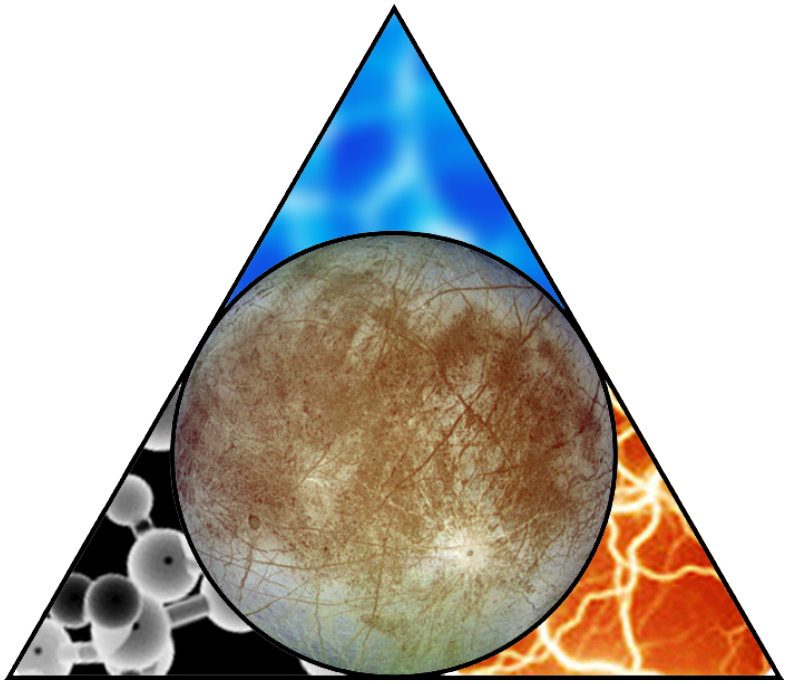
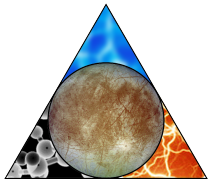


Europa Clipper SDT Briefing

13F7-A21 Trajectory



Europa Clipper Mission: 13-F7 Trajectory Overview

Brent Buffington

Mission Design and Navigation

Jet Propulsion Laboratory, California Institute of Technology

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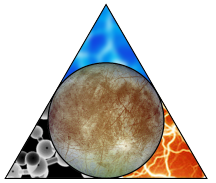
Mission Design Assumptions



- Jupiter capture: Ganymede-assisted JOI
- ~200-day capture orbit
- Flyby altitude: Step-down approach
  - 500 km → 250 km → 100 km → 50 km → 25 km
- Keep average time-of-flight between flyby at ≥~14 days
- Two deterministic maneuvers between each flyby
  - Special cases exist (short TOF permits only one determinstic maneuver)
- Solar conjunction (assuming X-band up):
  - Prior to solar conjunction: ≥ 2 days of tracking must be obtained at SEP ≥ 10º when a maneuver is to be performed
  - No maneuver can be performed below 5º SEP (telemetry data cannot be downlinked and scheduling backup maneuver windows are troublesome)
  - After solar conjunction, maneuvers must be at least 3 days after 10º SEP to allow for 2 days of tracking plus an additional day to design the maneuver

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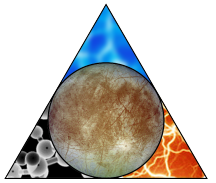

May 2012 Notional Baseline Instruments

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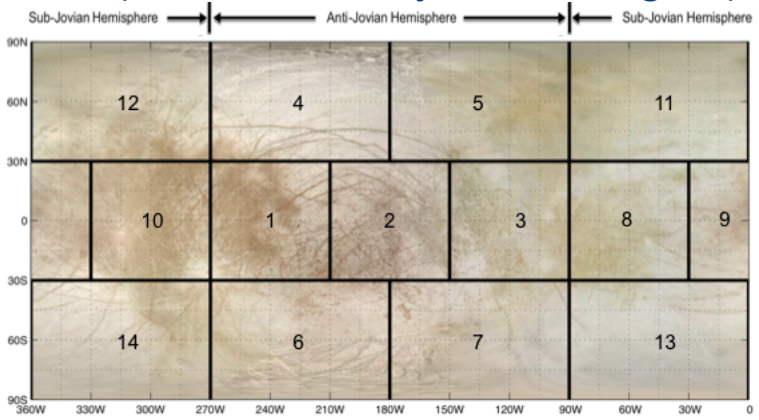
May 2012 Clipper Mission Design Drivers

