JUICE: Jupiter Tour for the CReMA 3.1

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Issue/Revision: 1.0
Reference:
Status: N/A

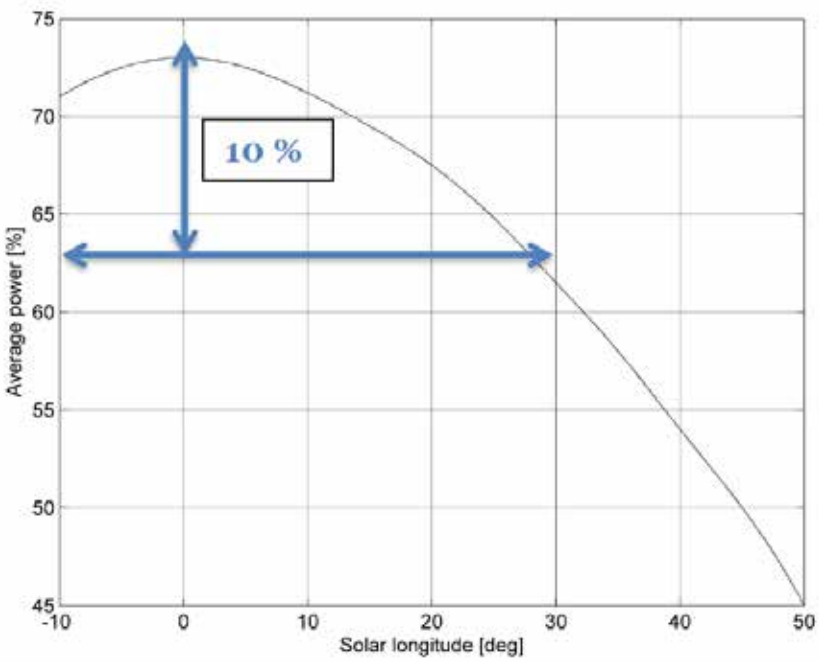
Objective of the Tour Design

- The tour shall match with the interplanetary option 141a
- All constraints as per CReMA 3.0 apply, except the Europa F/B illumination:
  - Degraded S/A illumination during the F/B
  - Long eclipse after E1
- In the CReMA 3.0, the GEO and GCO were prograde. The CReMA 3.1 shall feature two options: one prograde and one retrograde
- In terms of DeltaV (deterministic + stochastic), the objective is to fit in the envelope defined for option 141a in the CReMA 3.0

Target Europa F/B Illumination

- The duration of the eclipse after E1 is a function the solar longitude (if South F/B first): if the solar longitude is less than ~30 deg, there is no eclipse à Upper limit: 30 deg

- During F/B the S/C is in pushbroom mode
- During F/B the SADM are in hold mode
- à For any solar longitude, there is an optimal orientation of the S/A to maximise the average power
- à A 10% reduction w.r.t. the best case (0 deg solar longitude) leads to 30 deg
- à A 5% reduction leads to ~15 deg



- 1. The interval is now [-10 30] deg
- 2. Finding cases around 10 deg is better than 30 deg

From JOI to Europa Science

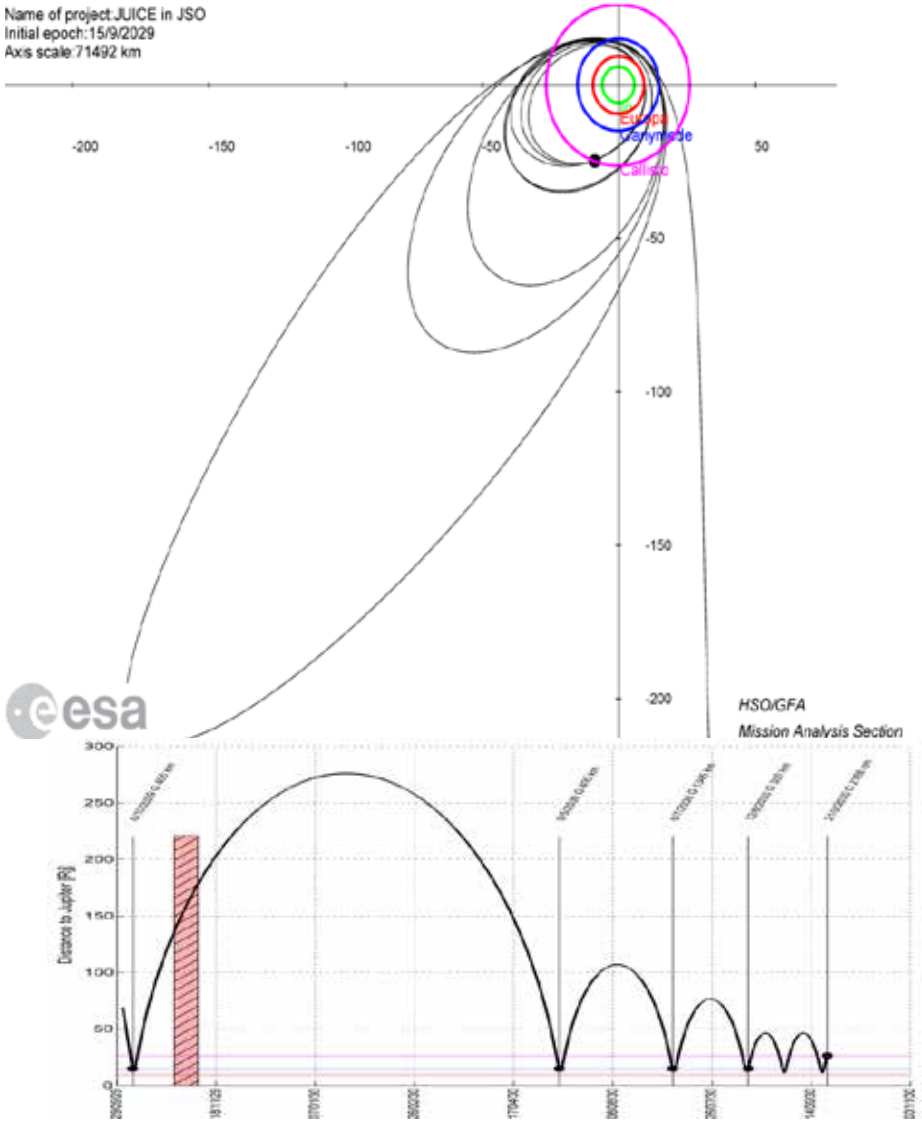
- In a memo issued in April 2016, 5 options have been presented

Option	Ls(E1) [deg]	Ls(E2) [deg]	ΔV det. [m/s]	ΔV stoch. [m/s]	ΣΔV [m/s]	Radiation [krad]	South flyby	North flyby
1a	14	18	+4	+8	+12	+14	OK	close to the edge
1b	21	24	+4	+8	+12	+9	OK	close to the edge
1c	23	26	-21	+0	-21	7	OK	centered
2	13	17	+18	+0	+18	+6	OK	no intersection
3	31	35	+6	+8	+14	+25	OK	centered

- Two options were favoured in terms of illumination: 1a and 2
- Option 2 was favoured thanks to lower radiation dose, but we are 18 m/s behind CReMA 3.0 at the end of the Europa phase

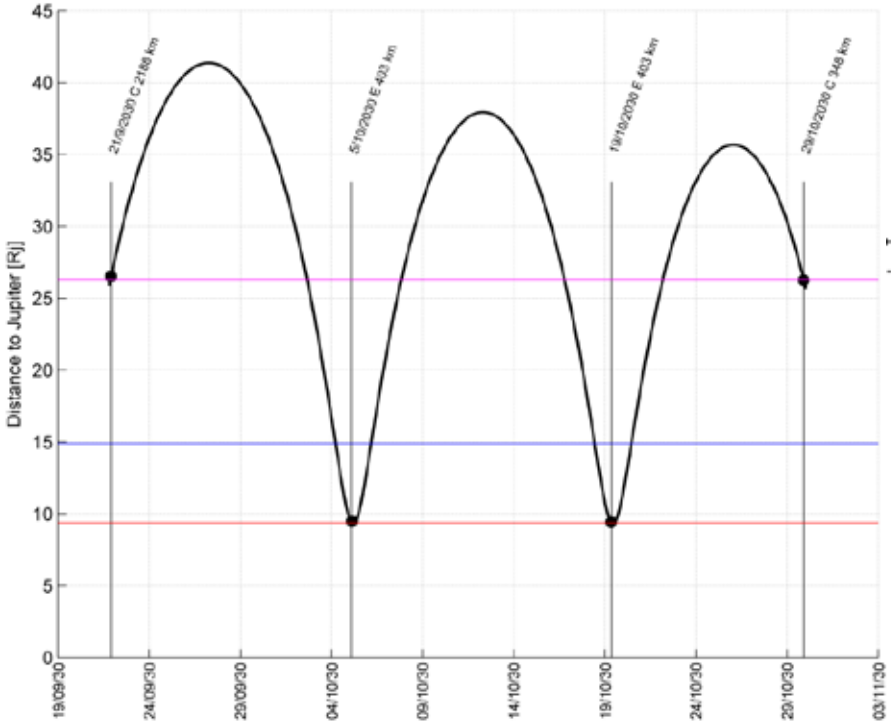
Part I: JOI and Energy Reduction Phase

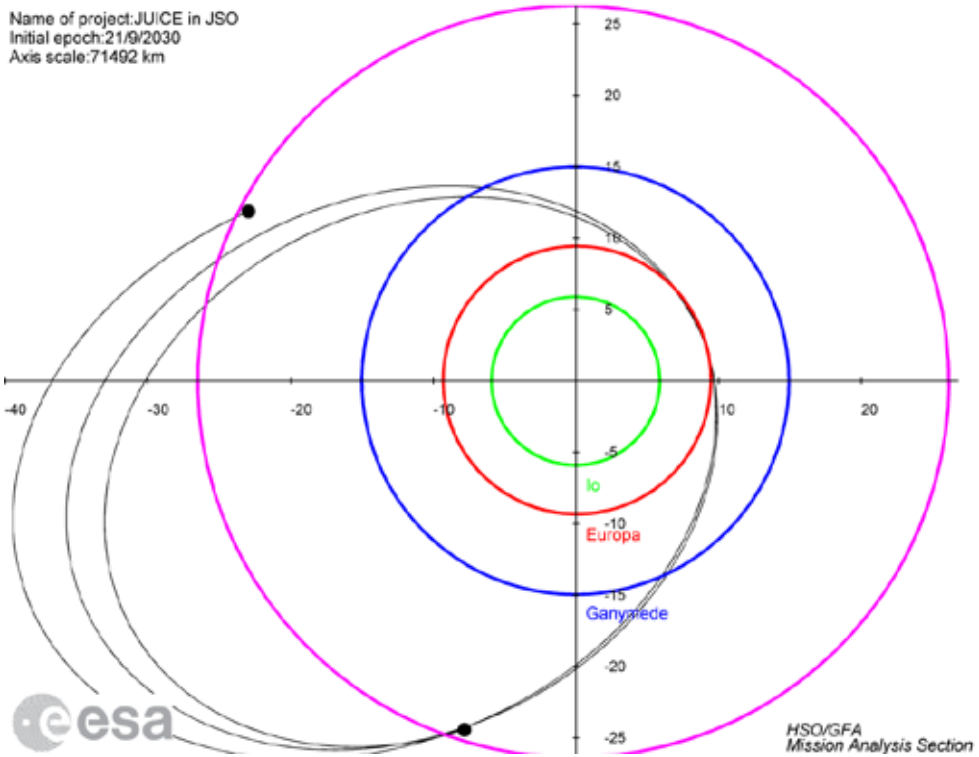
- Sequence used with Ganymede: 30:1 (JOI of 789 m/s), 8:1, 5:1^{+} (no need for the 3:1)
- Infinite velocity reduction @Ganymede: from 7.1 km/s @1G1 to 5.8 km/s @2G2 via the PRM (107 m/s)
- The Vinf at Callisto is rather high (5.4 km/s), thus leading to a low return velocity (4.7 km/s), which is an asset
- First superior conjunction (2029) is avoided during the 30:1



Part II: Europa Phase

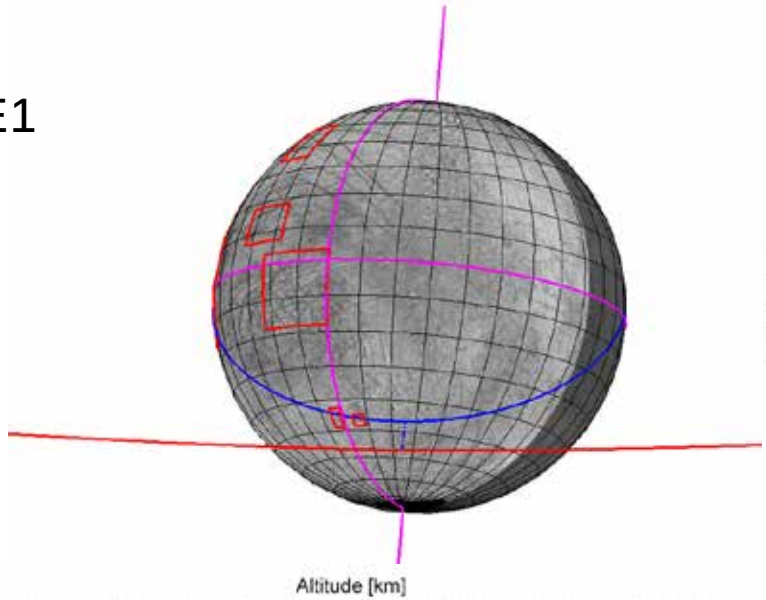
- EGA1: vinf = 3.9 km/s, Ls = 15 deg (Pro.) 13 deg (Retro.)
- DSM: 29 m/s during the 4:1
- EGA2: vinf =3.7 km/s, Ls = 18 deg (Pro.) 15 deg (Retro.)

