MEMO

Date 30/04/2020 **Ref**

From Arnaud Boutonnet, Gabor Varga **Visa**

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Subject: JUICE: Definition of the GCO with Cycles

1 CONTEXT

For years, the GCO was defined by a mean s.m.a., which roughly corresponded to an altitude of 500 km. Depending on the CReMA version, differences in inclination (prograde/retrograde or even small variation within the same class) leads to slightly different effect of Ganymede J_2 and Jupiter gravity pull. The different secular drift of the RAAN leads itself to different groundtrack patterns. When there is an overlap of the groundtracks, it is detrimental to science objectives in terms of coverage.

Consequently it has been decided to introduce the concept of repetitive groundtrack within a cycle. It is a common feature of Earth observation missions.

2 REPETITIVE GROUNDTRACK THEORY

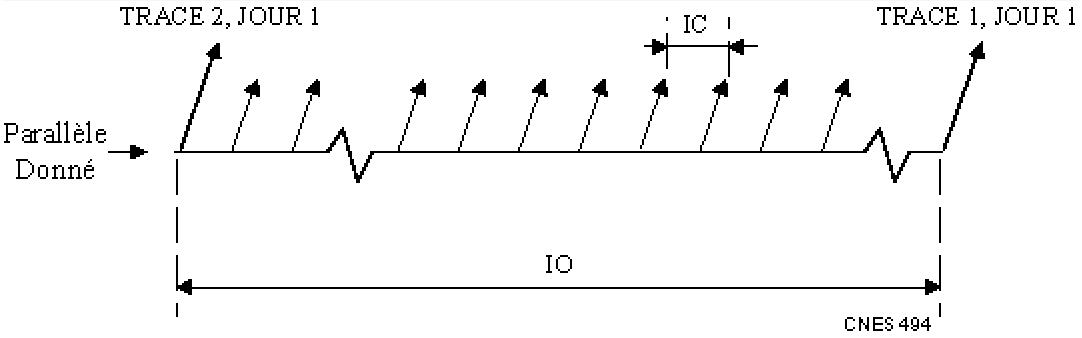
The concept is described in standard textbooks, e.g. CNES Spaceflight Dynamics. A cycle is defined by a triplet of integers (N,P,Q).
The Q parameter is equal to the cycle duration, in days. When applied to Ganymede, it corresponds to Q Ganymede sidereal days, i.e. Q x~7.1 day. The duration of the GCO is 130 days, therefore the longest cycle will be either 18 G-days (128.8 (Earth) days) or 19 G-days (134.9 days). It could also be interested to have shorter cycles that are repeated several times, like 3 identical cycles of 6 G-days (to observe time-varying parameters).
The N parameter is the closest number of ascending equator crossings per day. From one equator passage to the next, the body rotates as shown below for the Earth.

CNES Spaceflight Dynamcis

Assuming Ganymede and an altitude of 500 km, it corresponds to an orbital period of 185 min or ~3h. In one G-day it corresponds to 55.4 revolutions. Hence N=55. Assuming Keplerian dynamics, the equatorial distance between two consecutive equator ascending crossings is 6.5 deg to the West, or 299 km. This distance is the orbital intertrack (IO).

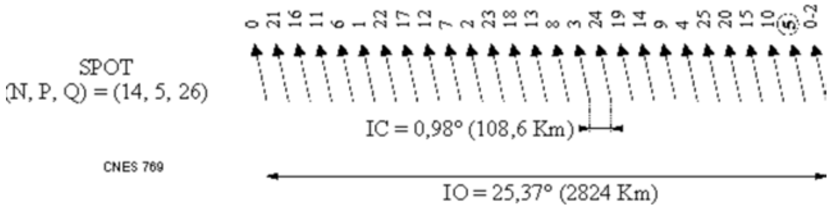
To be more accurate in the dynamics modelling, the orbital plane is not fixed and the RAAN changes due to orbital perturbations. For Ganymede it is mainly the moon oblateness (J_2) and third body gravity (Jupiter). This affects at second order the value of IO.

After one day, the groundtrack can overlap the initial point. In this case: Q=1. Usually longer cycles are sought. Hence the groundtrack will intersect the equator somewhere between the initial point and the first crossing to the west of the first day as shown below.



