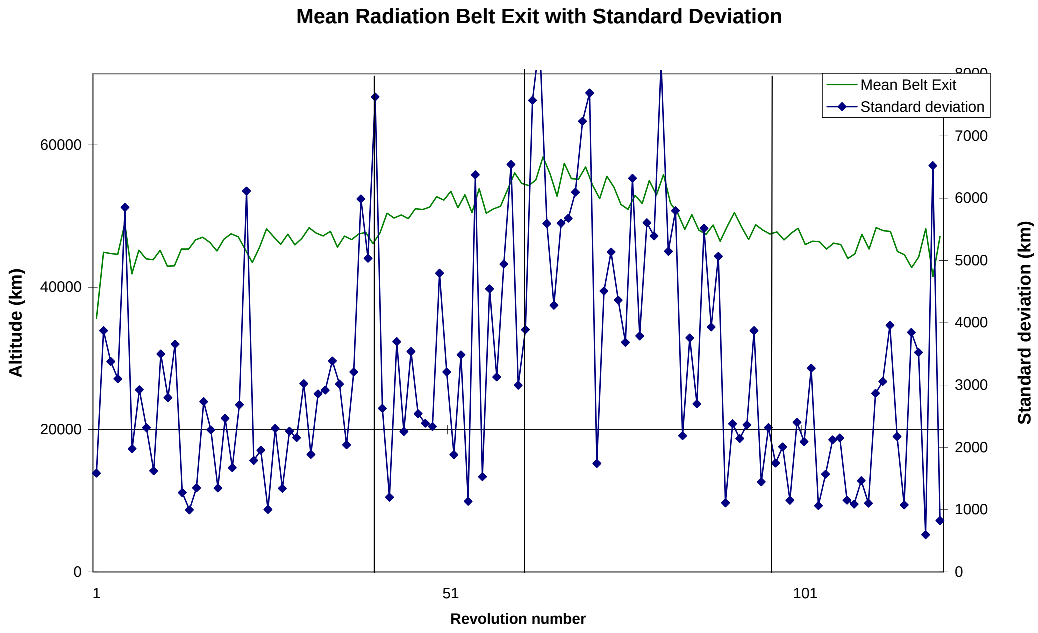

Figure 6: Mean and Standard deviation of Radiation Belt Exit Altitudes for last 5 seasons

The previous 4 'Pre-perigee' eclipses reached their peak duration on revolutions 902, 1015, 1127 & 1240 respectively. The precession of the line of nodes is predictable (see figure 13, and table 1), and a peak eclipse duration was observed on rev 1240. Allowing a small margin, the belts exit altitude should be raised on rev 1342, and lowered again on ca. rev 1394. Similarly for the subsequent peak eclipse duration on revolution 1473, the belt would be raised on revolution 1459 and lowered on 1511. During the last inter eclipse period, the belt altitude was set to 50000km. No spacecraft problems were experienced during this period, and as the value of the argument of perigee will remain stable for the next year, a similar altitude would appear to be appropriate again. Figures 7 & 8 give a prediction based on Flight Dynamics orbital assessment together with the belt exit & entry altitude.