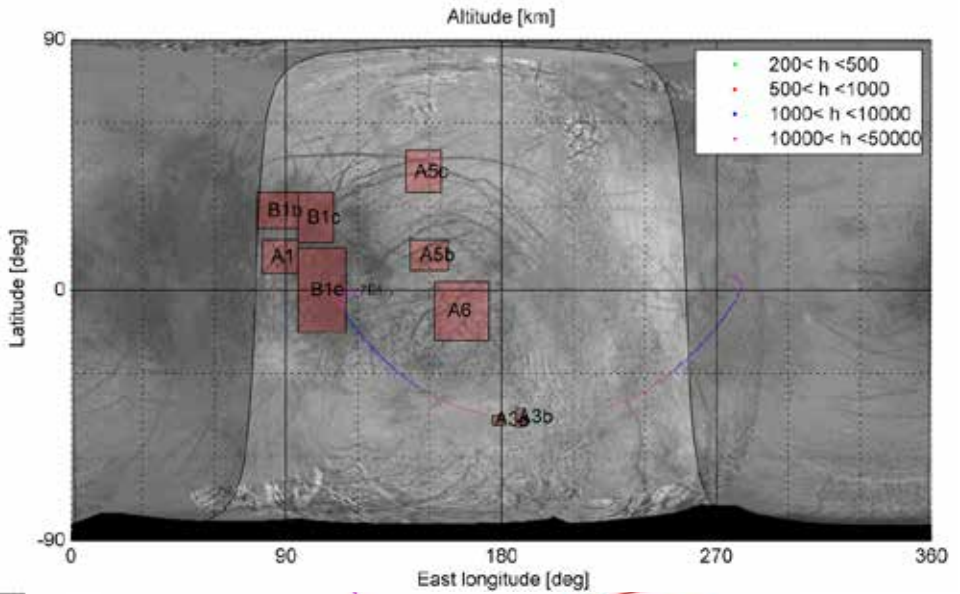


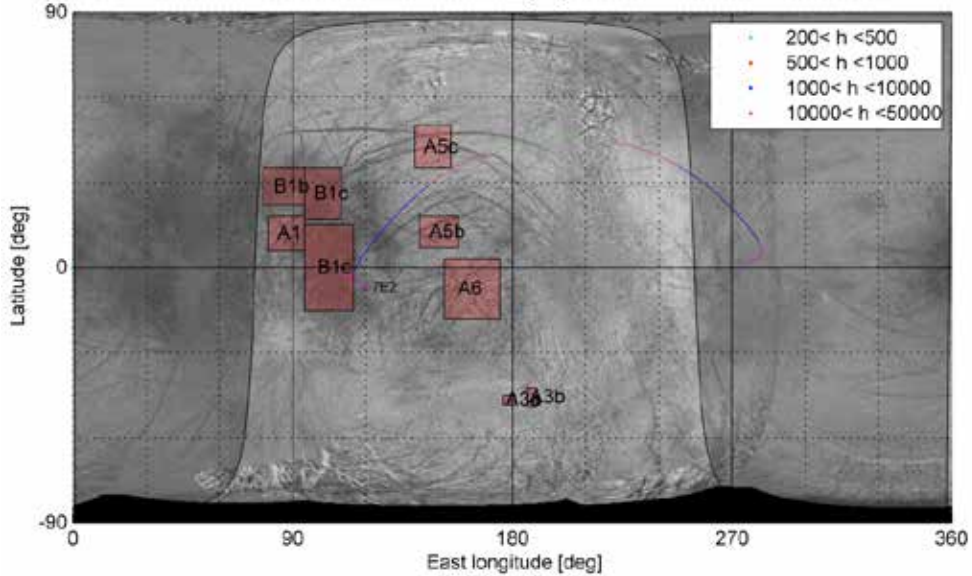


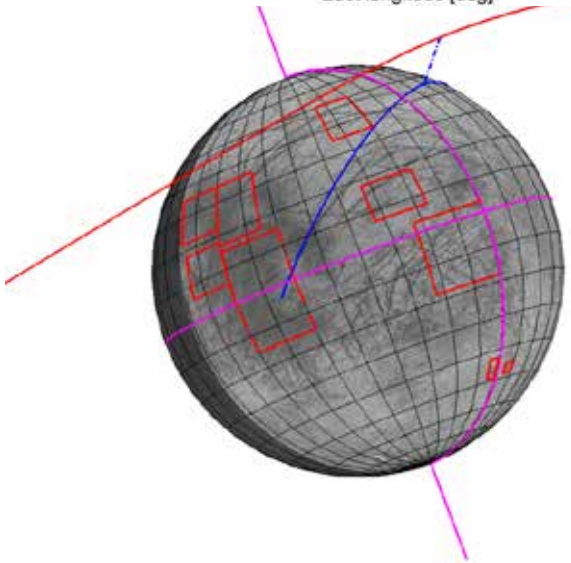
Part II: Europa Phase

6E1





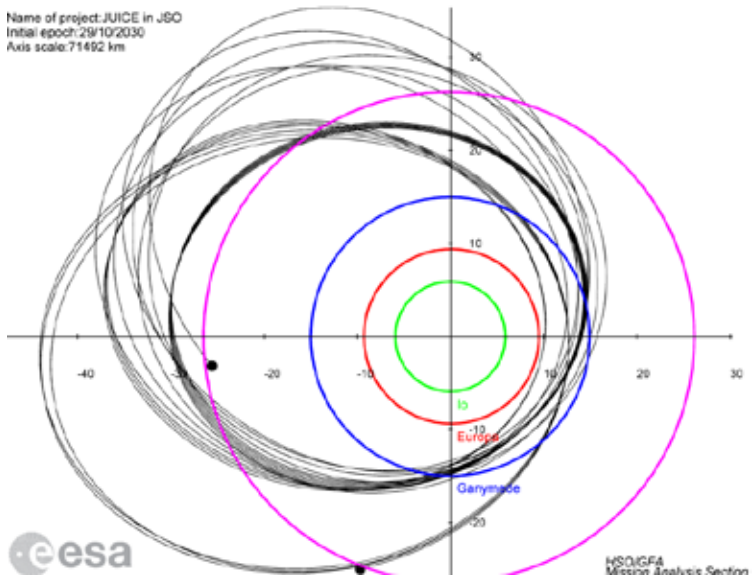




7E2

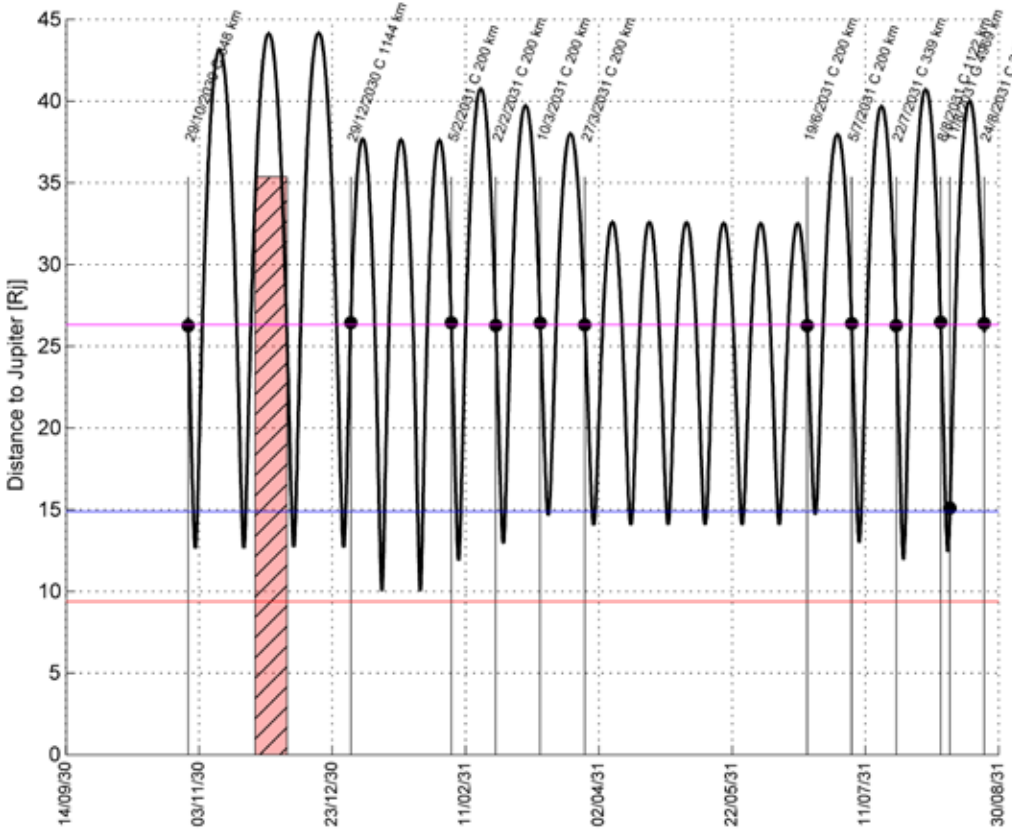
Part III: Jupiter High Latitudes Phase

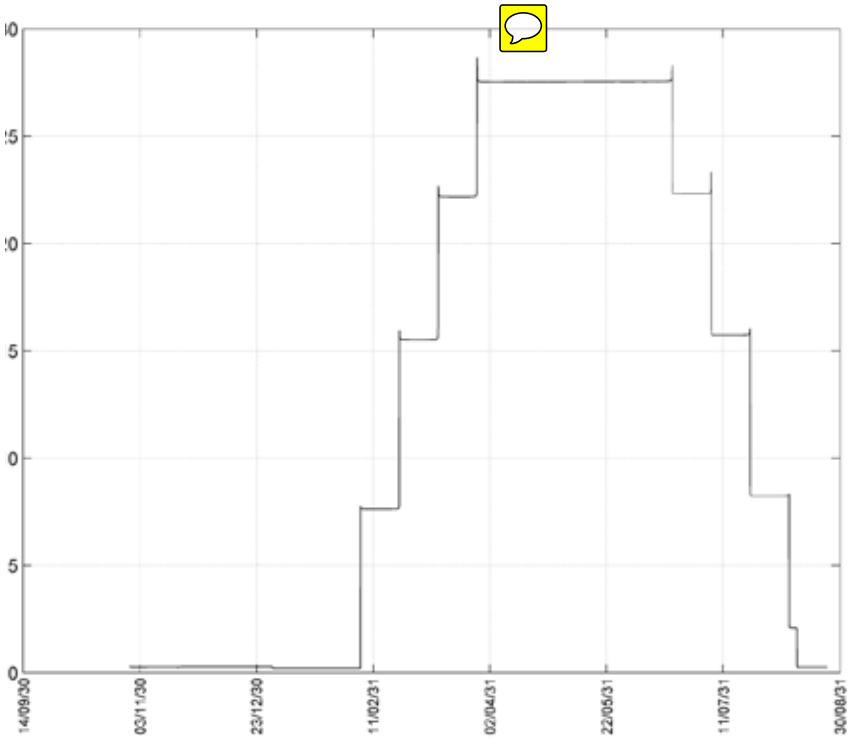
- The superior solar conjunction has to be avoided close to the beginning: the 2:2 $^{+}$ of CReMA 3.0 cannot be reached in terms of flyby altitude. Instead a 3:3^{+} was used (hp = 348 km)
- Then Ganymede plays a very detrimental role if the standard sequence is applied: once in the ascending part, one in the descending
- The best strategy found was to introduce a 2:2^{-} before crank up
- Then follows a sequence of 4 CGA: 3 x 1:1 + 5:6 to reach a maximum inclination of 28 deg
- After 83 days in the 5:6, the orbit is cranked down via 3 x 1:1



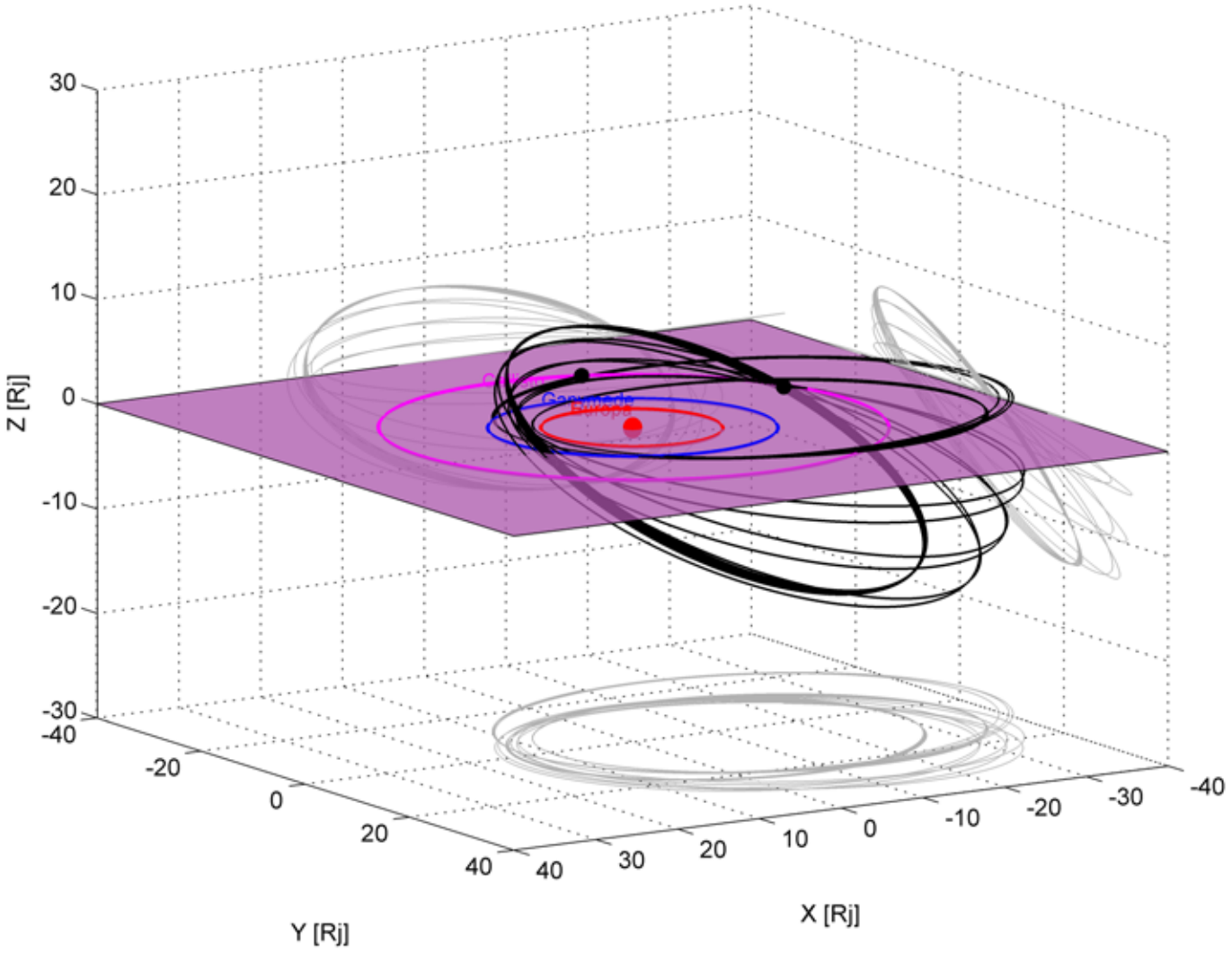
- On the way down, there is a untargeted GGA 3 days after a CGA:
  - This is a violation of the MRD requirement (min. 8 days)
  - The fly-by is not tight (9000 km for the prograde, 5000 km for the retrograde). Parametric analyses are on-going to assess the DeltaV penalty to impose a minimum altitude of e.g. 10000 km or 20000 km for both cases
  - The navigation allocation DeltaV for the next CGA was doubled to cover dispersions
- The duration of this phase excluding the solar superior conjunction is 200 days