Ice Penetrating Radar and Topographic Imager

- Solar phase 50-70º (20-80º acceptable) when alt ≤ 400 km
- Closest approach (c/a) relative velocity < 5 km/s
- c/a altitude: 25–100 km
- Coverage: Satisfy the following constraints in **11 of 14 panels**:
  - Three 800 km groundtracks in anti-Jovian panels, and two 800 km groundtrack segments in each sub-Jovian panel (altitude ≤ 400 km)
  - Each groundtrack must intersect another groundtrack (intersection may be outside the panel of interest) below 1,000 km (when altimetry mode begins)
  - Cover anti-Jupiter hemisphere first (preference)



NMS

- c/a relative velocity < 7 km/s
- c/a altitude: < 200 km (lower the better)

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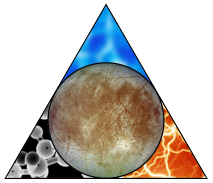
May 2012 Clipper Mission Design Drivers



IR Spectrometer (SWIRS)

- Local Solar Time: 9 am - 3 pm (the closer to noon the better)
- Solar phase angles < 45 degrees (preferred)
- c/a relative velocity < 6 km/s
- c/a altitude: 25–100 km
- Coverage:
  - Ability to target specific geologic features that are globally distributed (300 m/pixel, **11 of 14 panels**)
  - ≥ 70% coverage at ≤ 10 km per pixel

Other considerations:

- Total ionizing dose (TID)
- Tour time-of-flight
- Total Δv

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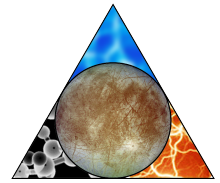

Enhanced Instruments

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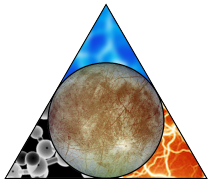
Enhanced Clipper Mission Design Drivers



Gravity Science

- c/a altitude: ≤100 km
- Flybys distributed between near Europa's periapsis and near Europa's apoapsis and at 2 different locations; occur far from solar conjunction
- Spacecraft must not be occulted by Europa during ±2 hr around c/a

Magnetometer and Langmuir Probes

- c/a altitude: 25-100 km
- Flybys across a range orbital phases (true anomaly) and variety of Jovian System III longitudes

Reconnaissance Camera

- c/a altitude: ≤ 50 km
- 4 required, 15 sites desired (Each site: 5 x 10 km)
- Solar phase angles of 20-80º, >45º preferred, (70º ideal)

Thermal Imager

- Local solar time: 10 AM - 3 PM (and 3 AM – 6 AM for layers and hot spot investigations)
- Image same terrain as reconnaissance camera

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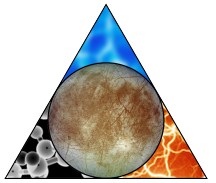