CNES Spaceflight Dynamcis

Every day of the cycle there will be a new crossing until the cycle is over after Q days. Therefore there will be Q intervals within IO. The size of an interval, or cycle intertrack, is denoted IC and is defined by IC=2*π/M, where M is the total number of revolutions during the cycle. An example for a full grid is given below for the Earth observation mission Spot.



CNES Spaceflight Dynamcis

The position of the groundtrack on day #2 defines the last parameter P. For the example of Spot, the groundtrack on day #2 (labeled '1') is the fifth, hence P=5. The parameter P can be negative: if the groundtrack on day #2 is on the western side of IO, P>0; if the groundtrack on day #2 is on the eastern side of IO, P<0.

By definition –Q/2<P<Q/2. One also has M=N*Q+P. If follows that there is a finite set of options to be analysed once a range of altitude and cycle duration are chosen.

Following the grid given for Spot, an interesting by-product is the sub-cycle, i.e. the time to wait until the groundtrack is the closest from day #1, i.e. exactly at the distance IC of the initial point (or on the other side of IO). The sub-cycle is denoted 's' (it is equal to 5 days for Spot (it is a coincidence that s=P for this case)).

3 APPLICATION TO THE GCO

In order to let the SWT choose their favorite options, it has been agreed to compute all options for a cycle of 19 G-days. hence Q=19. Consequently P can vary between -9 and +9. The range of altitudes considered was from 470 to 570 km. That range of altitude corresponds to a range for N between 54 and 57. In order to calculate the orbital perturbations, the inclination is necessary. The one used is the mean inclination of the baseline at 500 km: 100.3 deg. The following tables list all options.

Option	N	P	Q	Cycle [day]	h [km]	IO [km]	IC [km]	s [day]
1	57	-1	19	136.5	465.7	290.4	15.3	1
2	57	-2	19	136.5	467.6	290.7	15.3	9
3	57	-3	19	136.5	469.5	291.0	15.3	6
4	57	-4	19	136.5	471.4	291.2	15.3	5
5	57	-5	19	136.5	473.4	291.5	15.3	4
6	57	-6	19	136.5	475.3	291.8	15.4	3
7	57	-7	19	136.5	477.2	292.1	15.4	8
8	57	-8	19	136.5	479.1	292.3	15.4	7
9	57	-9	19	136.5	481.1	292.6	15.4	2
10	56	9	19	136.5	483.0	292.9	15.4	2
11	56	8	19	136.5	484.9	293.1	15.4	7
12	56	7	19	136.5	486.9	293.4	15.4	8
13	56	6	19	136.5	488.8	293.7	15.5	3
14	56	5	19	136.5	490.7	294.0	15.5	4
15	56	4	19	136.5	492.7	294.2	15.5	5
16	56	3	19	136.5	494.6	294.5	15.5	6
17	56	2	19	136.5	496.6	294.8	15.5	9
18	56	1	19	136.5	498.6	295.1	15.5	1
19	56	-1	19	136.5	502.5	295.6	15.6	1
20	56	-2	19	136.5	504.4	295.9	15.6	9
21	56	-3	19	136.5	506.4	296.2	15.6	6
22	56	-4	19	136.5	508.4	296.5	15.6	5
23	56	-5	19	136.5	510.4	296.7	15.6	4
24	56	-6	19	136.5	512.3	297.0	15.6	3
25	56	-7	19	136.5	514.3	297.3	15.6	8