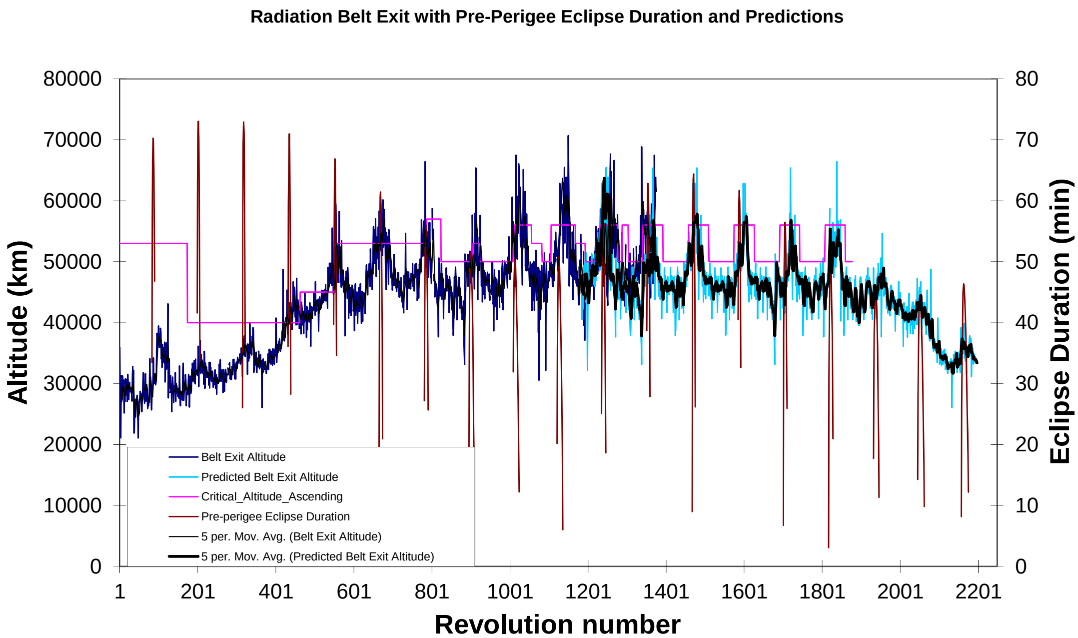

Figure 7: Radiation Belt Exit with Pre-Perigee Eclipse Duration & Critical Altitude Ascending with Prediction

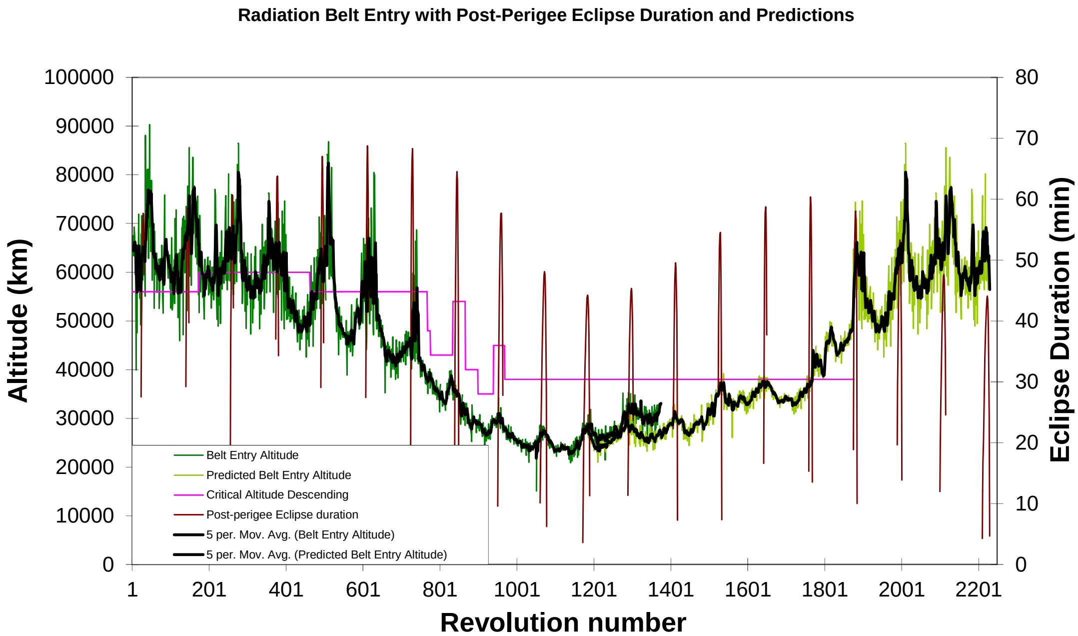

Figure 8: Radiation Belt Entry with Post-Perigee Eclipse Duration & Critical Altitude Descending with Prediction

N.B., the last eclipse duration is a prediction, and may change slightly.

1.3 Dependency of the altitude of the radiation belt exit on the IREM counts

As an additional check, by plotting the time from perigee to the point when the electron count as measured by IREM first exceeds 64, against revolution number, for the previous 18 months, an independent check can be obtained. The graph is shown below.