Part III: Jupiter High Latitudes Phase





Part III: Jupiter High Latitudes Phase



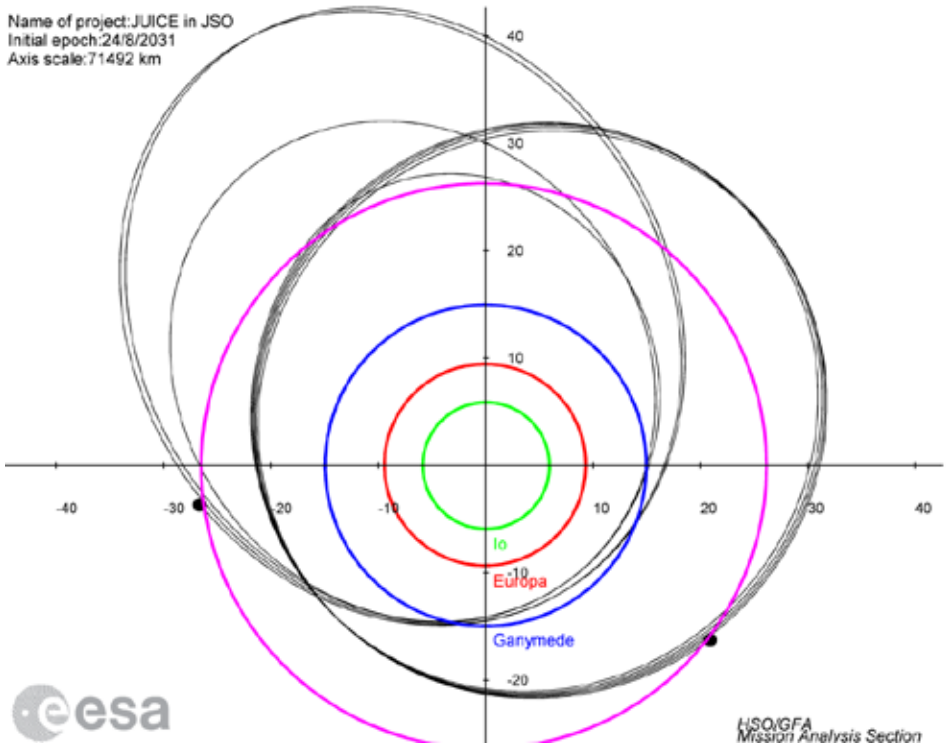
Prograde and Retrograde Options

- Until this point, the prograde and the retrograde options were similar
- At 17C11 both tours noticeably diverge because a different signed beta angle is aimed at GOI:
  - From -30 to -20 deg for the prograde case (as in CReMA 3.0)
  - From 20 to 30 deg for the retrograde case
- For part IVa (Callisto-Ganymede ladder) the initial sequence is the same: CGGC. The parameters, which are different are:
  - Number of moon and spacecraft revolutions in the CG, then GC legs
  - Type of encounter: inbound or outbound
  - Type of resonant transfer (full or pseudo) in the intermediate 2:1 GG
  - Number and type of Callisto resonant transfer at the end to rotate the line of apsides and avoid the superior solar conjunction. It is also chosen to offer a high entry gate into the low energy endgame
- For part IVb (low energy endgame) the number of resonant legs are different, but also the resonance ratios:
  - To target the beta angle
  - To maximize the beneficial effect of Callisto conjunctions to freely raise the perijove

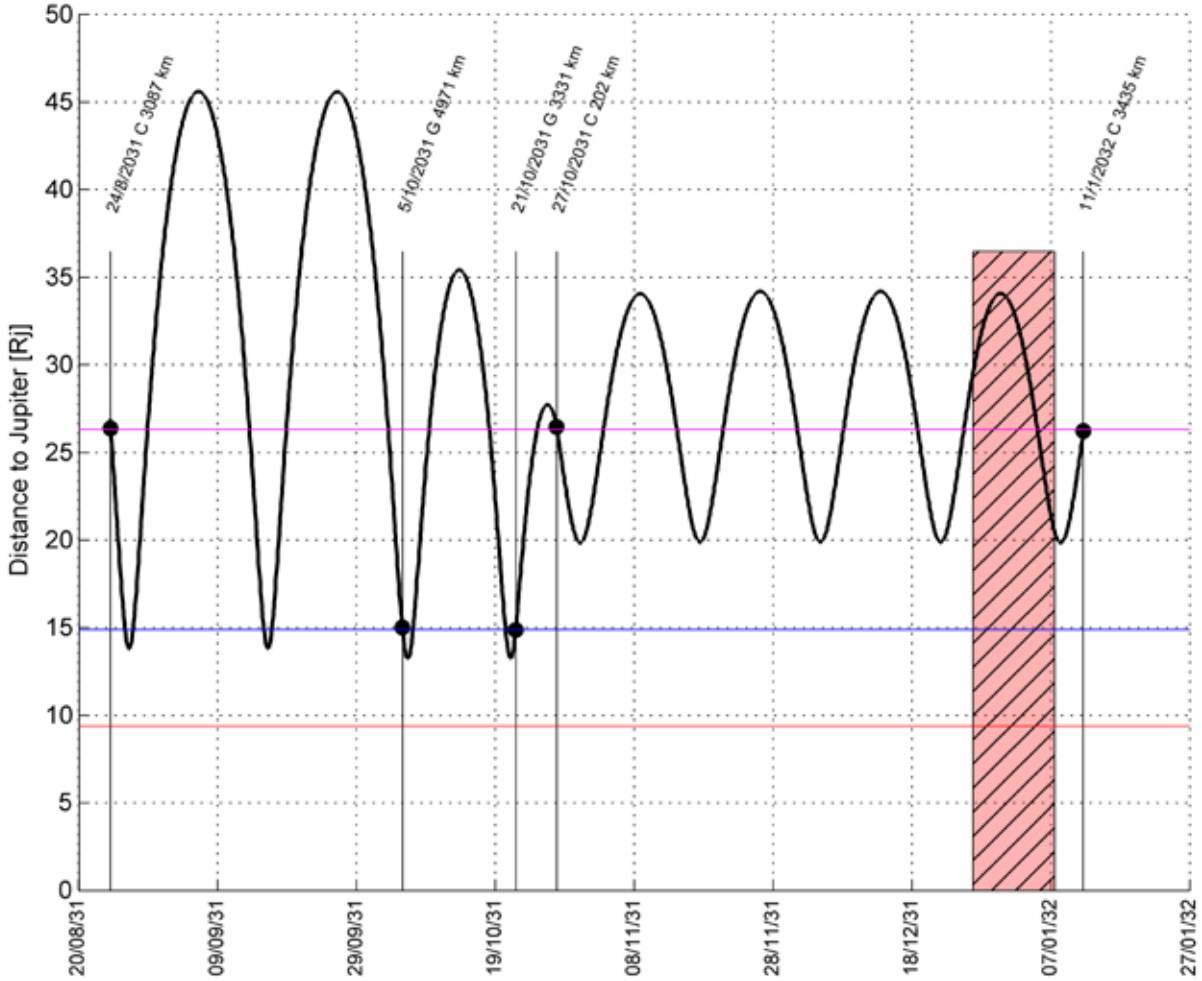
PROGRADE OPTION

Part IVa: Callisto-Ganymede Ladder

- The CG leg is performed in 2.25 revs for an inbound encounter with Ganymede at 3.8 km/s
- Then a GG 2:1^{+} is used
- The GC leg is performed in 0.55 revs for an inbound encounter with Callisto (transfer time is 6 days) at 2.12 km/s
- à This is a violation of the MRD (min. 8 days)
- à A solution was found with more than 6 days, but it cost 20 m/s more
- A single CC 4:4^{+} is used to avoid the solar superior conjunction and to be in the sweet spot to initiate the low energy endgame (number of perijove passage from Callisto to Ganymede and entry height)