Interplanetary Trajectories

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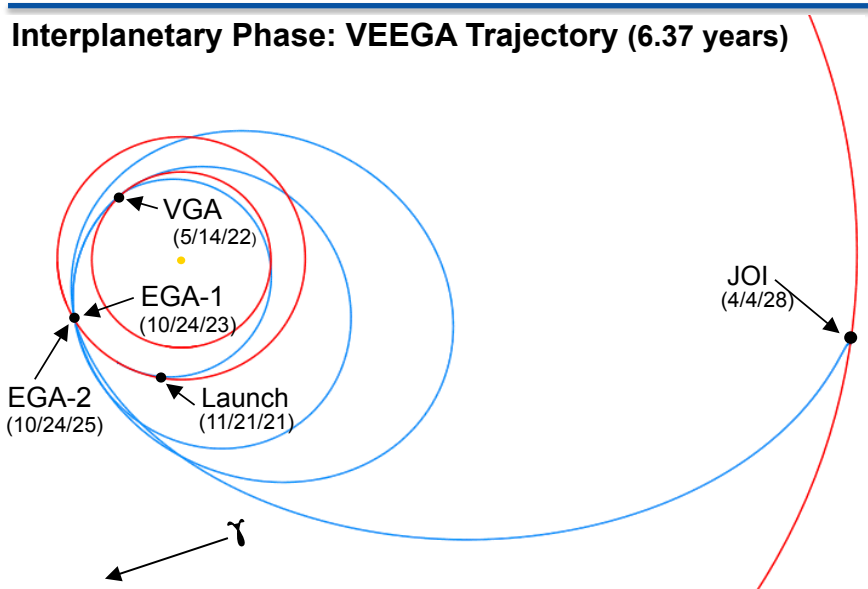
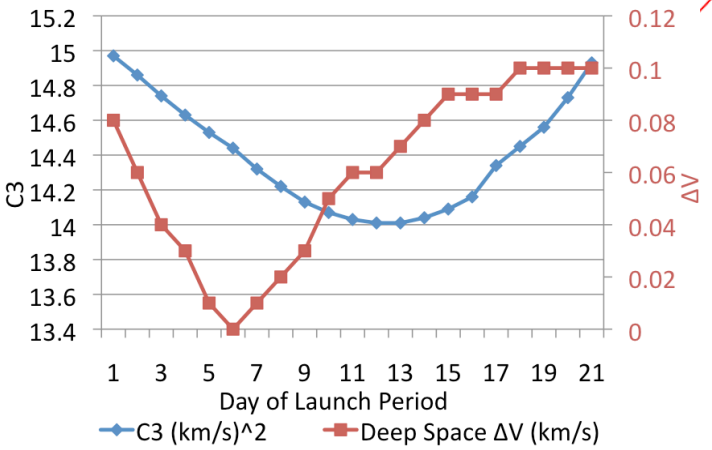
Baseline Interplanetary Trajectory

[2021 VEEGA; Launch Vehicle: Atlas V 551]

Interplanetary Phase: VEEGA Trajectory (6.37 years)





Nominal IP Trajectory		
Event	**Date**	**Flyby Alt. (km)**
Launch	**21 Nov 2021**	**-**
Venus	**14 May 2022**	**318**
Earth	**24 Oct 2023**	**11764**
Earth	**24 Oct 2025**	**3336**
G0	**03 Apr 2028**	**500**
JOI	**04 Apr 2028**	**12.8 R_J**

Nominal

Annual Launch Opportunities				
Launch Date	**Flyby Path**	**TOF to JOI (yrs.)**	**C_3 ($km^2 \cdot s^{-2}$)**	**Atlas V 551 Capability (kg)**
23 Mar 2019	EVEE	6.91	10.5	5011
29 Feb 2020	VEE	5.8	12.8	4794
27 May 2021	VEE	6.87	14.5	4541
21 Nov 2021	**VEE**	**6.37**	**15.0**	**4494**
15 May 2022	EVEE	7.22	10.2	4935
23 May 2023	VEE	6.18	16.4	4339
03 Sep 2024	VEE	6.71	13.8	4562