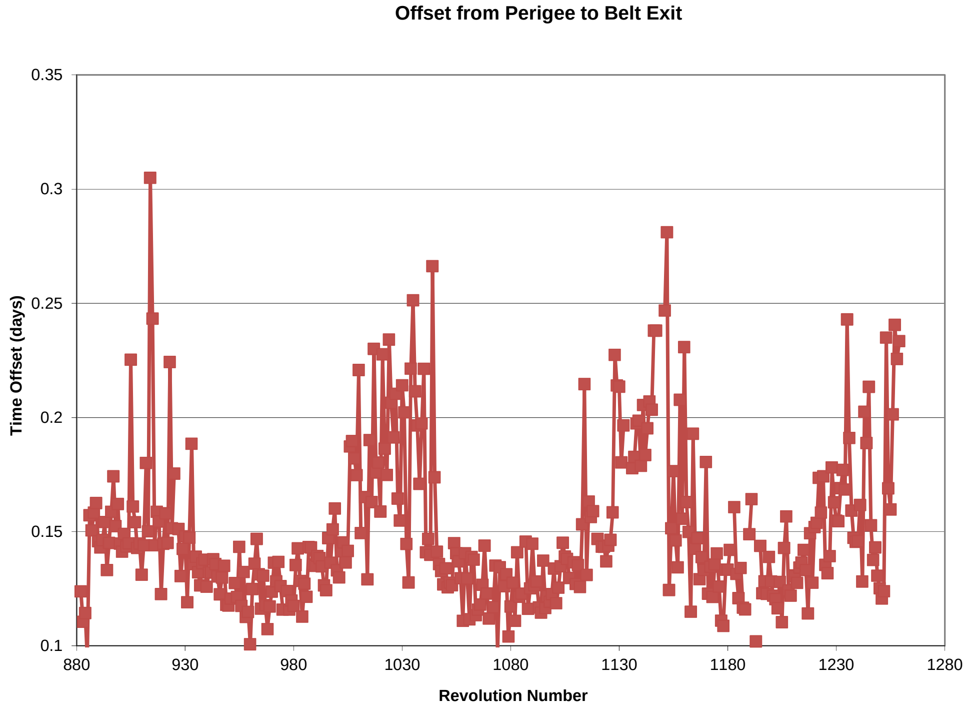

Figure 9: Offset from Perigee to Belt Exit as measured by IREM.

This plot shows that the belt exit altitude dropped sharply on revolution 1045.

Figures 10 to 14 show the evolution of some of the more critical orbital parameters. The number of and duration of the eclipses and consequently the number of high altitude belt crossings is heavily dependent on the perigee altitude and inclination, figures 10 & 11 show this evolution.

