EUROPA CLIPPER

MISSION DESIGN UPDATE

NEW 2022 TOURS, 2023 TOUR DEV. SCHEDULE AND PLANNED TOUR DESIGNS

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Outline

- Original Schedule and Strategy: Path to CDR Tour Selection
- Overview of New Tours (2022 launch opportunity)
- Updated Tour Design Schedule due to 2023 Launch Slip
- 2023 Tour Design Considerations

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Original Schedule and Strategy: Path to CDR Tour Selection

Brent Buffington

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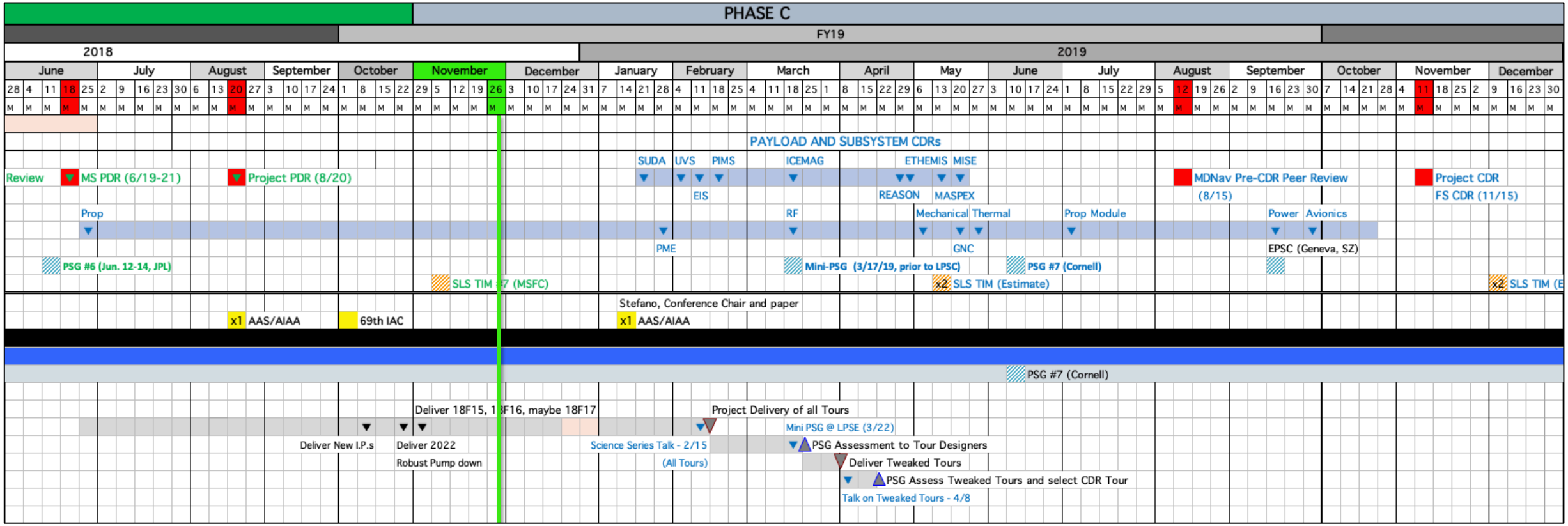
Original Tour Dev. Schedule for CDR



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New Tours: 2022 Launch Opportunity

17F12/17F13
Derived Trajectories

17F12

- **COMPLETE**
  18F15
  - 17F12 w/ alternate ending
  - MISE leading hem. coverage
  - Jupiter impact disposal
- **T1**
  - Add nightside COT-3 before S.F.
  - MISE leading hem. coverage
  - Jupiter impact disposal set-up

17F13

- **COMPLETE**
  18F16
  - 17F13 w/ alternate ending
  - MISE leading hem. coverage
  - Jupiter impact disposal
- **COMPLETE**
  18F17 (T2)
  - MISE leading hem. coverage
  - Callisto petal rot. for lighting change
  - Jupiter impact disposal set-up

STOPPED DEV DUE TO LAUNCH YEAR CHANGE

2022 Earth-Jupiter Interplanetary Trajectory, Extended Pump Down
Derived Trajectories

Extended Pump Down
(ΔV savings, pass through Europa's environment prior to E1)

- **T4**
  Mimic 18F15 design
- **T5**
  Mimic 18F16 design
- **T6**
  Mimic T1 design
- **T7**
  - COT-1 with 5:1 res.
  - COT-2 with 4:1 res.
  - 18F15 strategy thereafter

STOPPED DEV DUE TO LAUNCH YEAR CHANGE

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New Tours: 2022 Launch Opportunity

[cont.]

- Three new 2022 tour designed: 18F15, 18F16, and 18F17
  - No longer Baseline Trajectory candidates
  - Benefit is to understand how different tour strategies affect science performance
  - Released tours include corresponding VERITaS runs (evaluation against measurement reqs.)
  - Available for assessment for iCDRs (per current schedule)

- Feedback from 18F15 – 18F17 due no later than 1/15/19

- Mission Design is currently working on 2023-compatible tours
  - New tour design schedule in subsequent slides

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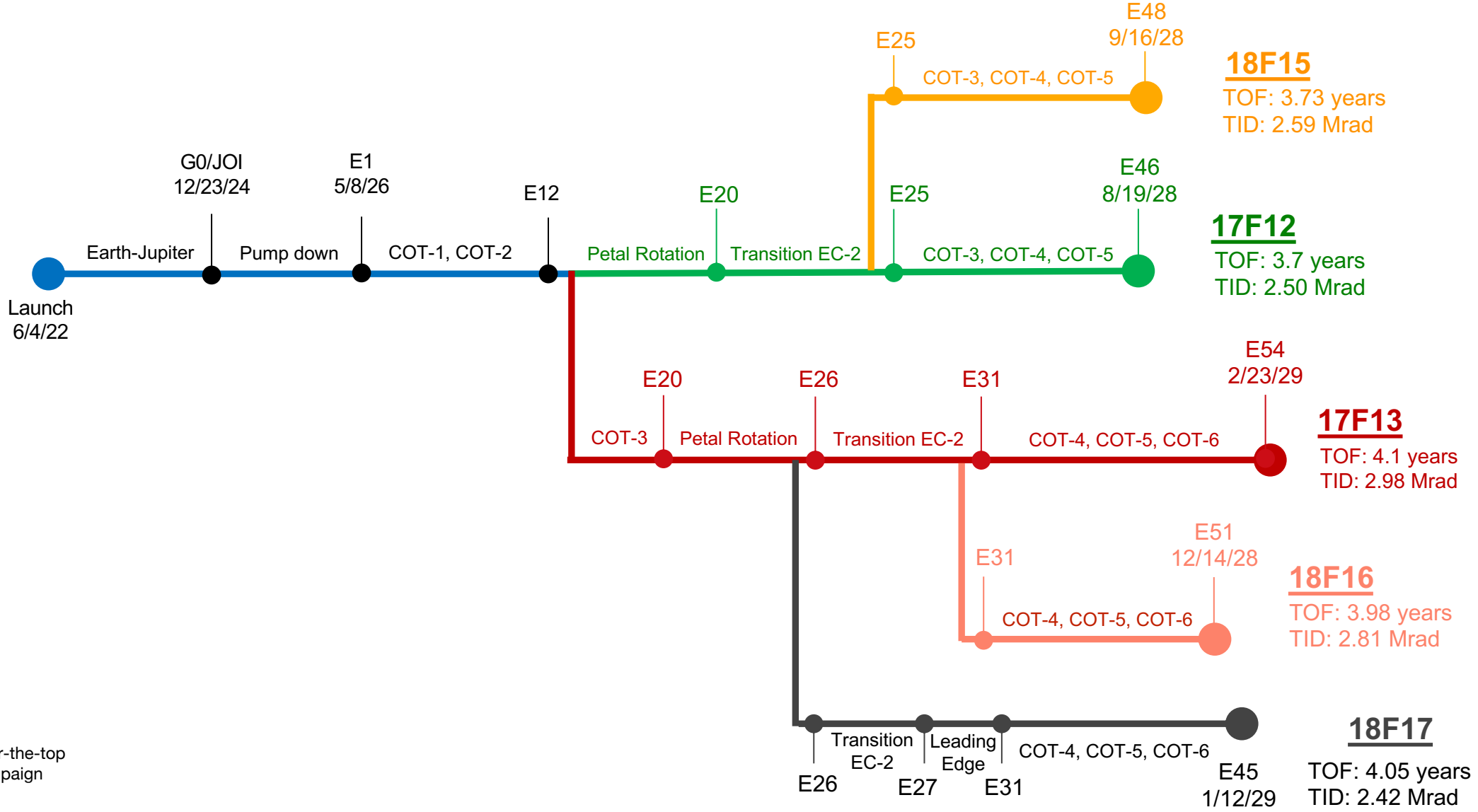
Tour Timelines



COT: Crank-over-the-top
EC: Europa Campaign

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Tour Comparison

	JUP230		JUP310							
Tour[1]	**14F8**	**15F9**	**15F10**	**16F11**	**17F12_V2**	**17F13**	**18F14**	**18F15**	**18F16**	**18F17**
Launch Date	6/14/2022	6/2/2022	6/14/2022	6/17/2022	6/4/2022	6/4/2022	2023	6/4/2022	6/4/2022	6/4/2022
Arrival Date	3/5/2030	1/15/2030	3/5/2025	5/1/2025	12/23/2024	12/23/2024	1/14/2026	12/23/2024	12/23/2024	12/23/2024
Tour Duration (years)[2]	3.7	3.3	3.4	3.2	3.7	4.1	4.05	3.73	3.98	4.05
Number of Flybys[3]										
Europa	45	40	42	43	46	54	44	48	51	45
Ganymede	5	5	4	4	4	4	5+5	4+5	4+	6+
Callisto	7	8	8	9*	9	9	12	9	8	9
No. of Night Side Europa Flybys	5		5	7	9	10	13	10	13	7
No. of Jupiter Orbits[2]	86	70	76	64	70	84	67	72	79	71
Time between Flybys (days)										
Maximum	50.0	78.7	50.0	100.2	229.0	229.0	217**	229.0**	229.0**	229.0**
Minimum	8.3	8.3	8.3	5.4	5.4	4.2	8.9	5.4	3.7	13
Minimum (Europa-to-Europa)	10.6	10.6	10.6	10.1	10.1	10.6	13.8	10.1	10.6	13.9
Deterministic ΔV, post-PRM (m/s)	174	150	118	155	182	188	TBD	164	192.5	200
Maximum Inclination (deg.)	21.2	19.8	21.2	18.8	18.9	18.0	6.9	18.9	18.1	5.9
No. of Jupiter Eclipses	57	44	48	45	47	55	54	51	50	62
Maximum Eclipse Duration (hours)	8.8	8.8	8.8	9.15	9.15	9.14	9.23	9.17	9.18	9.20
Total Ionizing Dose (Mrad)[4]	3.14	2.74	2.86	2.33	2.50	2.98	2.3	2.59	2.81	2.42

(1) The satellite ephemerides used is shown above the corresponding tour name
(2) From **G0** to EOM (last Europa flyby)
(*) Two (2) Distant Flybys > 30,000 km Alt.
(3) Includes last Europa flyby necessary to set-up Callisto impact
(4) Calculated using **GIRE-2p** model from **G0** to EOM (last Europa flyby); **Si** behind 100 mil **Al**; spherical sheldl
(**) Excludes the pump-up to setup disposal into Jupiter

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18F15

Try Lam

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18F15 Summary

- 18F15 is similar to 17F12
  - Includes a leading edge flyby (E26) post Switch-Flip to meet MISE measurement requirement
  - COT-3, COT-4, and COT-5 are similar to 17F12
  - Disposal is a Jupiter impactor after pumping-up using Ganymede flybys
  - Flyby altitude for the latter part of the tour still needs to be adjusted based on feedback from Nav

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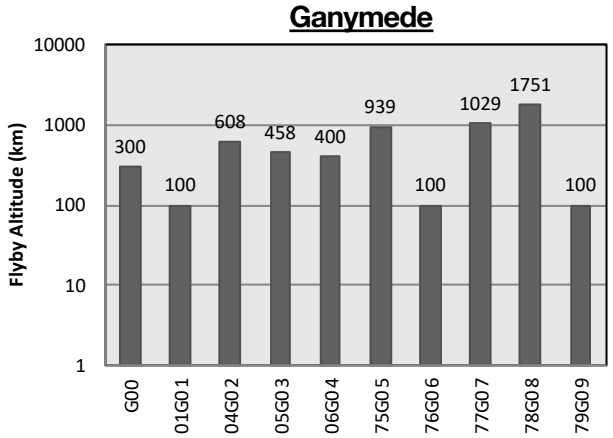
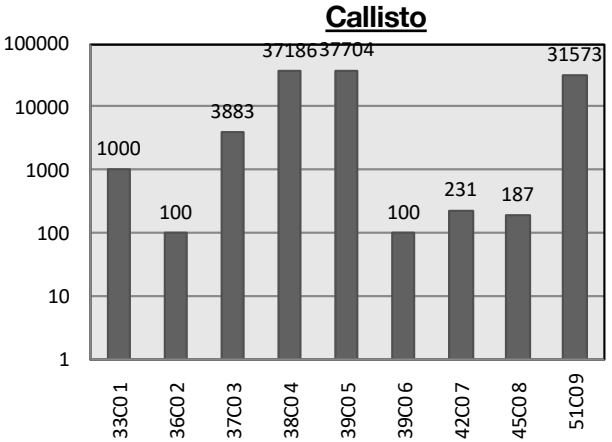
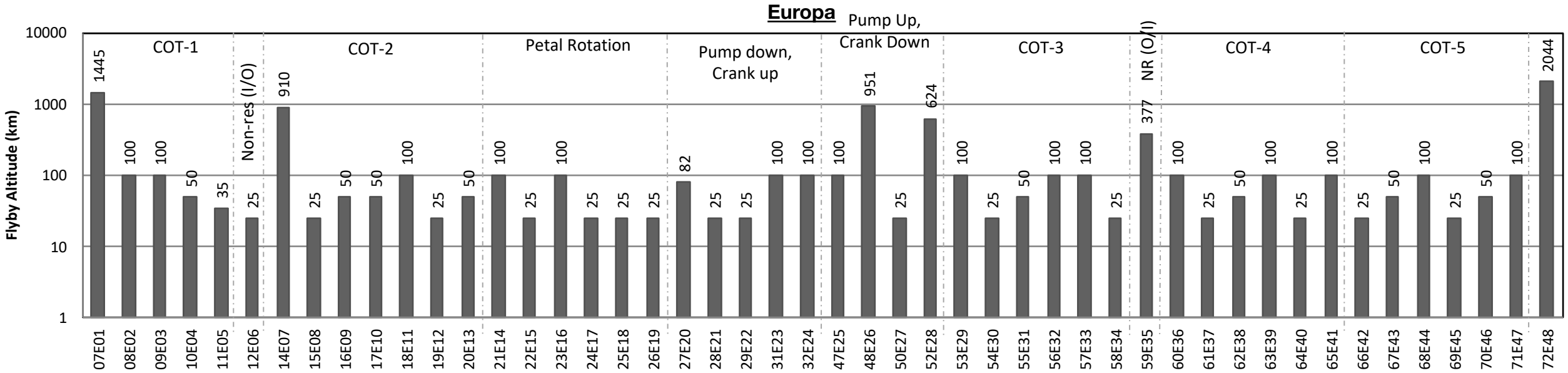
18F15: Flyby Altitude Profile

Europa Altitude Bin	17F12_V2
>1000 km	2
100 – 1000 km	20
50 – 99 km	9
25 – 49 km	17







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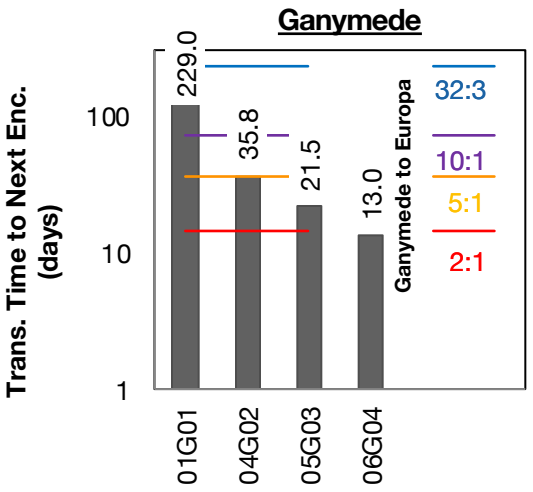
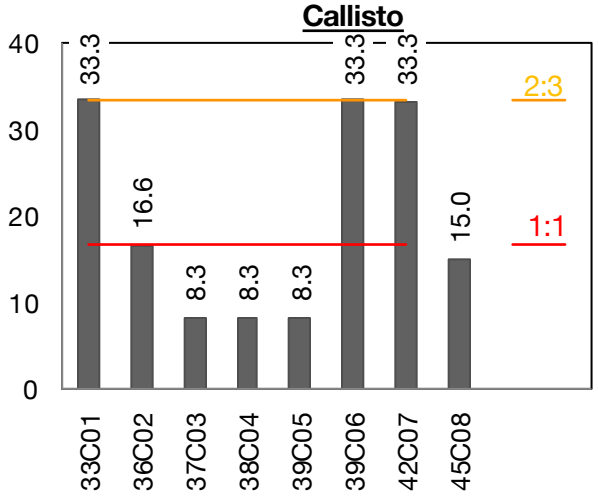
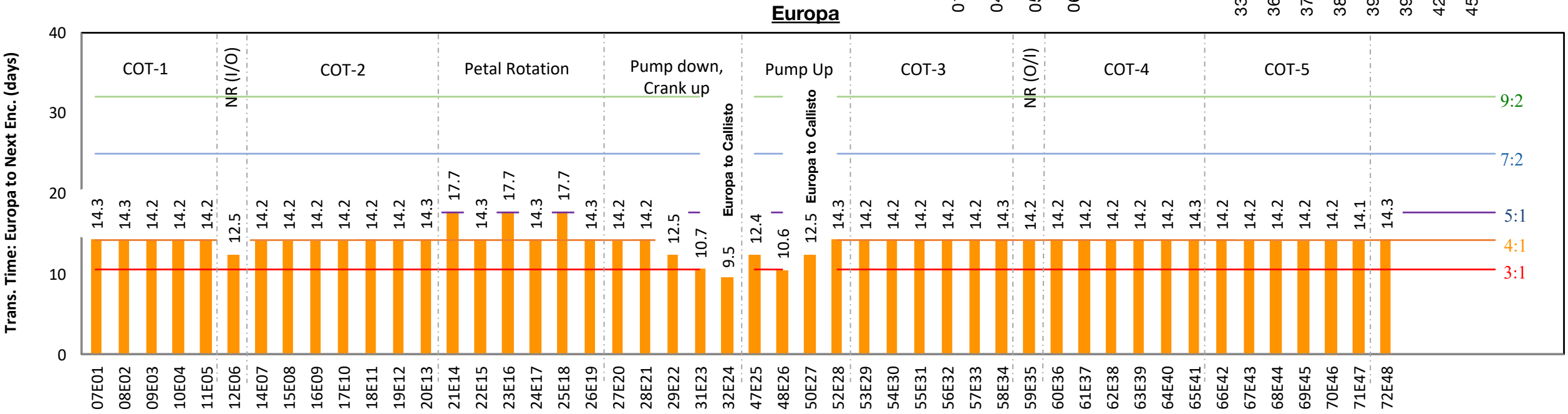
18F15: Transfer Time Profile

Europa-to-Europa Trans. Bin	18F15
< 14.2 days	7
≅ 14.2 days	38
> 14.2 days	3







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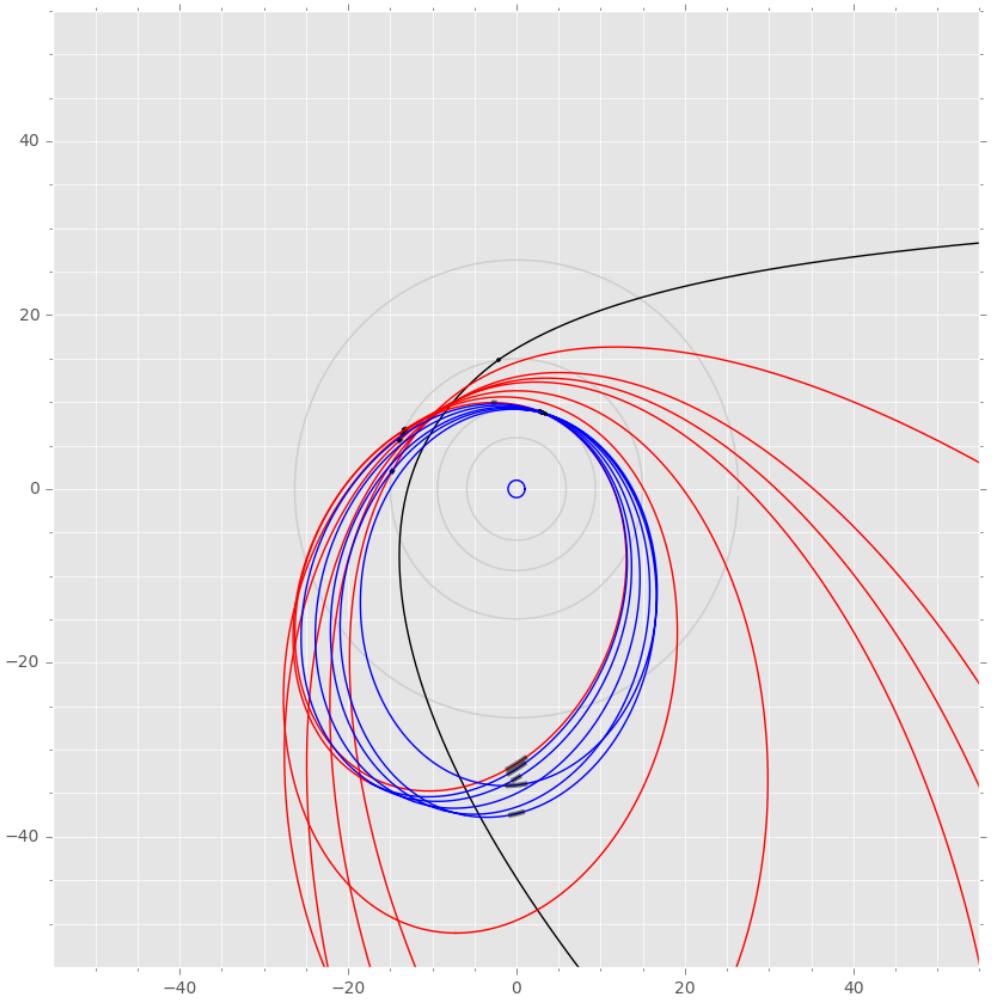
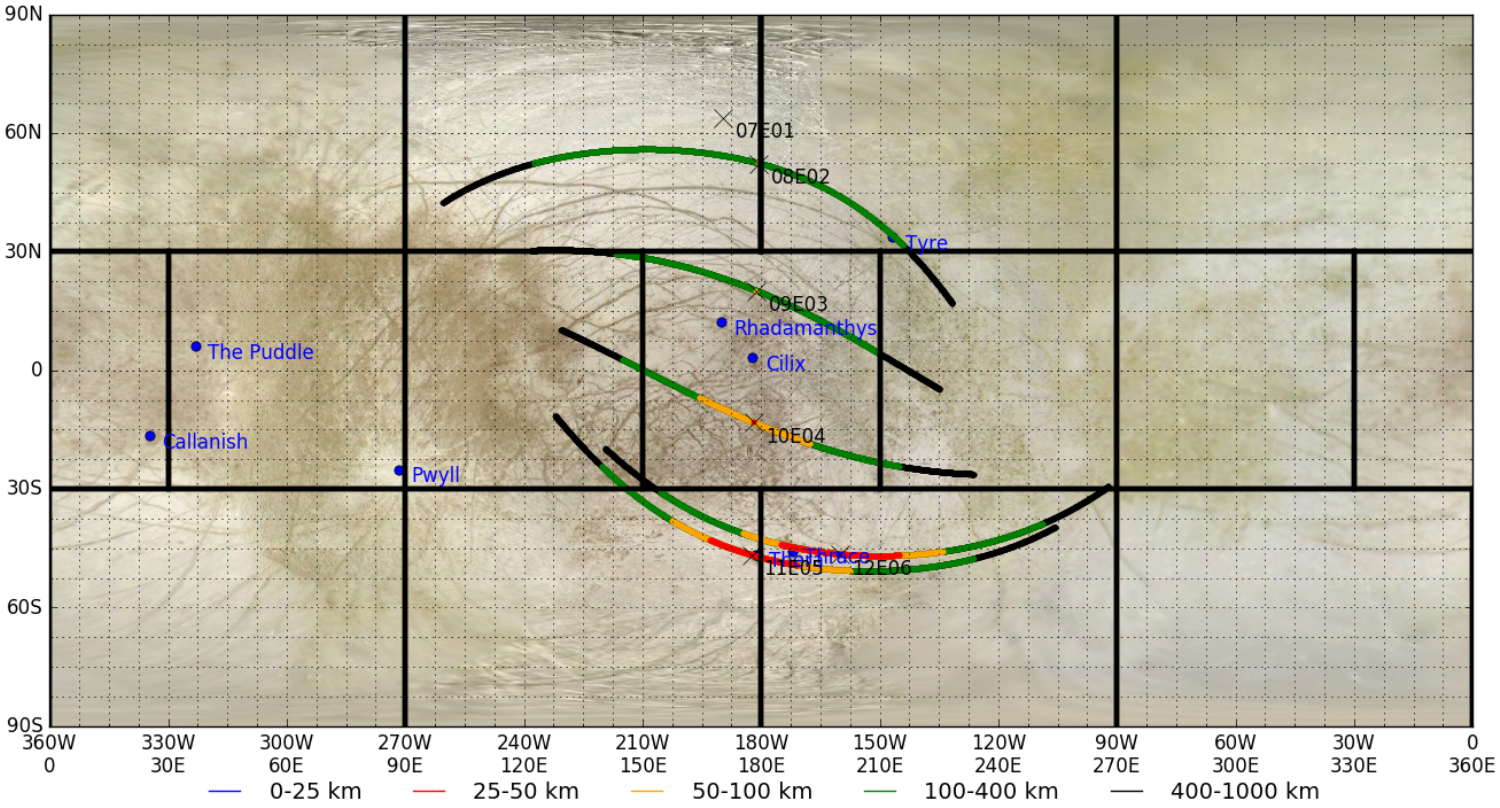
18F15: Trajectory and Groundtrack Buildup