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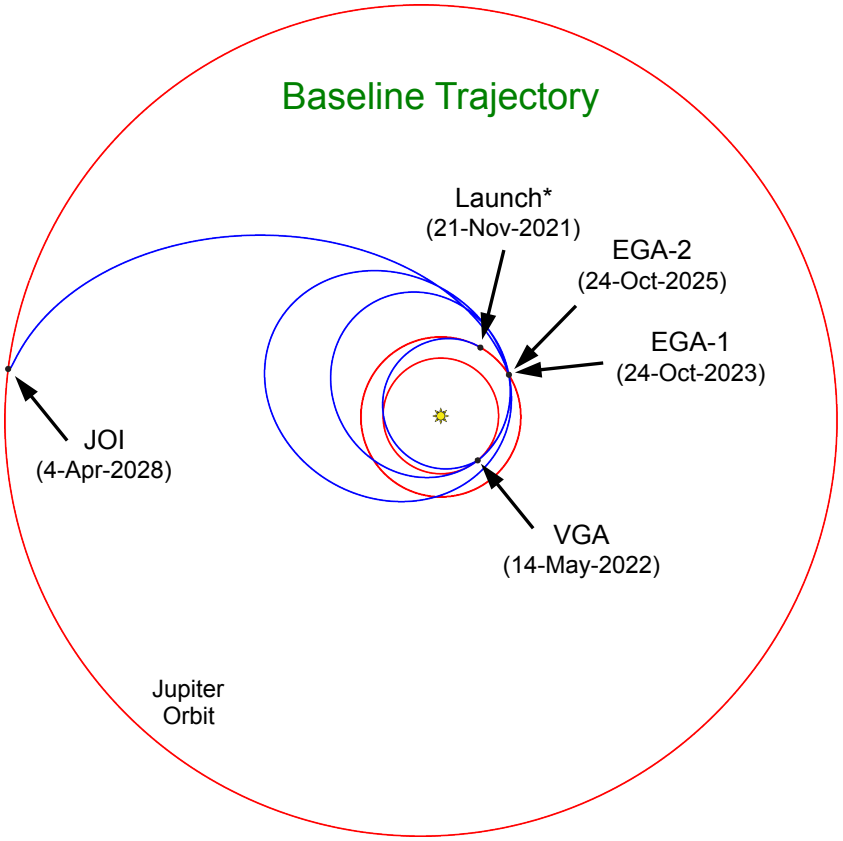
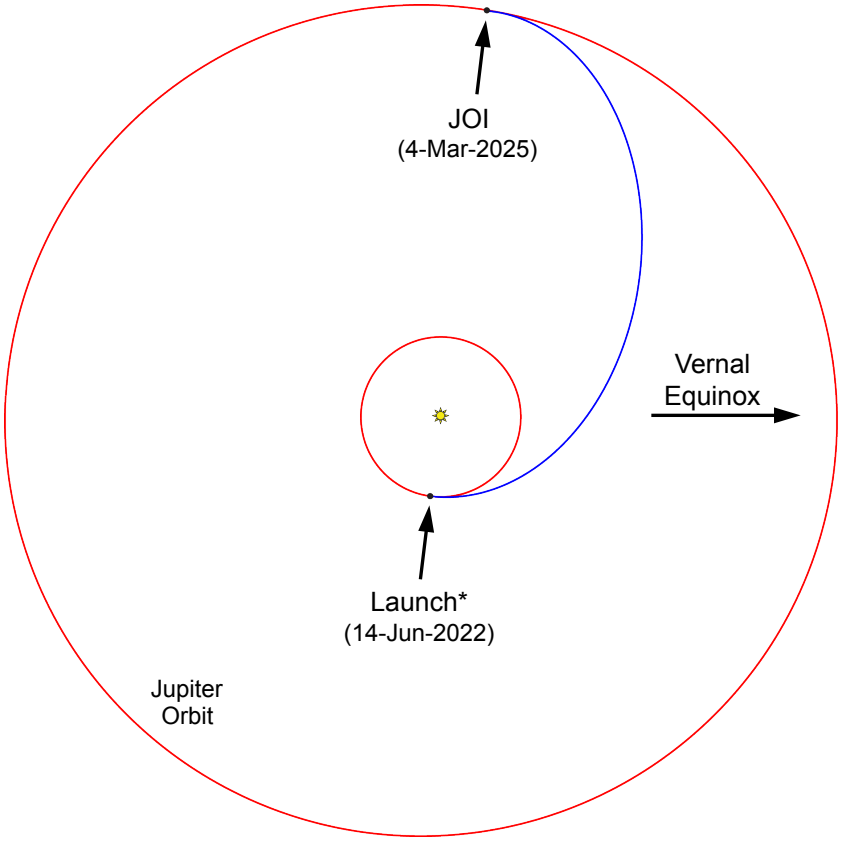
Interplanetary Trajectory Options

Atlas V 551
2021 VEEGA Trajectory
(6.37 year flight time)



SLS
2022 Direct-to-Jupiter Trajectory
(2.73† year flight time)



* Launch dates shown are the optimal launch dates, not the open of a launch period

†**Opportunities exist to reduce flight time down to 1.9 yrs.**

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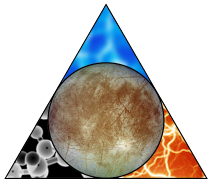

13F7-A21 Trajectory

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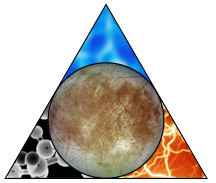
13F7 Design Goals