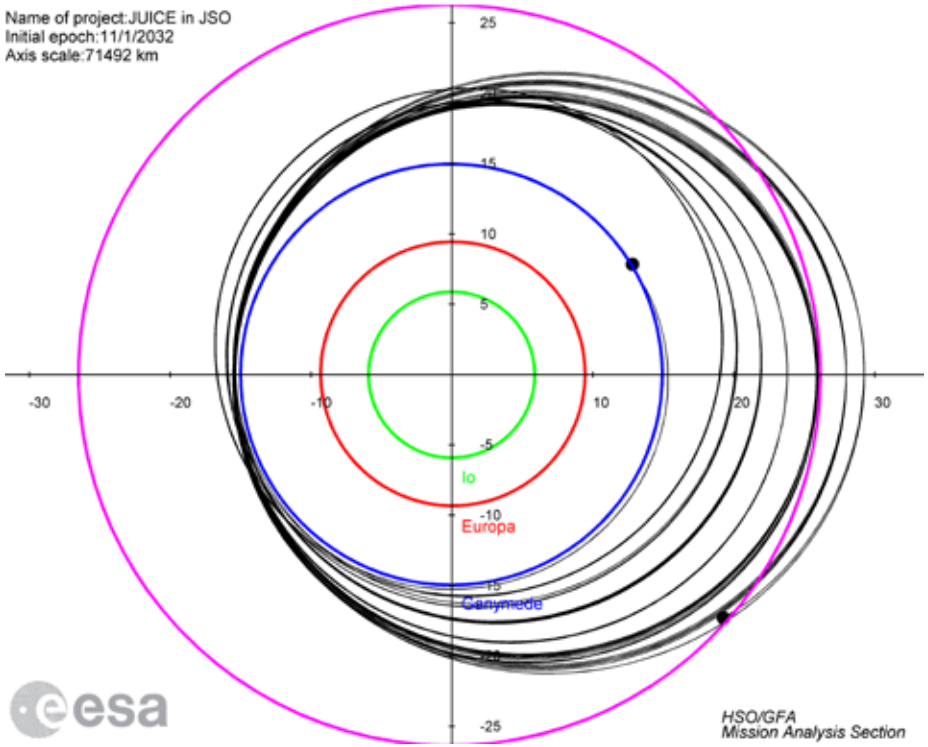


Part IVa: Callisto-Ganymede Ladder

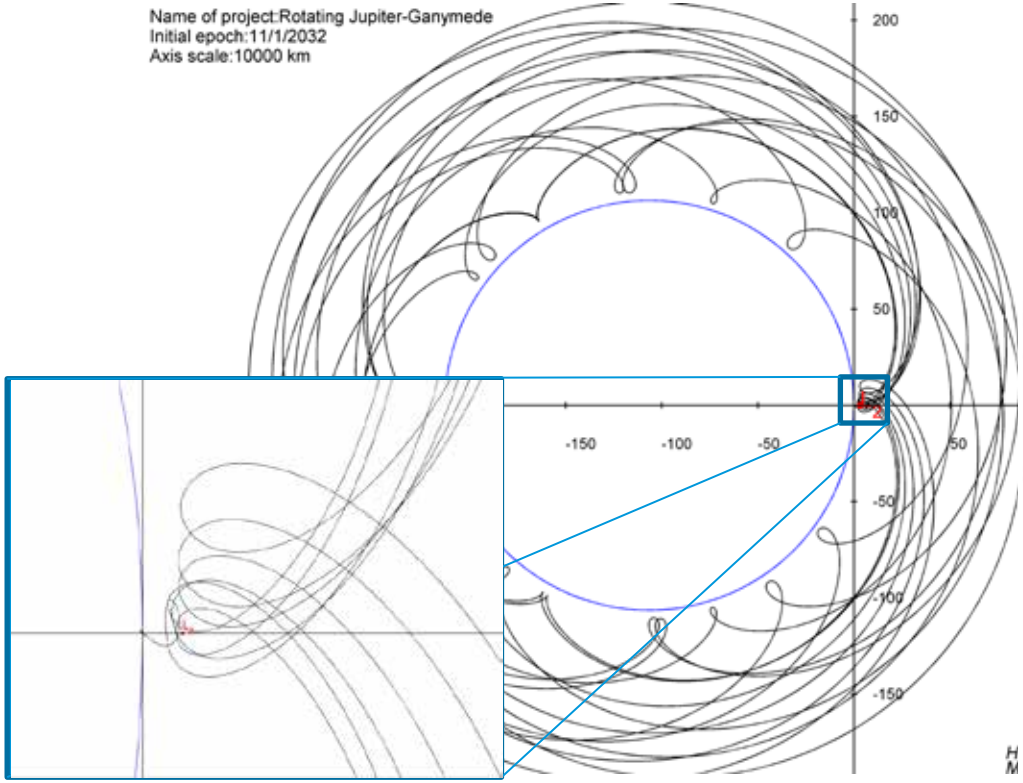


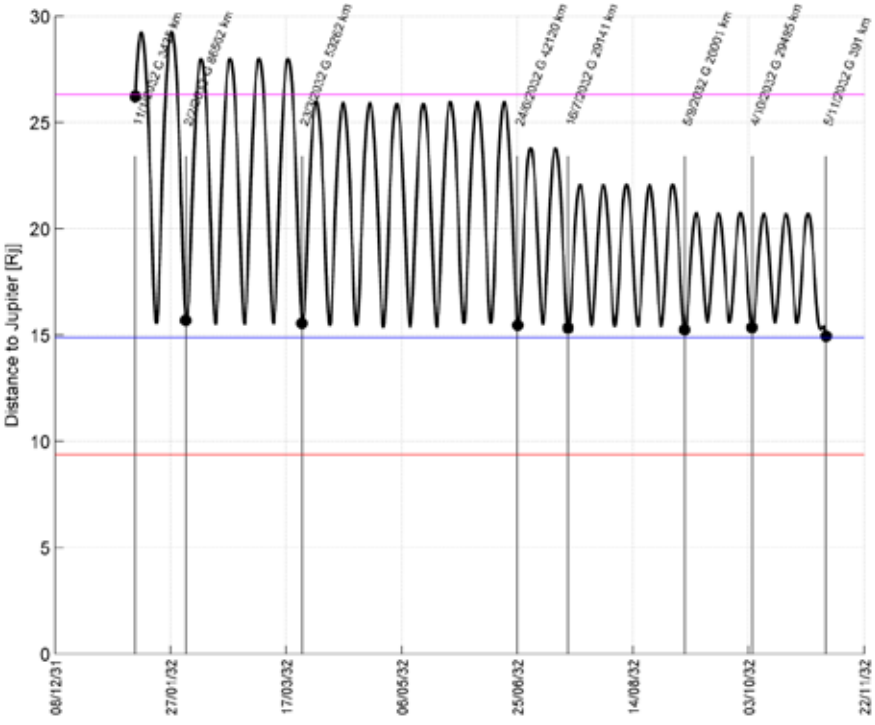
Part IVb: Low Energy Endgame

- The first Ganymede encounter (24G8) is performed at the 2nd perijove passage after 23C14
- The entry gate is high: perijove 47000 km above Ganymede orbital radius
- The C/A is extremely far (87000 km) and thus justifies no stochastic DeltaV allocation
- The sequence is 7:4, 13:8, 3:2, 7:5, 4:3, 4:3 (the additional 4:3 is used to rotate the line of apsides by 24 deg)
- This sequence benefits from a positive conjunction with Callisto, which raises the perijove by 8000 km
- Two DSM summing to 43 m/s are used: one in the 13:8 (8 m/s) and one in the second 4:3 (35 m/s) to be (optimally) close to the L2 libration point energy level (+15000 km in perijove radius)
- GOI of 135 m/s on 05/11/2032
- Beta angle @GOI: -20 deg

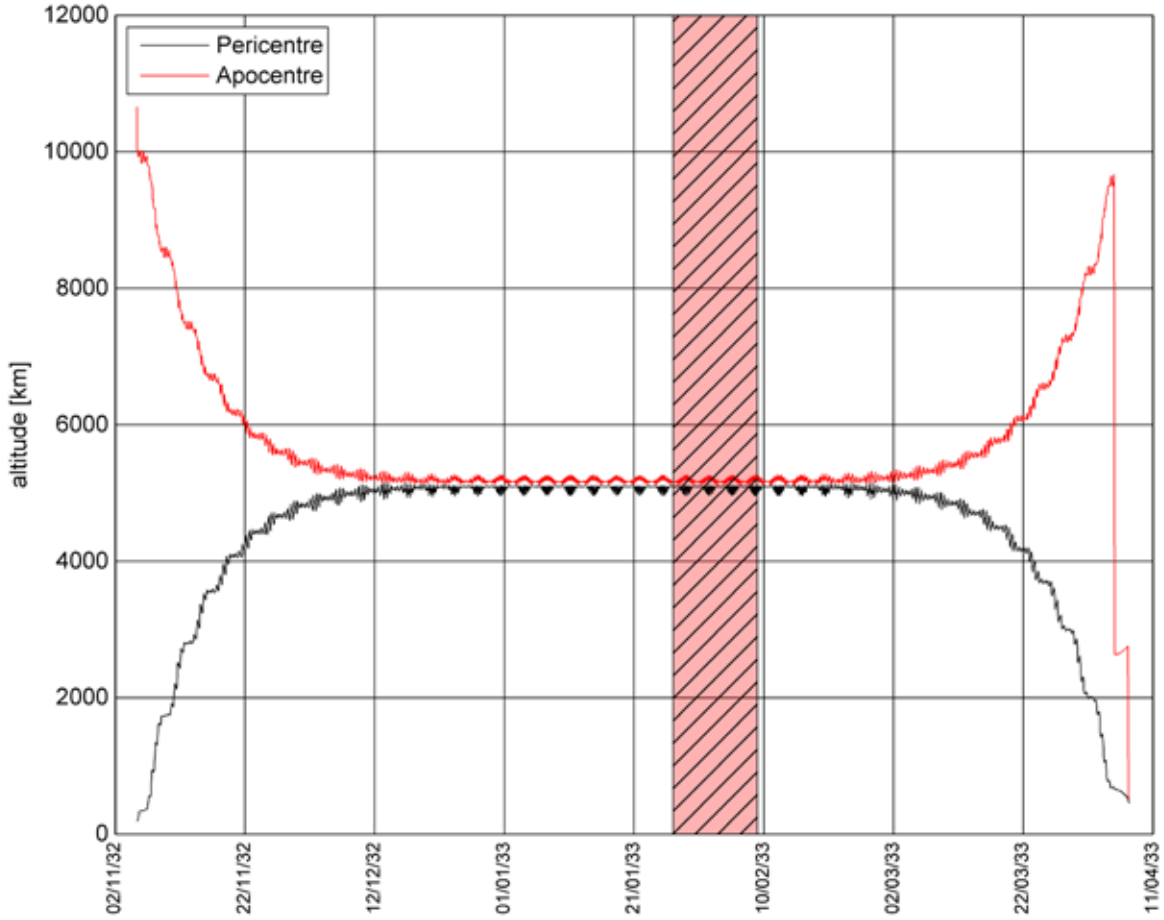


Part IVb: Low Energy Endgame





Part Va: GEO



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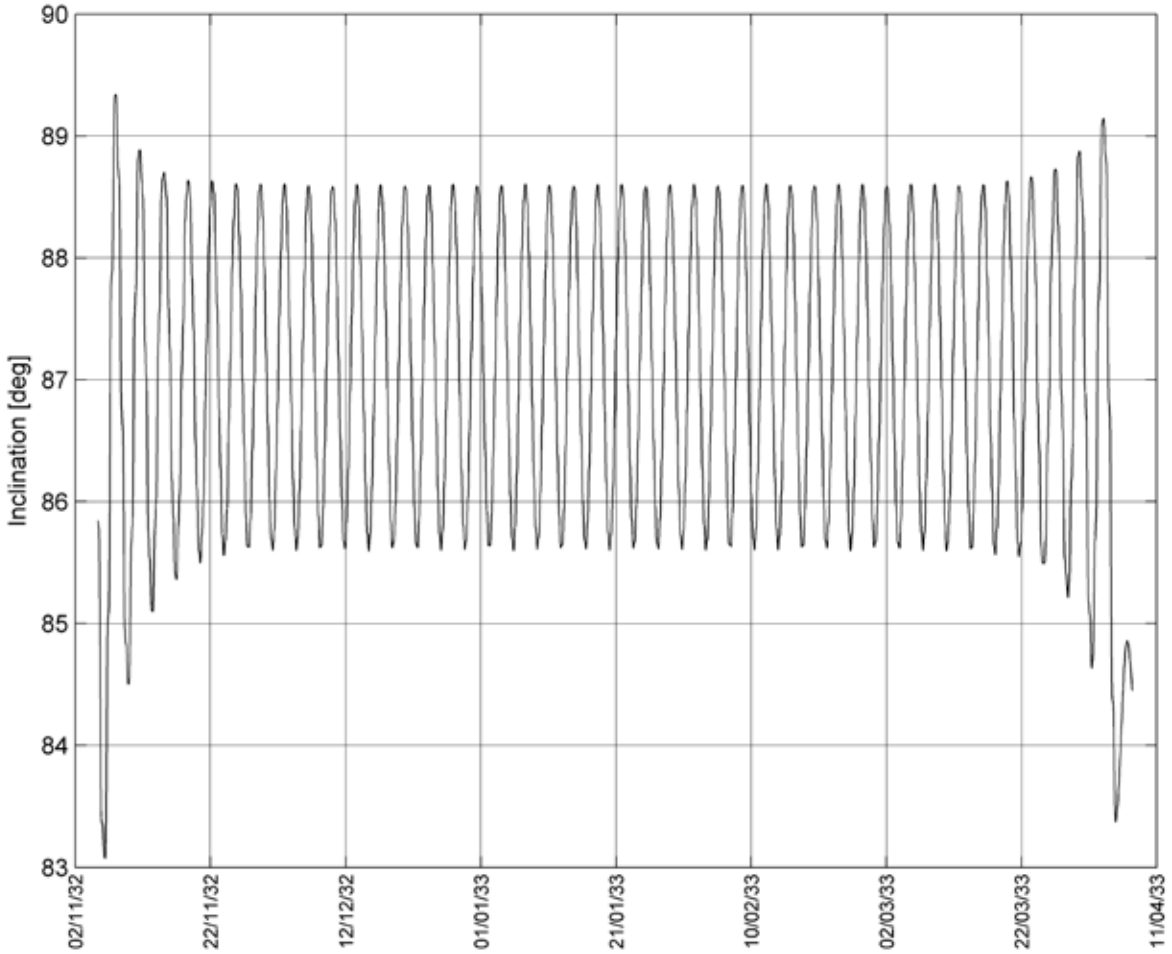