COT-1

Trajectory Build-up



Groundtrack Build-up



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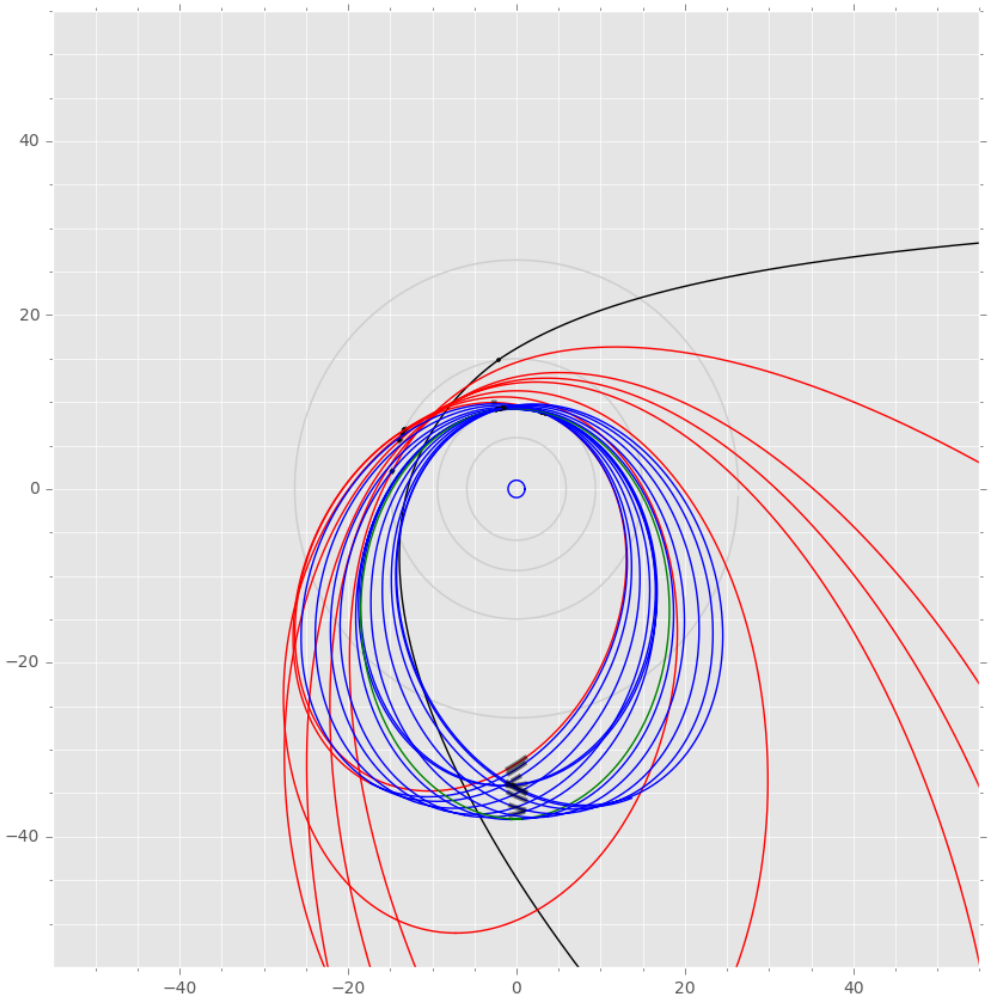
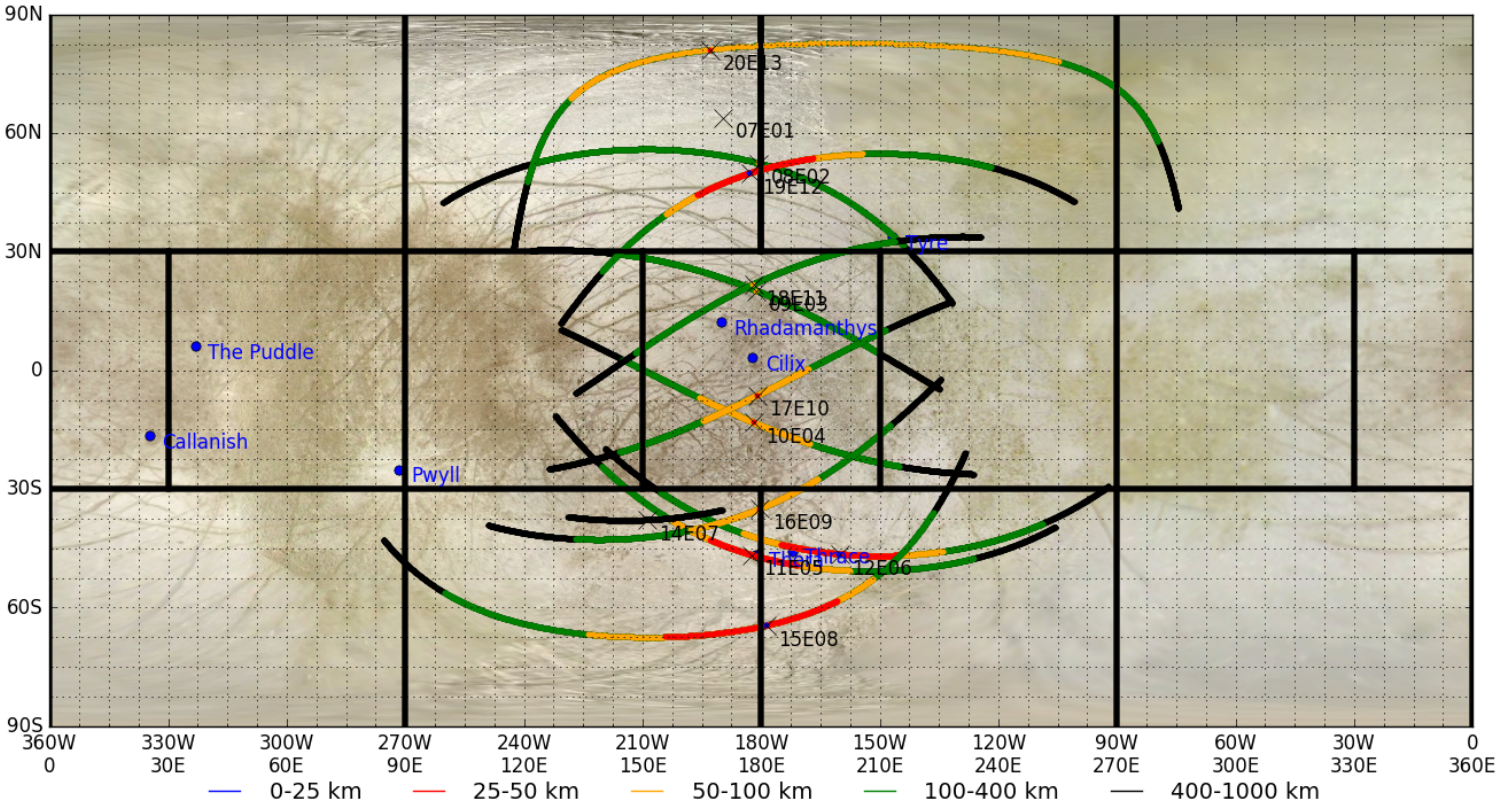
18F15: Trajectory and Groundtrack Buildup

To COT-2

Trajectory Build-up



Groundtrack Build-up



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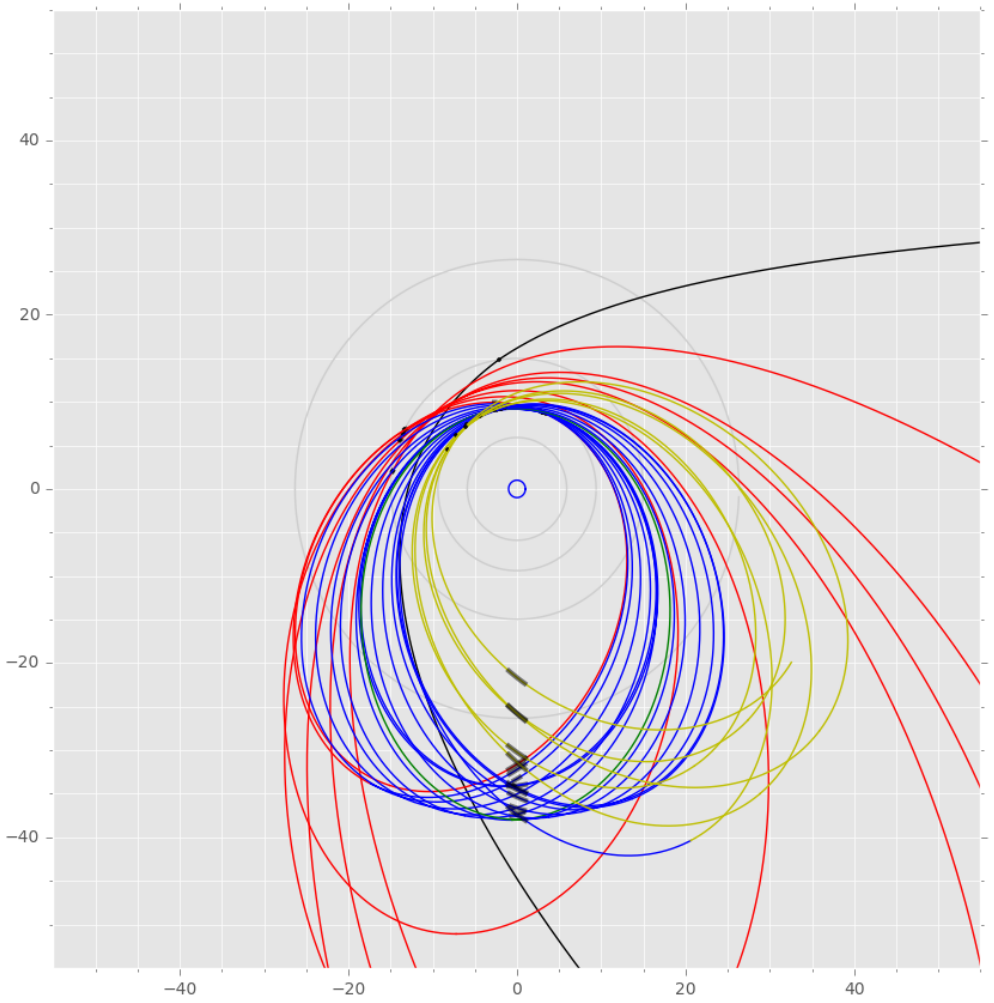
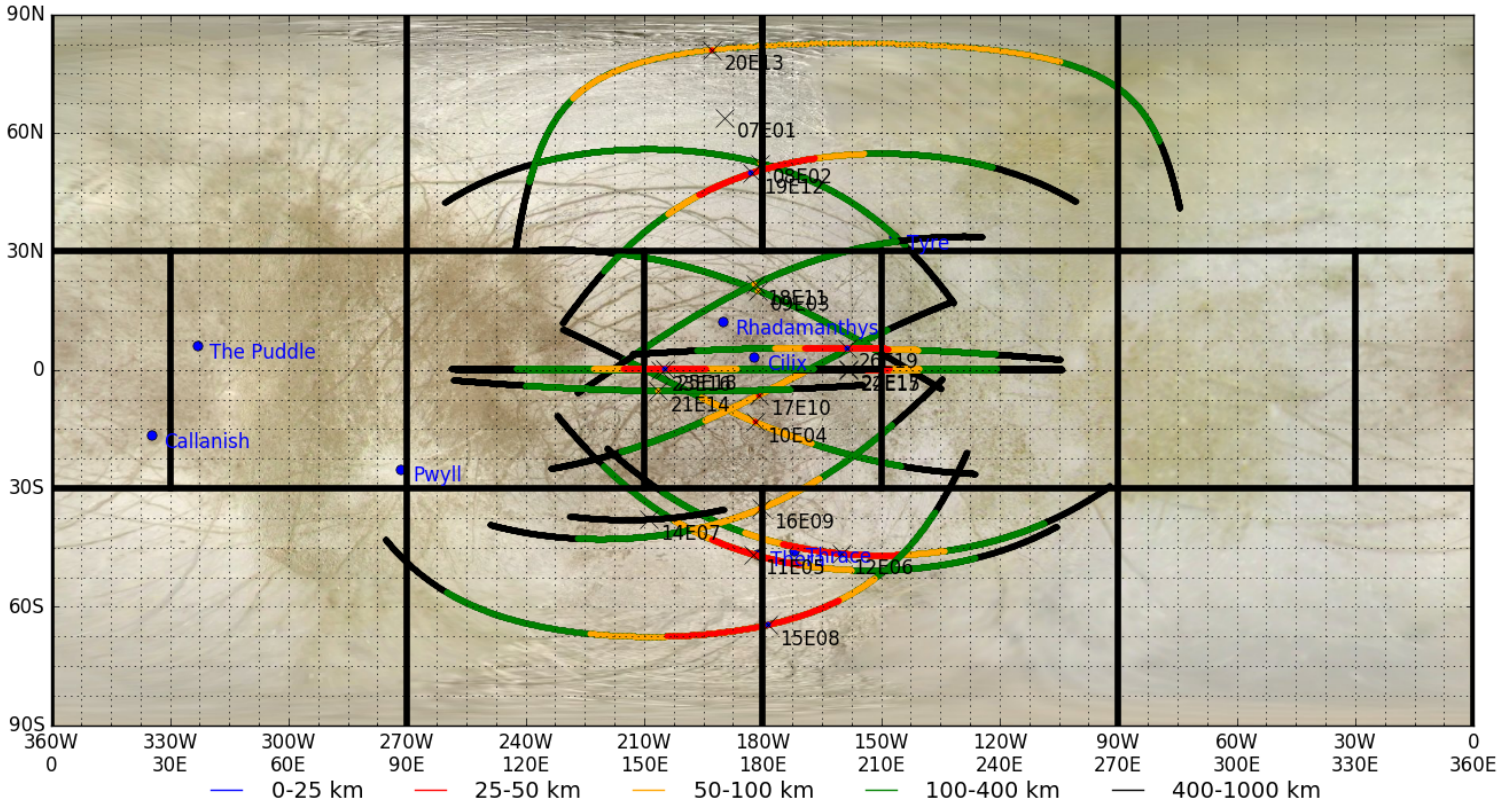
18F15: Trajectory and Groundtrack Buildup

To Petal Rotation

Trajectory Build-up



Groundtrack Build-up



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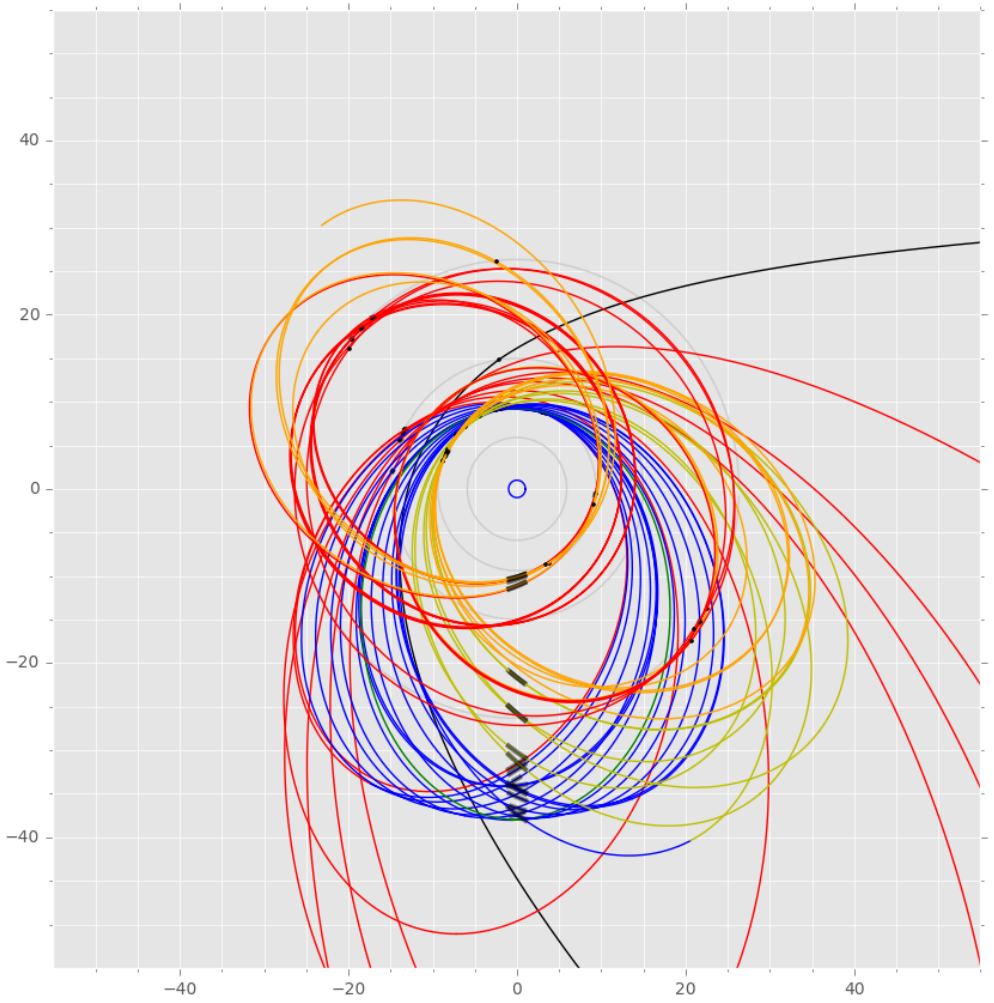
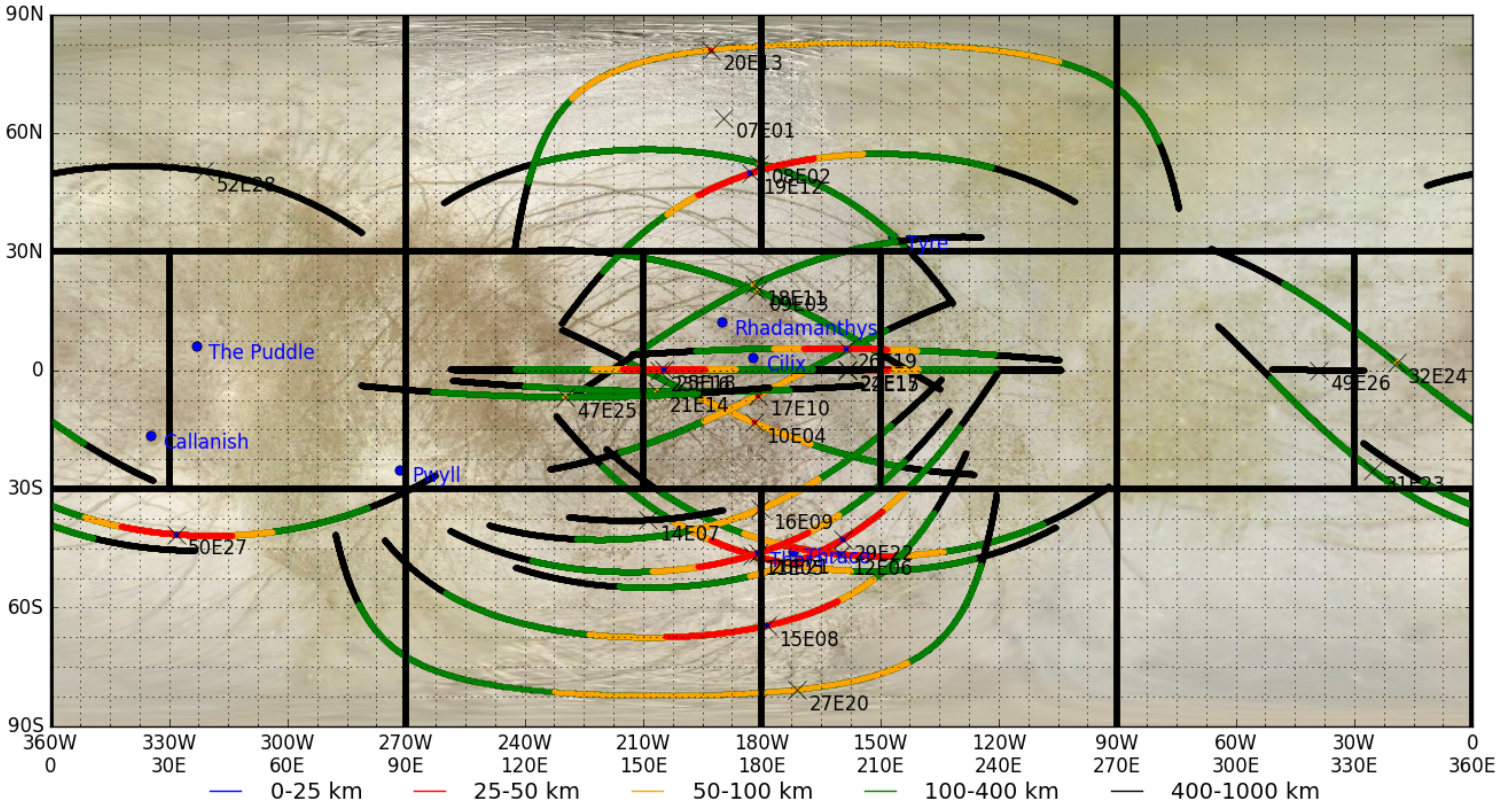
18F15: Trajectory and Groundtrack Buildup

To Switch Flip + Leading Edge

Trajectory Build-up



Groundtrack Build-up



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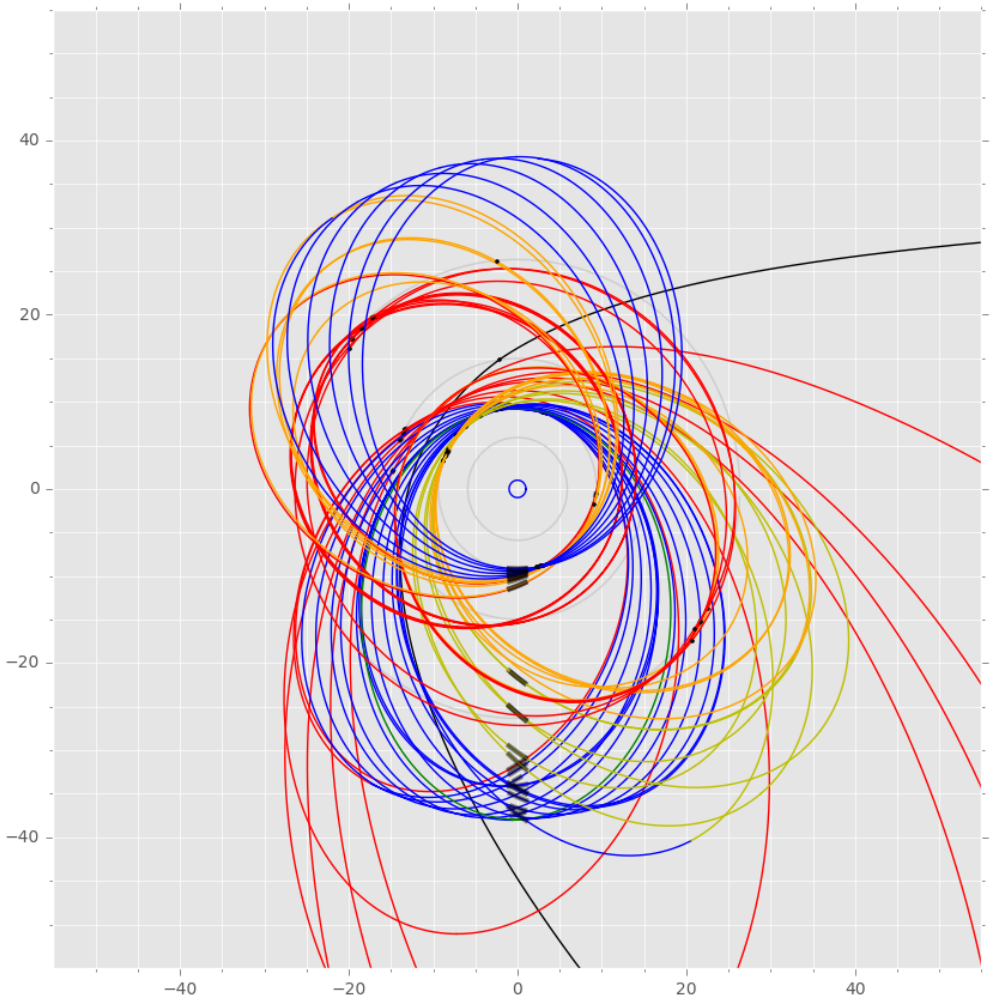
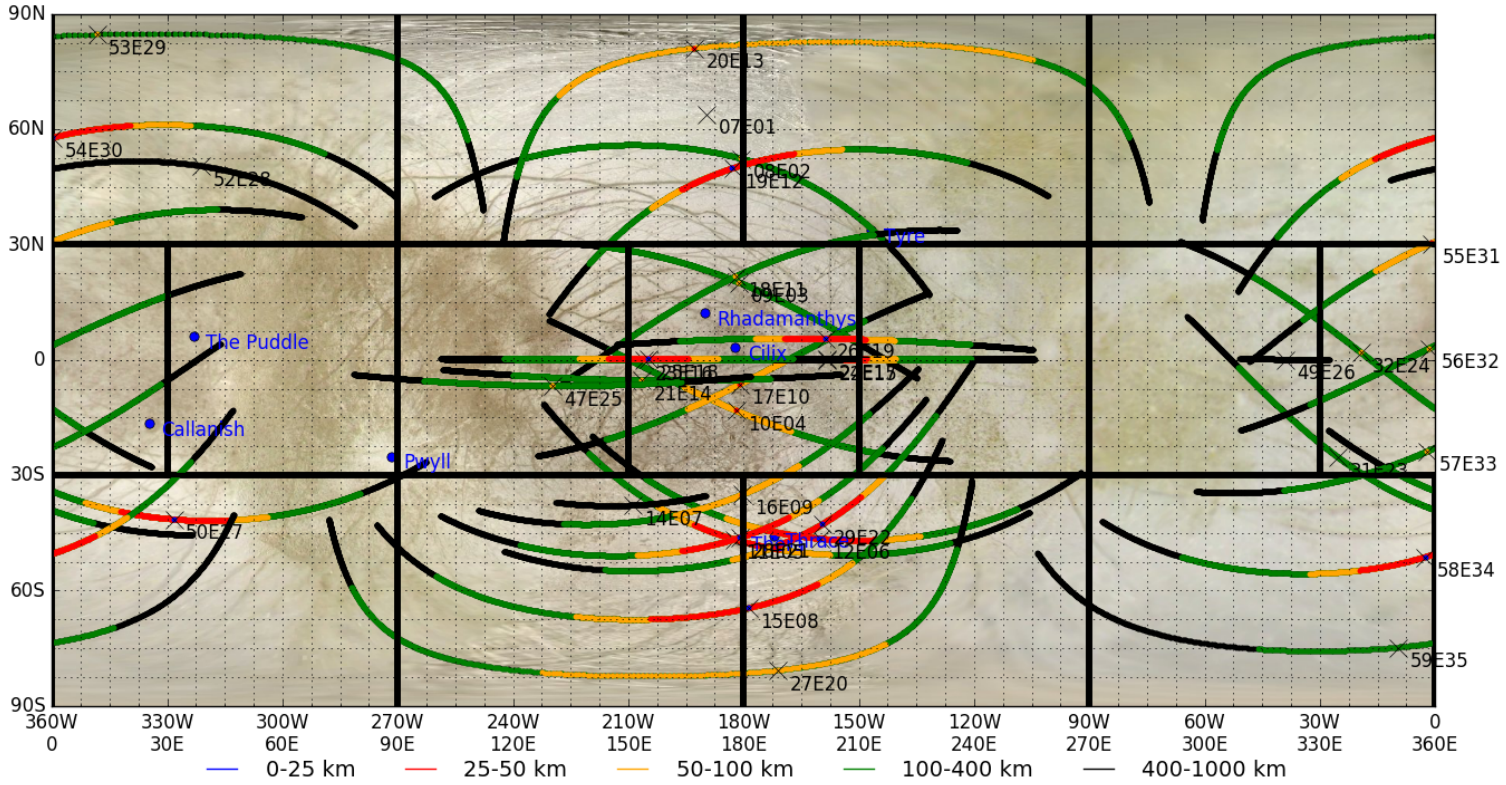
18F15: Trajectory and Groundtrack Buildup