- Maintain and improve May 2012 notional baseline instrument coverage
  - SWIRS
  - IPR
  - NMS
  - Topographic Imager
- Implement and optimize enhanced instrument observations
  - Reconnaissance Imaging (thermal and visible)
  - Gravity science
  - Magnetometry
- Minimize cost functions: ΔV, TID, and time-of-flight

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13F7-A21 / 11F5-A21 Comparison

	11-F5	13F7-A21	Comments
Tour Duration	2.4 years	3.5 years	Initial conditions from Nov 2021 VEEGA trajectory
Number of Flybys: Europa Ganymede Callisto	 34 9 0	 45 5 9	
Time between Flybys: Maximum Minimum Mean	 28.7 days 3.5 days 15.5 days	 50.0 days 5.5 days 18.3 days	Maximum and mean values excluding the 200 and 50 day orbits post JOI and G1
Deterministic ΔV post-PRM	157 m/s *	147 m/s	* Value for 11-F5A tour was 143 m/s
Maximum Inclination	15º	20.1º	
Maximum Eclipse Duration	6.8 hours *	4.5 hours	* Value for 11-F5A tour was 9.6 hours
Total Ionized Dose (TID)	2.06 Mrad	2.08 Mrad	Si behind 100 mil Al, spherical shell

- Key Improvements
  - Significantly increases science return
  - Reduces maximum Jupiter solar eclipse durations
  - Increases data margins by increasing the average time-of-flight between Europa flybys
  - Avoids placing key events (flybys and maneuvers) during solar conjunction periods
  - More conservative flyby altitude step-down approach for Europa
    - 500 km → 250 km → 100 km → 50 km → 25 km (Ganymede and Callisto skip 250 km step)