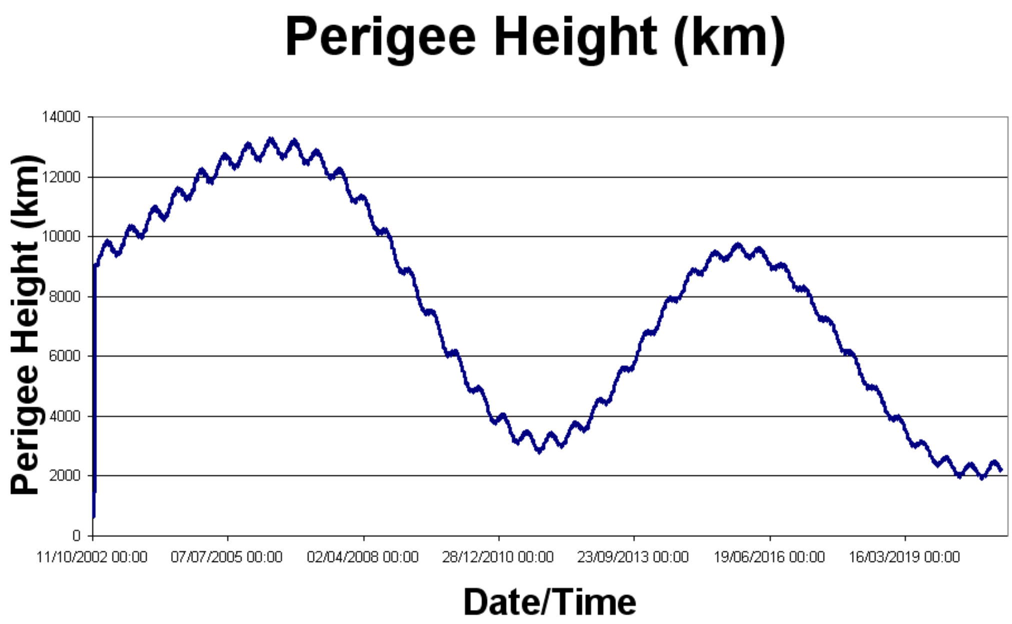

Figure 10: Perigee Height

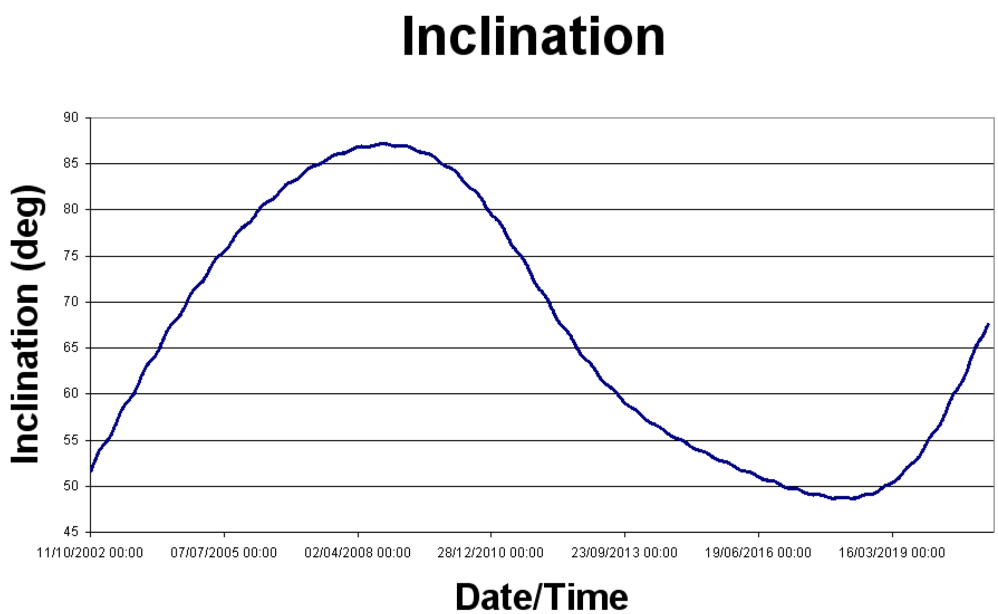

Figure 11: Inclination

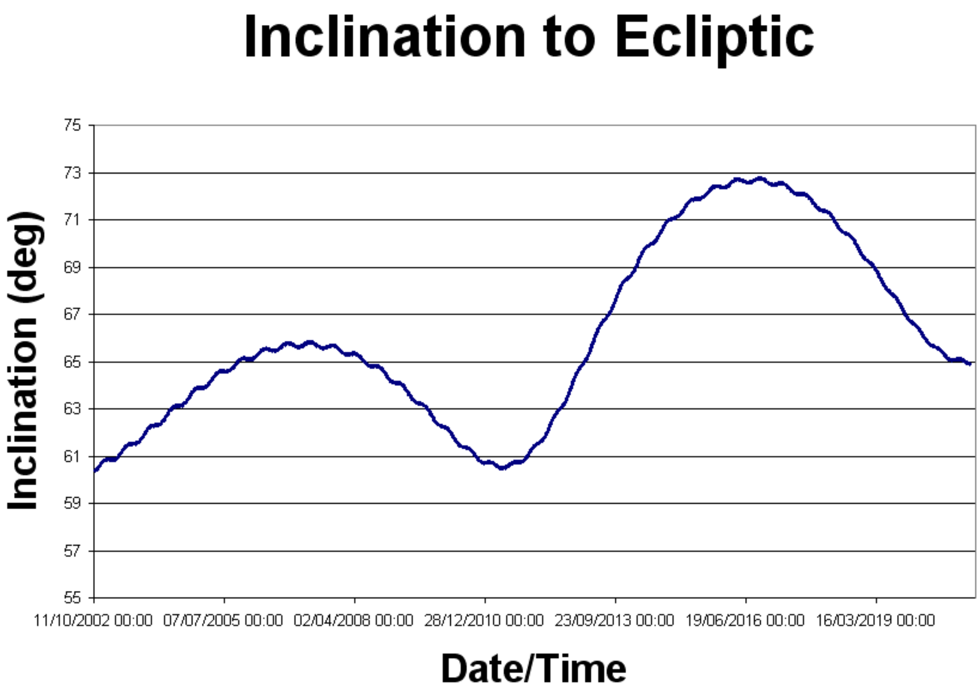

Figure 12: Inclination to Ecliptic

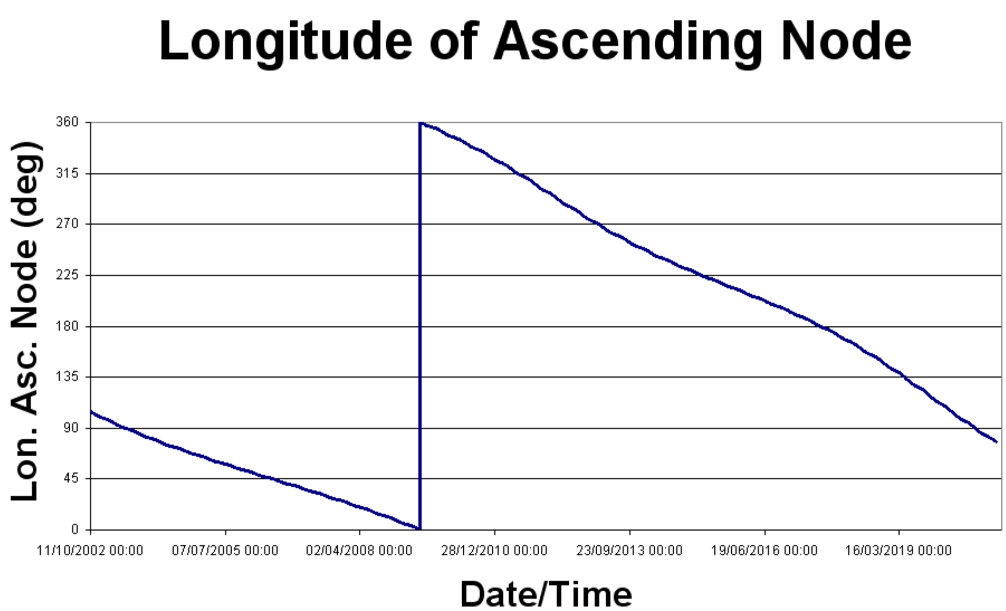

Figure 13: Ascending Node

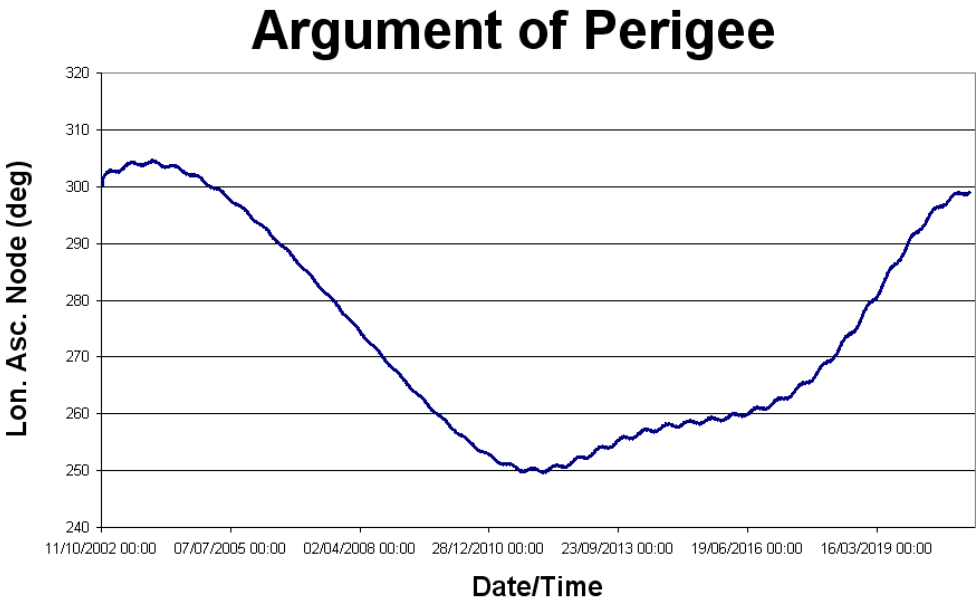

Figure 14: Argument of Perigee

1.4 Time interval between eclipse seasons

The phase of the eclipse entry wrt to the time of year and consequently of the radiation belt crossing altitudes is mainly dependent on the longitude of ascending node, which is shown in the figure 12. If the orbital plane was inertially fixed, the period between eclipse season cycles would be almost exactly 122 revolutions. However, due to the precession of this node eclipse seasons advance forward year on year. The following table shows the revolution with the maximum eclipse duration each season together with the number of revolution since the previous maximum. Note that recently, the rotation of the line of nodes has accelerated. This was caused by the reduction in perigee altitude (figure 9), which increases the effect of the Earth's oblateness. In future years, when the perigee altitude starts to increase, it is expected that the rotation of the line of nodes will slow down once more. (Revolutions shown in italics are predictions)