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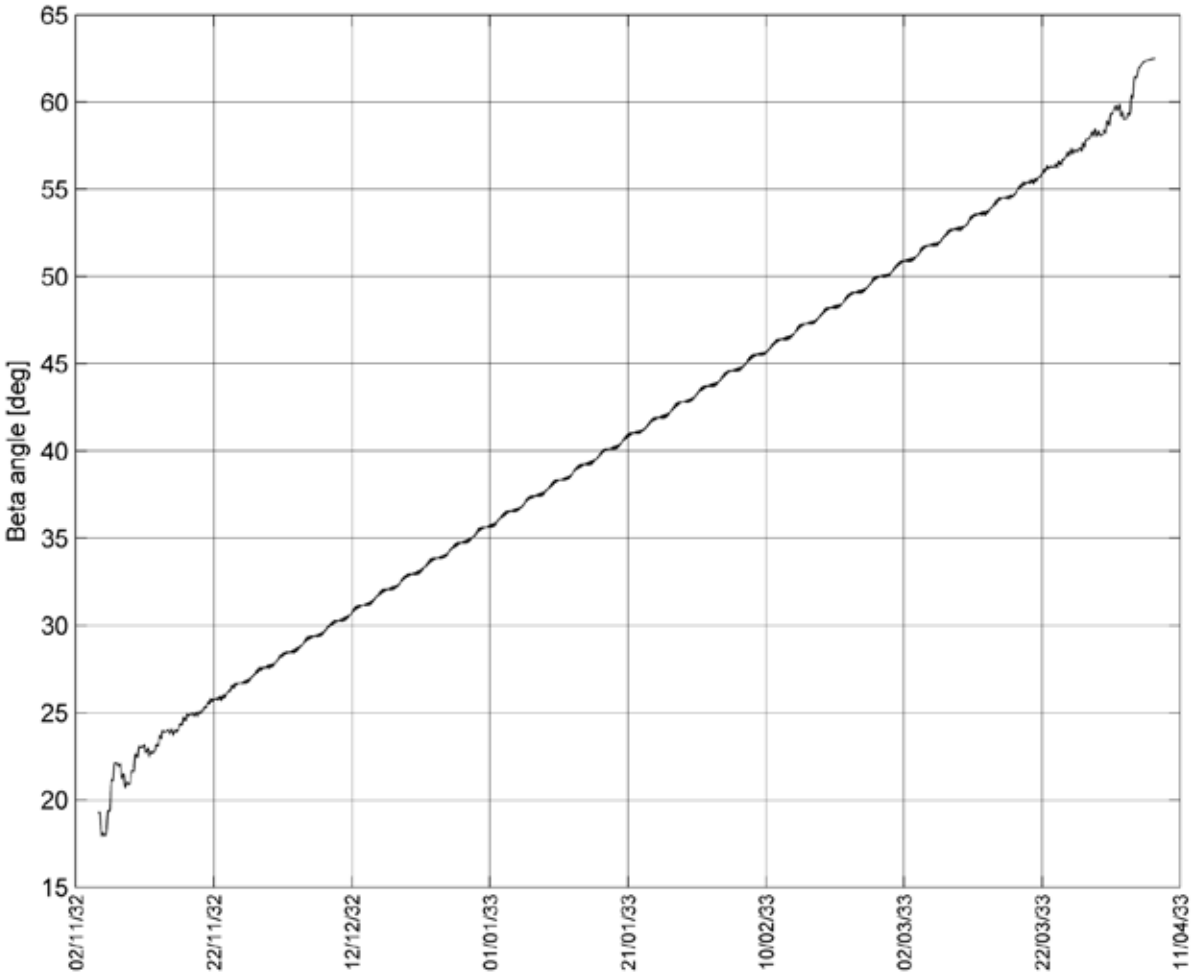
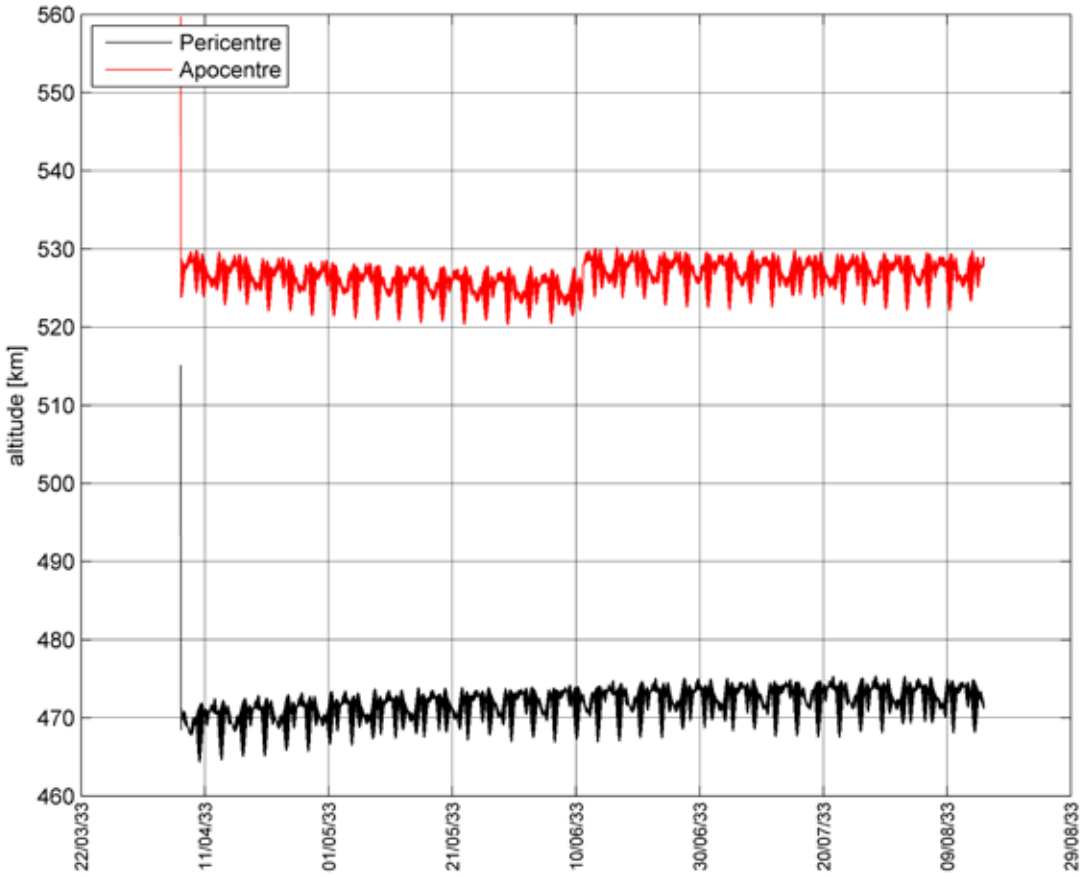
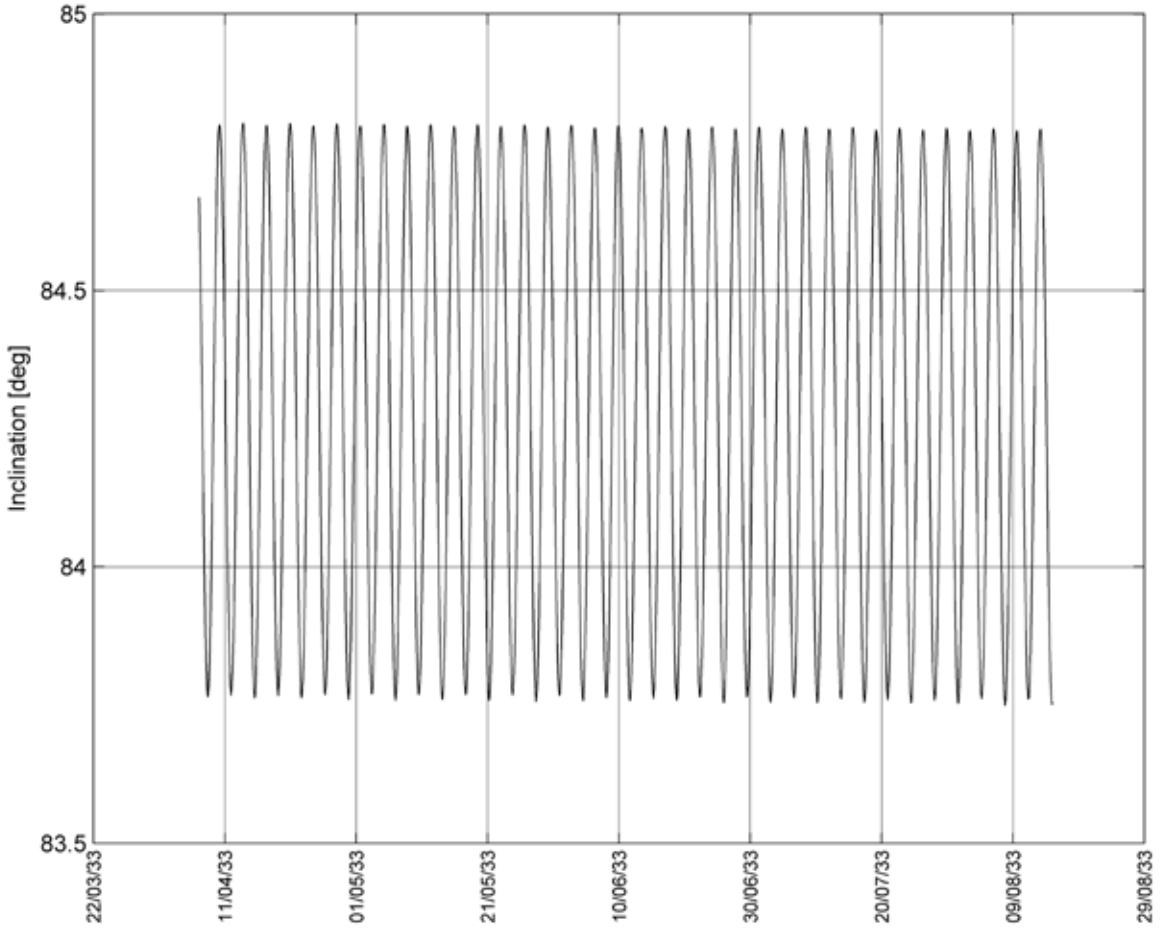

Beta angle [deg]
65
60
55
50
45
40
35
30
25
20
15
02/11/32
22/11/32
12/12/32
01/01/33
21/01/33
10/02/33
02/03/33
22/03/33
11/04/33

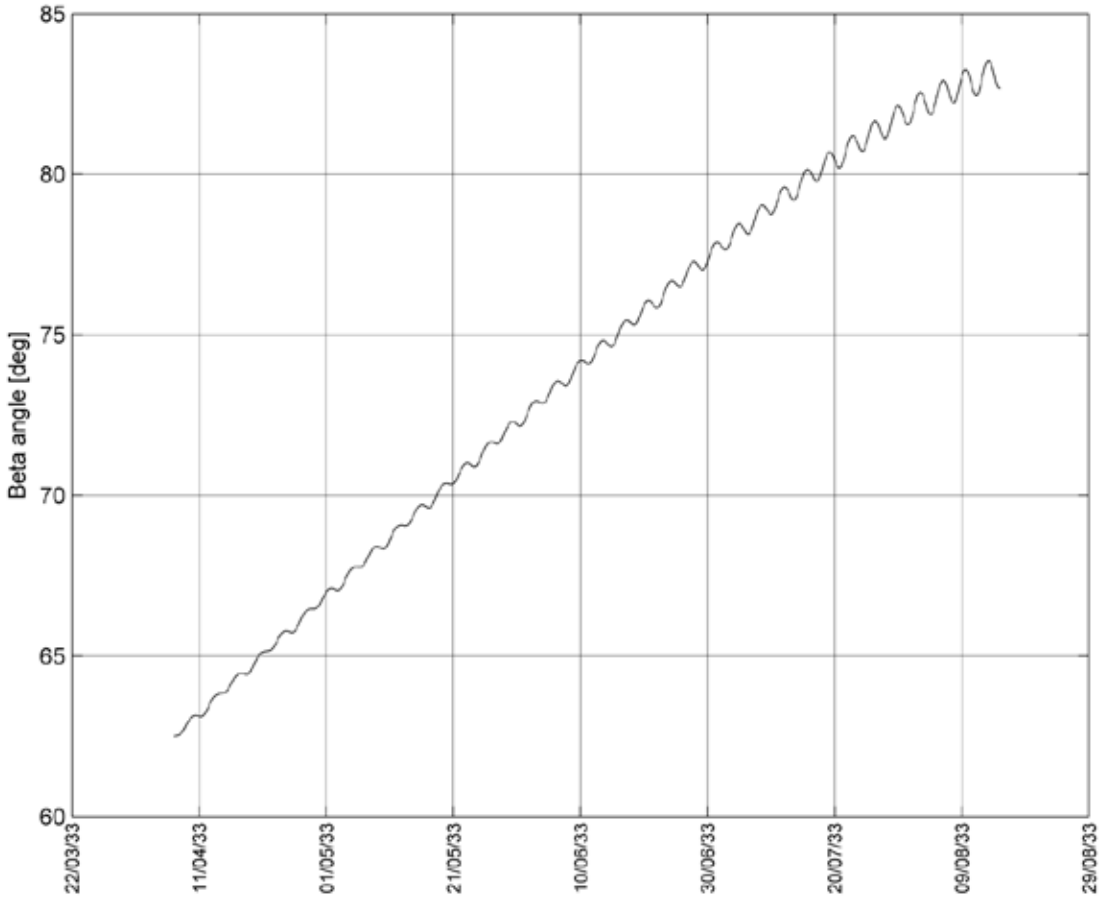
Part Vb: GCO-500



Part Vb: GCO-500



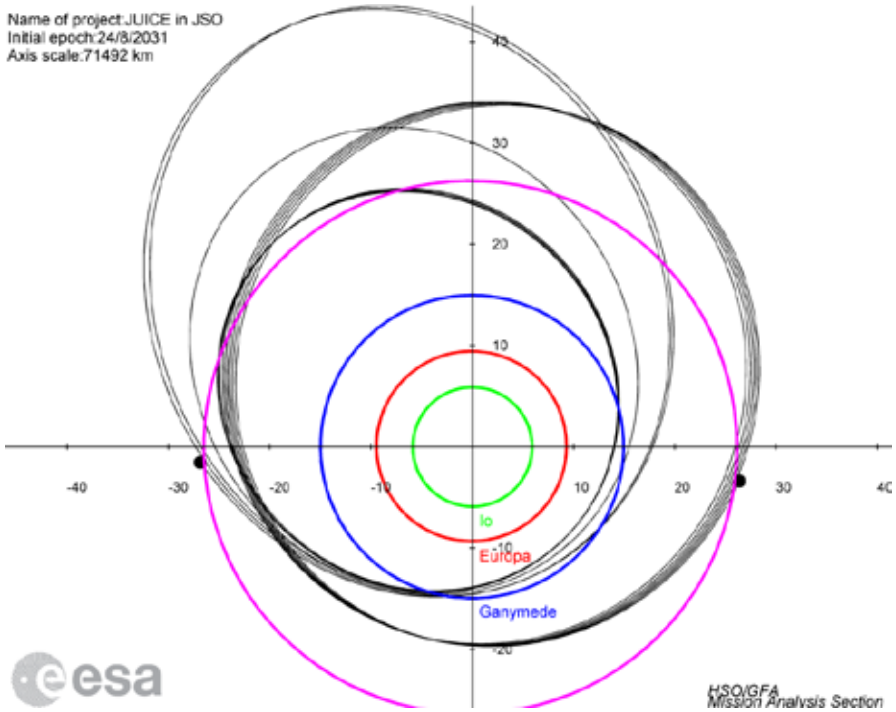
Part Vb: GCO-500



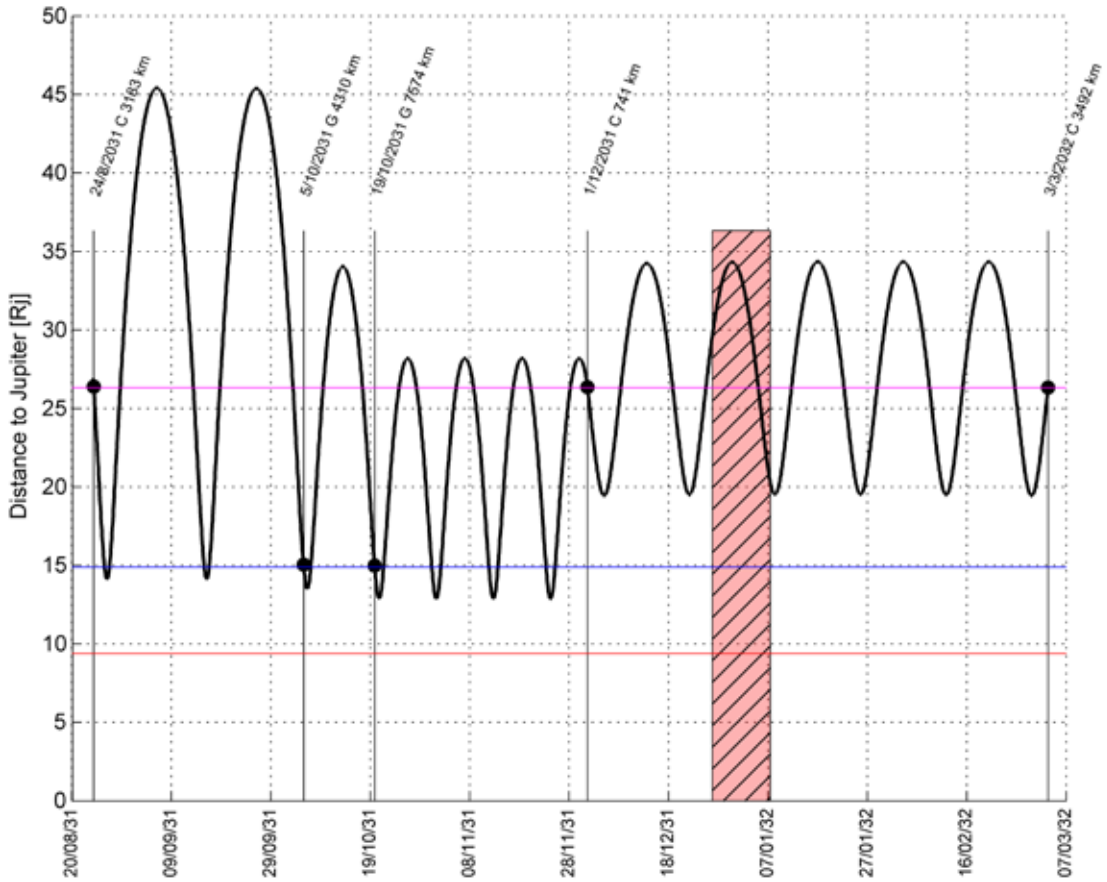
RETROGRADE OPTION

Part IVa: Callisto-Ganymede Ladder

- The CG leg is performed in 2.25 revs for an inbound encounter with Ganymede at 3.8 km/s (identical to the prograde case)
- Then a GG 2:1 is used (instead of $2{:}1^{+}$ for the prograde option)
- The GC leg is performed in 3.75 revs for an inbound encounter with Callisto at 2.22 km/s
- A single CC $5{:}5^{+}$ is used to avoid the solar superior conjunction and to be in the sweet spot to initiate the low energy endgame