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13F7-A21 Flybys

Phase		Flyby		In/ Out	Date (ET)	Altitude (km)	B-Plane Ang (deg)	V_∞ (km/s)	Inc. (deg.)	Peri (R_J)	Apo (R_J)	SEP Angle (deg)	m	n	Period (days)	Time to Next Encounter (days)	Total Time-of-Flight (months)
Jupiter Approach		Ganymede0	0G0	I	03-Apr-2028 11:58:34	500	0.1	7.97	5.4	12.96	265.1	156	N	R	200	202.2	0.0
Approach to Europa Science		Ganymede1	1G1	O	22-Oct-2028 17:14:57	100	-152.7	6.39	3.7	12.00	107.8	17	8	1	57.2	57.2	6.7
		Ganymede2	2G2	O	18-Dec-2028 23:07:28	100	-147.9	6.44	1.3	11.09	64.4	64	5	1	28.6	28.6	8.6
		Ganymede3	3G3	O	16-Jan-2029 13:49:12	1035.5	188	6.43	0.8	10.20	45.9	90	N	R	18.3	14.9	9.6
		Callisto1	4C1	I	31-Jan-2029 12:29:59	911.6	156.2	5.54	1.6	12.33	55.0	105	N	R	24.1	27.3	10.1
		Ganymede4	5G4	O	27-Feb-2029 18:42:49	523.6	163.5	5.24	0.2	11.17	37.0	133	N	R	14.6	16.5	11.0
		Callisto2	6C2	I	16-Mar-2029 06:22:27	2635.9	178.3	4.35	0.2	9.22	33.9	150	N	R	12.4	9.7	11.6
Europa Anti-Jupiter Hemisphere Coverage	COT-1	Europa1	7E1	O	25-Mar-2029 22:26:46	752.7	-36.2	4.00	1.4	9.29	38.0	161	4	1	14.2	14.2	11.9
		Europa2	8E2	O	09-Apr-2029 02:40:15	250	-71.1	3.93	3.8	9.37	37.9	176	4	1	14.2	14.2	12.4
		Europa3	9E3	O	23-Apr-2029 07:42:56	100	-44.3	3.96	5.7	9.44	37.9	168	4	1	14.2	14.2	12.8
		Europa4	10E4	O	07-May-2029 12:42:32	100	-15.9	3.97	6.3	9.48	37.8	152	4	1	14.2	14.2	13.3
		Europa5	11E5	I	21-May-2029 17:42:13	50	14.7	3.97	5.5	9.47	37.8	137	4	1	14.2	14.2	13.8
		Europa6	12E6	I	04-Jun-2029 22:42:16	25	46.7	3.96	3.3	9.40	37.9	123	4	1	14.2	14.2	14.2
	Non-Res (I/O)	Europa7	13E7	I	19-Jun-2029 03:44:29	100	78	3.93	0.5	9.38	38.1	109	4	1+	14.3	14.5	14.7
	COT-2	Europa8	14E8	O	03-Jul-2029 15:16:07	100	80.8	3.97	2.5	9.38	37.9	96	4	1	14.2	14.2	15.2
		Europa9	15E9	O	17-Jul-2029 20:14:27	25	53	3.99	4.7	9.41	37.9	84	4	1	14.2	14.2	15.7
		Europa10	16E10	O	01-Aug-2029 01:15:16	50	27.3	4.00	5.8	9.45	37.9	72	4	1	14.2	14.2	16.2
		Europa11	17E11	I	15-Aug-2029 06:11:34	25	-2.5	4.00	5.5	9.42	37.9	60	4	1	14.2	14.2	16.6
		Europa12	18E12	I	29-Aug-2029 11:07:50	50	-34.1	4.00	4.0	9.31	38.0	49	4	1	14.2	14.2	17.1
		Europa13	19E13	I	12-Sep-2029 16:00:57	25	-63	3.98	1.4	9.25	38.1	38	4	1	14.2	14.2	17.6
	Petal Rotation	Europa14	20E14	I	26-Sep-2029 21:15:22	565.2	-88.7	3.92	0.9	9.25	38.2	26	4	1+	14.3	14.5	18.0
		Europa15	21E15	O	11-Oct-2029 09:12:54	1872.2	21.6	3.96	0.6	9.29	41.9	15	9	2–	16.0	31.7	18.5
		Europa16	23E16	I	12-Nov-2029 01:39:22	2710.3	10.7	4.08	0.4	9.16	38.3	10	4	1+	14.3	14.6	19.6
		Europa17	24E17	O	26-Nov-2029 14:57:34	50	-1.9	4.02	0.4	9.28	45.5	21	5	1–	17.7	17.6	20.1
		Europa18	25E18	I	14-Dec-2029 04:40:32	50	-0.3	4.01	0.5	9.18	38.3	35	4	1+	14.3	14.5	20.7
		Europa19	26E19	O	28-Dec-2029 17:39:59	81.2	0.1	4.04	0.5	9.30	45.5	47	5	1–	17.7	17.6	21.1
		Europa20	27E20	I	15-Jan-2030 07:07:07	50	0.5	4.04	0.5	9.19	38.3	62	4	1+	14.3	14.5	21.7
		Europa21	28E21	O	29-Jan-2030 20:00:01	100	0.1	4.04	0.5	9.37	45.4	75	5	1–	17.7	17.6	22.2
		Europa22	29E22	I	16-Feb-2030 09:40:09	50	0.2	4.04	0.5	9.27	38.2	91	4	1+	14.3	14.5	22.8
		Europa23	30E23	O	02-Mar-2030 22:49:08	50	-0.8	4.08	0.4	9.39	45.4	105	5	1–	17.7	17.6	23.3
		Europa24	31E24	I	20-Mar-2030 12:05:36	100	-4.9	4.08	0.5	9.29	38.2	122	4	1+	14.3	14.5	23.9

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13F7-A21 Flybys [cont.]