Revolution	Pre-Perigee Eclipse Duration	Post-Perigee Eclipse Duration	Difference ($Rev_n – Rev_{n-1}$)
30		57.67	
87	70.27		
146		58.45	116
203	73.03		116
262		60.68	116
319	72.93		116

Revolution	Pre-Perigee Eclipse Duration	Post-Perigee Eclipse Duration	Difference (Rev_n–Rev_{n-1})
379		63.8	117
436	70.97		117
496		67.02	117
553	66.87		117
613		68.75	117
670	61.42		117
730		68.32	117
786	56.08		116
846		64.53	116
901	51.4		115
961		57.7	115
1014	50.48		113
1073		48.1	112
1127	50.82		113
1185		44.23	112
1240	57.27		113
1299		45.33	114
1355	62.83		115
1414		*49.55*	*115*
1473	*64.38*		*118*
1530		*54.52*	*116*
1590	*61.7*		*117*
1647		*58.73*	*117*
1706	*56.45*		*116*

Table 1: Revolution/Eclipse Duration

1.5 Variation of Belt Exit Altitude around 'Pre-Perigee' Eclipse Seasons.

The underlying trend of the nature of the belt crossings is heavily dependent on the argument of perigee, (there is also a component coming from the inclination and perigee altitude). The figure 13 shows the variation of this parameter since launch, and into the future. As the argument of perigee strays away from 270 degrees (when the orbit is 'upright' wrt to the earth), the satellite will tend to pass through high radiation pockets , which lie in belts above the equator, at a higher altitude. In the early part of the mission where the argument of perigee was around 300 degrees, this affected the belt entry condition. Now with the value of this parameter around 250 degrees, the belt exit is affected.