To COT-3

Trajectory Build-up



Groundtrack Build-up



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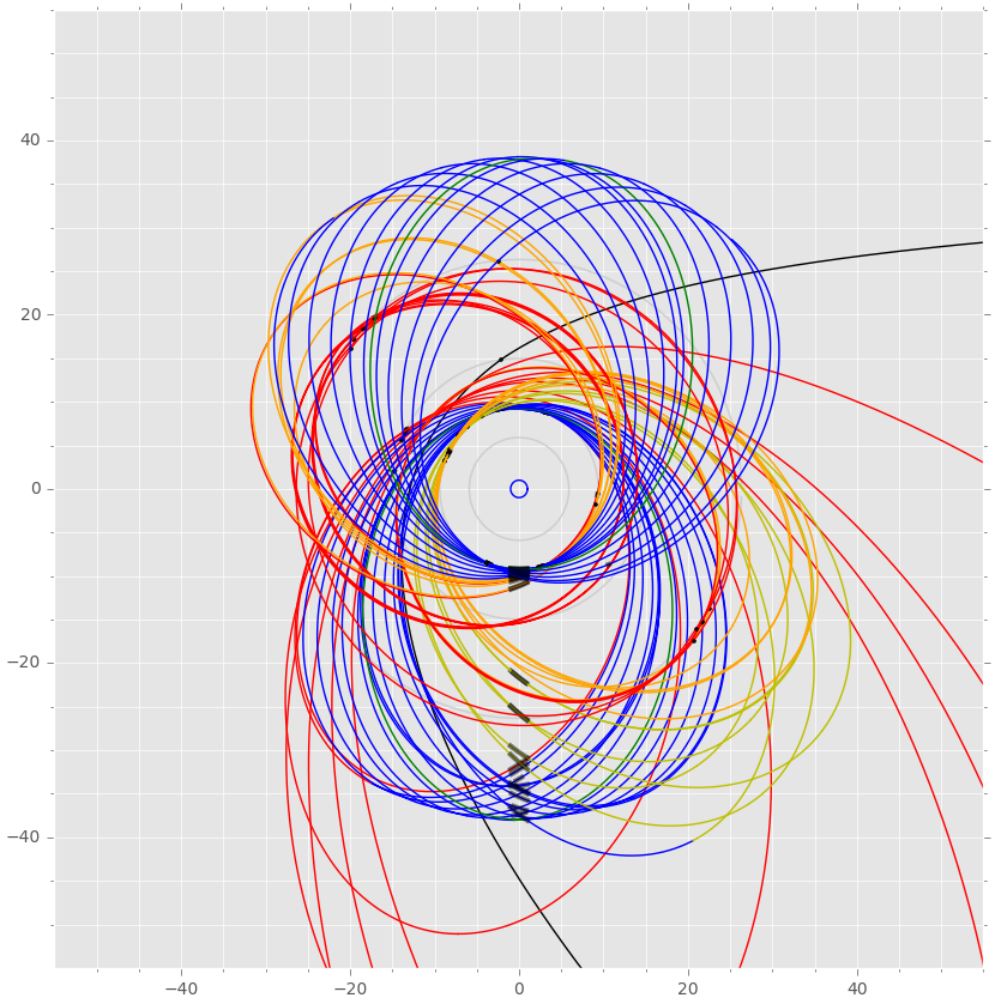
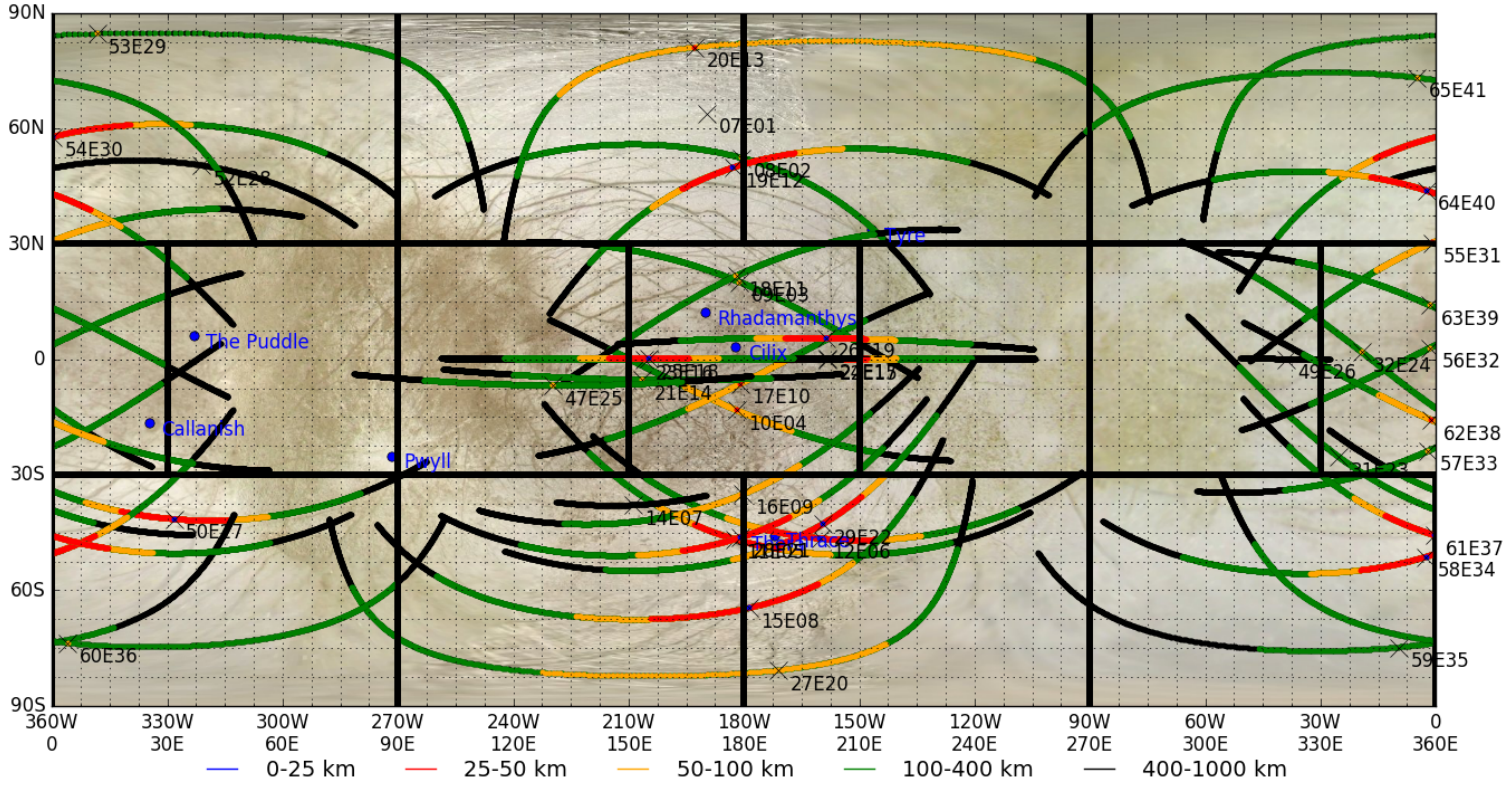
18F15: Trajectory and Groundtrack Buildup

To COT-4

Trajectory Build-up



Groundtrack Build-up



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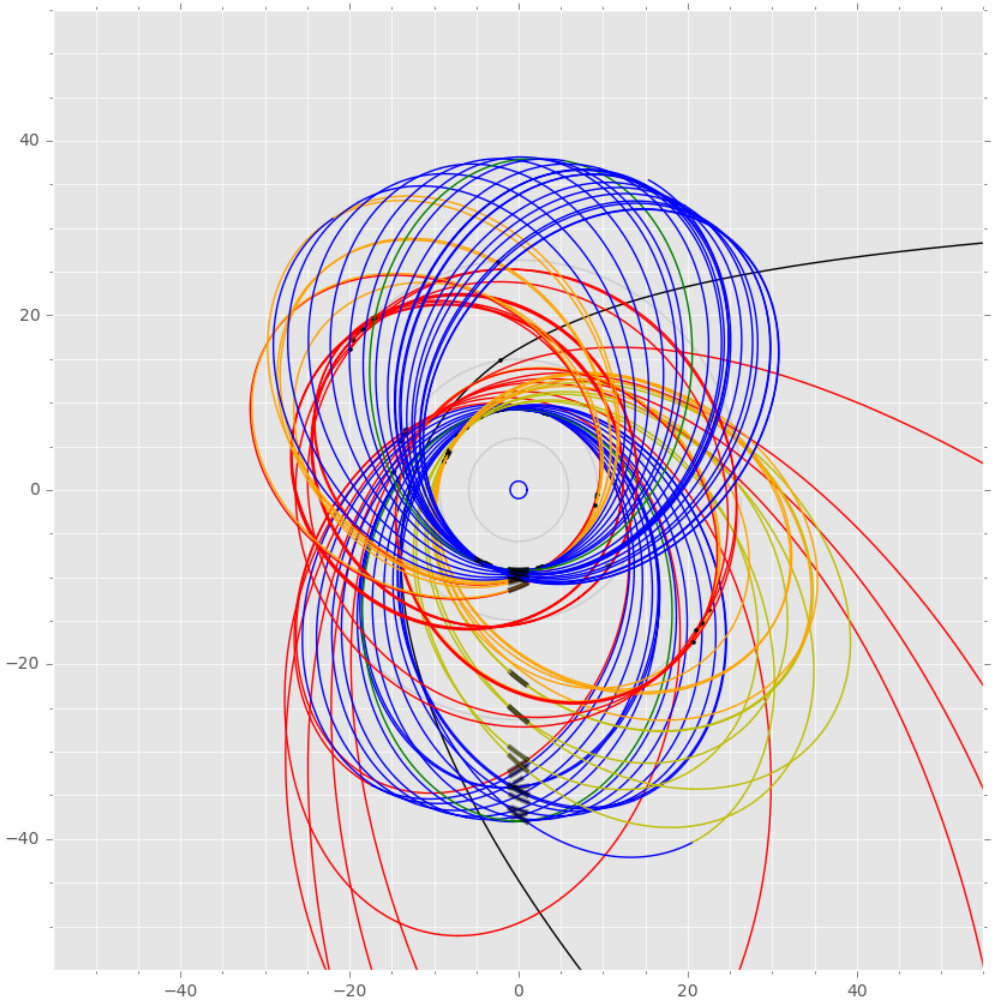
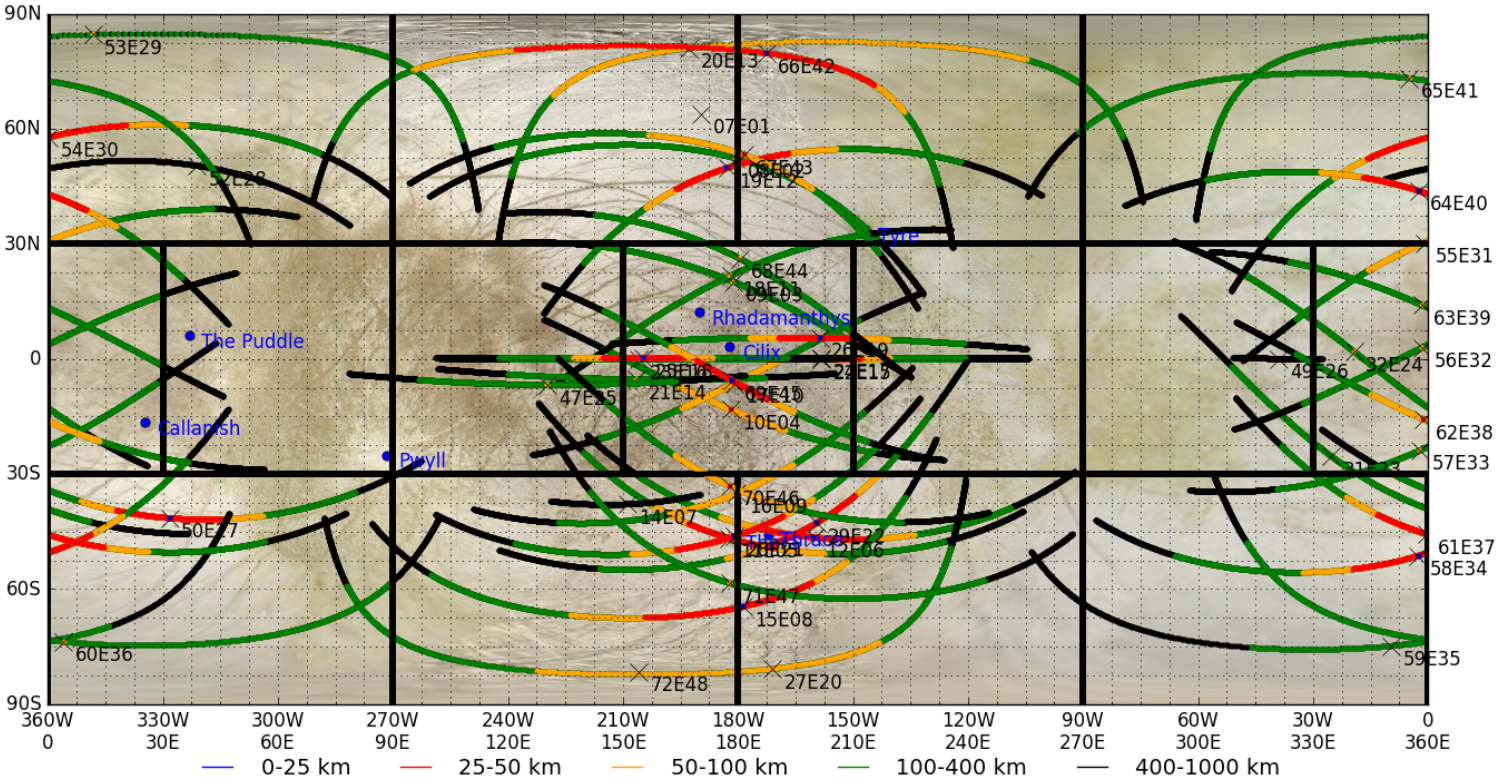
18F15: Trajectory and Groundtrack Buildup

To COT-5

Trajectory Build-up



Groundtrack Build-up



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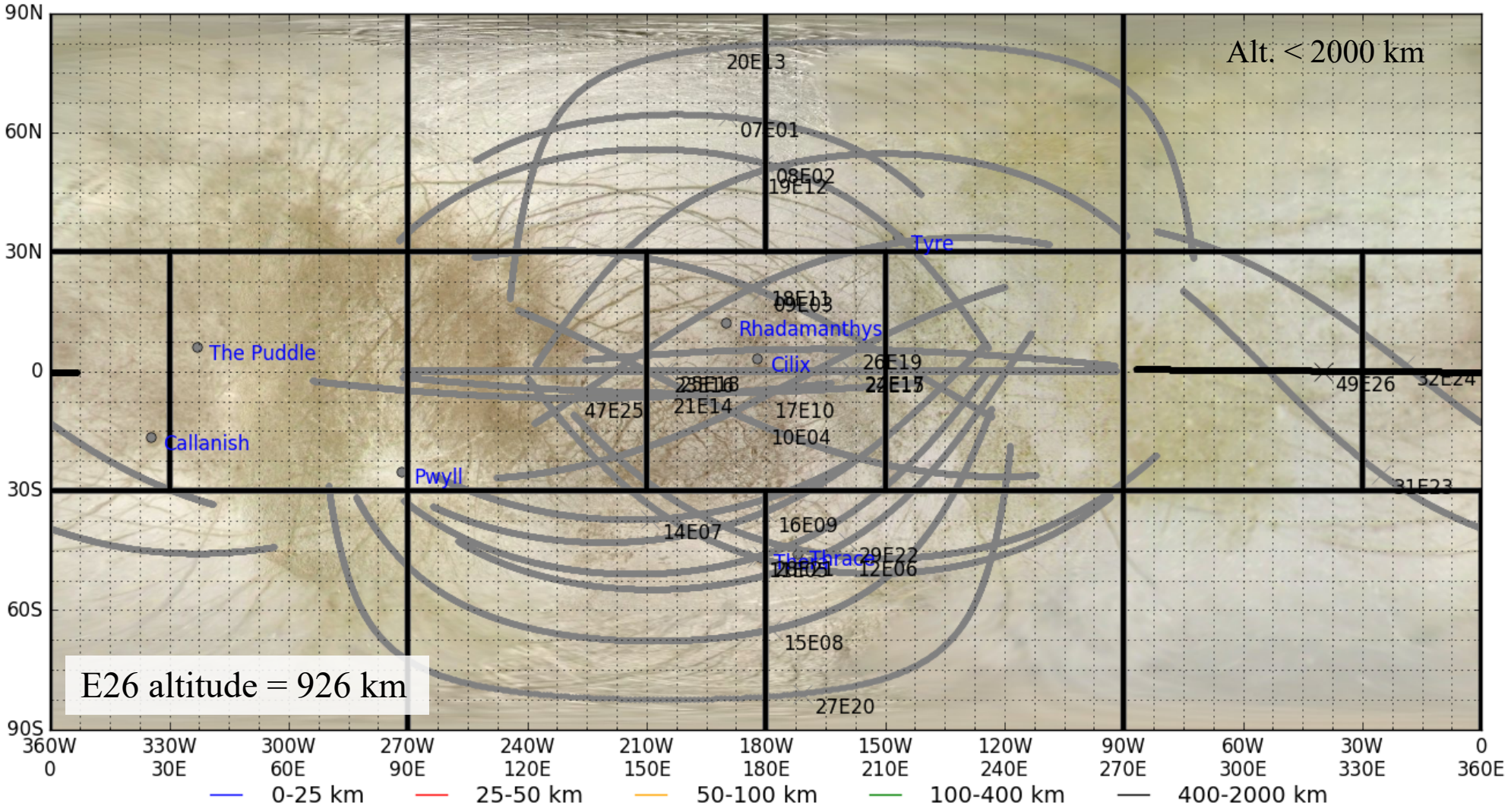
18F15: Leading Hemisphere Flyby (E32)



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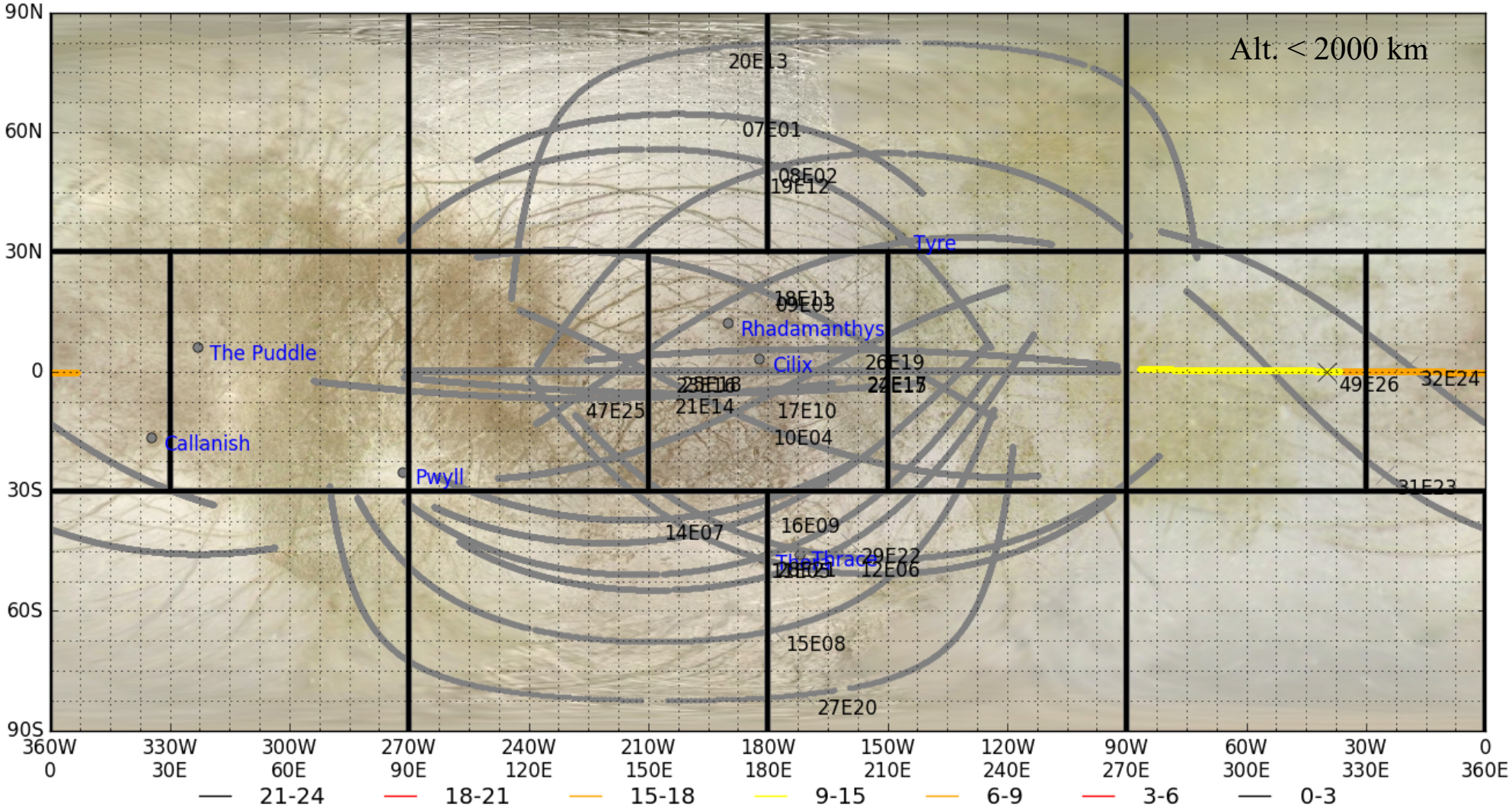
18F15: Leading Hemisphere Flyby (E32)



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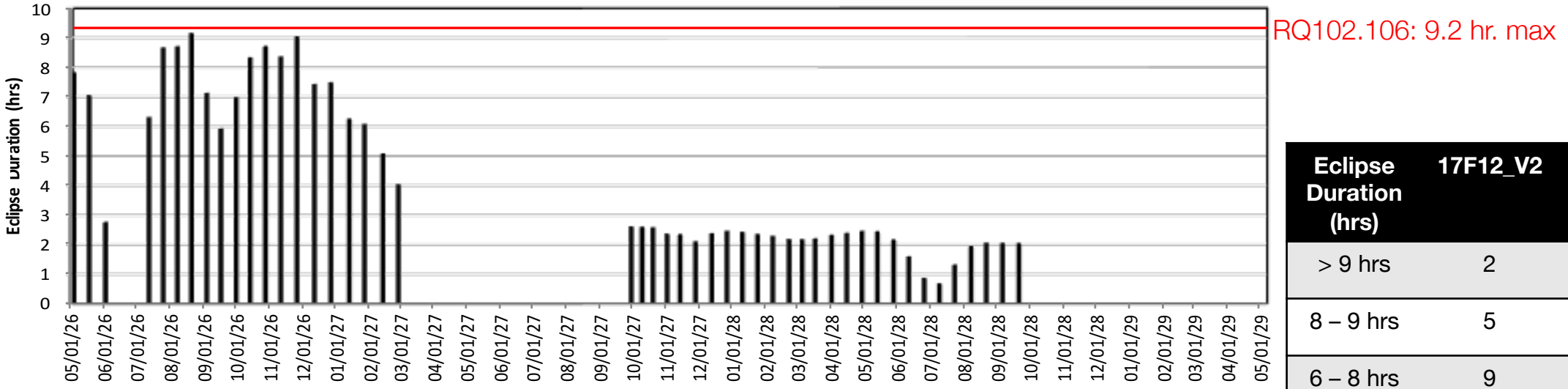
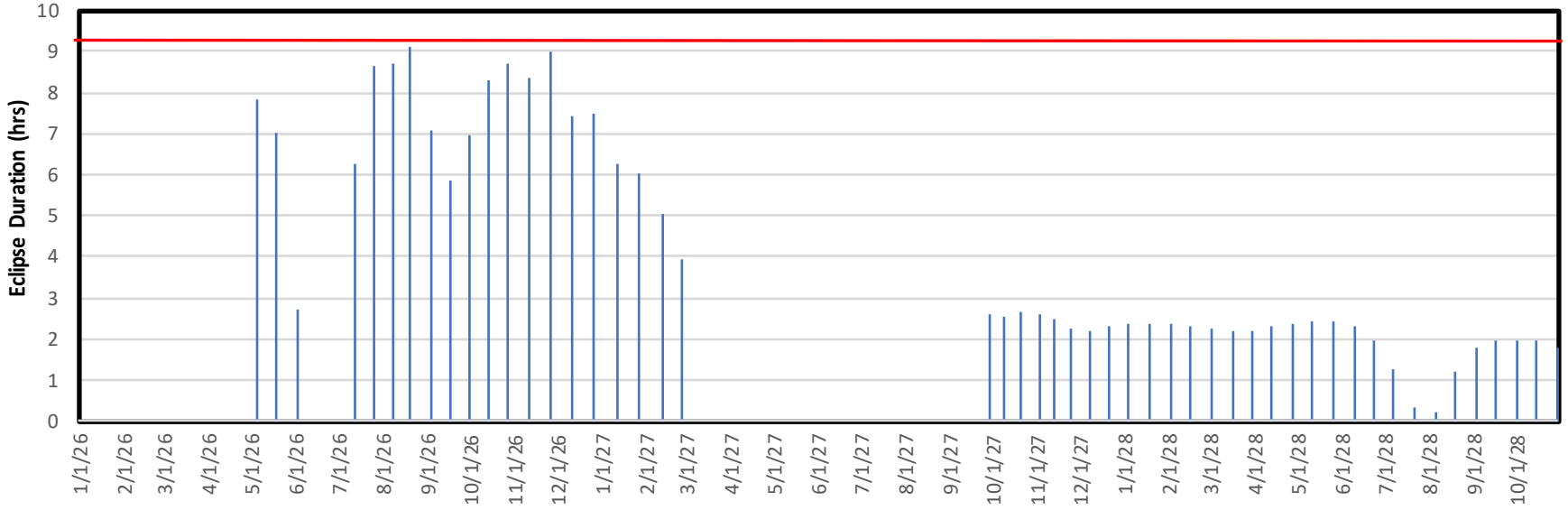
Eclipses

(17F12_V2 vs. 18F15)

17F12_V2



18F15



Eclipse Duration (hrs)	17F12_V2	18F15
> 9 hrs	2	2
8 – 9 hrs	5	5
6 – 8 hrs	9	9
4 – 6 hrs	3	3
2 – 4 hrs	23	23
< 2 hrs (non-zero)	5	11

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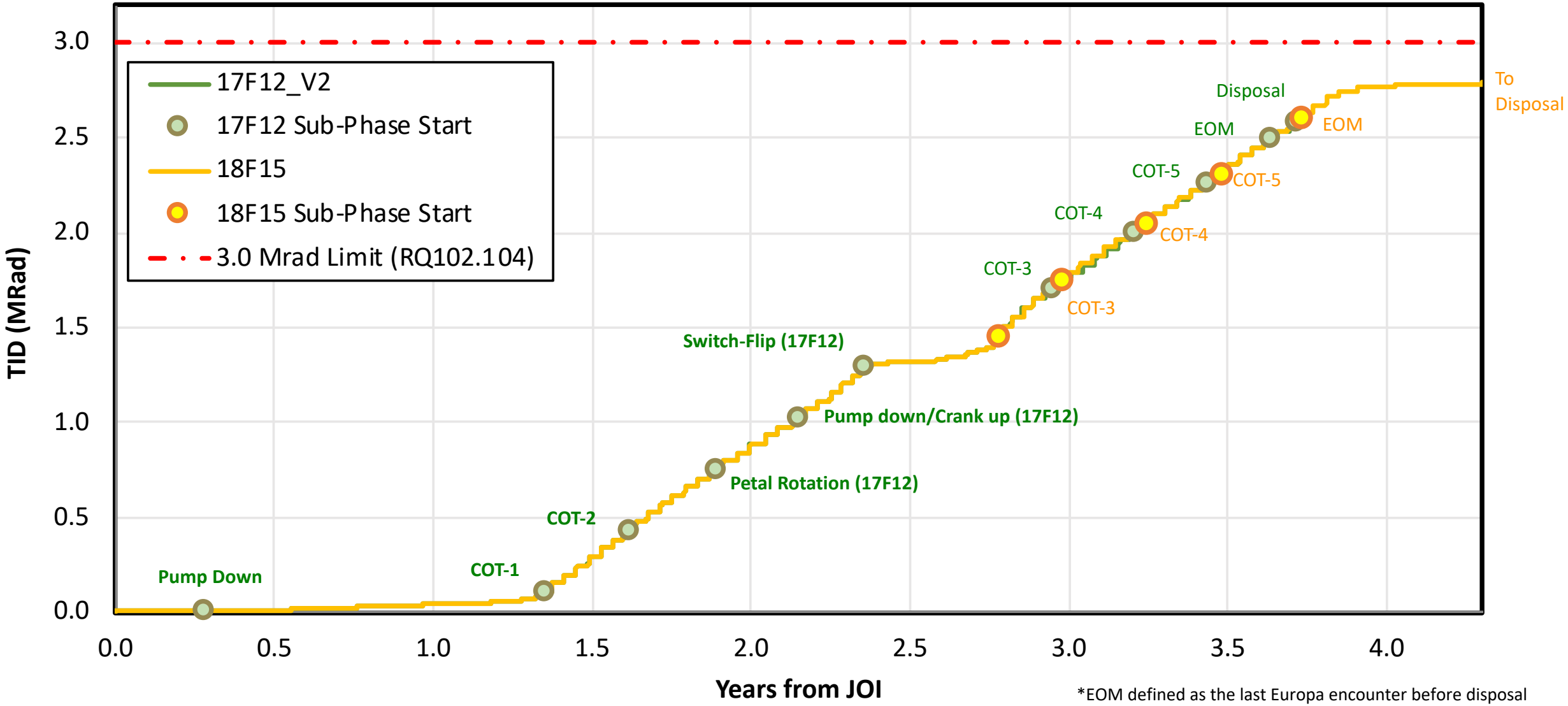
TID Build-Up: 17F12_V2 vs. 18F15