	Phase	Flyby		In/ Out	Date (ET)	Altitude (km)	B-Plane Ang (deg)	V_∞ (km/s)	Inc. (deg.)	Peri (R_J)	Apo (R_J)	SEP Angle (deg)	m	n	Period (days)	Time to Next Encounter (days)	Total Time-of-Flight (months)
Change Illuminated Hemisphere	Crank Up Pump Down	Europa25	32E25	O	04-Apr-2030 01:17:21	50	84.8	4.10	3.0	9.31	38.0	137	4	1	14.2	14.2	24.4
		Europa26	33E26	O	18-Apr-2030 06:13:37	50	63.1	4.12	5.4	9.40	37.9	153	4	1	14.2	14.2	24.8
		Europa27	34E27	O	02-May-2030 11:03:14	50	74.2	4.13	7.9	9.45	33.9	168	7	2	12.4	24.9	25.3
	Switch-Flip	Europa28	36E28	O	27-May-2030 07:36:51	25	109.5	4.14	10.4	9.36	26.9	165	N	R	9.5	5.5	26.1
		Callisto3	37C3	I	01-Jun-2030 20:43:23	466.5	-138	2.84	14.5	14.77	28.7	159	3	4	12.5	50.0	26.3
		Callisto4	41C4	I	21-Jul-2030 21:11:53	100	-98.8	2.84	19.0	23.05	28.7	109	1	1	16.7	16.6	28.0
		Callisto5	42C5	I	07-Aug-2030 12:47:17	1828.2	-64.1	2.84	20.1	26.11	29.6	94	pi-trans		16.7	8.2	28.5
		Callisto6	43C6	O	15-Aug-2030 18:43:56	100	-177.6	2.81	17.4	21.84	26.5	86	1	1	16.7	16.6	28.8
		Callisto7	44C7	I	01-Sep-2030 10:18:29	50	-40.7	2.83	13.6	12.47	30.8	72	2	3	11.1	33.3	29.4
		Callisto8	47C8	I	04-Oct-2030 17:52:50	25	-106.3	2.80	1.1	11.15	27.8	45	2	3	11.0	33.5	30.5
		Callisto9	50C9	I	07-Nov-2030 06:37:49	3673.1	-4.4	2.97	0.5	9.01	29.2	18	N	R	9.7	32.7	31.6
Europa Sub-Jupiter Hemisphere Coverage	Pump Up, Avoid Sol. Conj.	Europa29	53E29	I	09-Dec-2030 22:16:02	546.7	173.6	3.99	0.4	9.18	27.9	7	10	3+	11.8	35.9	32.7
		Europa30	56E30	O	14-Jan-2031 21:03:57	1009	-8.7	4.05	0.7	9.34	32.8	36	4	1–	14.1	13.9	33.9
	COT-3	Europa31	57E31	I	28-Jan-2031 18:06:21	100	-108.7	3.99	3.1	9.36	37.8	48	4	1	14.2	14.2	34.3
		Europa32	58E32	I	11-Feb-2031 23:08:16	100	-135.8	3.97	4.9	9.42	37.9	60	4	1	14.2	14.2	34.8
		Europa33	59E33	I	26-Feb-2031 04:12:04	50	-169.8	3.95	5.3	9.46	37.9	72	4	1	14.2	14.2	35.3
		Europa34	60E34	O	12-Mar-2031 09:13:49	50	152.7	3.96	3.9	9.39	37.9	84	4	1	14.2	14.2	35.8
		Europa35	61E35	O	26-Mar-2031 14:15:56	25	118.5	3.97	1.3	9.35	37.9	97	4	1	14.2	14.2	36.2
	Non-Res (O/I)	Europa36	62E36	O	09-Apr-2031 18:29:44	303.4	151.7	3.91	0.3	9.28	37.9	111	7	2–	12.4	24.5	36.7
	COT-4	Europa37	64E37	I	04-May-2031 06:22:09	50	105.1	3.89	3.1	9.33	33.9	135	7	2	12.4	24.9	37.5
		Europa38	66E38	I	29-May-2031 03:37:23	25	187.1	3.78	2.6	9.40	34.0	161	4	1	14.2	14.2	38.4
		Europa39	67E39	I	12-Jun-2031 07:37:03	50	96.4	3.81	5.5	9.41	37.9	177	7	2	12.4	24.9	38.8
		Europa40	69E40	I	07-Jul-2031 04:32:14	25	-139.5	3.79	3.5	9.38	33.9	157	4	1	14.2	14.2	39.7
		Europa41	70E41	I	21-Jul-2031 08:16:17	50	124.8	3.80	5.9	9.41	37.9	142	7	2	12.4	24.9	40.1
		Europa42	72E42	O	15-Aug-2031 05:17:42	50	-112.9	3.80	3.1	9.38	33.9	117	4	1	14.2	14.2	41.0
		Europa43	73E43	O	29-Aug-2031 08:56:27	25	-210.5	3.76	4.6	9.35	37.9	104	7	2	12.5	24.9	41.4
		Europa44	75E44	O	23-Sep-2031 05:37:41	50	-82.1	3.74	1.7	9.34	33.8	81	4	1	14.2	14.1	42.3
		Europa45	76E45	O	07-Oct-2031 08:47:53	25	-177.6	3.68	1.5	9.28	37.9	69	7	2	12.5	NA	42.7