Option	N	P	Q	Cycle [day]	h [km]	IO [km]	IC [km]	s [day]
26	56	-8	19	136.5	516.3	297.6	15.7	7
27	56	-9	19	136.5	518.3	297.9	15.7	2
28	55	9	19	136.5	520.3	298.2	15.7	2
29	55	8	19	136.5	522.3	298.4	15.7	7
30	55	7	19	136.5	524.3	298.7	15.7	8
31	55	6	19	136.5	526.3	299.0	15.7	3
32	55	5	19	136.5	528.3	299.3	15.8	4
33	55	4	19	136.5	530.3	299.6	15.8	5
34	55	3	19	136.5	532.3	299.9	15.8	6
35	55	2	19	136.5	534.3	300.1	15.8	9
36	55	1	19	136.5	536.3	300.4	15.8	1
37	55	-1	19	136.5	540.4	301.0	15.8	1
38	55	-2	19	136.5	542.4	301.3	15.9	9
39	55	-3	19	136.5	544.4	301.6	15.9	6
40	55	-4	19	136.5	546.5	301.9	15.9	5
41	55	-5	19	136.5	548.5	302.2	15.9	4
42	55	-6	19	136.5	550.5	302.5	15.9	3
43	55	-7	19	136.5	552.6	302.7	15.9	8
44	55	-8	19	136.5	554.6	303.0	15.9	7
45	55	-9	19	136.5	556.7	303.3	16.0	2
46	54	9	19	136.5	558.7	303.6	16.0	2
47	54	8	19	136.5	560.8	303.9	16.0	7
48	54	7	19	136.5	562.8	304.2	16.0	8
49	54	6	19	136.5	564.9	304.5	16.0	3
50	54	5	19	136.5	567.0	304.8	16.0	4
51	54	4	19	136.5	569.0	305.1	16.1	5

The selection of one or several options is then up to the SWT. The selection is based on pure scientific return. From a missions analysis point of view, the only difference is the target altitude, hence the DeltaV to reach it.

In a separate document[1], the final selection was given:

- Option #14 (N=56 P=5 Q=19)
- Option #23 (N=56 P=-5 Q=19)
- Option[2] #50 (N=54 P=5 Q=19)

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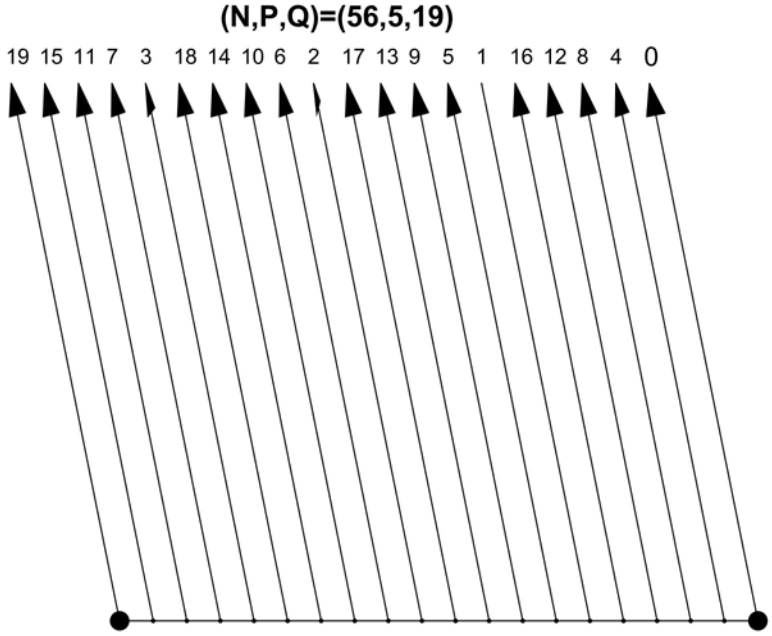
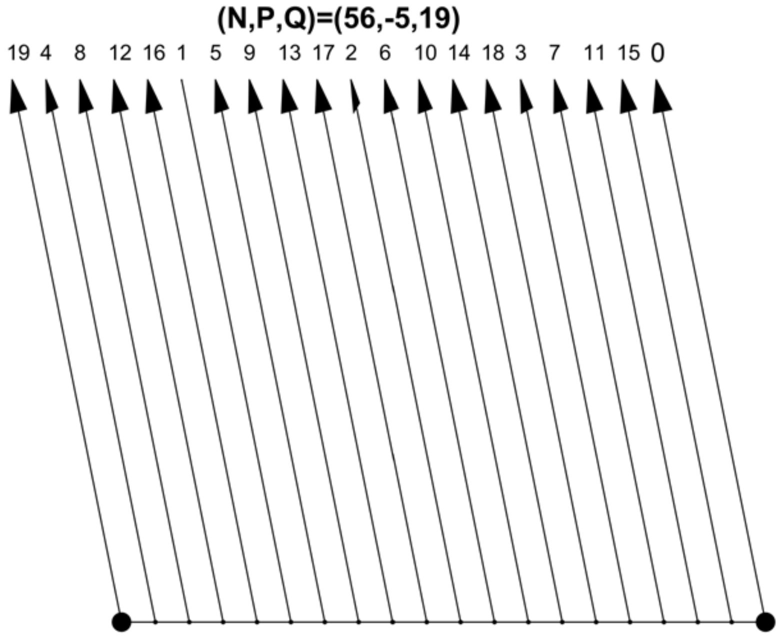
[1] JUICE Science Working Team recommendation, SWT#15, March 2020