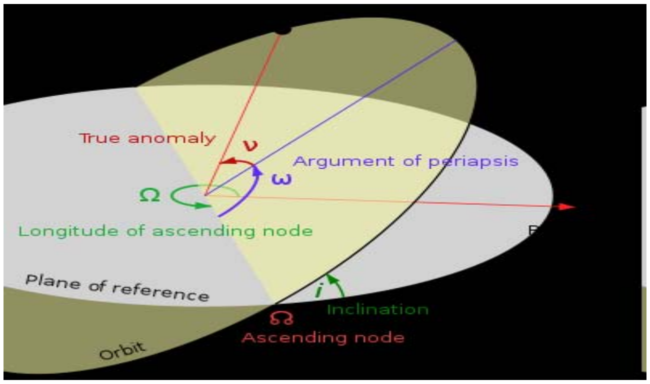

Figure 15: Angular orbital elements (Argument of Periapsis=Argument of Perigee).

1.6 The inclination relative to the ecliptic

As the orbit plane is perturbed, the inclination relative to the ecliptic plane changes considerably (see figure 12). If these planes coincide, or are close to one another, there will be eclipses over an extended period, or even all year round. This would mean the periods of high belt entry and exit could extend for months, depending on how close the planes were aligned. Fortunately, for the next 4 years at least, the geometry is favourable and predicted to improve further.

1.7 The 11 Year Solar Cycle

An effect of the maximum solar activity during the 11 year cycle is sudden flares, which increase solar radiation throughout the orbit. These are random in nature, and impossible to predict for more than a few days in advance. When these flares die down, the observed belt entry/exit altitudes return to more reasonable values. Another effect of solar flares is to reduce the number of galactic cosmic rays. It is anticipated, that the solar cycle will not affect the values to be commanded for the radiation belts entry or exit.