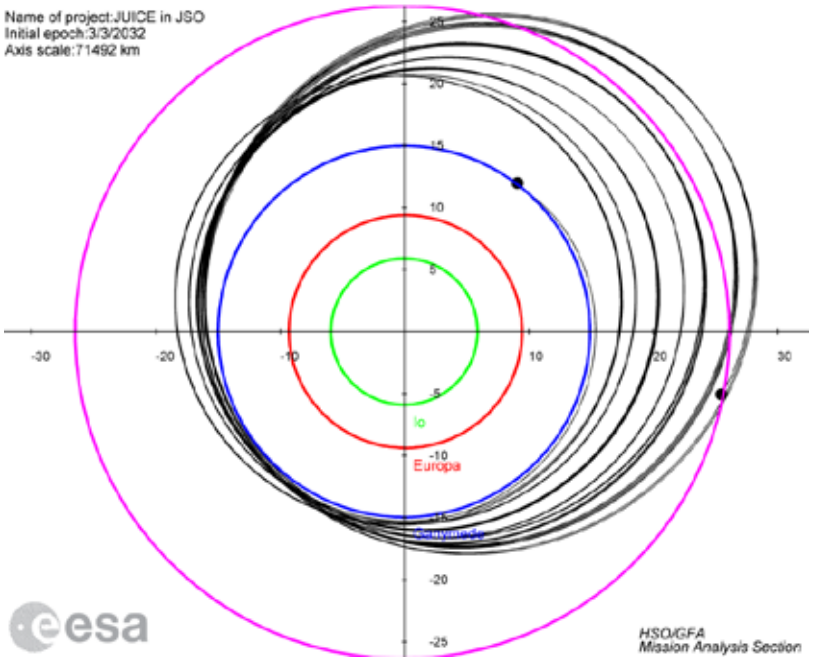


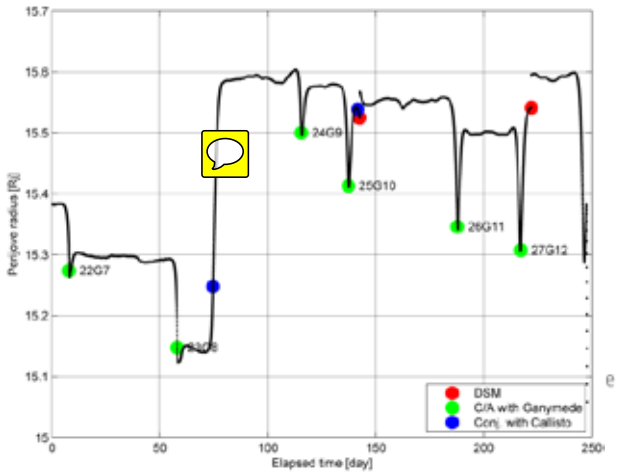
Part IVa: Callisto-Ganymede Ladder



Part IVb: Low Energy Endgame

- The first Ganymede encounter (24G8) is performed at the 2nd perijove passage after 23C14
- The entry gate is good: perijove 35000 km above Ganymede orbital radius
- The C/A is much closer (29000 km)
- The sequence is 7:4, 8:5, 3:2, 7:5, 4:3, 4:3 (the additional 4:3 is used to rotate the line of apsides by 27 deg)
- This sequence highly benefits from a positive conjunction with Callisto in the 8:5, which raises the perijove by 31000 km (C/A @ 190000 km)
- Two DSM summing to 16 m/s are used: one in the 7:5 (7 m/s) and one in the second 4:3 (9 m/s) to be (optimally) close to the L2 libration point energy level
- GOI of 133 m/s on 04/12/2032
- Beta angle @GOI: 20 deg





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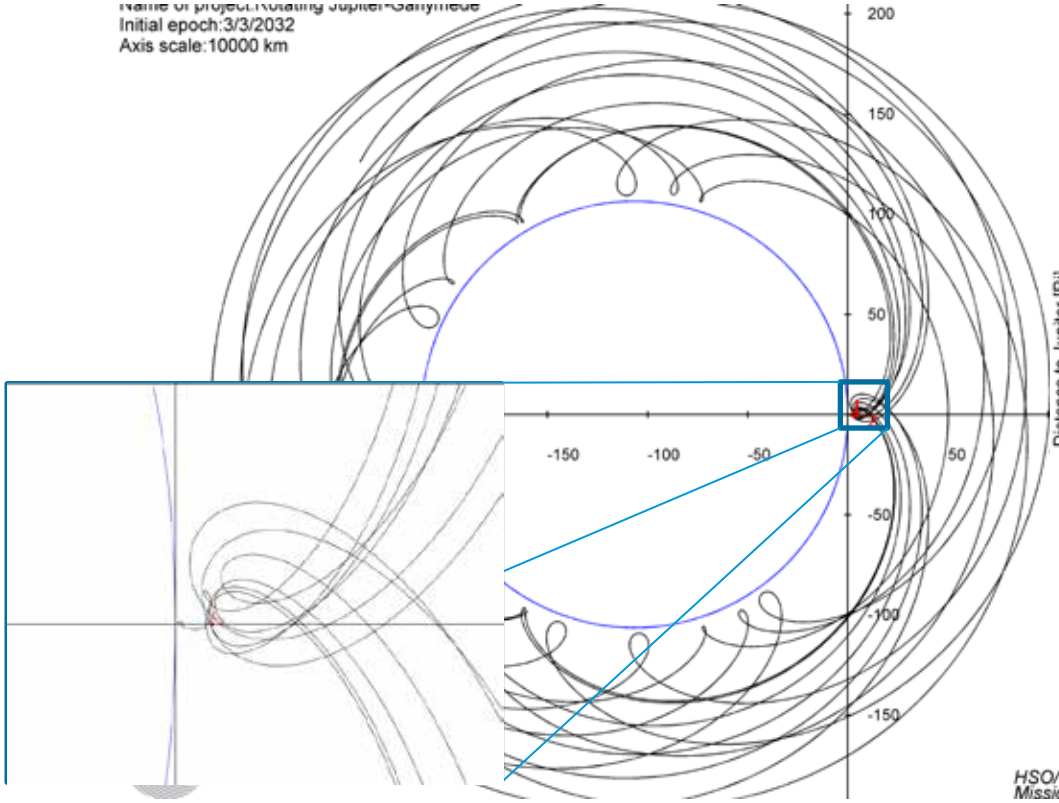
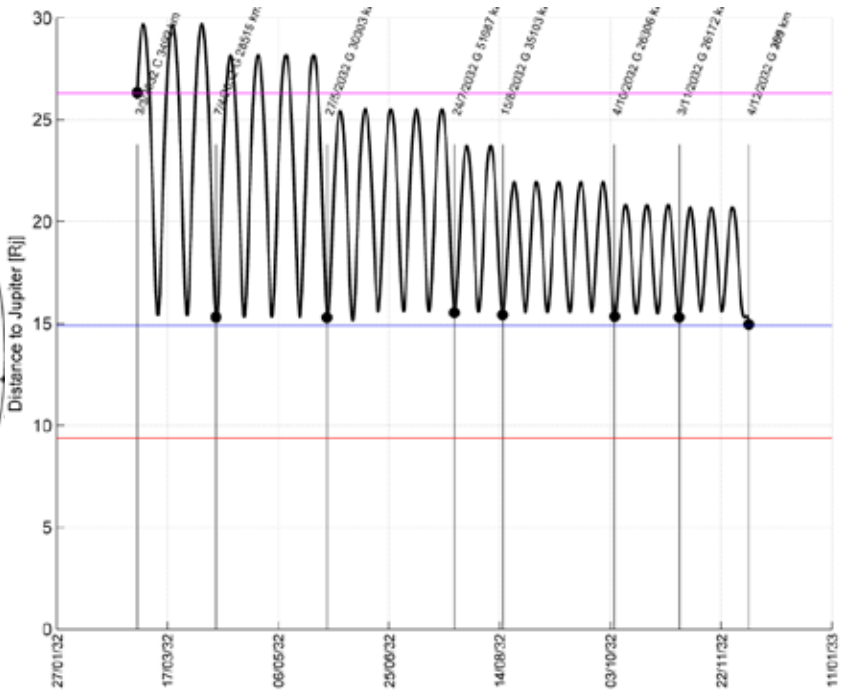
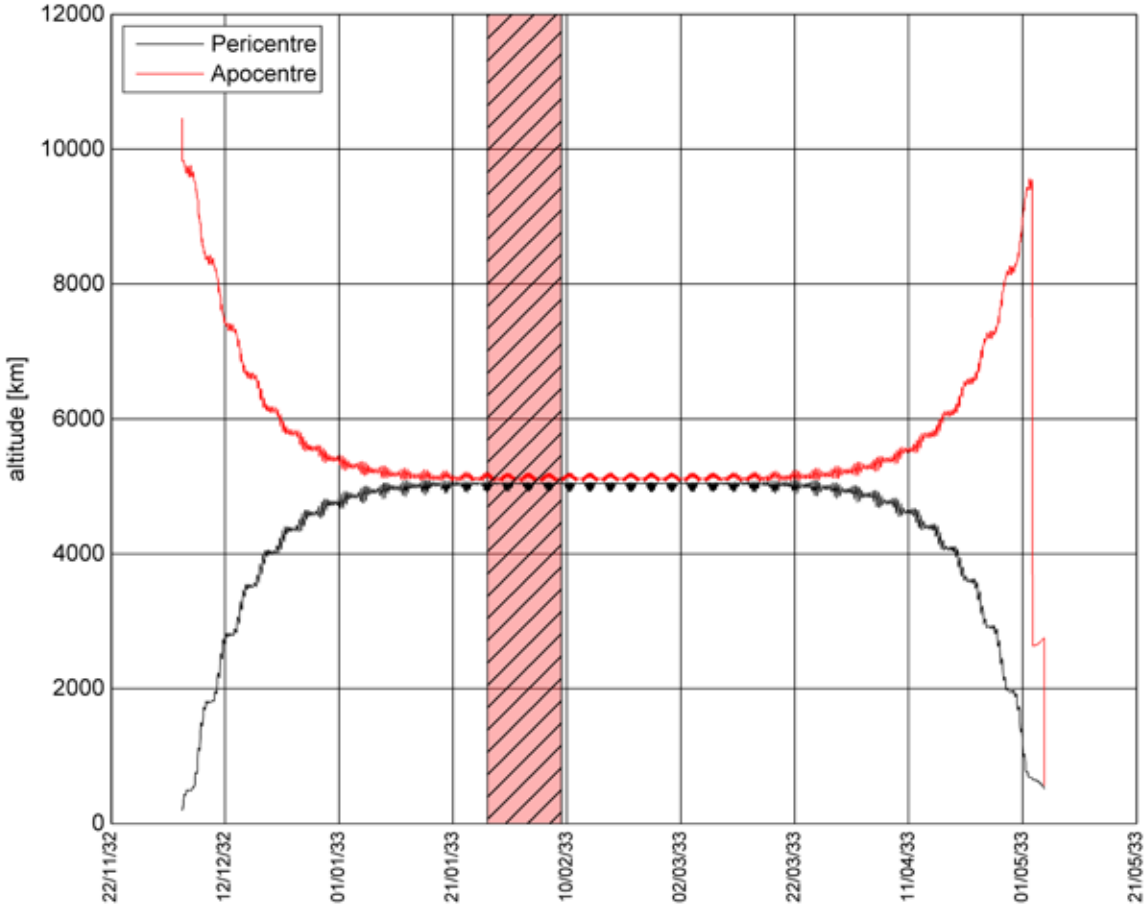