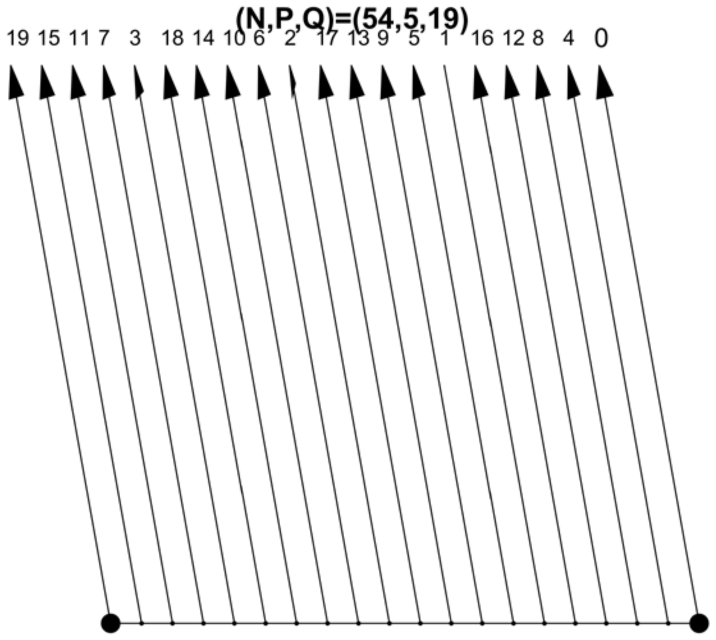
[2] In the input document, this option is labelled #36. The reason is that the original table used by the SWT had only 35 entries. This additional option was added by the SWT as #36. The full exhaustive scan leads to #50 instead

Options #14 and #23 are close to the reference altitude: 490.7 km and 510.4 km. The option #50 is higher: 567.0 km. The three options have a sub-cycle s=4 days, which is considered scientifically optimal. The options #14 and #23 being low in terms of altitude, they also lead to a smaller IC (15.5 km and 15.6 km) than the higher option #50 (16.0 km), which is more constraining for instrument swath.

The cycle grids are given for the three options below. The sub-cycle s=4 is clearly visible for each grid: to the West of the first groundtrack on day #1 for the options #14 and #50, to the East of the second groundtrack on day #1 for the option #23.




(N,P,Q)=(56,-5,19)
19 4 8 12 16 1 5 9 13 17 2 6 10 14 18 3 7 11 15 0


(N,P,Q)=(54,5,19)
19 15 11 7 3 18 14 10 6 2 17 13 9 5 1 16 12 8 4 0

4 VALIDATION WITH THE HIGH FIDELITY S/W

In order 1. to validate these results and 2. to provide the SWT with oem files, an optimization was conducted with the in-house high fidelity S/W.

The Ganymede's North pole time evolution is that of the Report of the IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites (Seidelmann 2009).

The optimization converges to the grids presented in Chapter 3. Due to the simplified nature of the model used before (central term of the gravity potential + J_2 + third body), all parameters slightly change. In terms of mean altitude, it gives:

- Option #14: the theoretical altitude is 490.7 km. The observed mean altitude is 487.5 km
- Option #23: the theoretical altitude is 510.4 km. The observed mean altitude is 507.2 km
- Option #50: the theoretical altitude is 567.0 km. The observed mean altitude is 564.0 km

The oem files cover the GCO-500 only, the rest of the trajectory is identical to the baseline (JUICE_CReMA4d1_Baseline_0001.oem). They are named:

- Option #14: JUICE_CReMA4d1_Baseline_0001_GCO_N56_Pp5_Q19.oem
- Option #23: JUICE_CReMA4d1_Baseline_0001_GCO_ N56_Pn5_Q19.oem
- Option #50: JUICE_CReMA4d1_Baseline_0001_GCO_ N54_Pp5_Q19.oem

When doing a careful analysis, it is observed that the grids are not exactly regular: the IC varies from one longitude to the next. Probably due to the presence of the complex Ganymede gravity potential[3] (non-negligible high order sectorial and tesseral terms), the osculating evolution of the orbital elements lead to a non-constant IC as shown in the three figures below.