*EOM defined as the last Europa encounter before disposal

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18F16

Try Lam

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18F16_V3 Summary

- 18F16_V3 is similar to 17F13
  - Includes a leading edge flyby (E32) post Switch-Flip to meet MISE measurement requirement
  - COT-4, COT-5, and COT-6 is similar to 17F12 EC2 (not 17F13 EC2)
  - Ends with a Ganymede flyby setting up a pump-up for a Jupiter impactor
  - Flyby altitude for the latter part of the tour still needs to be adjusted based on feedback from Nav
  - In an attempt to save flight time and TID, some high latitude flybys were eliminated
- 18F16_V3 evolved from V1 due to feedback from Nav and Mission Planning

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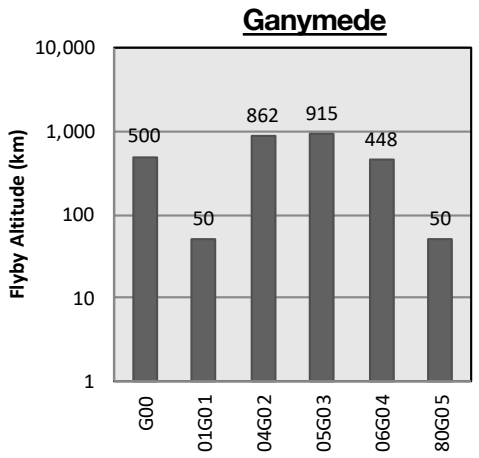
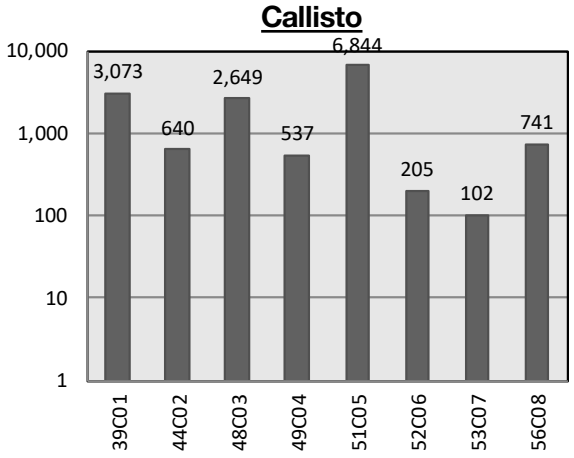
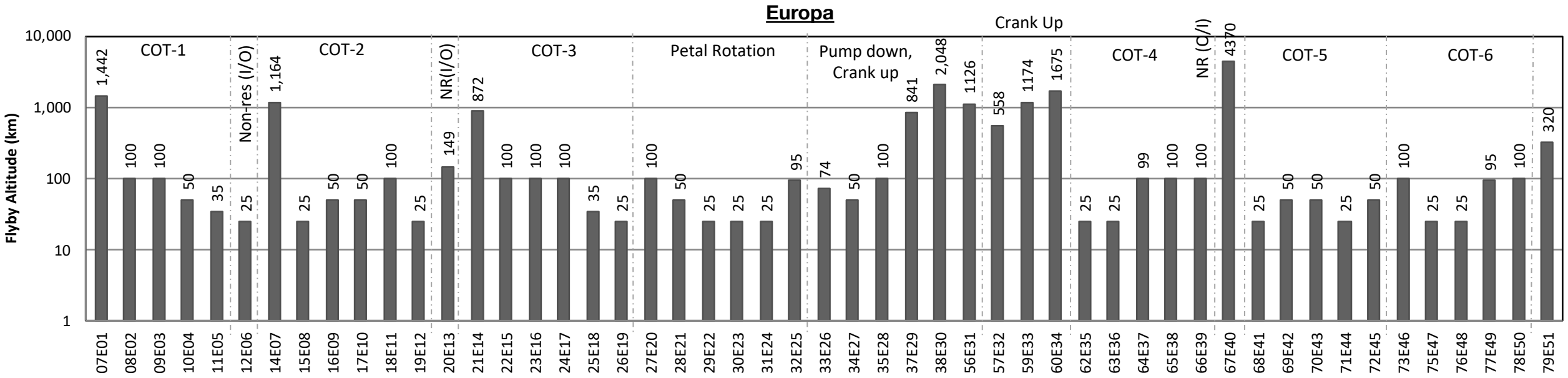
18F16: Flyby Altitude Profile

Europa Altitude Bin	17F12_V2
>1000 km	5
100 – 1000 km	19
50 – 99 km	12
25 – 49 km	15







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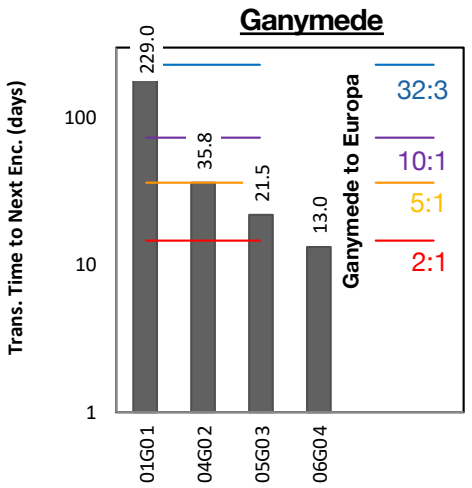
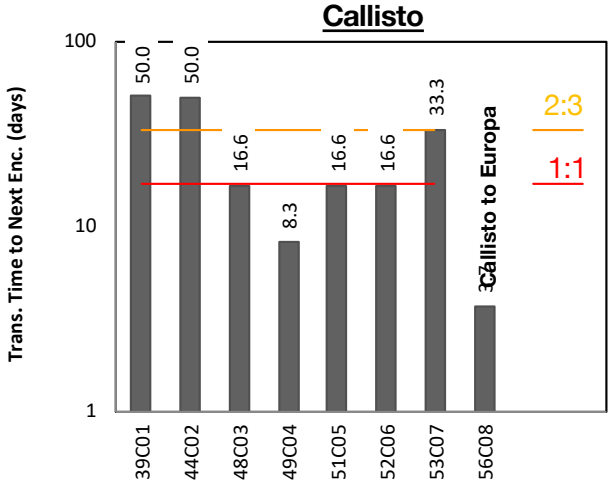
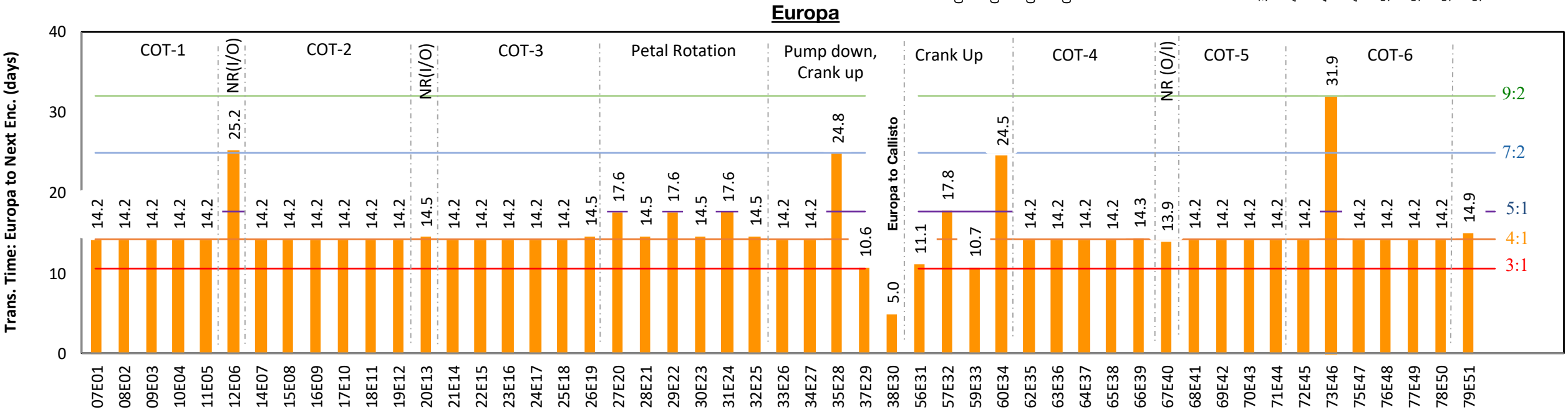
18F16: Transfer Time Profile

Europa-to-Europa Trans. Bin	18F16
< 14.2 days	4
≅ 14.2 days	39
> 14.2 days	8







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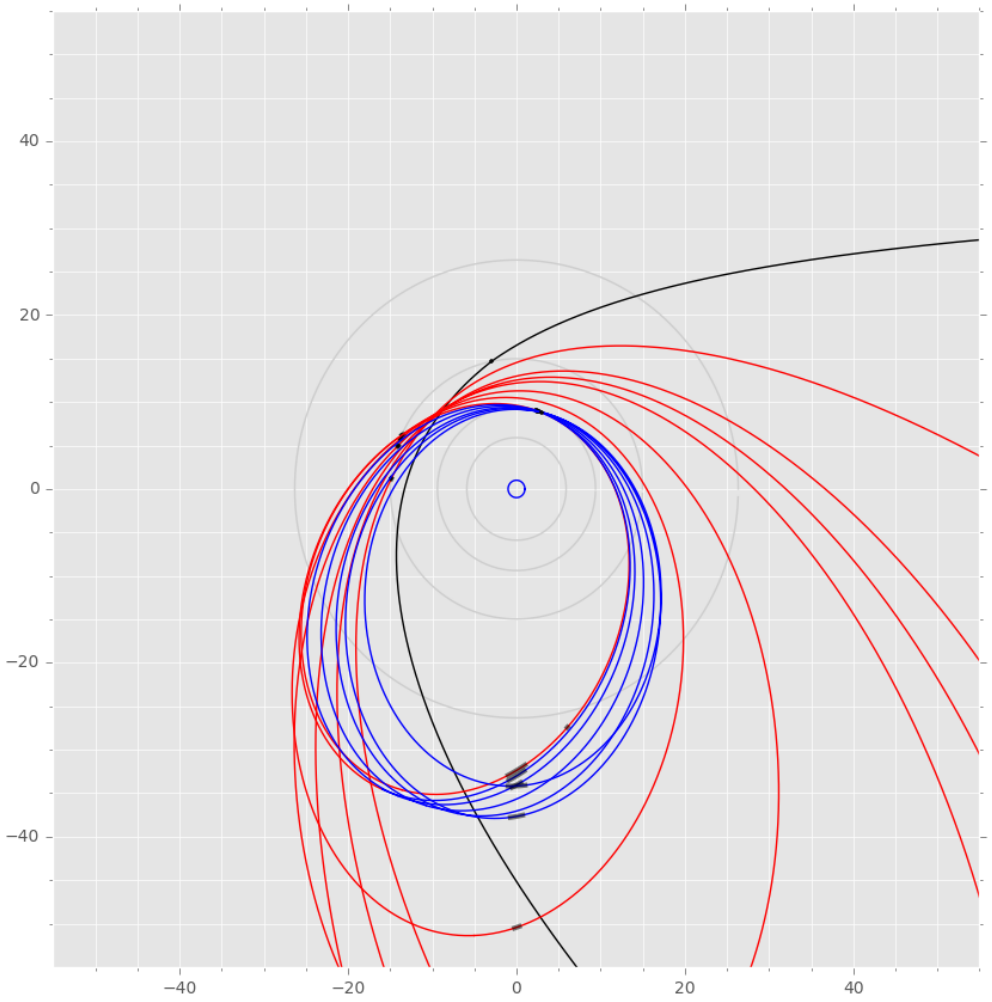
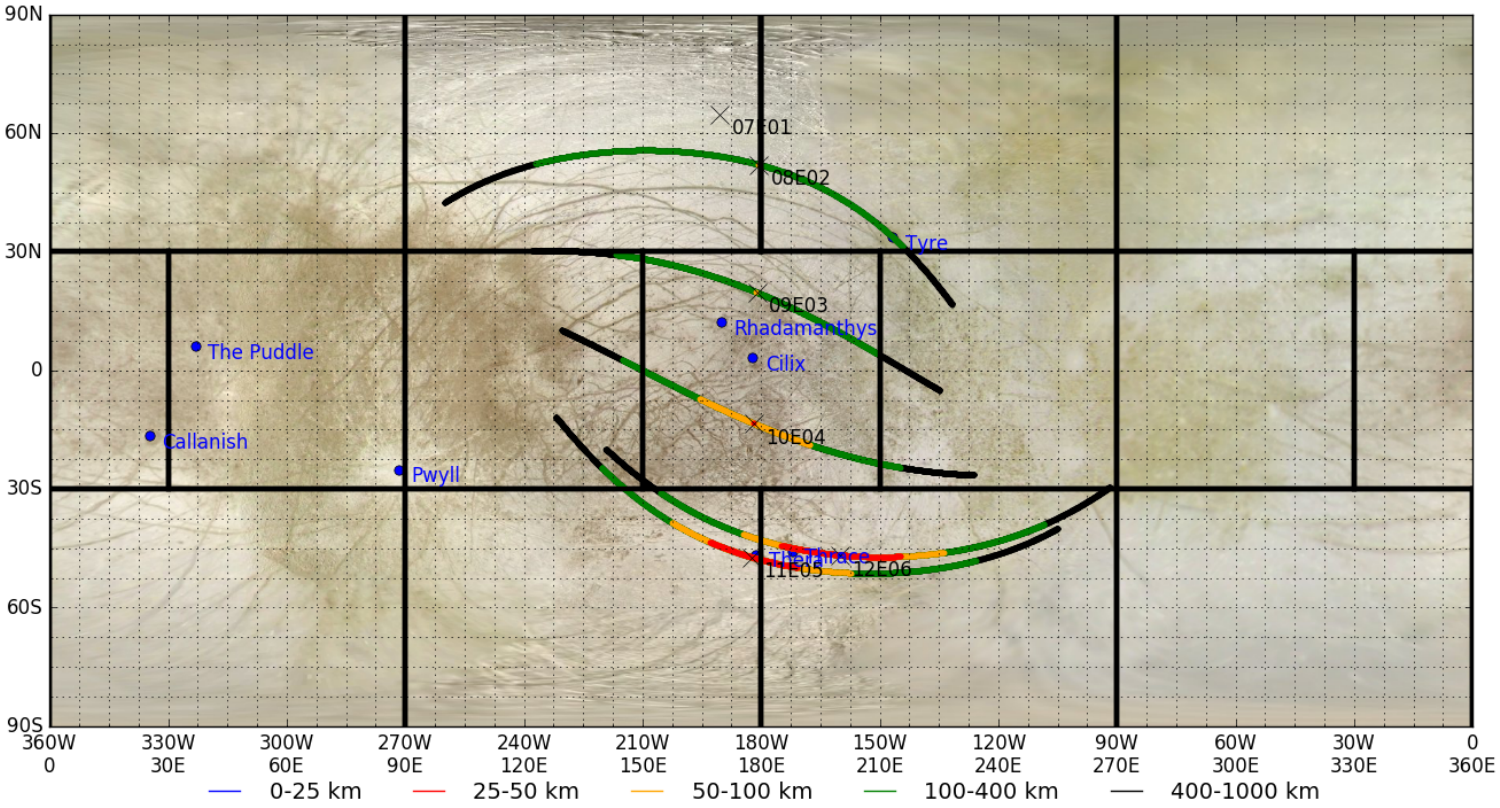
18F16: Trajectory and Groundtrack Buildup

COT-1

Trajectory Build-up



Groundtrack Build-up



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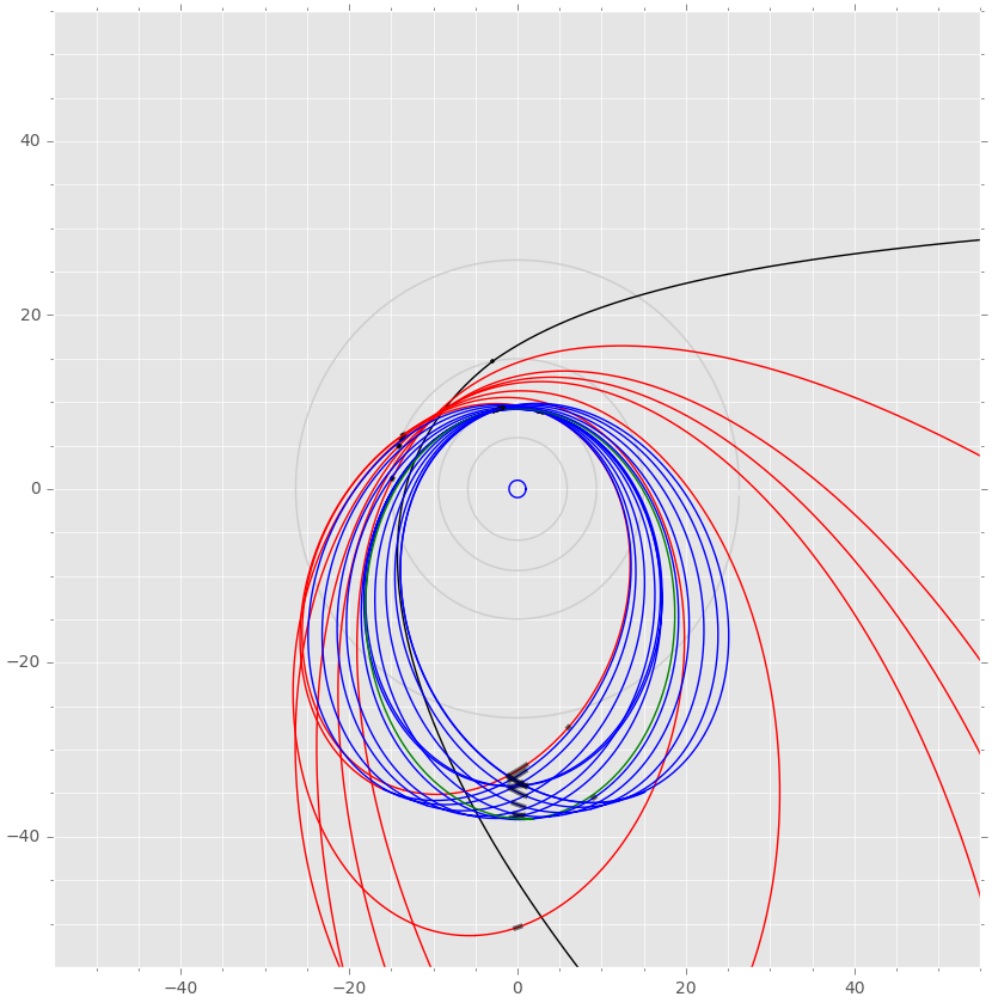
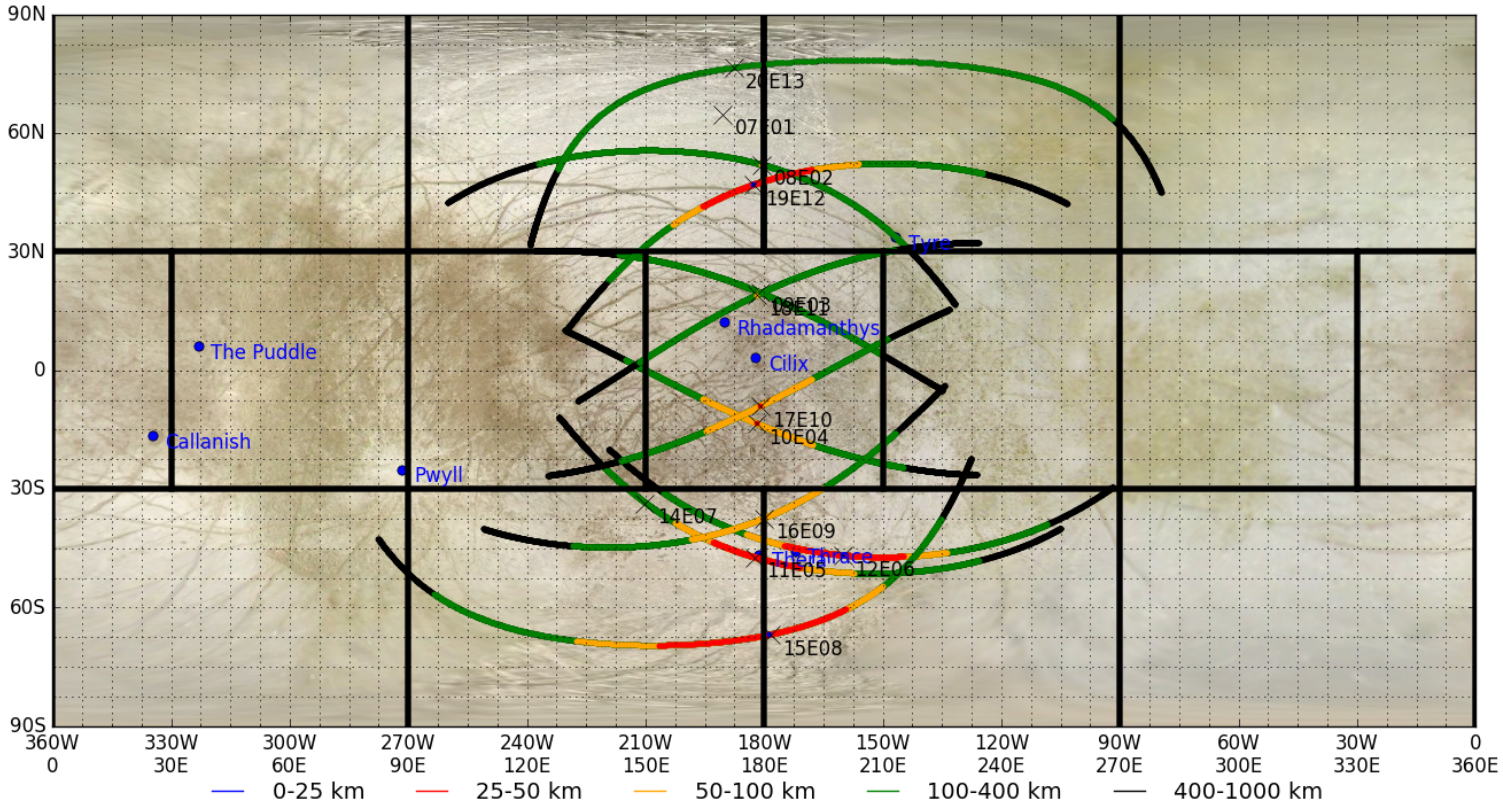
18F16: Trajectory and Groundtrack Buildup

To COT-2

Trajectory Build-up



Groundtrack Build-up



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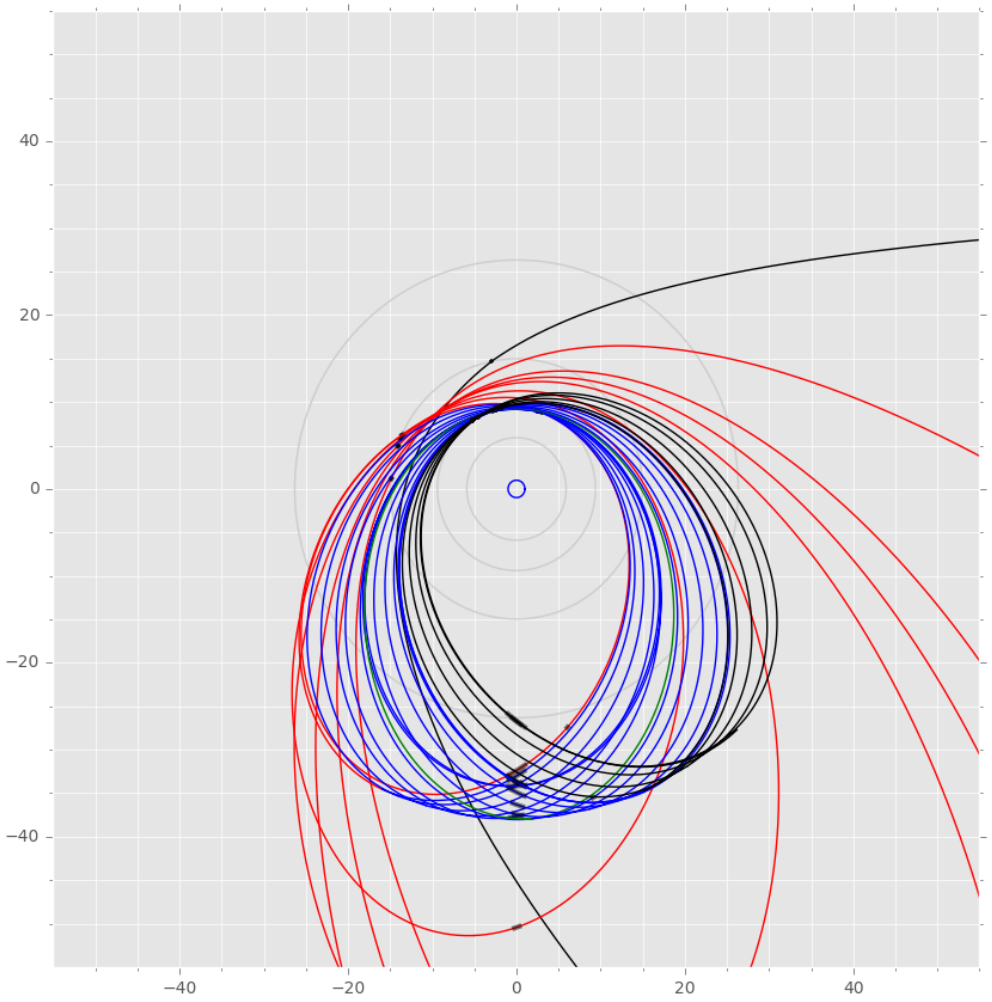
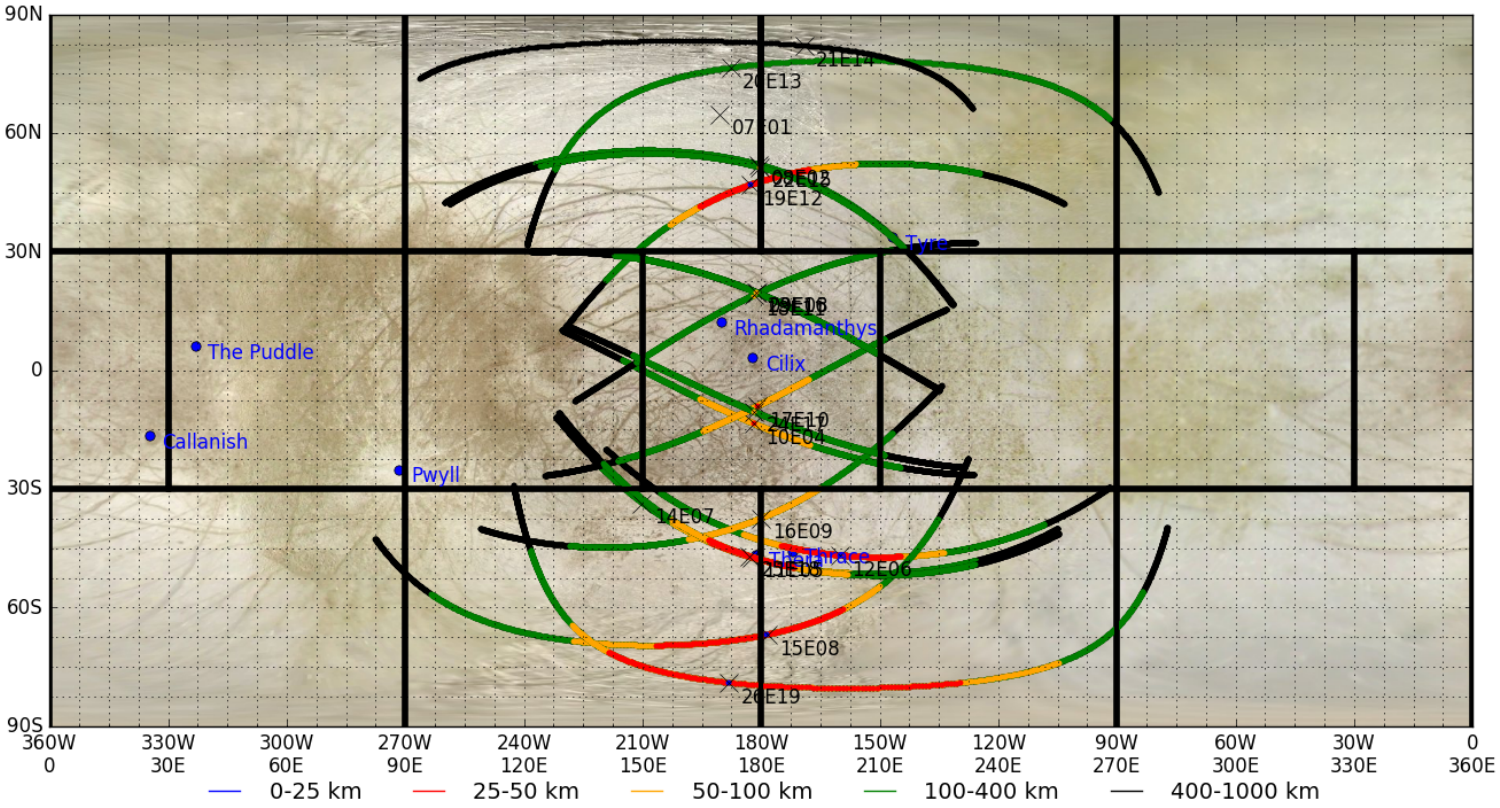
18F16: Trajectory and Groundtrack Buildup