HSO/GFA
Mission Analysi

European Space Agency

Part Va: GEO



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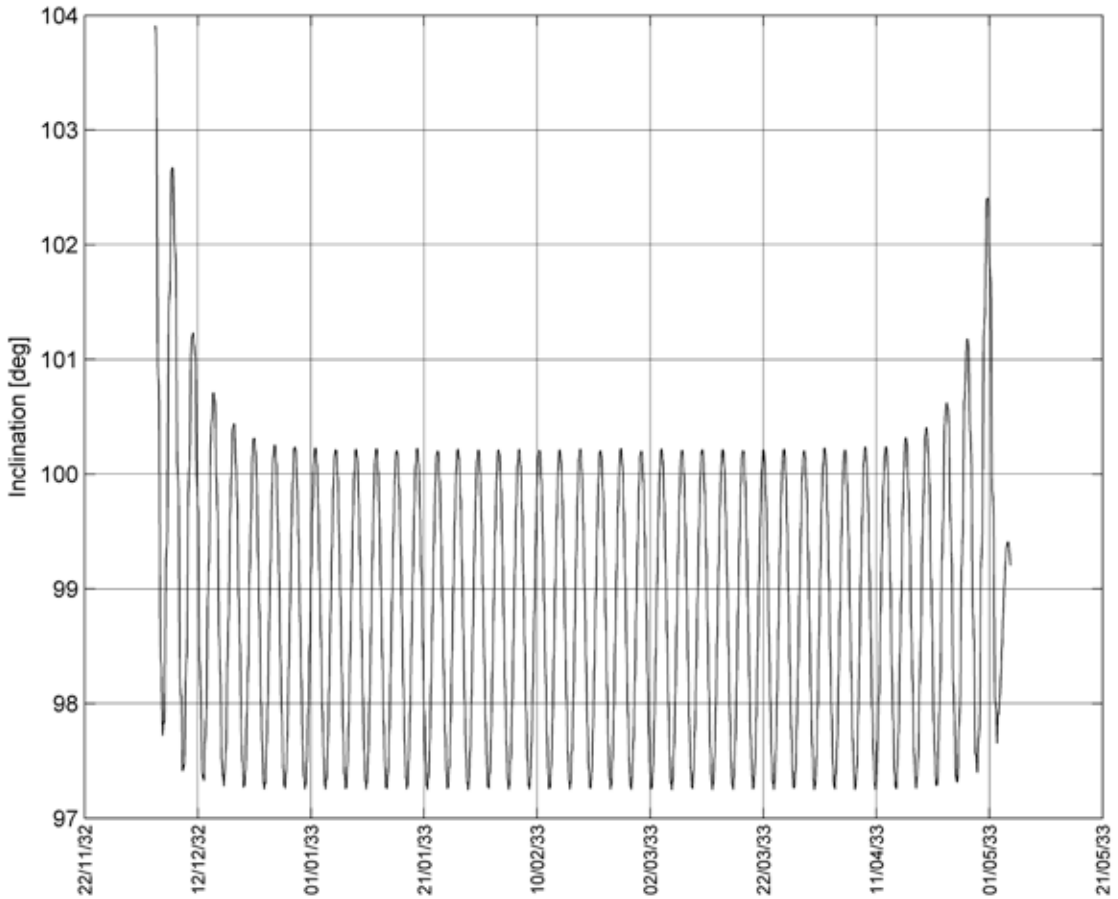
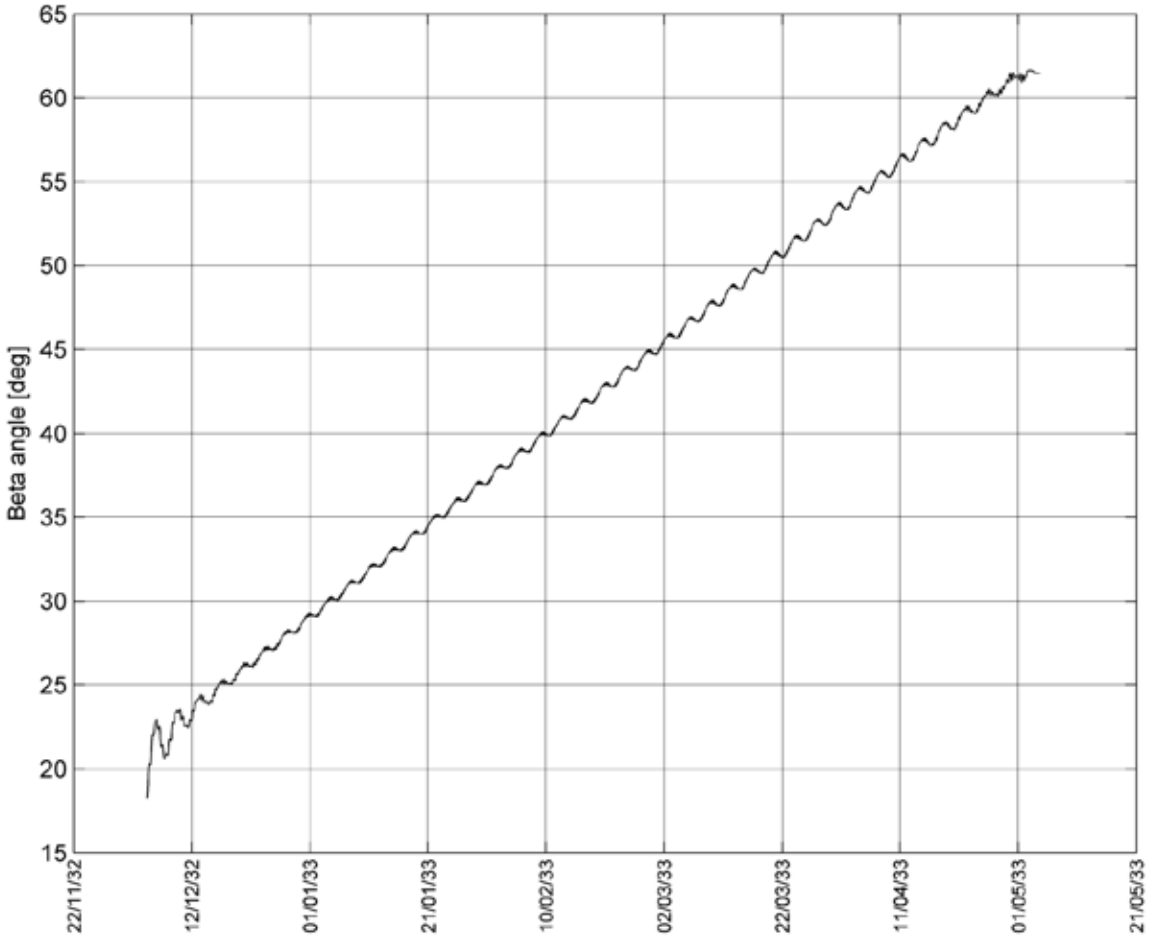
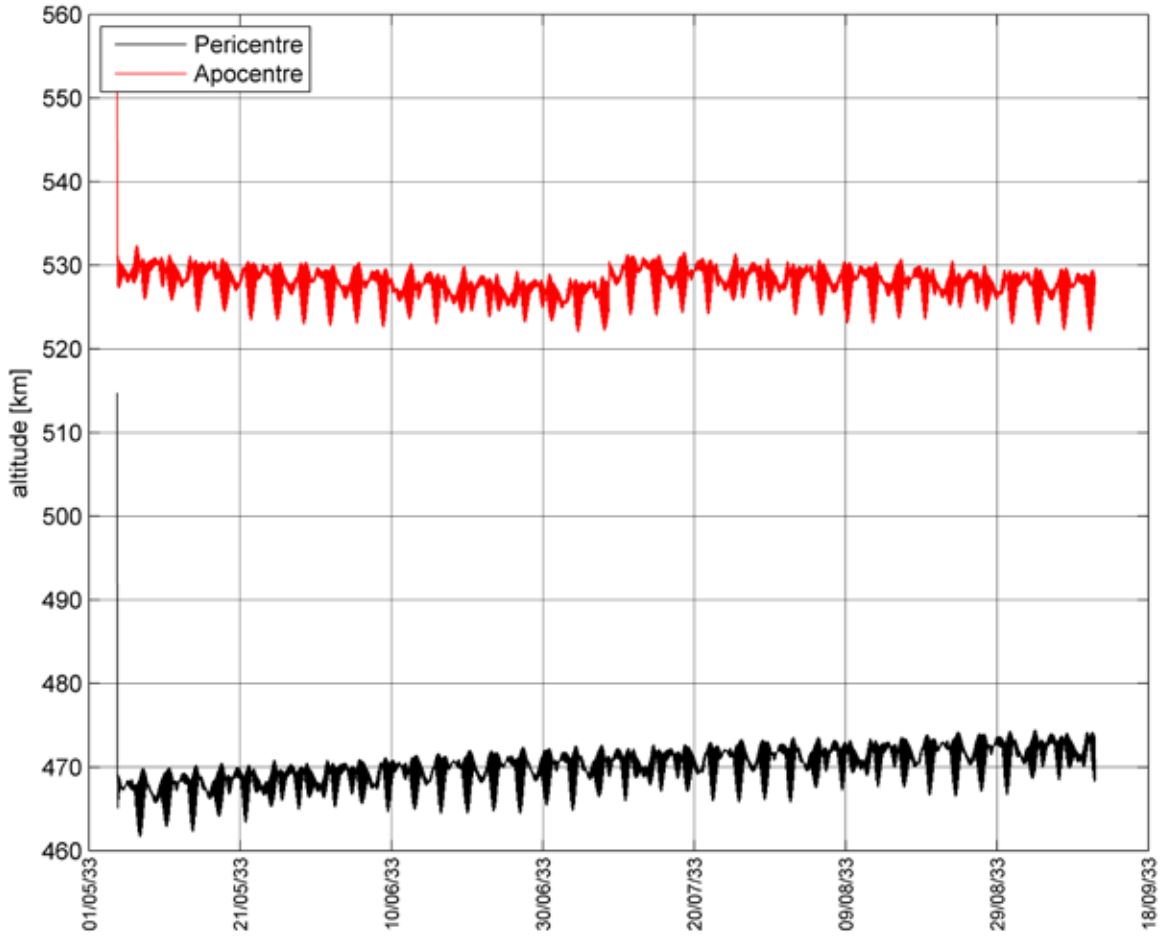


Part Va: GEO



Part Vb: GCO-500



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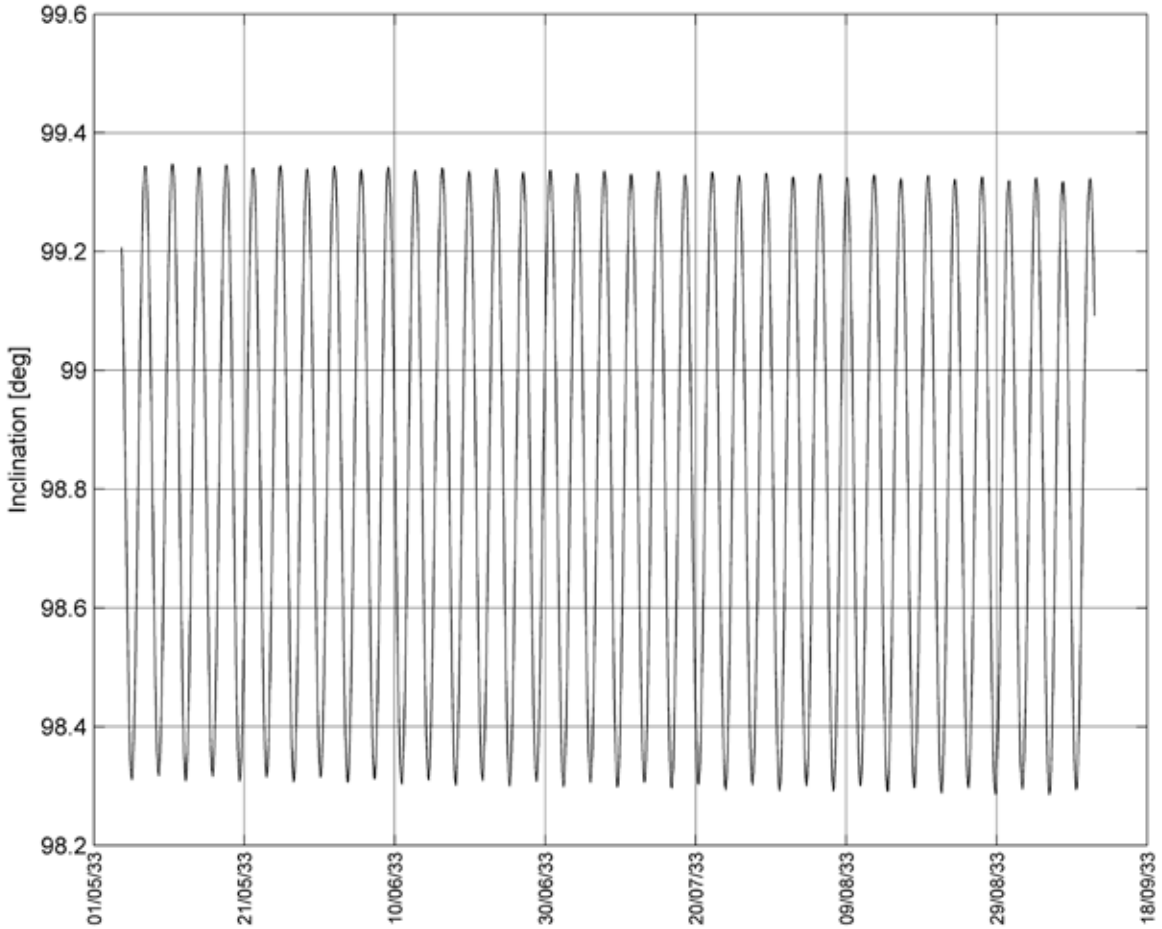