A complete plot of the belt entry/exit altitudes is shown below (as compiled by ISDC).

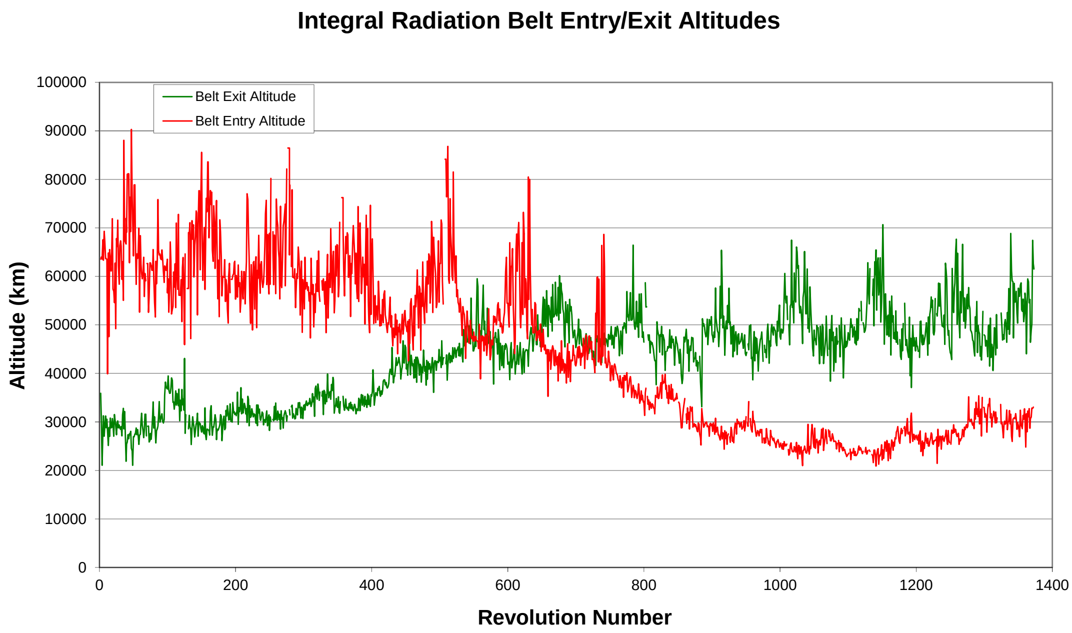

Figure 16: Integral Radiation Belt Entry/Exit Altitudes

This plot might seem to indicate that the belt exit altitude will climb as high as the entry altitude experienced earlier in the mission. This is, however, unlikely in view of the plot showing the variation of the argument of perigee over time. At the start of the mission this angle was between 300 and 305 degrees, i.e. canted 30 to 35 degrees away from the 270 degree point. The predictions for the argument of perigee indicate that it will drop to around 250 degrees before climbing and stabilizing around 260 degrees. This means that the altitude at which the orbit passes through the equatorial plane (i.e. the radiation belts) during the inter-eclipse period will remain stable for the next year or so, before dropping back to levels seen around revolution 900. It is therefore considered unlikely that the trend seen during the inter-eclipse periods of rising radiation belt exit will continue much further.

2 CURRENT DEFINITIONS OF ED PLACEMENTS WITHIN THE EPOS

The following EDs are affected by a change in the radiation belt exit.

GEBEXT01	3 minutes before POST_BELT_CONF_CLOSE
KEACAL01	16 minutes before IBIS_CAL_CLOSE
LEACAL01	15 minutes before IBIS_CAL_CLOSE
EEXIT-03	if POST_ECLIPSE_OPEN is present, then it is placed 5 minutes after the critical altitude ascending.
GEBENT02	Uplinked 10 minutes before POST_BELT_CLOSE time-tagged for 5 minutes after the critical altitude descending.

KESAFE02	if AOS_CHECK_OPEN is present, then it is placed 5 seconds before the critical altitude descending plus 7000km. (This ED is currently disabled, but will be reintroduced as the belt entry altitude evolves)
LESAFE02	if AOS_CHECK_OPEN is present, then it is placed at the critical altitude descending plus 7000km. (This ED is currently disabled, but will be reintroduced as the belt entry altitude evolves)
EENTRY03	if NEXT_ECLIPSE_OPEN is present, it is placed 8 minutes before the critical altitude descending.