To COT-3

Trajectory Build-up



Groundtrack Build-up



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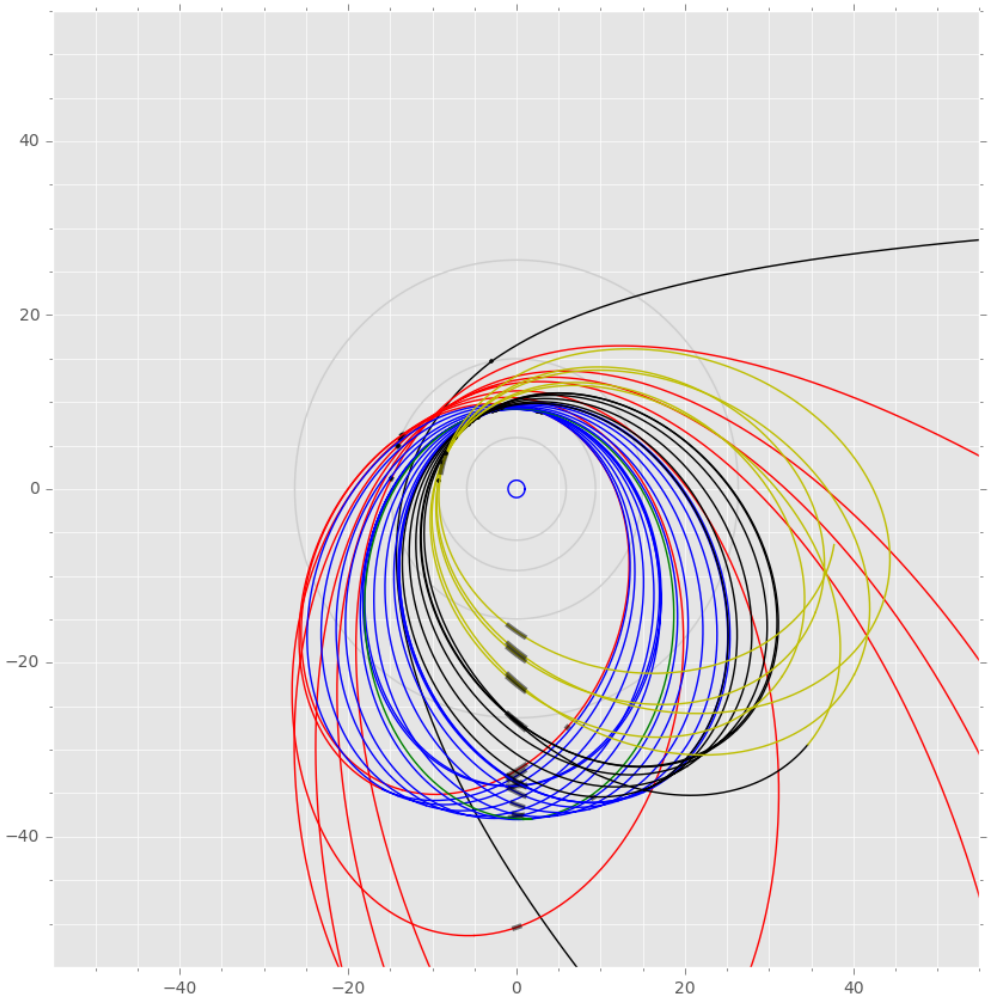
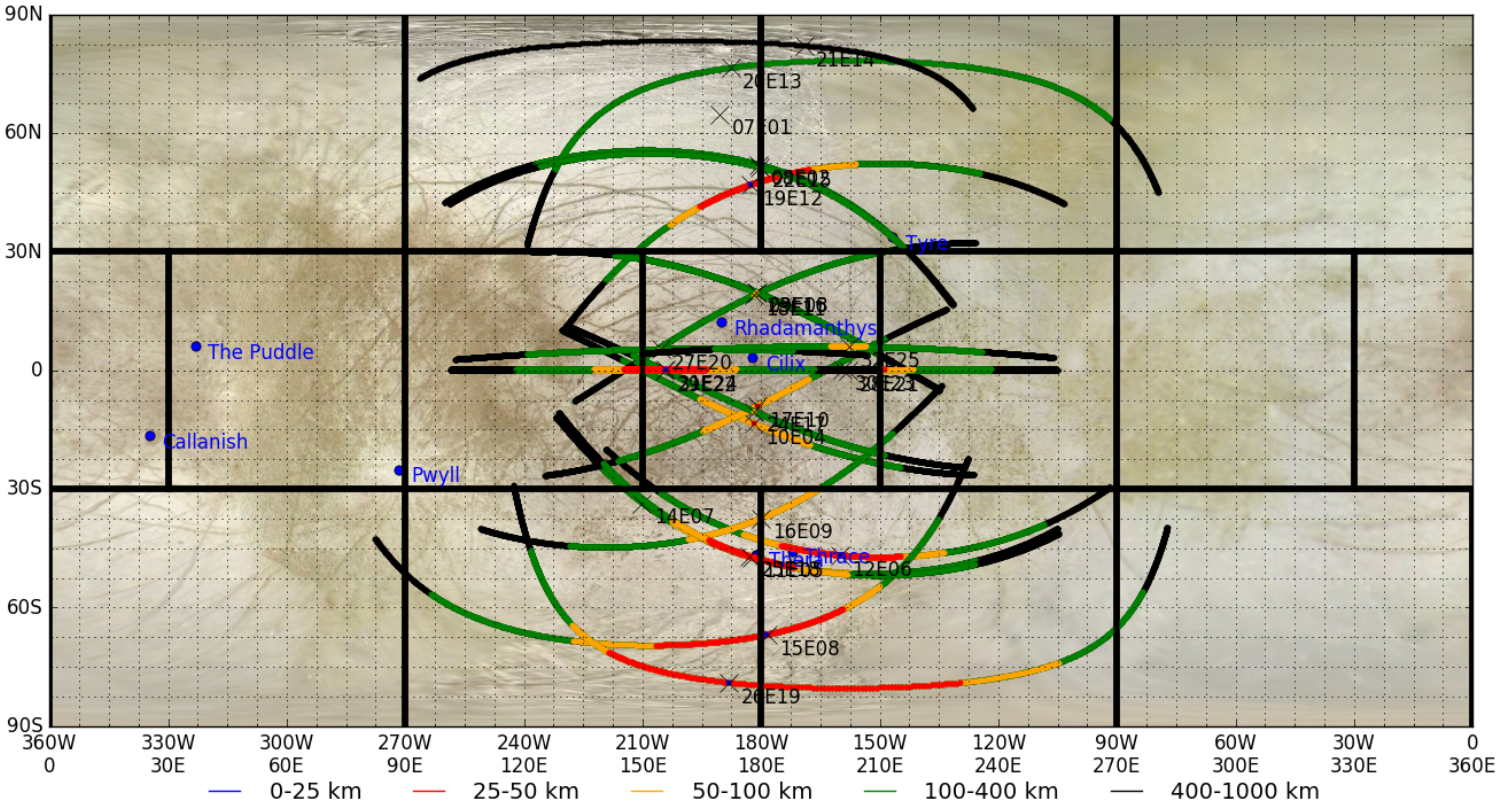
18F16: Trajectory and Groundtrack Buildup

To Petal Rotation

Trajectory Build-up



Groundtrack Build-up



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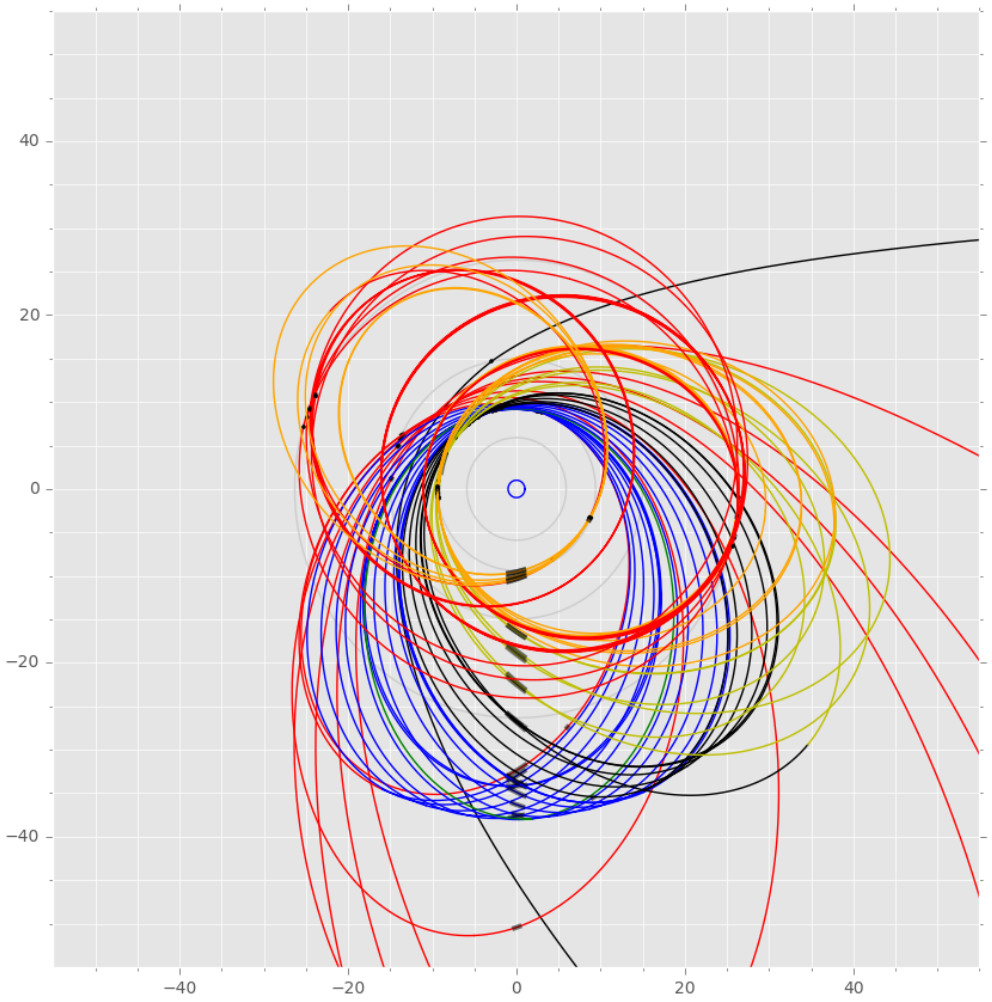
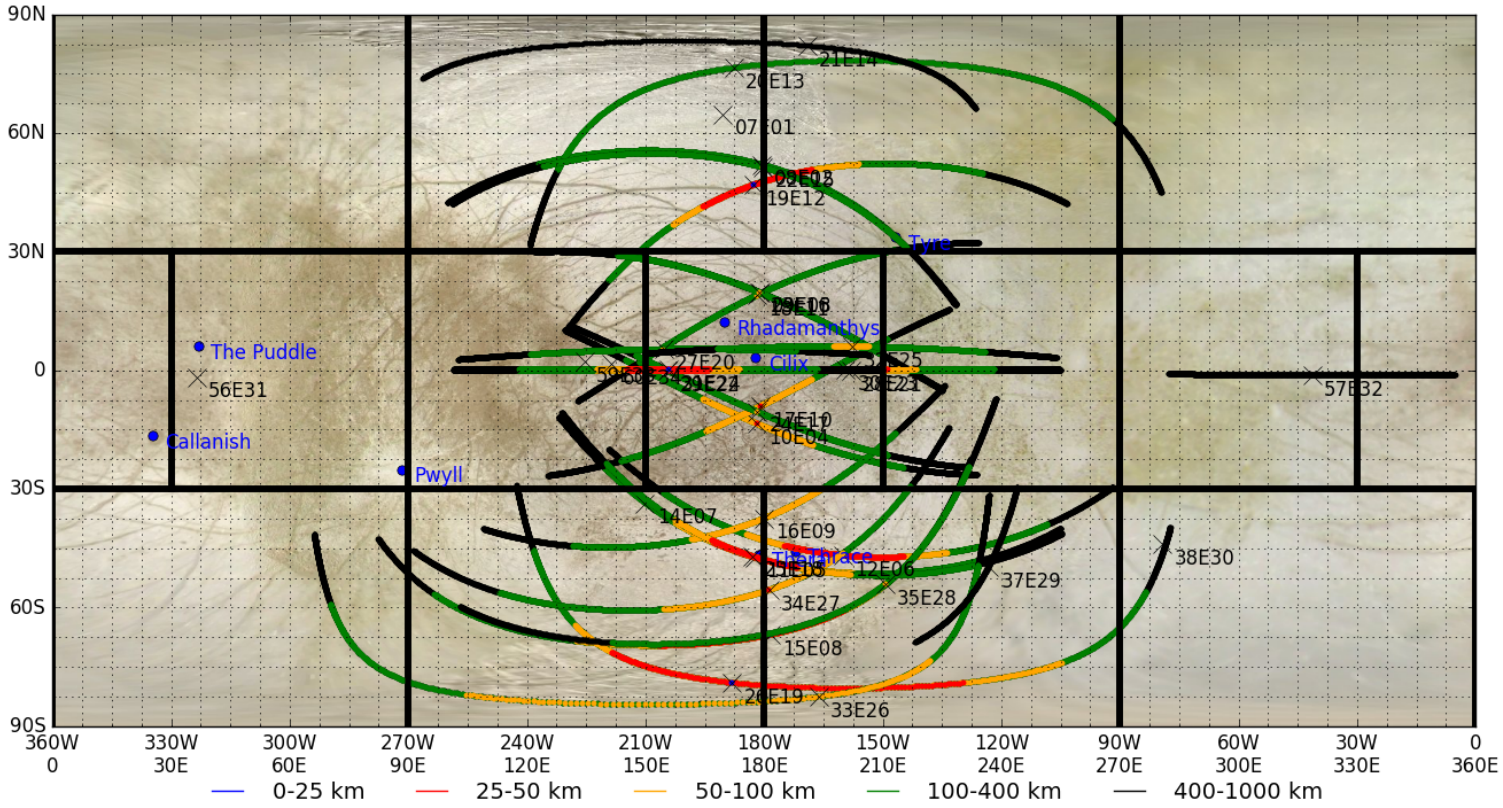
18F16: Trajectory and Groundtrack Buildup

To Switch Flip + LE

Trajectory Build-up



Groundtrack Build-up



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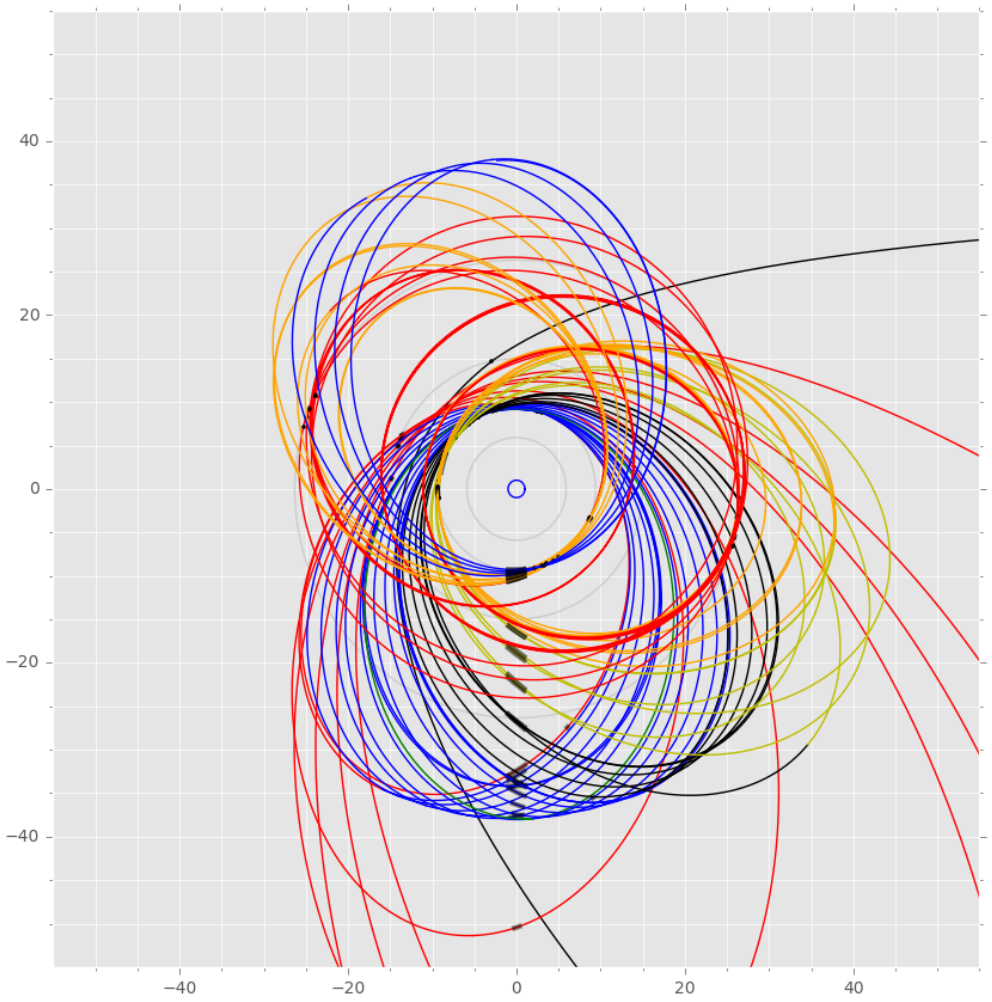
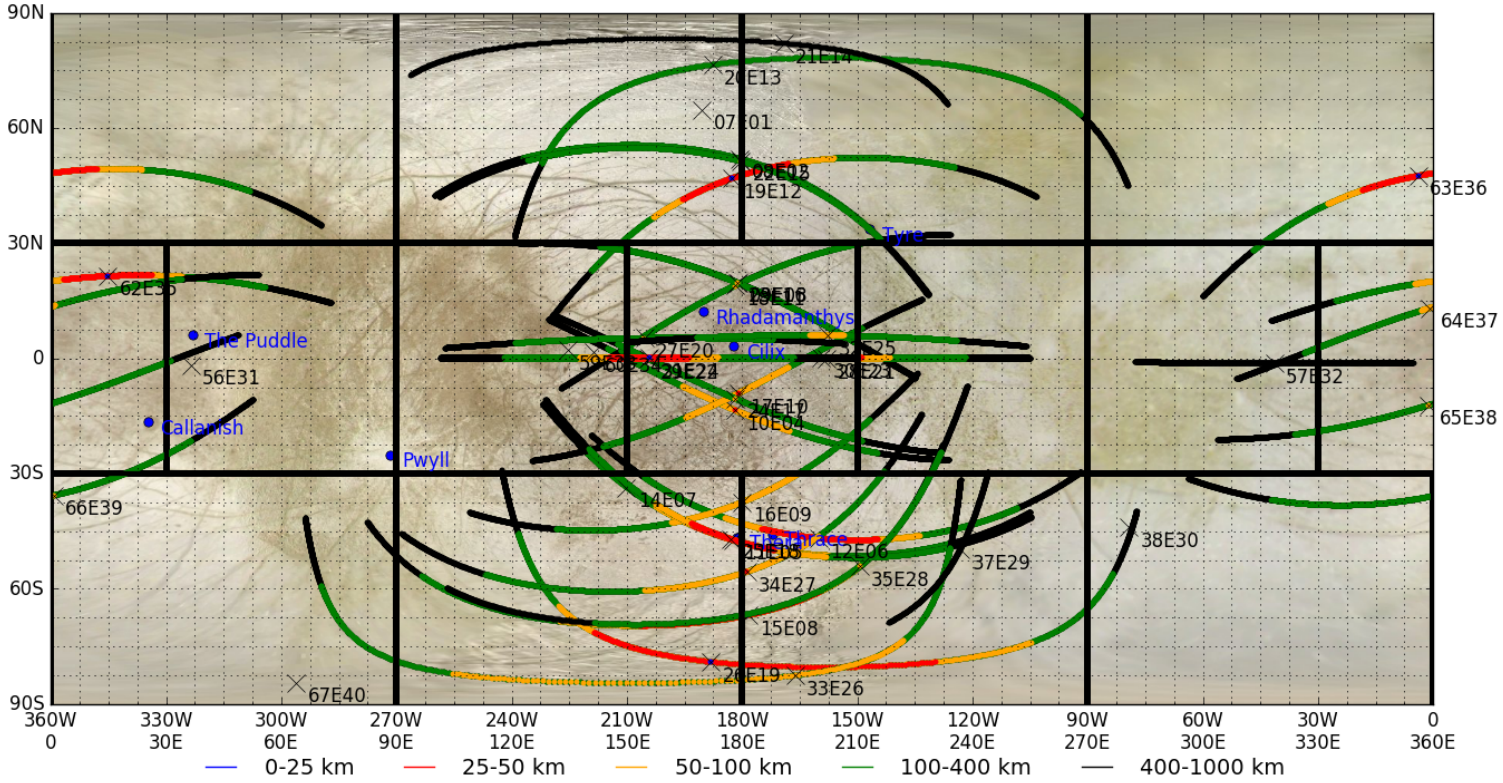
18F16: Trajectory and Groundtrack Buildup

To COT-4

Trajectory Build-up



Groundtrack Build-up



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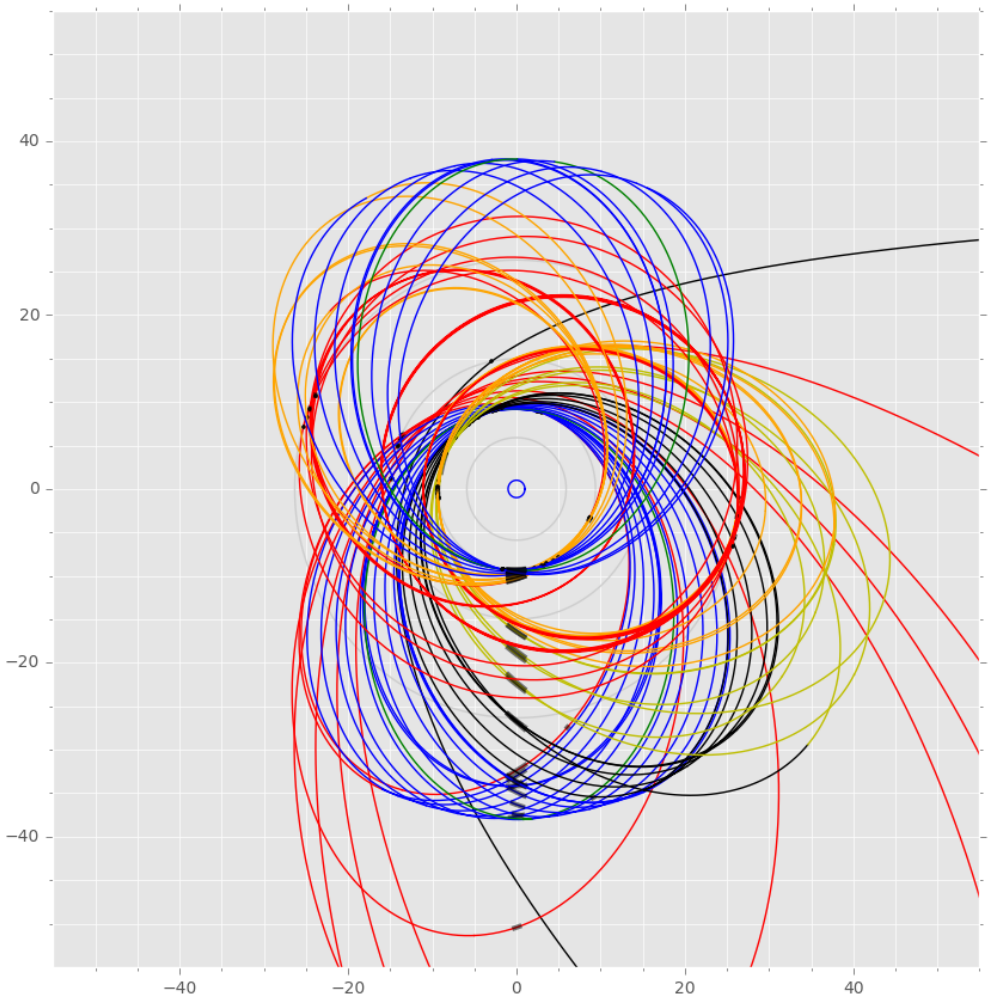
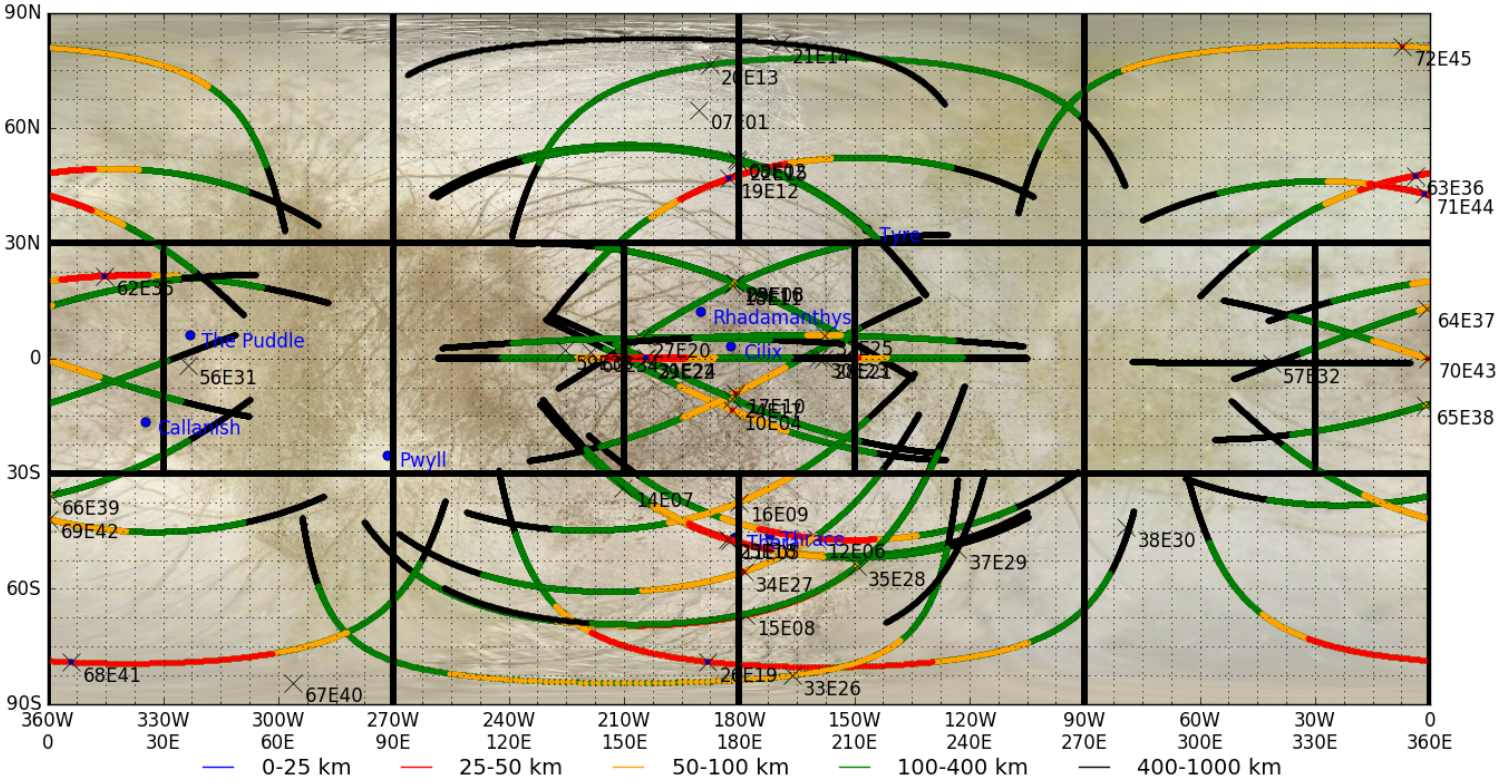
18F16: Trajectory and Groundtrack Buildup