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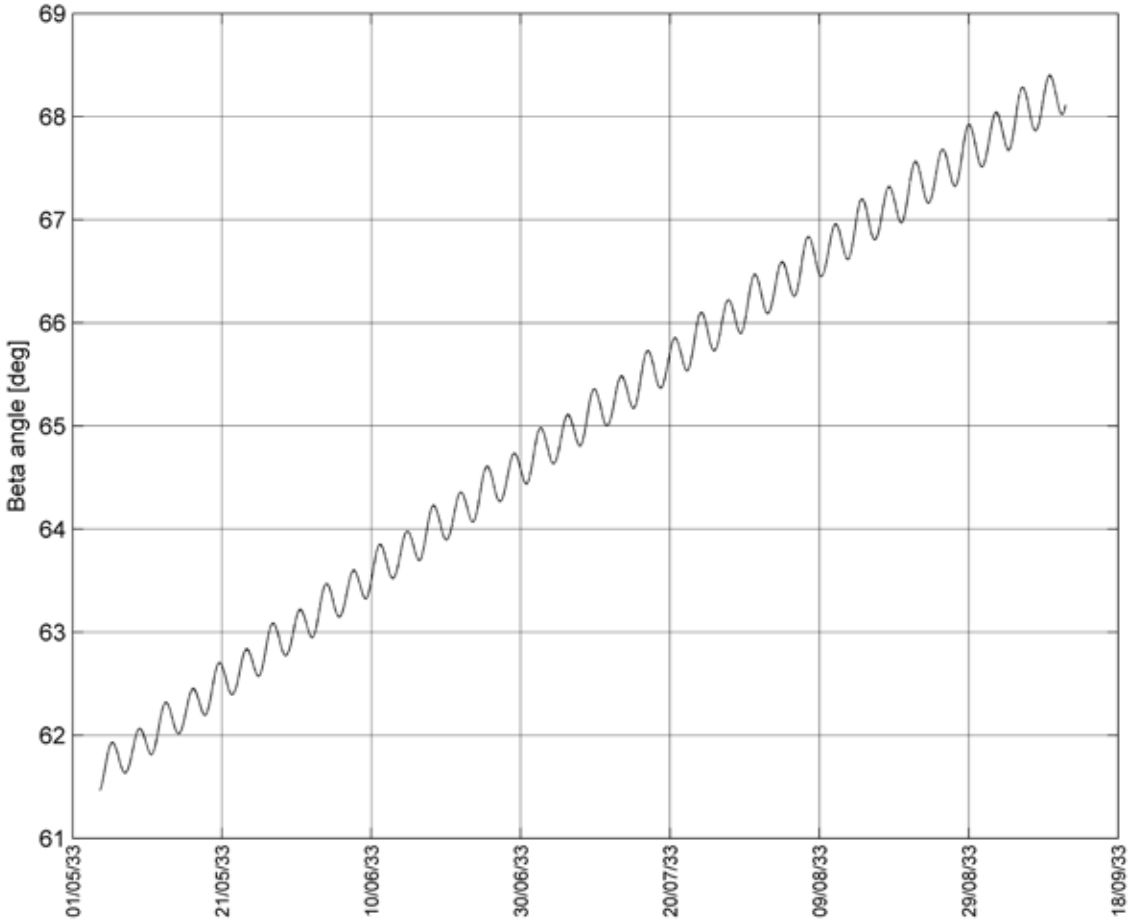

Jupiter Tour Summary: Prograde

Phase	F/B label	Date yy/mm/dd	I/O	Acc. time [day]	Δt since last evt [days]	Acc. ΔV [m/s]	C/A [km]	v_∞ [km/s]	rp Long. [deg]	rp Lat. [deg]	Beta angle [deg]	Sun-Jup-Moon [deg]	Post Fly-by Period [days]	Post Fly-by n:m	Post Fly-by rp [Rj]	Post Fly-by Inc. [deg]	Post Fly-by Jac. Cst	Acc. Rad. [krad]
Energy reduction	1G1	29/10/06	I	0	0	0	400	8.8	248	5	10	0	212.4	30:1	10.3	4	-1.000	0
	2G2	30/05/09	I	215	215	919	400	5.8	232	-22	2	6	57.2	8:1	12.8	4	2.726	5
	3G3	30/07/06	I	272	57	925	563	5.8	239	-58	15	1	36.5	5:1$^+$	12.3	0	2.722	7
	4G4	30/08/13	O	310	38	932	300	5.8	284	-3	5	108	19.1	/	11.2	0	2.718	13
Europa Science	5C1	30/09/21	O	350	40	932	2093	5.4	252	-5	6	156	15.8	/	9.4	1	2.565	25
	6E1	30/10/05	I	363	13	932	403	3.9	200	-47	37	15	14.2	4:1	9.4	2	2.926	30
	7E2	30/10/19	I	378	14	961	403	3.7	192	41	33	18	13.2	/	9.3	0	2.929	43
	8C2	30/10/29	I	388	11	961	415	4.7	110	-0	3	252	18.1	3:3$^+$	12.6	0	2.665	51
Jupiter High Latitudes	9C3	30/12/29	O	449	61	961	1099	4.8	253	1	2	124	14.4	2:2$^-$	9.9	0	2.650	63
	10C4	31/02/05	I	487	38	964	200	4.8	99	-64	50	214	16.7	1:1	11.8	8	2.652	83
	11C5	31/02/22	I	504	17	968	200	4.8	3	-72	48	212	16.7	1:1	12.8	15	2.654	88
	12C6	31/03/11	I	520	17	971	200	4.8	1	-59	44	210	16.7	1:1	14.5	22	2.656	91
	13C7	31/03/27	I	537	17	973	200	4.8	325	-29	13	209	13.9	5:6	13.9	28	2.657	92
	14C8	31/06/19	I	620	83	980	200	4.8	144	28	7	202	16.7	1:1	14.6	22	2.656	104
	15C9	31/07/05	I	637	17	982	200	4.8	178	59	34	201	16.7	1:1	12.9	16	2.654	105
	16C10	31/07/22	I	654	17	983	422	4.8	178	71	35	199	16.7	1:1	11.9	8	2.654	108
	17C11	31/08/08	I	670	17	983	1164	4.8	132	72	30	198	17.7	/	12.1	2	2.653	112
	18G5	31/08/11	O	674	3	983	9097	4.9	290	-56	27	19	16.5	/	11.9	1	2.794	116
Transfer to Ganymede	19C12	31/08/24	I	687	13	983	3087	4.6	104	14	3	190	20.0	/	13.8	0	2.680	116
	20G6	31/10/05	I	729	42	983	4971	3.8	241	-9	5	257	14.8	2:1$^+$	13.2	0	2.886	120
	21G7	31/10/21	O	745	16	983	3331	3.6	286	-6	5	357	11.1	/	12.3	0	2.885	125
	22C13	31/10/27	I	751	6	983	202	2.1	117	-3	0	130	17.3	4:4$^+$	19.9	0	2.929	125
	23C14	32/01/11	O	827	76	983	3435	2.1	254	-10	6	320	13.1	/	15.5	1	2.930	126
	24G8	32/02/02	I	849	22	983	86562	/	235	-0	2	158	12.5	7:4	15.5	1	2.999	128
	25G9	32/03/23	I	899	50	983	53262	/	220	-4	2	163	11.6	13:8	15.4	1	3.000	132
	26G10	32/06/24	I	992	93	991	42120	/	210	-12	9	167	10.8	3:2	15.5	1	3.002	142
	27G11	32/07/16	I	1014	22	991	29141	/	193	-23	23	183	10.0	7:5	15.4	1	3.003	145
	28G12	32/09/05	I	1065	51	991	20001	/	187	-12	20	202	9.6	4:3	15.6	2	3.002	152
	29G13	32/10/04	I	1094	29	1026	29495	/	176	22	3	226	9.5	4:3	15.6	1	3.005	157
Ganymede in-orbit	GOI	32/11/05	/	1126	32	1163	391	/	312	5	19	27	/	/	/	/	/	181
	Man1	33/04/05	/	1276	151	1421	731	/	274	-66	62	36	/	/	/	/	/	233
	Man2	33/04/07	/	1278	2	1647	521	/	164	-54	62	138	/	/	/	/	/	234
	END	33/08/15	/	1408	130	1647	494	/	85	10	83	184	/	/	/	/	/	280

Jupiter Tour Summary: Retrograde

Phase	F/B label	Date yy/mm/dd	I/O	Acc. time [day]	Δt since last evt [days]	Acc. ΔV [m/s]	C/A [km]	v_∞ [km/s]	rp Long. [deg]	rp Lat. [deg]	Beta angle [deg]	Sun-Jup-Moon [deg]	Post Fly-by					Acc. Rad. [krad]
													Period [days]	n:m	rp [Rj]	Inc. [deg]	Jac. Cst	
Energy reduction	1G1	29/10/06	I	0	0	0	400	7.6	239	4	11	11	212.9	30:1	11.6	4	-1.000	0
	2G2	30/05/09	I	215	215	897	400	5.8	234	-24	1	4	57.2	8:1	12.7	3	2.721	3
	3G3	30/07/06	I	272	57	905	1345	5.9	242	-51	14	359	36.5	5:1$^+$	12.2	0	2.719	5
	4G4	30/08/12	O	310	38	915	300	5.8	283	-2	5	107	19.1	/	11.1	0	2.715	11
Europa Science	5C1	30/09/21	O	350	40	915	2188	5.4	252	-5	6	154	15.8	/	9.4	1	2.563	23
	6E1	30/10/05	I	363	13	915	403	3.9	200	-47	38	13	14.2	4:1	9.4	2	2.926	28
	7E2	30/10/19	I	377	14	954	403	3.8	194	45	36	15	13.2	/	9.3	0	2.928	41
	8C2	30/10/29	I	388	11	954	348	4.7	110	-0	3	250	18.7	3:3$^+$	12.7	0	2.667	49
Jupiter High Latitudes	9C3	30/12/29	O	449	61	954	1144	4.8	253	1	2	122	14.4	2:2$^-$	10.0	0	2.654	61
	10C4	31/02/05	I	487	38	954	200	4.8	98	-64	49	211	16.7	1:1	11.9	8	2.655	81
	11C5	31/02/22	I	503	17	958	200	4.8	2	-72	46	210	16.7	1:1	12.9	16	2.658	85
	12C6	31/03/10	I	520	17	960	200	4.8	1	-59	42	208	16.7	1:1	14.6	22	2.659	88
	13C7	31/03/27	I	537	17	962	200	4.8	325	-29	11	207	13.9	5:6	14.1	28	2.660	89
	14C8	31/06/19	I	620	83	970	200	4.7	144	28	5	200	16.7	1:1	14.7	22	2.659	100
	15C9	31/07/05	I	637	17	972	200	4.8	178	58	32	198	16.7	1:1	13.0	16	2.657	102
	16C10	31/07/22	I	653	17	973	339	4.8	178	71	33	197	16.7	1:1	11.9	8	2.657	104
	17C11	31/08/08	I	670	17	973	1122	4.7	126	69	26	195	18.1	/	12.4	2	2.656	109
	18G5	31/08/11	O	674	3	973	4969	4.7	290	-62	25	12	16.5	/	12.2	0	2.809	112
Transfer to Ganymede	19C12	31/08/24	I	686	13	973	3184	4.5	103	0	2	185	20.1	/	14.1	0	2.693	112
	20G6	31/10/05	I	729	42	973	4310	3.5	237	-0	1	257	14.3	2:1	13.5	0	2.905	115
	21G7	31/10/19	I	743	14	973	7574	3.5	249	-0	1	254	11.5	/	12.9	0	2.904	118
	22C13	31/12/01	I	786	43	973	741	2.2	114	-1	2	159	17.3	5:5$^+$	19.5	0	2.922	131
	23C14	32/03/03	O	878	93	973	3492	2.2	254	-14	3	351	13.2	/	15.4	2	2.921	133
	24G8	32/04/07	I	914	36	973	28515	/	191	-27	14	205	12.5	7:4	15.3	1	2.993	136
	25G9	32/05/27	I	964	50	973	30303	/	211	-28	14	201	11.5	8:5	15.6	1	2.992	140
	26G10	32/07/24	I	1022	58	974	51687	/	213	-17	13	210	10.8	3:2	15.6	1	3.005	147
	27G11	32/08/15	I	1043	22	974	35103	/	199	-16	22	225	10.0	7:5	15.6	2	3.004	149
	28G12	32/10/04	I	1094	51	981	26306	/	185	6	18	242	9.6	4:3	15.5	1	3.004	157
	29G13	32/11/03	I	1123	29	981	26172	/	179	30	2	269	9.5	4:3	15.6	1	3.004	162
Ganymede in-orbit	GOI	32/12/04	/	1154	31	1122	355	/	331	9	19	48	/	/	/	/	/	180
	Man1	33/05/02	/	1304	149	1377	1356	/	82	20	62	342	/	/	/	/	/	232
	Man2	33/05/04	/	1306	2	1604	1035	/	343	31	62	84	/	/	/	/	/	233
	END	33/09/11	/	1435	129	1604	528	/	215	-80	69	100	/	/	/	/	/	279

Conclusions: Impact of Europa Fly-bys Illumination

- Optimal EGA illumination taken into account:
  - Ls = 15 deg (resp. 13) @ 6E1, Ls = 18 (resp. 15) deg @ 7E2 for the prograde (resp. retrograde) option
  - à Average power reduction ~5% (25% for CReMA 3.0)
  - à No eclipse after 6E1
- But:
  - +18 m/s / CReMA 3.0
  - +6 krad / CReMA 3.0
  - Detrimental geometry with Ganymede during the Jupiter high latitude phase

Conclusions: Constraints

- Europa fly-bys illumination: compliant (~15 deg)
- Beta angle @ JOI: compliant (20 to 30 deg)
- GEO duration: compliant (150 days)
- GCO duration: compliant (130 days)
- Max eclipse duration: compliant (<4.5 hours)
- Min duration between flybys: not compliant (>8 days):
  - Between 17C11 and 18G5 (prograde and retrograde): 3 days (but fly-by is not tight (9000 km for prograde and 5000 km retrograde), DeltaV penalty is currently analysed for altitude of 10000 km and 20000 km, stochastic DeltaV allocation for 19C12 is doubled)
  - Between 21G7 and 22C13 (prograde only): 6 days (an alternative solution was found but it requires +20 m/s deterministic)

Conclusions: Comparison w/ CReMA 3.0

		Prograde	Retrograde
Tour duration	[month]	+2.4	+3.4
Total nb of F/B	[]	+2	+3
Nb of F/B in the high. lat. phase	[]	+1	+1
Deterministic DeltaV	[m/s]	+5	-38
Stochastic DeltaV	[m/s]	+16	+24
Total DeltaV	[m/s]	+21	-14
Radation dose	[krad]	+44	+43
Radiation dose / CReMA 2.1	[krad]	+22	+21

- Specific ESOC MA recommendations for DeltaV:
  - Both options lie close to the CReMA 3.0 allocation. BUT…
  - The dramatic reduction after the Europa phase for the retrograde option (-51 m/s w.r.t. CReMA 3.0) is considered exceptional à It shall not be used as a baseline for DeltaV

Conclusions: Perspectives for Trajectory Design

- Compliance with the minimum time between two consecutive fly-bys
  - Current options: use the full potential of the Ganymede spurious encounter right after the end of the Europa science phase as suggested by Y. Langevin
  - New options: relax the objective on the constraint on the Europa fly-bys illumination (up to 25 deg)
- Applicability of the tour for other options (how generic is it?)
- Consequence of the Sun declination (the Sun reaches Jupiter's equatorial plane in early 2033 à Longer eclipse violating the 4.5 hours constraint from JOI to the low energy endgame)