3 CURRENT DEFINITIONS FOR KEY WORDS

RAD_ENTRY window	Chosen for mission planning purposes for end of instrument
RAD_EXIT	Chosen for mission planning purposes for start of instrument window
POST_BELT_ CONF_CLOSE	The end of the instrument configuration window after radiation belt exit.
IBIS_CAL_CLOSE	The end of the IBIS calibration activity window before the INSTRUMENT window opens

4 NECESSARY CHANGES TO UPDATE RAD-BELT ENTRY/EXIT

<u>For radiation belt exit changes.</u>

Requirements:

- Revolution number at which change to be made.
- Value of the Critical Altitude Ascending in km.

At PSF generation level (Flight dynamics to perform the modifications):

- From the desired revolution onward, the value for the CRIT_INST_ALT_ASC should be changed, and the location of the keywords JEM-X1_START/ JEM-X2_START changed accordingly.

At EPOS generation level (Flight dynamics to perform the modifications):

- The location of the ED EEXIT-03 to be updated.

The locations of GEBEXT01, KEACAL01 & LEACAL01 are linked to altitude related events in the PSF, and do not require modification.

- The parameter RAD_EXIT within the ED GEBPG100, must be updated to correspond to the new value for the radiation belt exit altitude, starting in the previous revolution.

<u>For radiation belt entry changes.</u>

Requirements:

- Revolution number at which change to be made.
- Value of the Critical Altitude Descending in km.

At PSF generation level (Flight dynamics to perform the modifications):

- From the desired revolution onward, the value for the CRIT_INST_ALT_DESC should be changed, and the location of the keywords JEM-X1_STOP/ JEM-X2_STOP changed accordingly.

At EPOS generation level (Flight dynamics to perform the modifications):
The locations of GEBENT02, KESAFE02, LESAFE02 are linked to altitude related events in the PSF, and do not require modification.

- The location of the ED EENTRY03 to be updated.
- The parameter RAD_ENTRY within the ED GEBPG100, must be updated to correspond to the new value for the radiation belt entry altitude.

Submit a CCR & OCR, and get approval for both before getting the PSF changed.

5 HISTORY OF THE RADIATION BELT ENTRY & EXIT ALTITUDES.

Radiation Belt Entry Altitude is defined by the broadcast packet.

Revolution Number (from)	Date	Entry Altitude (km)	Exit Altitude (km)
Launch	17/10/2002	60000	40000
464	01/08/2006	56000	45000
555	30/04/2007		53000
769	29/01/2009	48000	
777	22/02/2009	43000	
788	27/03/2009		57000
825	15/07/2009		50000
835	14/08/2009	54000	
868	24/11/2009	40000	
901	03/03/2010	35000	

Revolution Number (from)	Date	Entry Altitude (km)	Exit Altitude (km)
907	18/03/2010		53000
924	08/05/2010		50000
941	06/06/2010	45000	
970	25/09/2010	38000	
1010	20/01/2011		53000
1014	01/02/2011		56000
1057	10/06/2011		53000
1084	29/08/2011		50000
1107	06/11/2011		56000
1163	22/04/2012		53000
1193	20/07/2012		50000
1226	27/10/2012		53000
1233	17/11/2012		56000
1278	01/04/2013		50000
1289	03/05/2013		56000
1305	20/06/2013		50000
1316	26/07/2013	K/LESAFE02 removed	
1342	09/10/2013		56000
1378	25/01/2014		57400
1393	10/03/2014		50000
1400	31/03/2014	K/LESAFE02 re-instated	

Table 2: History of radiation belt entry/exit altitudes as defined by the on-board broadcast packet.

Radiation observations around the belt entry/exit of revolution 1342 were masked by a solar flare during the preceding revolution, however, there were no reports of instruments being affected by high radiation either before or after the change.

6 CONCLUSIONS

It is recommended to lower the CRIT_INST_ALT_ASC from revolution 1393 onwards from 57400km to 53000km. This will mean a gain of about 30 minutes science time for all instruments.

Also re-insert the KESAFE02 & LESAFE02 EDs from revolution 1400 onward at CRIT_INST_ALT_DESC + 7000km – 5 seconds and CRIT_INST_ALT_DESC + 7000km respectively. This will mean a loss of about 40 minutes science time for JEM-X.