To COT-5

Trajectory Build-up



Groundtrack Build-up



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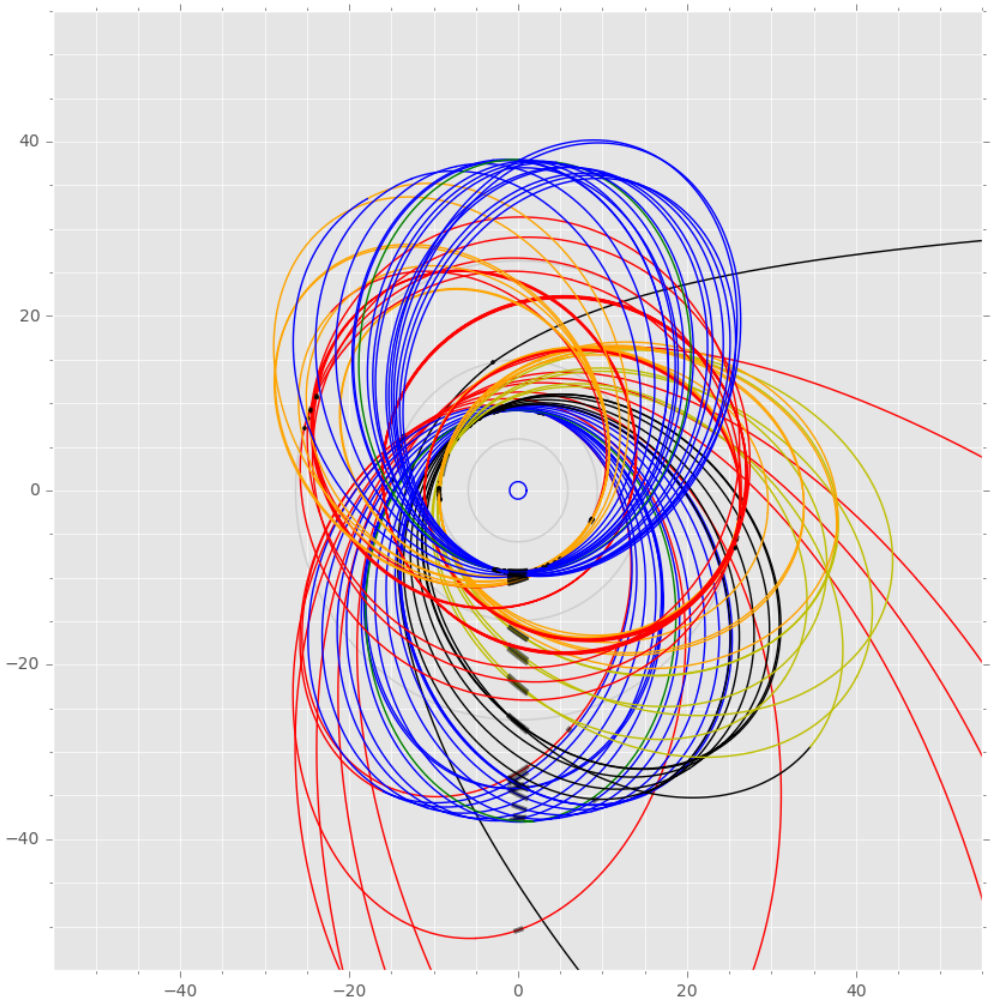
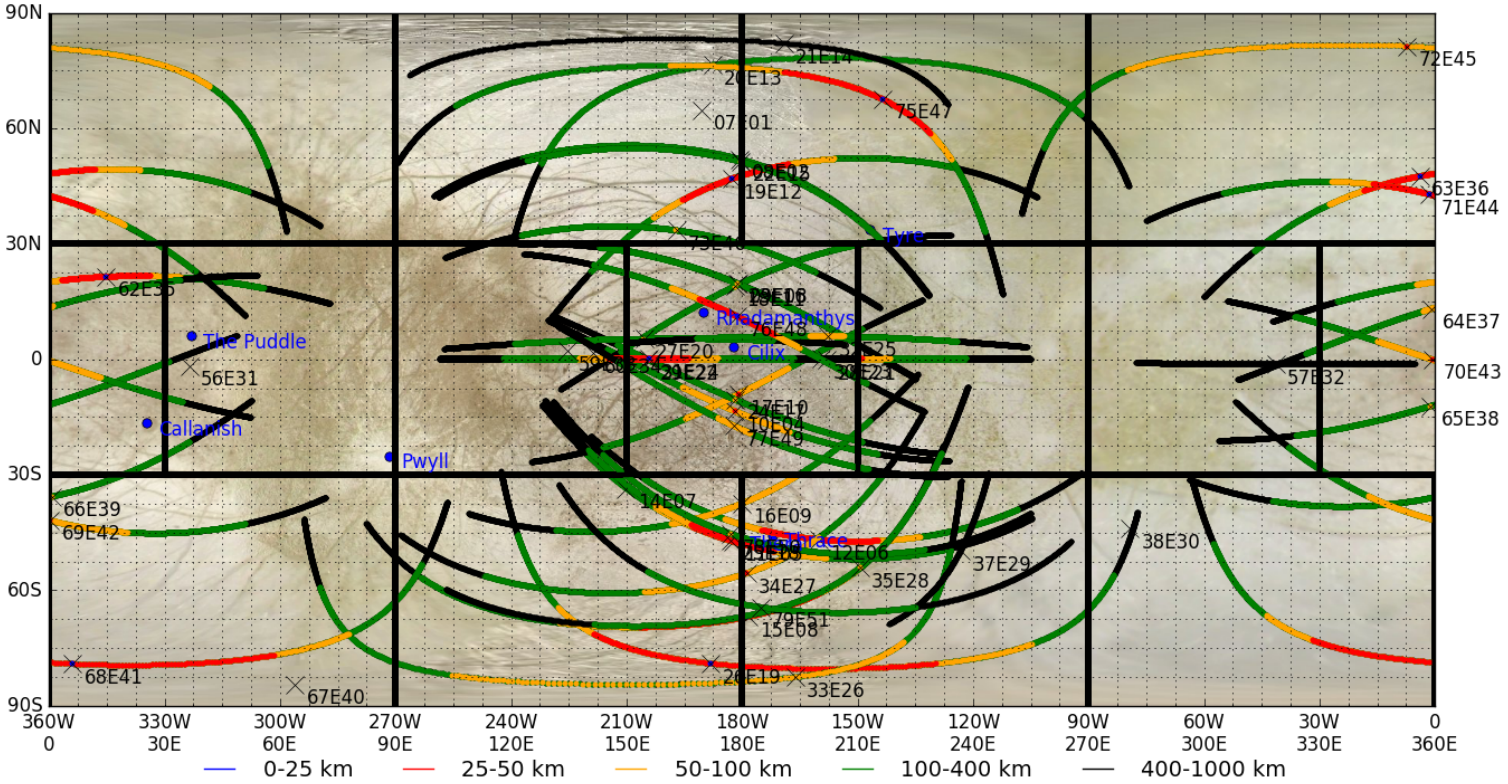
18F16: Trajectory and Groundtrack Buildup

To COT-6

Trajectory Build-up



Groundtrack Build-up



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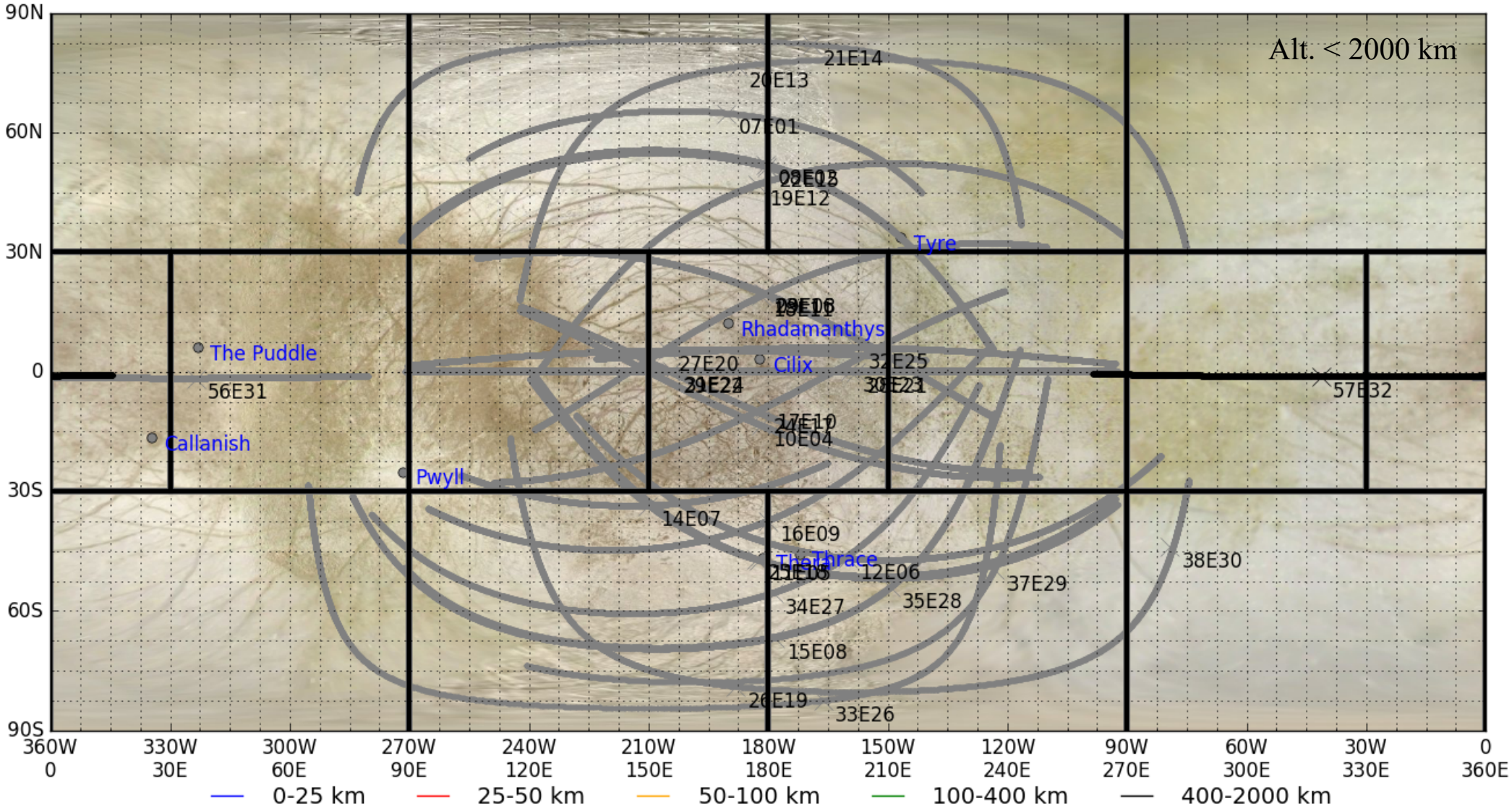
18F16: Leading Hemisphere Flyby (E32)



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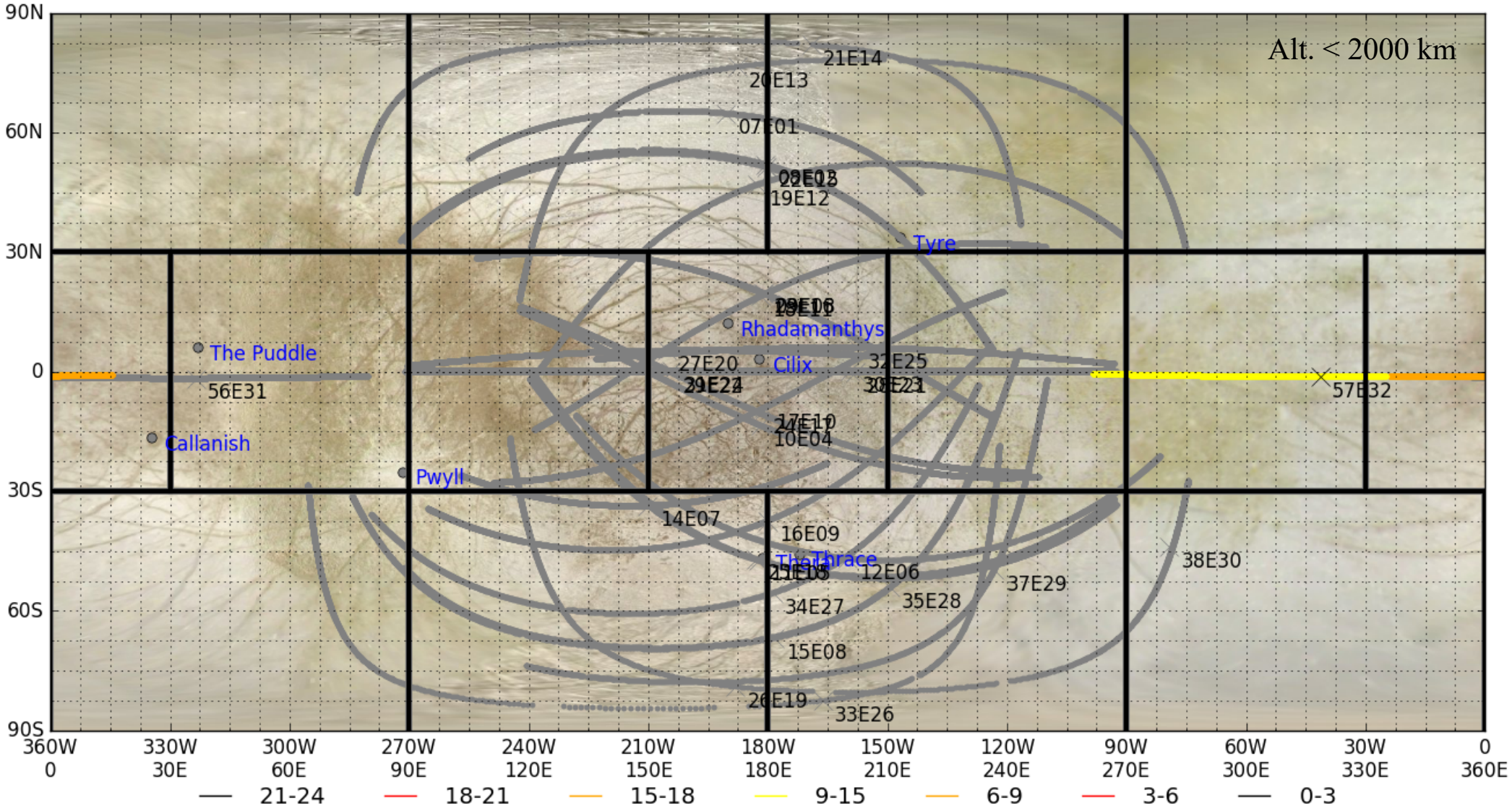
18F16: Leading Hemisphere Flyby (E32)



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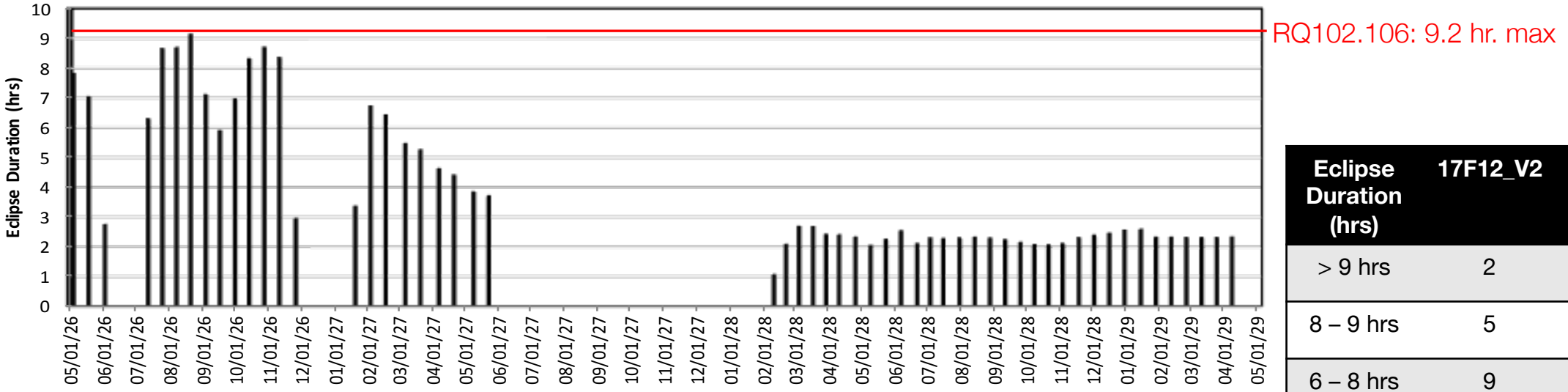
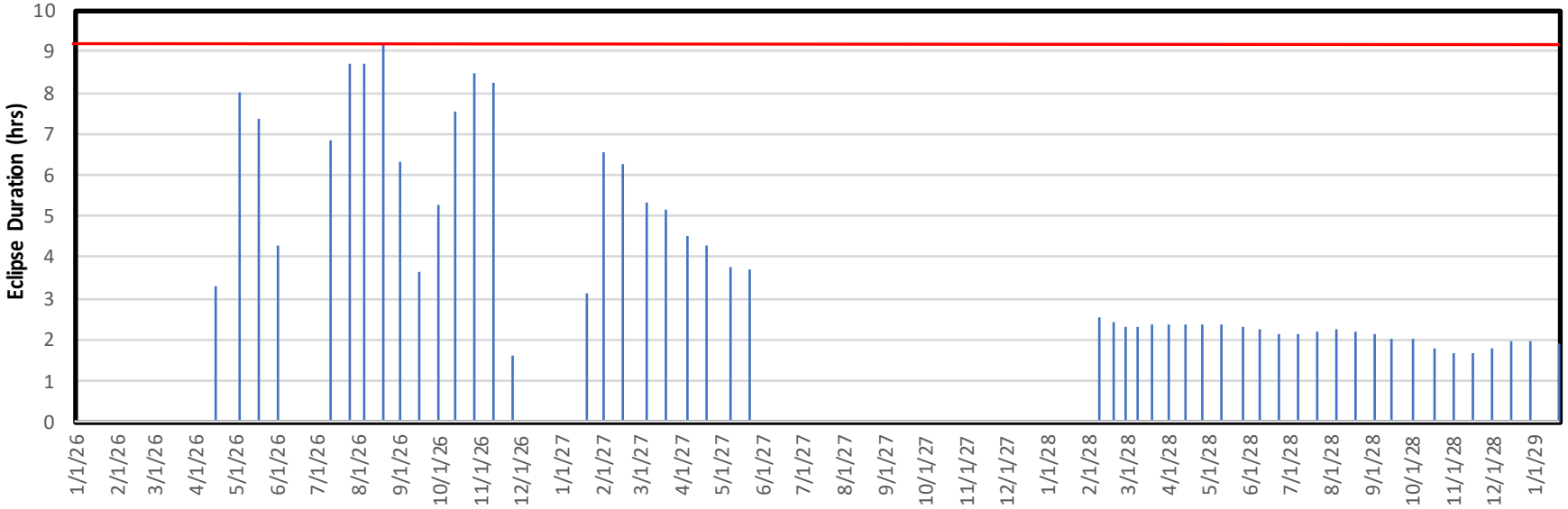
Eclipses

(17F13 vs. 18F16)

17F13



18F16



Eclipse Duration (hrs)	17F12_V2	18F16
> 9 hrs	2	1
8 – 9 hrs	5	5
6 – 8 hrs	9	6
4 – 6 hrs	3	6
2 – 4 hrs	23	24
< 2 hrs (non-zero)	5	8

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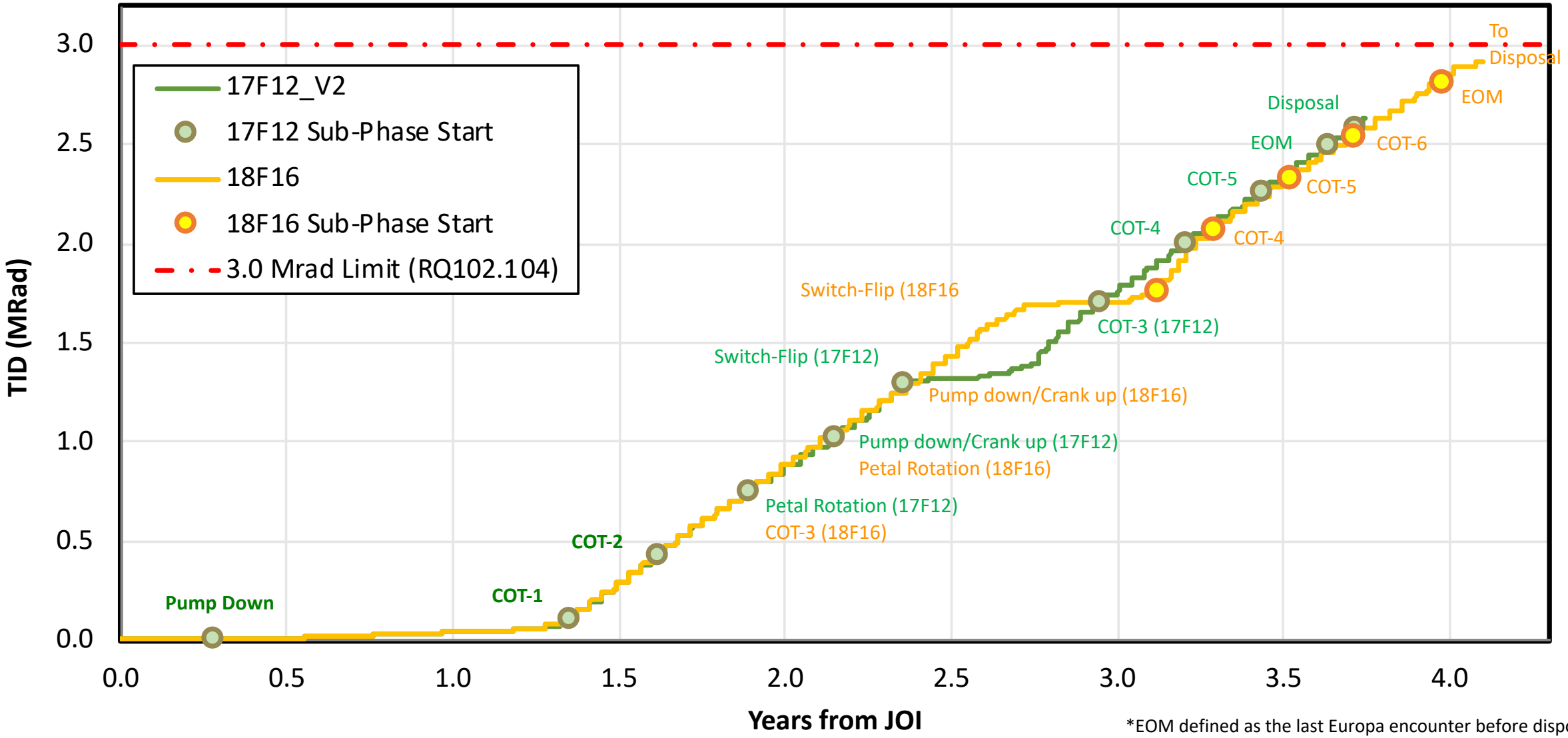
TID Build-Up: 17F12_V2 vs. 18F16



*EOM defined as the last Europa encounter before disposal

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18F17

Stefano Campagnola

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18F17_V2 Summary

- Implements the same EC1 as 17F13/18F16 (i.e., 3 anti-Jovian COTs)
- Utilizes different method to get to opposite side of Jupiter (details on following slide)
- <2.5 Mrad even with COT3

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Key features

- Tour design features:
  - New Transition to EC-2 quickly pull out of the radiation, without low-period orbits
    - Saves 200-400 kRad, allowing for a 17F13-like tour with comparable TID to 17F12_V2
    - Increase minimum time between flybys to 13 days
    - Lessons learned from 18F14 (first 2023 tour)
    - Utilizes Ganymede and Callisto flybys for TEC-2 instead of switch-flip
  - Low TID leading edge coverage with $5:1^{+}/4:1^{-}$ after TEC-2 (transition to Europa campaign 2)
  - 5:1 cadence in COT4-COT5

- Preliminary science concerns/issues:
  - Insufficient long gap of limb profile (EIS.015/EIS.085), because of missing 2 useful flybys in other TEC-2 [will be fixed in subsequent tours]
  - EC-2 flybys violate SUDA boresight constraints (SUD.002,SUD.003), due to flyby location. Common problem to other tours (17F13, 18F16)
    - Needs to be discussed and/or fixed in subsequent tours
  - Fewer high-latitude flybys (PIM.025) [will be fixed in subsequent tours]
  - Short COT-4 seems to have no major impact, thanks to extra flybys during leading edge campaign. [can be adjusted in subsequent tours, if needed]

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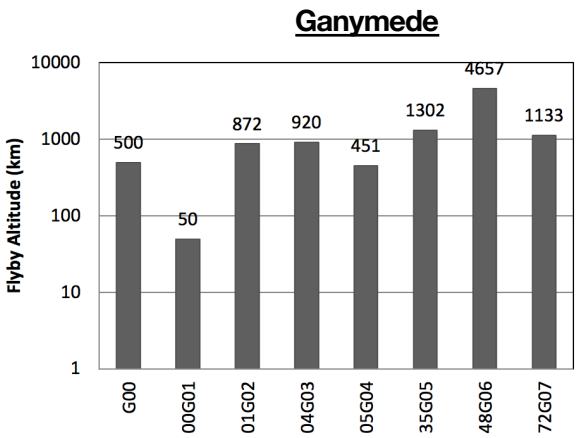
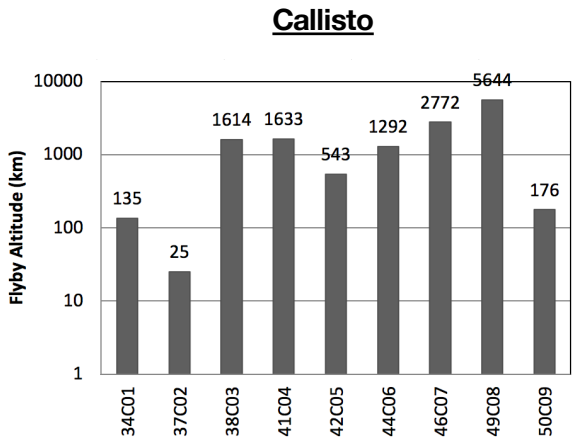
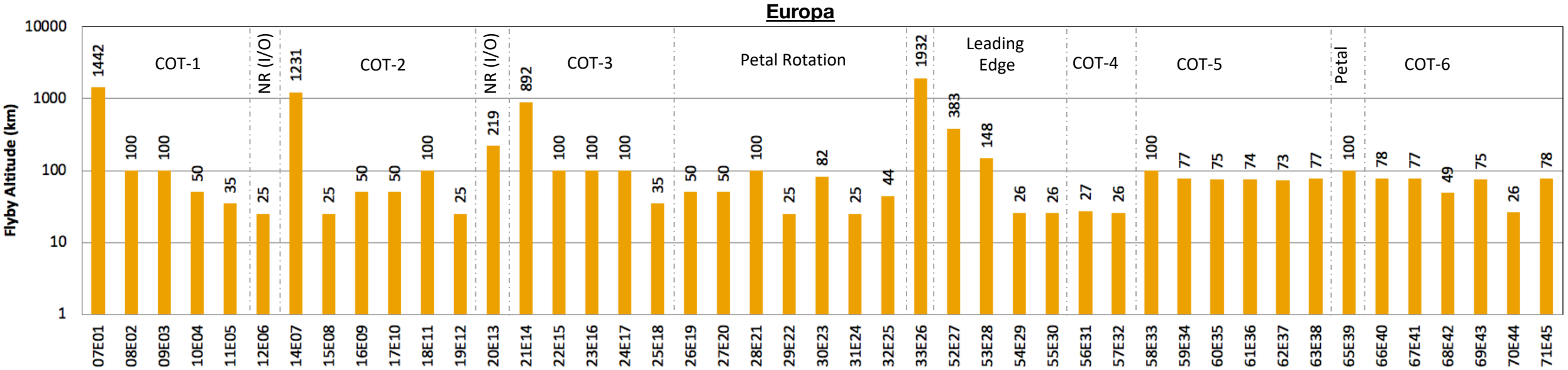
18F17 Flyby Altitude Profile