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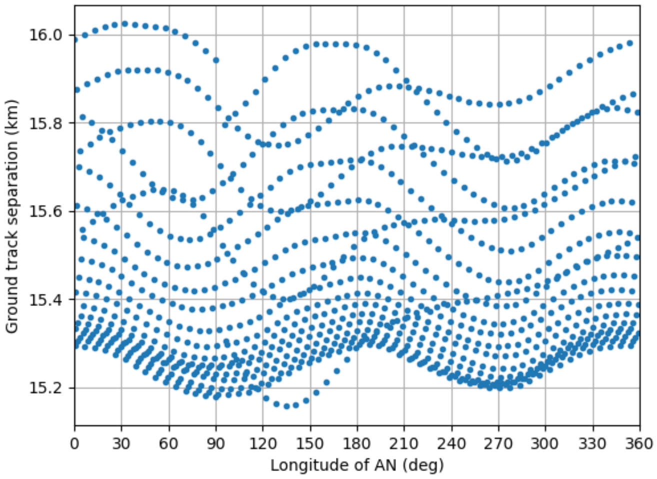
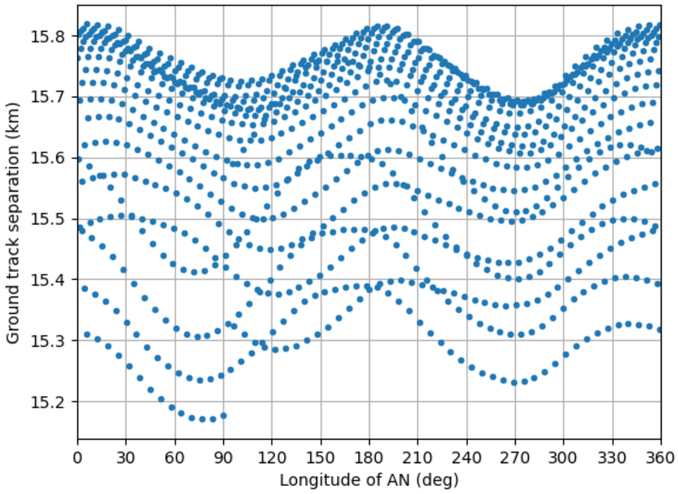
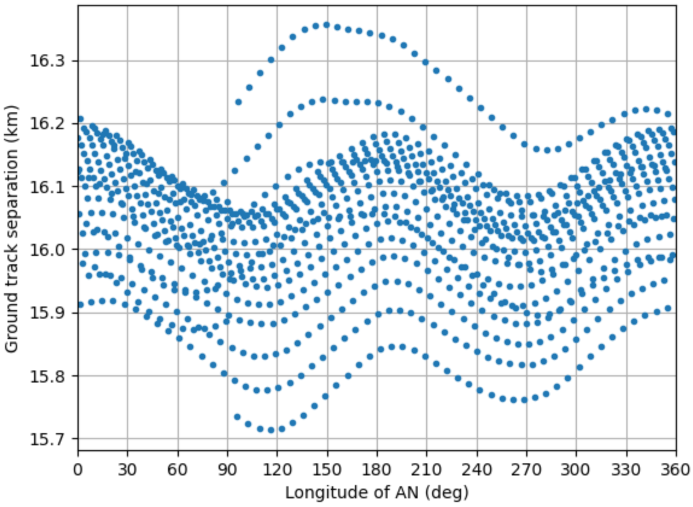
[3] Very strong field taken from "Reference Gravity Fields for Ganymede", Luciano Iess, Stefano Finocchiaro and Marco Ducci, Rome, 3 June 2010