Europa Altitude Bin	18F17_V2
>1000 km	3
100 – 1000 km	12
50 – 99 km	16
25 – 49 km	14







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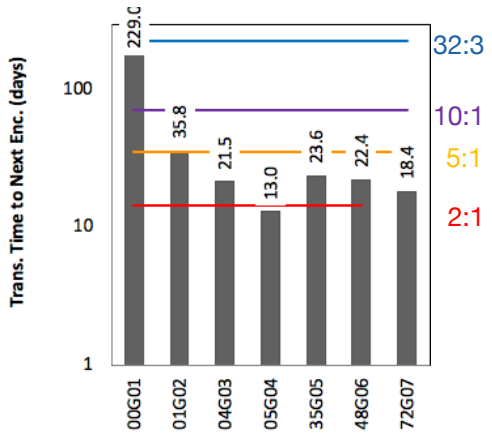
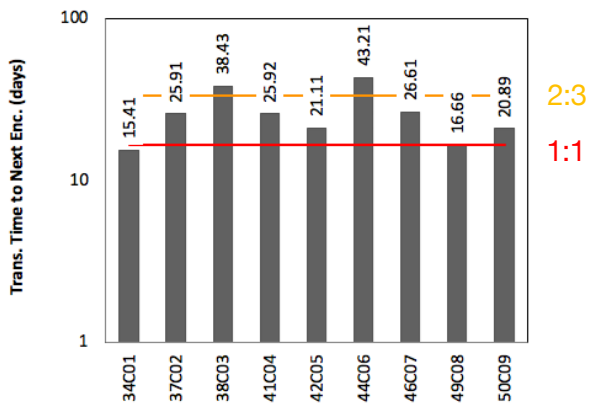
18F17: Transfer Time Profile

Europa-to-Europa Trans. Bin	18F17_V2
< 14 days	0
≅ 14 days	29
> 14 days	14

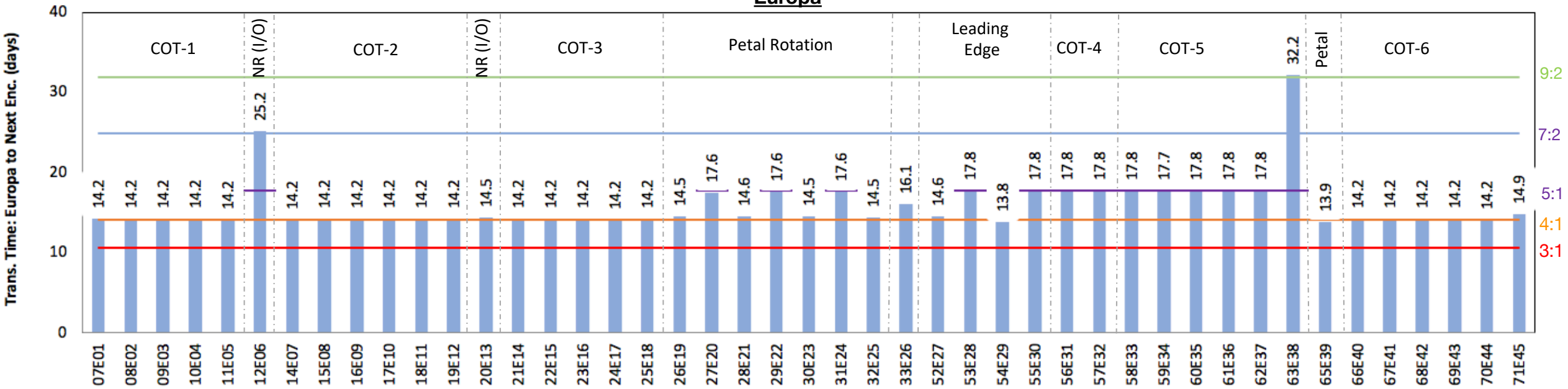
Ganymede



Callisto



Europa



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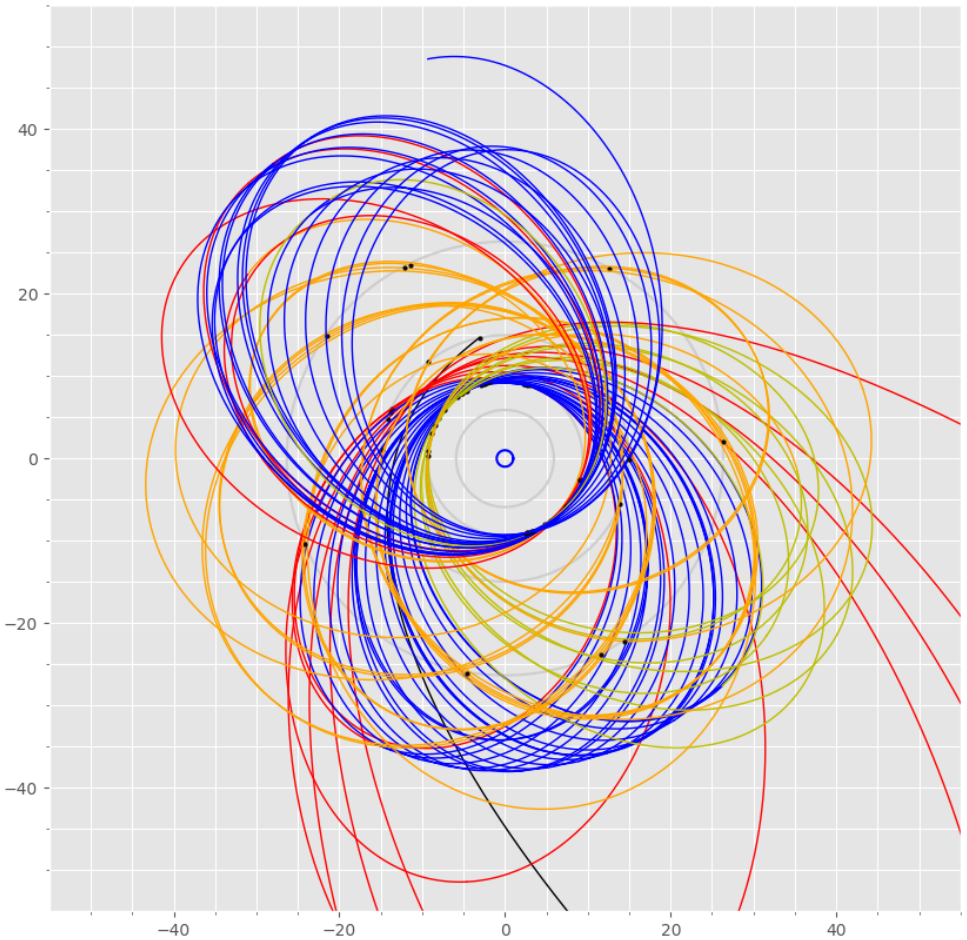
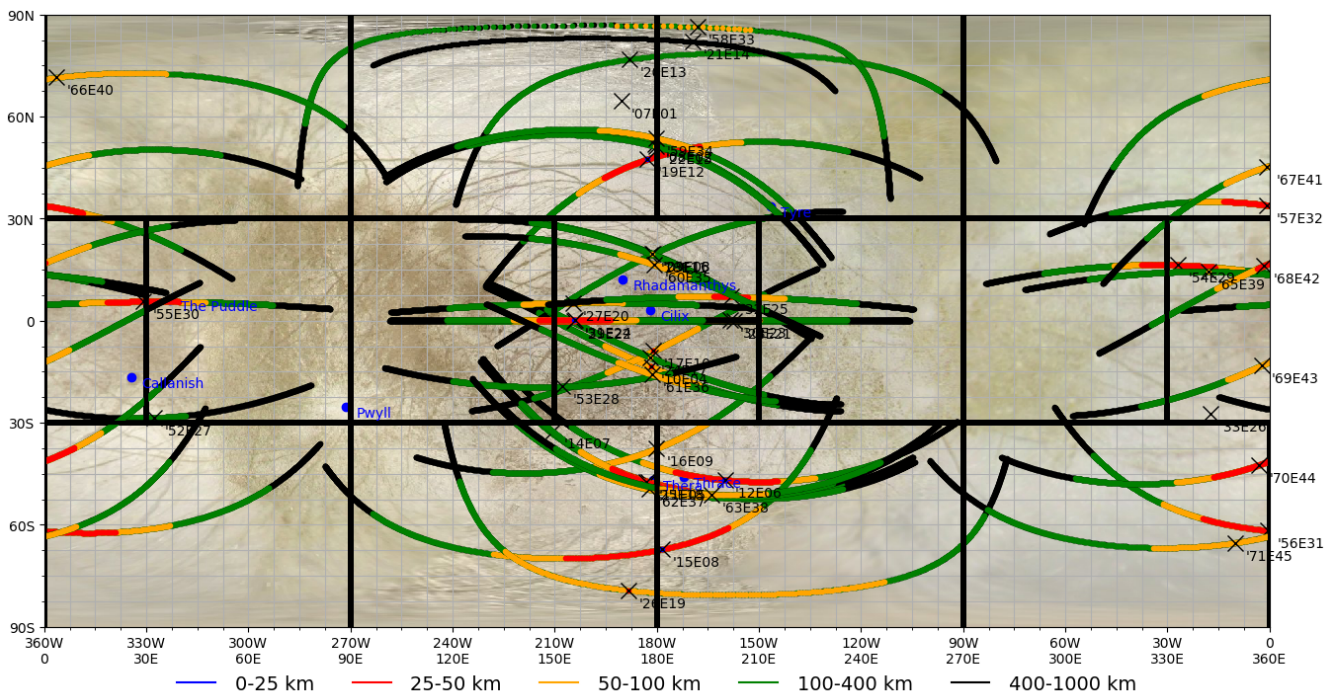
18F17 Trajectory and Groundtrack Buildup

Trajectory Build-up



Groundtrack Build-up



Pump-Down
COT-1
COT-2

COT-3
Petal
Transition

Leading Edge
COT-4
COT-5

COT-6 and
Ganymede

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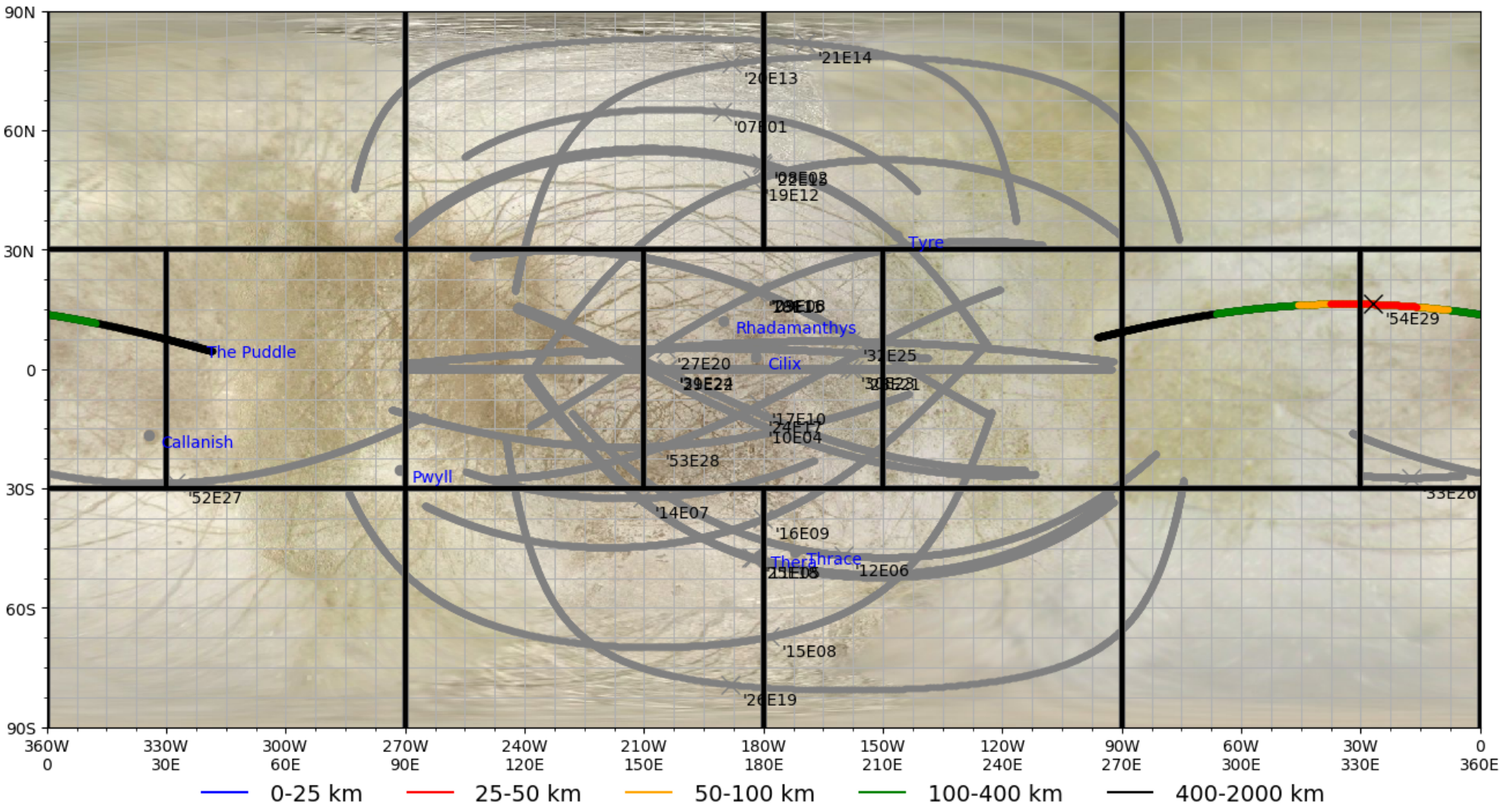
18F17: Leading Hemisphere Flyby (E29)



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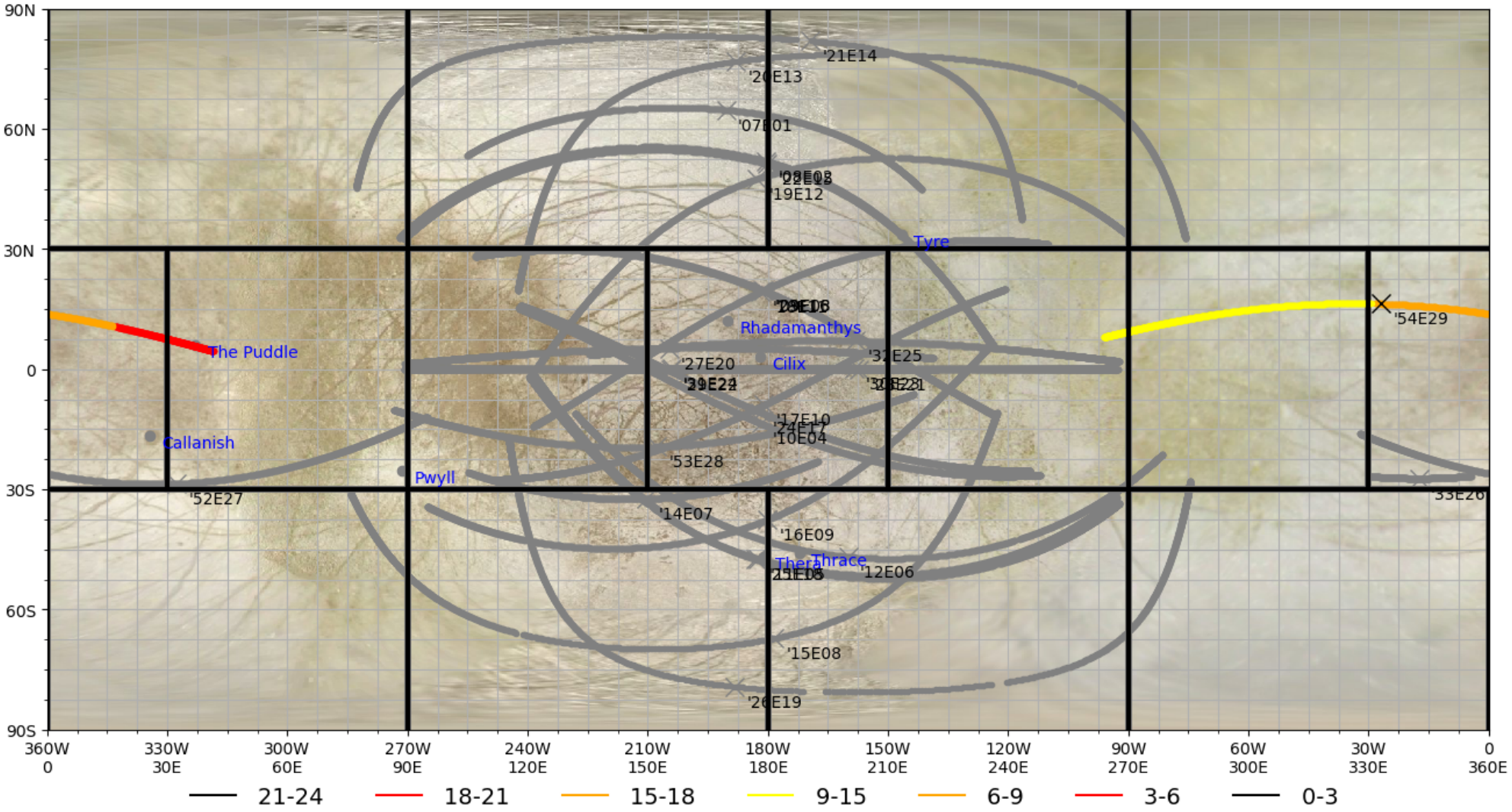
18F17: Leading Hemisphere Flyby (E29)



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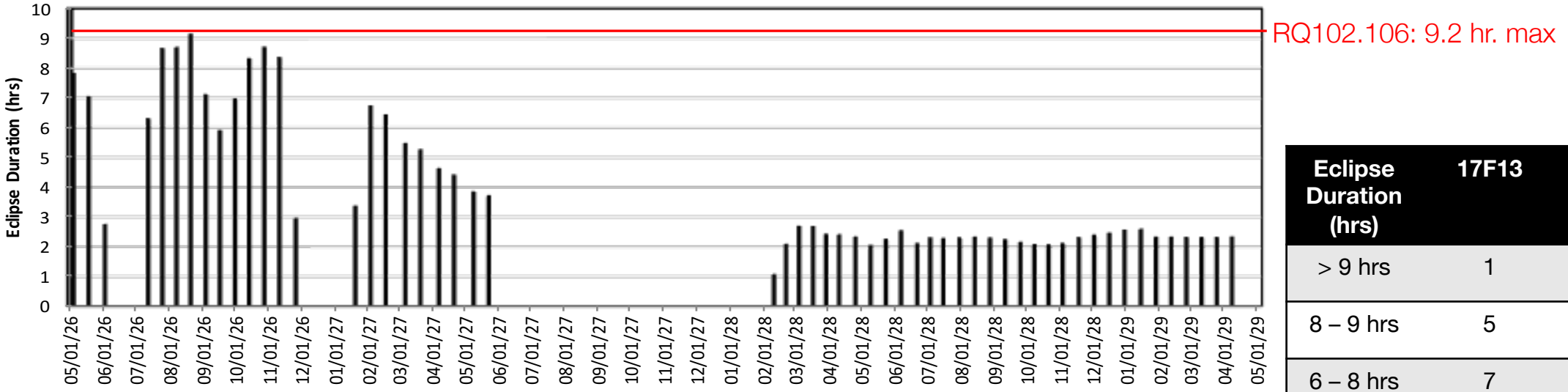
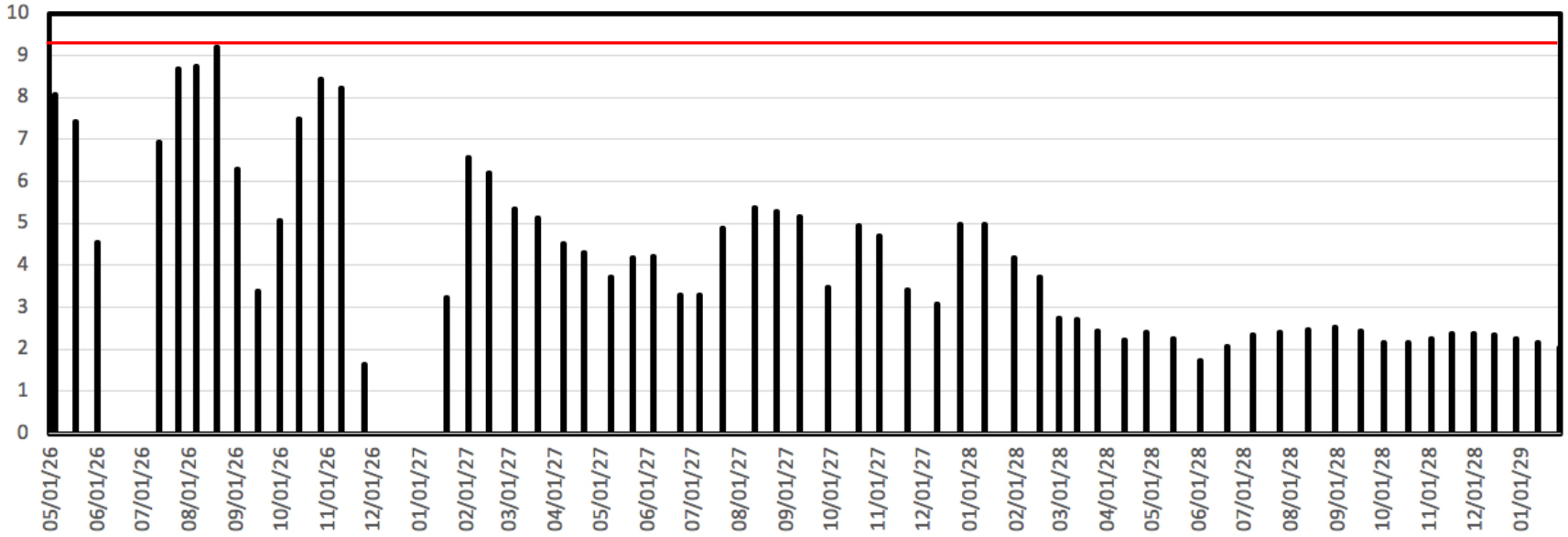
Eclipses

(17F13 vs. 18F17)

17F13



18F17



Eclipse Duration (hrs)	17F13	18F17
> 9 hrs	1	1
8 – 9 hrs	5	5
6 – 8 hrs	7	6
4 – 6 hrs	5	18
2 – 4 hrs	36	30
< 2 hrs (non-zero)	1	2

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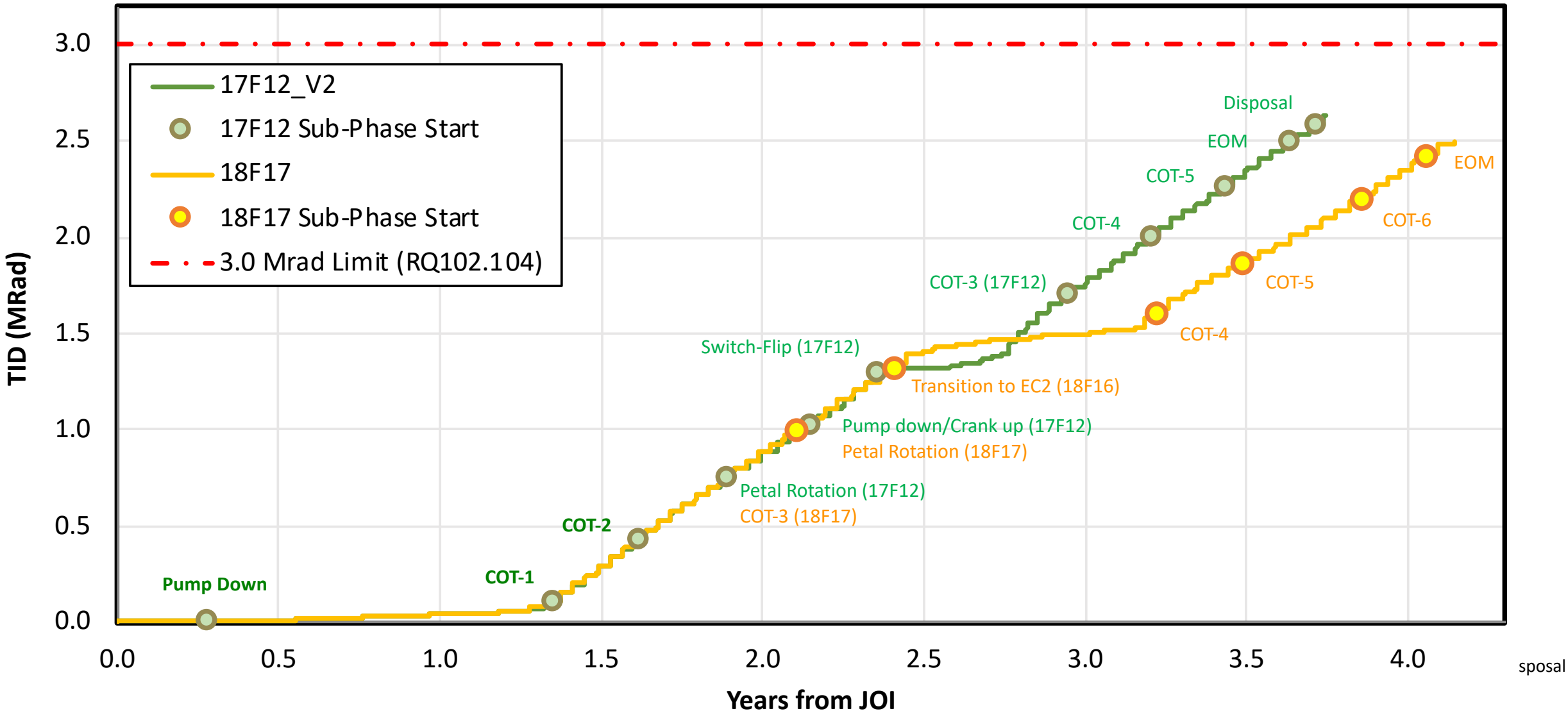
TID Build-Up: 17F12_V2 vs. 18F17



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Updated Tour Design Schedule

Brent Buffington

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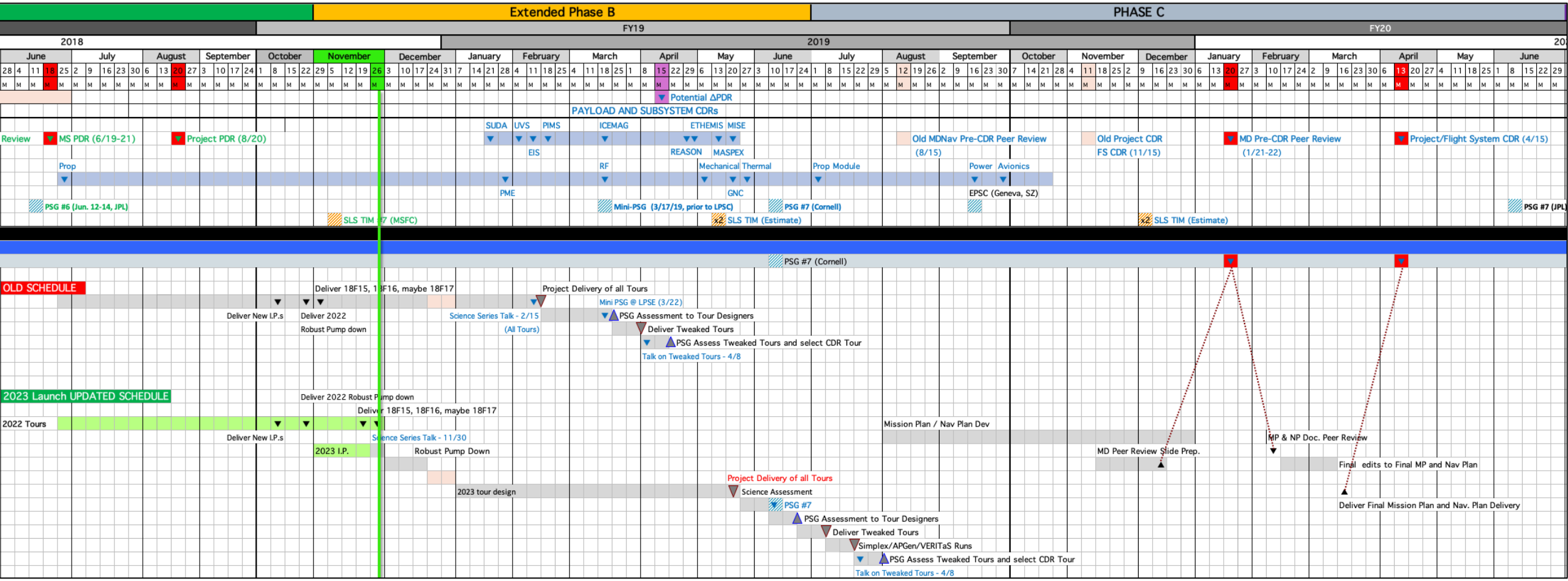
NEW Tour Dev. Schedule for CDR



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2023 Tour Design Considerations

Brent Buffington

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Tour Design Objectives

(The Same as Before)

- Maximize science return per unit time while adhering to environmental, operational, and spacecraft constraints
  - Environmental: Radiation, solar conjunctions, eclipses, and potential Europa plumes
  - Operational: Frequency of events (maneuvers and flybys), navigation feasibility, mission agility, and required delivery accuracy
  - Spacecraft: ΔV (system margins), frequency of events (downlink margins, onboard storage, battery sizing, etc.), duration and location of eclipses, and flyby velocities

- Optimize/balance across a number of quantities:
  - Science return
  - ΔV
  - Total Ionizing Dose (TID)
  - Mission complexity
  - Time-of-flight

- Tours will be designed to the measurement requirements from Project PDR

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2023 Tour Design Considerations

- Dual vs. single arrival date strategy for Earth-Jupiter interplanetary trajectories
  - Previous studies have concluded in order to inject sufficient mass across a 21-day launch period for our mission a dual Jupiter arrival strategy was needed
  - Newly developed software can fully map trade space, taking the the launch vehicle performance out of the cost function and apply it as a constraint
    - Results in a the ability to have a ≥21 day launch period for a **single arrival date**
- Improved Falcon Heavy performance (and the addition of Star 48BV kick-stage) could likely make a ΔVEGA 3-minus (or 3-plus) possible
  - This would replace the E/VEEGAs as our “Secondary” interplanetary option if proven feasible
  - Key attractive attribute: Does not require traversing well inside of 1 AU (much less driving from a thermal perspective than a E/VEEGA trajectories that go down to 0.65 AU)

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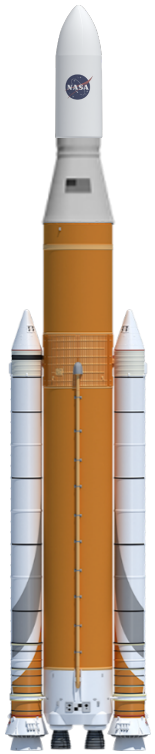
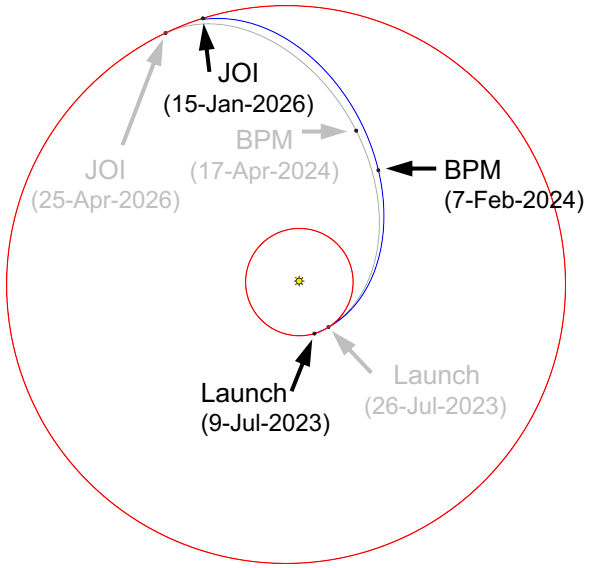
2023 Interplanetary Options

Baseline

Launch Period: 09-Jul-2023 – 29-Jul-2023

Potential Change: Single Arrival Date

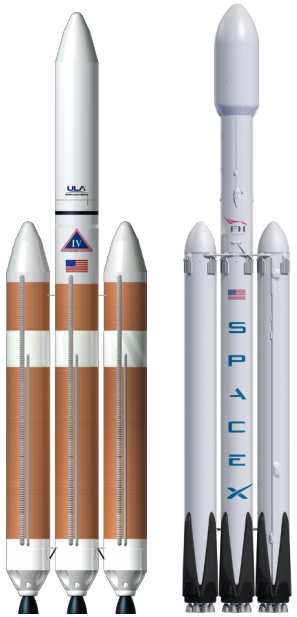


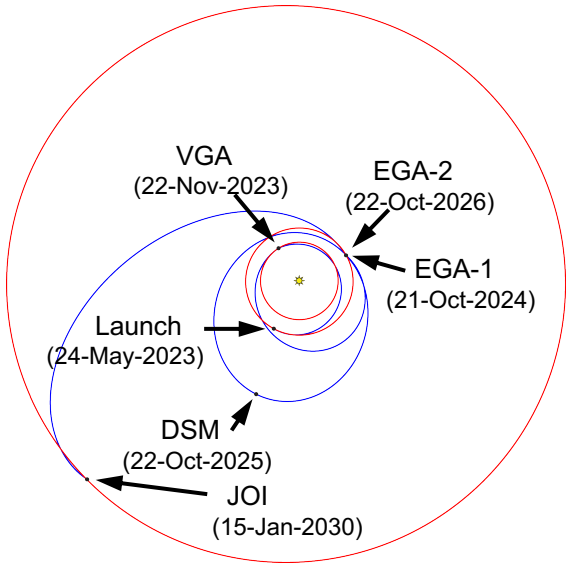


TOF: 2.5 – 2.7 yrs.

Secondary

Launch Period: 24-May-2023 – 13-Jun-2023

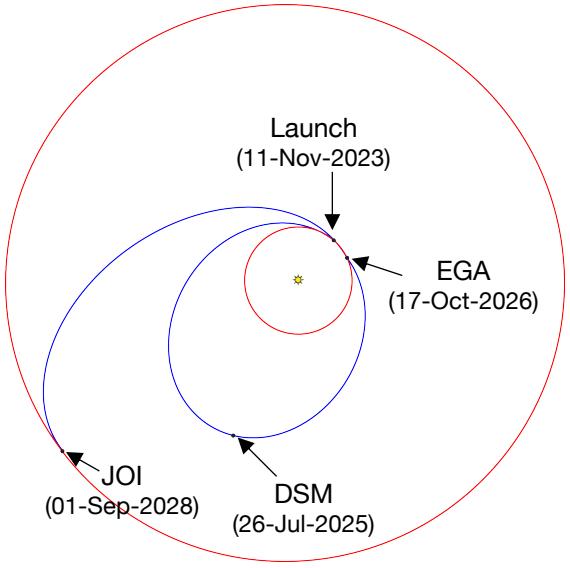




TOF: 6.6 yrs.

Potential New Secondary

Launch Period: 24-May-2023 – 13-Jun-2023



TOF: 5.9 yrs.

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2023 Tour Design Considerations (cont.)

Extended Pump Down:

- Objective:
  - Utilize one or more Callisto flybys to manipulate the relative velocity at Ganymede and Europa that would otherwise be done by the Periapsis Raise Maneuver (PRM)
- Benefit:
  - ΔV reduction: ~40 m/s (PRM magnitude)
  - Fly through the region of Europa's orbit prior to first Europa flyby
  - Potential variation: Attain early Europa flyby (v_∞ ~ 4.5-5 km/s, some additional TID cost)
- Cost:
  - Time-of-flight to E1: ~ 30-40 days
  - TID: 20-100 krads (additional ~60 krad for early Europa)

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Mission System PDR RFA: Flyby Cadence

- A number of concerns from the MS PDR stemmed from the repeated 14.2 day (4:1 resonant transfers) flyby cadence PDR tour (17F12_V2)
  - *"The complexity of the 14 day orbital operations suggests unnecessary or unacceptable risk to mission success (both Baseline and Threshold) may exist."* –Scott Bolton
  - *"The 14-day operations are complex and present risk of loss of flybys or measurement requirements associated with the remote sensing mapping instruments. The project should identify and understand the cost drivers in meeting the science requirements and the various options available (increasing orbit, decreasing operational complexity, relaxing science requirements or accepting a reduction in science margin)"* –Scott Bolton
  - *"…unclear whether the 14-day tour will allow the team to absorb minor anomalies and stay on pace without increased risk (of distraction, over-work, etc.)"* –Tracy Drain
  - *"The 14-day rhythm for the mission seems problematic. Its basic premise is the repeatability of each of the Europa encounters. This cadence places stress on the maneuver design, data playback, and update strategies. It also reduces the resilience of each segment to anomalies and places constraints on performance that seem limiting for a flagship mission with a full suite of instruments. I would suggest that the team examine longer period orbits to determine if more mission performance and less risk can be realized."* –Earl Maize

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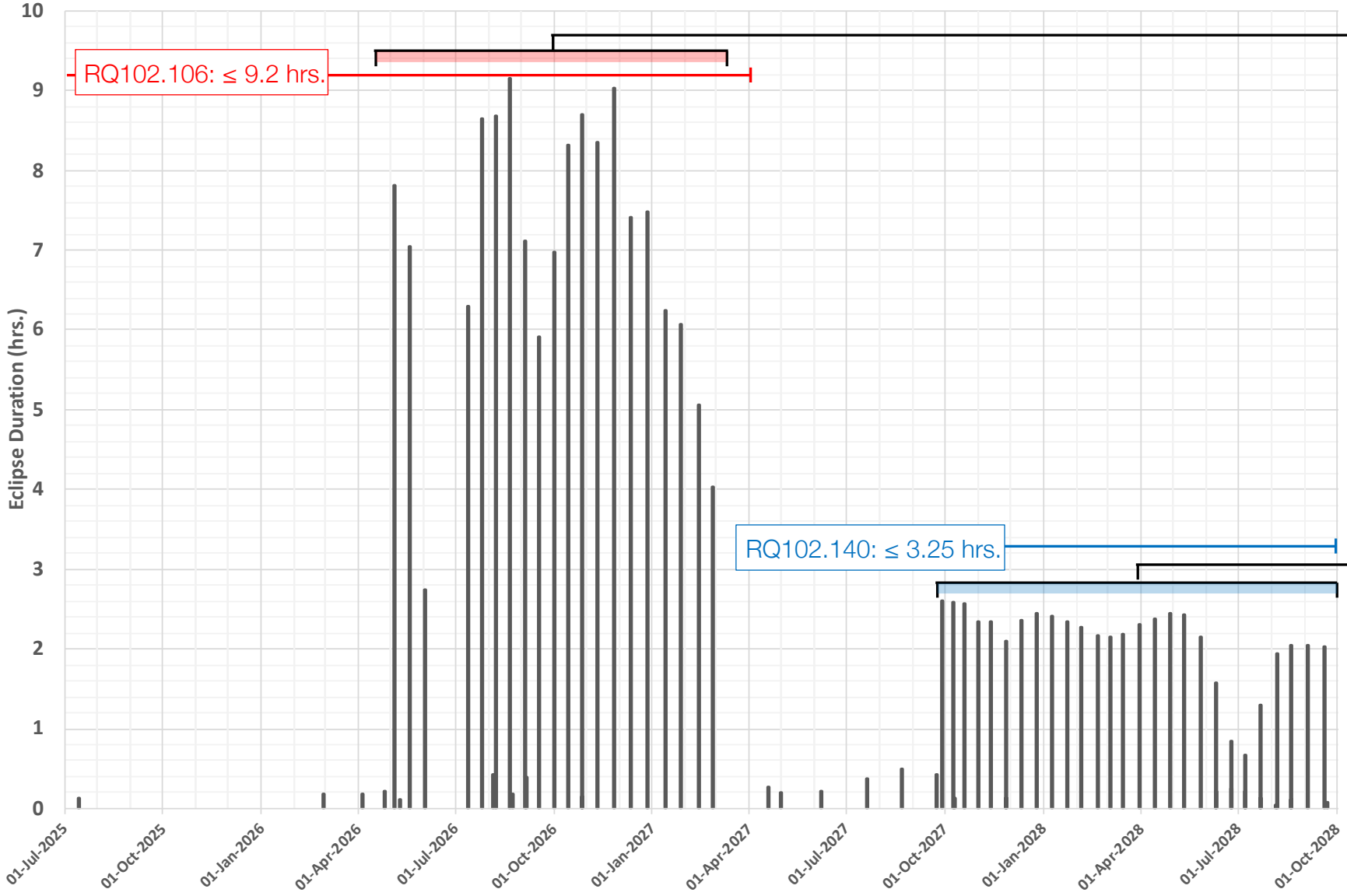
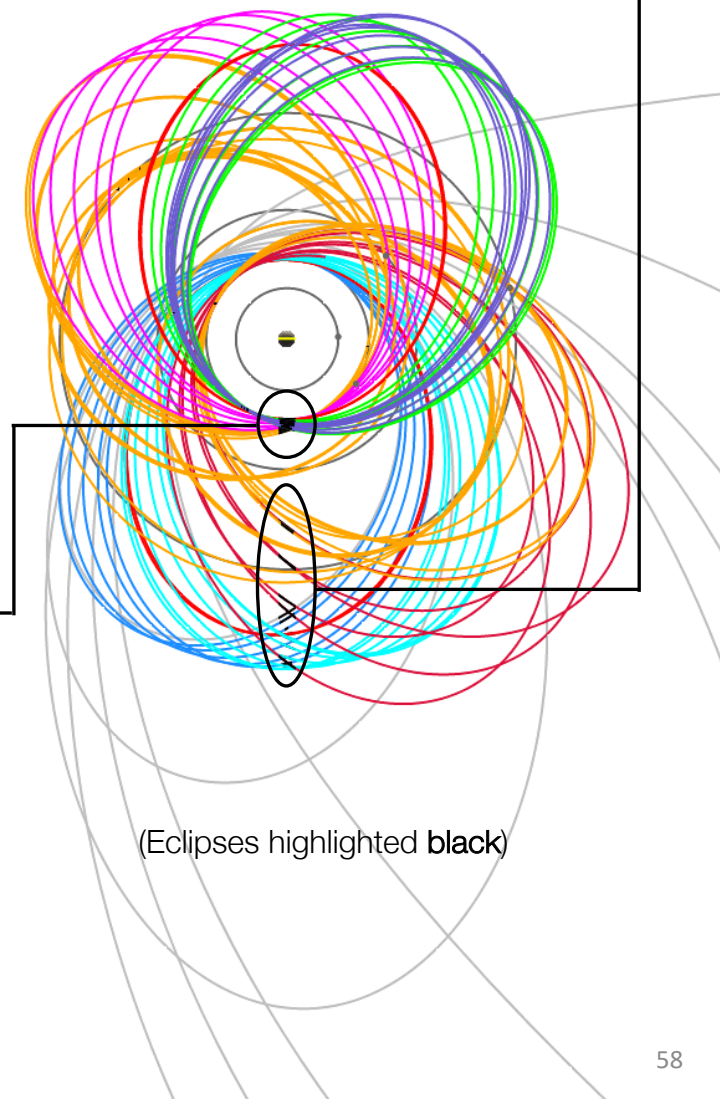
17F12 Eclipses





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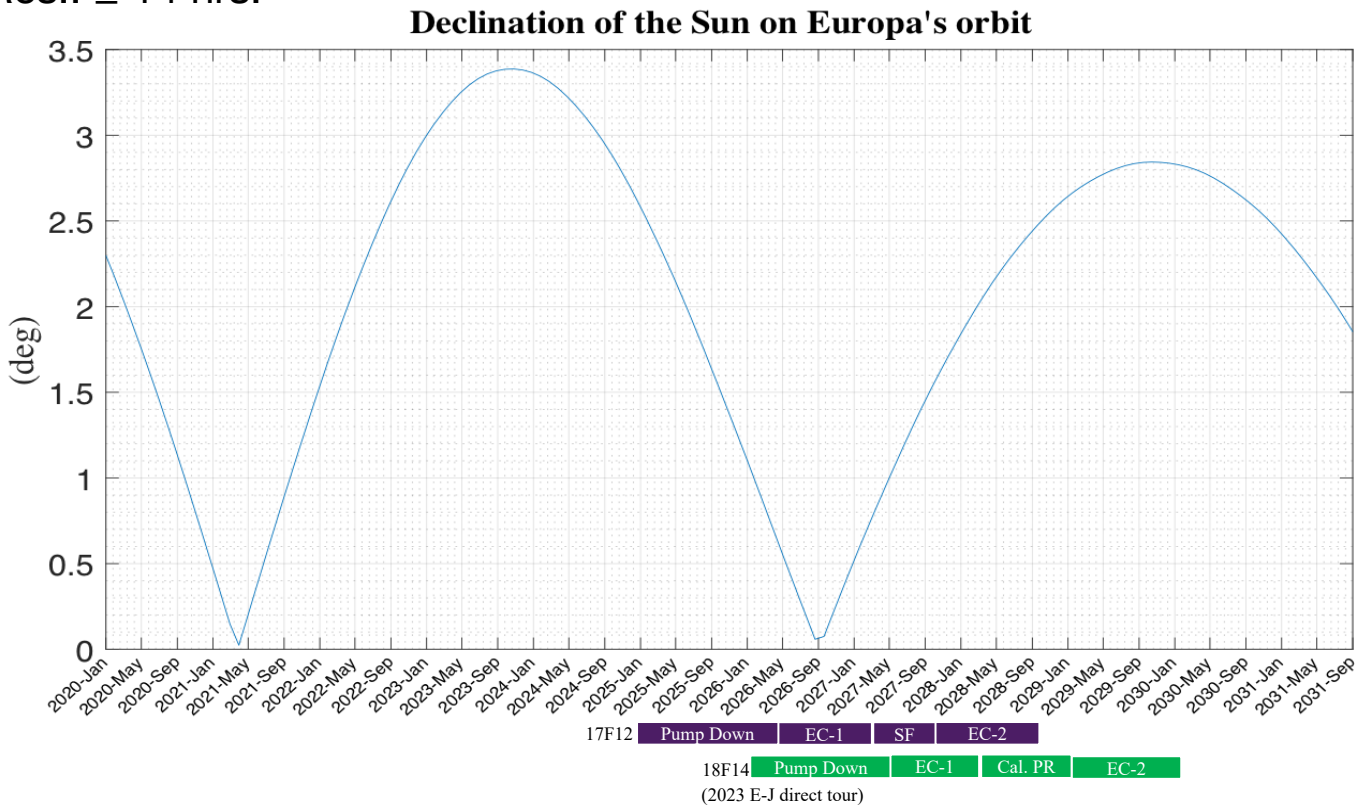
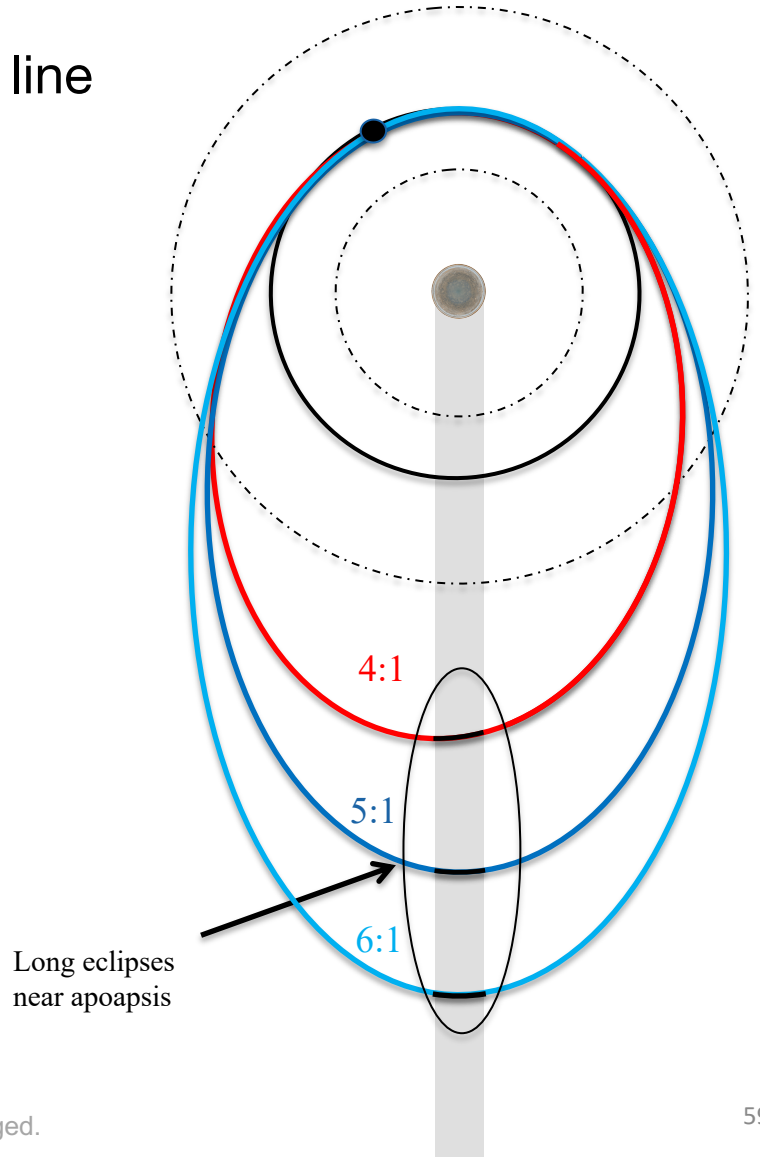
Eclipses (In general)

- The frequency and duration of Jupiter eclipses is a function of solar declination and orbit size and orientation relative to the Sun-Jupiter line
  - 4:1 Res.: ≤ 10 hrs.
  - 5:1 Res.: ≤ 12 hrs.
  - 6:1 Res.: ≤ 14 hrs.





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COT Groundtrack Density and Ground Speed

Resonance (Period)	# of GTs	V_∞ (km/s)	V_g @ 100 km	Min. Alt V_g = 4.5 km/s (km)
3:1 (10.65 days)	2	3.25	3.57	<25
	4	3.38	3.67	<25
	6	3.58	3.83	<25
	8	3.78	4	<25
4:1 (14.2 days)	2	3.7	3.93	<25
	4	3.79	4.01	<25
	6	3.94	4.13	<25
	8	4.1	4.27	<25
5:1 (17.75 days)	2	3.98	4.17	<25
	4	4.06	4.23	<25
	6	4.18	4.34	56
	8	4.33	4.47	89
6:1 (21.3 days)	2	4.19	4.35	49
	4	4.26	4.4	69
	6	4.36	4.49	98
	8	4.5	4.61	139
7:1 (24.8 days)	2	4.34	4.47	92
	4	4.4	4.53	110
	6	4.5	4.614	139
	8	4.63	4.73	177

Notes: 1) V_g will vary by 0.032 km/s based on c/a latitude

2) Min. Alt. V_g will vary by 10 km based on c/a latitude

- 4:1 resonant transfers chosen because:
  - Represented a slightly shorter time-of-flight between flybys as Cassini had proven feasible
    - Minimize Phase E costs while not requiring AutoNav
- 6 flybys per COT chosen because:
  - Represented a balance of latitudinal coverage and groundtrack density with TID in order to meet the global-regional requirement of the model (and later, the selected) payload
  - Allows flying over Thera/Thrace
    - While this is not a requirement, we know it does satisfy SUDA's requirement to fly over at least 2 "young features"

Red: Violates EIS.046, "When collecting local-scale imaging dataset measurements, the flight system ground speed on Europa shall be less than **4.5 km/s**."

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“Early” Europa Flyby Investigation

- Investigating the potential addition of an “early” Europa flyby
- Options (in order of complexity):
  1. Lower perijove down to 9.4 R_J during pump down for Flight System to experience radiation environment, but Europa not there
     - This comes for free when doing some extended pump downs
  2. Lower perijove down to 9.4 R_J during pump down and do a higher velocity Europa flyby (4.5 – 5 km/s) with lighting conditions that might not be exactly like EC1 and EC2
  3. Add time between E1 and E2
     I. Multi-rev transfer where every empty rev. increases TID just like a Europa flyby
     II. Get out of radiation and then come back
        – There is a TID “payment” for getting into and back out of the radiation
- OR, simply utilize an optional sunlit anti-Jovian COT-3 (i.e., 17F13-like tour design)

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Tours to be Developed
(2023 Launch Opportunity)

Minimum set:

1. 2023 Earth-Jupiter direct: 18F15-like
2. 2023 ΔVEGA 3-minus: 18F15-like
3. 2023 Earth-Jupiter direct: Tour utilizing 6:1 COTs

Bonus:

1. 2023 Earth-Jupiter direct: 18F17-like
2. 2023 Earth-Jupiter direct: 18F16-like
3. 2023 Earth-Jupiter direct: Tour utilizing 6:1 COTs in EC1 and 4:1 COTs in EC2
4. 2023 ΔVEGA 3-minus: Tour utilizing 6:1 COTs

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Tour Design Questions

1. How much of an advocate would Science be for longer time-of-flight cadence (i.e., 14.2 days to 21.3 days)?
2. Usefulness of early Europa flyby (all variations)

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Summary

- Three new 2022 tours have been developed
  - Associated VERITaS runs available as part of the tour evaluation
  - While no longer eligiable as CDR candidate tours, there's a benefit to understanding how different tour strategies affect science performance
  - Feedback from 18F15 – 18F17 due no later than 1/15/19
- New tours design schedule has been developed with sufficient time to develop, analyze and select a single tour for CDR in April 2020
  - Tours delivery prior to PSG #7
  - Final CDR tour selection in August 2019
- Tours compatible with 2023 launch opportunities currently under development

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Backup Slides

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Original Tour Dev. Schedule for CDR

- 6/25/18 – 12/3/18: CDR tour development
  - 10/29/18: Deliver tours to Nav. Team (for covariance analyses)
- 11/26/18: Project delivery of all tours (including VERITaS results)
- 11/26/18 – 12/15/18: PSG initial assessment
  - 12/15/18: Presentation of tours to PSG (post-AGU mini-PSG)
- 1/7/19 – 1/21/19: PSG feedback on tours (including suggested tweaks)
- 1/21/19 – 2/4/19: Develop and deliver any requested tweaked tours
- 2/4/19 – 2/12/19: PSG assessment of tweaked tours
- 2/13/19: Select tour for CDR

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NEW Tour Dev. Schedule for CDR

- 5/24/19: Project delivery of all tours (including VERITaS results)
- 5/24/19 – 6/10/19: Project assessment (PSG and Engineering)
- 6/11/19 – 6/13/19: PSG #7 (Ithaca, NY)
  - Presentation of tours to PSG
  - Tour designers will meet with each discipline working group
- 6/21/19: Tour assessment due to tour designers
- 6/24/19 – 7/12/19: Tweak tours based on input
  - 7/12/19: Deliver tweaked tours to Project
- 7/14/19 – 7/26/19: Final SIMPLEX/APGen/VERITaS runs on tweaked tours
- 7/29/19 – 8/9/19: PSG assessment of tweaked tours
  - 7/30/19: Presentation on tweaked tours
- 8/9/19: Select tour for CDR

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