Option #14



Option #23

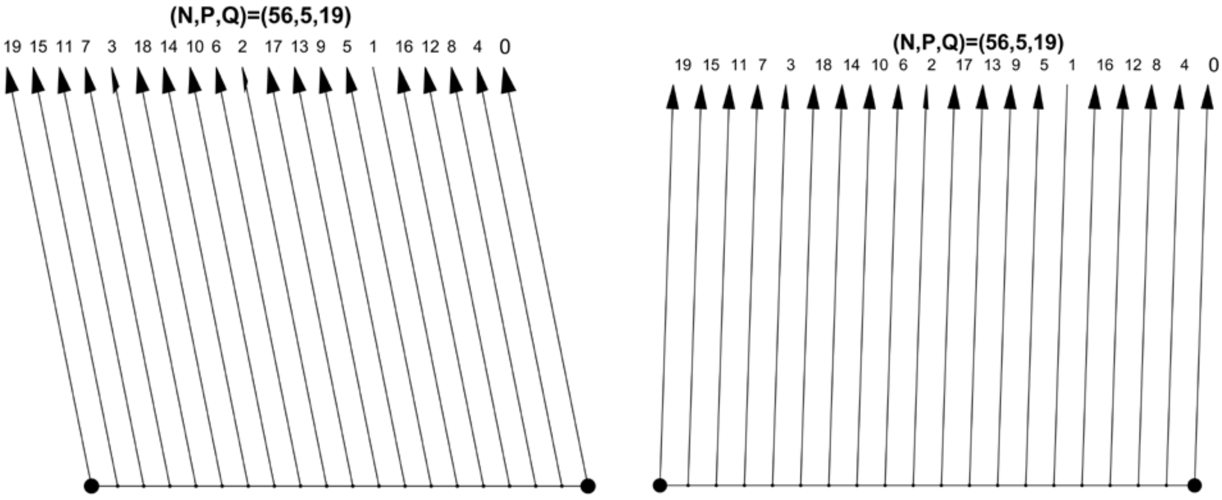


Option #50

In terms of IC, it gives:

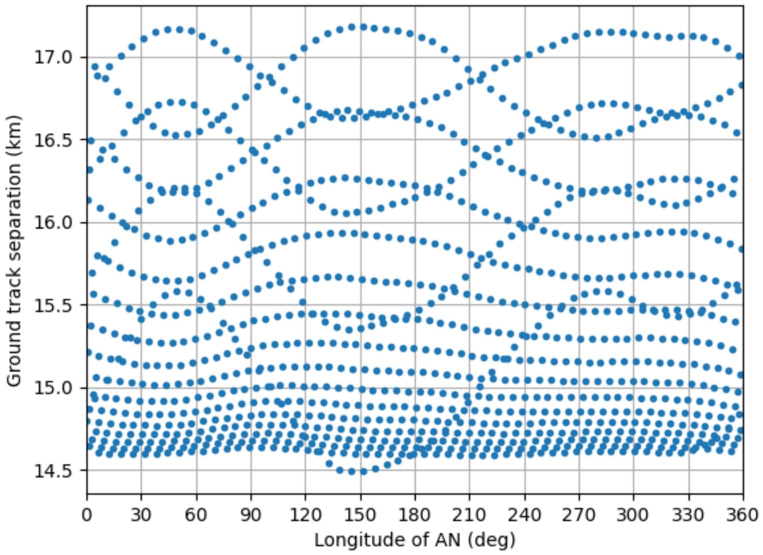
- Option #14: the theoretical IC is 15.5 km. The maximum observed IC is 16.0 km
- Option #23: the theoretical IC is 15.6 km. The maximum observed IC is 15.8 km
- Option #50: the theoretical IC is 16.0 km. The maximum observed IC is 16.4 km

For a given cycle – e.g. (56,5,19) - the altitude is a function of the inclination. For instance, the same analysis run for a mean inclination of 88.5 deg (that of the prograde option of CReMA 3.0) leads to a reduction of the altitude from 490.1 km to 481.3 km.



Cycle (56,5,19) for the retrograde solution (left) and prograde solution (right)

The refined analysis with the high fidelity S/W shows a larger dispersions of IC as shown below. The maximum IC jumps from 16.0 deg (retrograde) to 17.3 deg (prograde).


Ground track separation (km)
17.0
16.5
16.0
15.5
15.0
14.5
0
30
60
90
120
150
180
210
240
270
300
330
360
Longitude of AN (deg)