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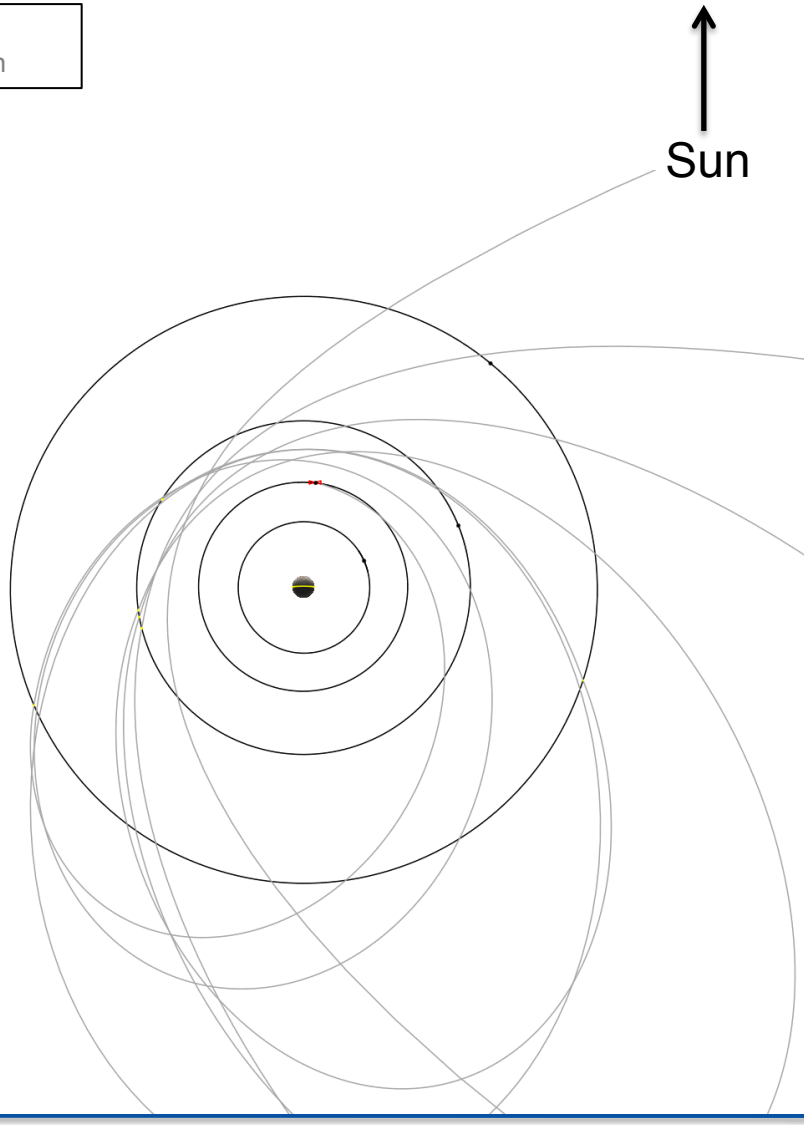
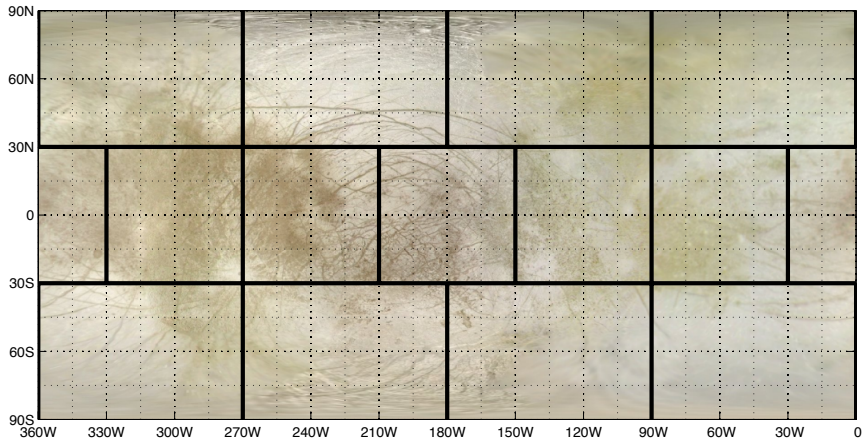
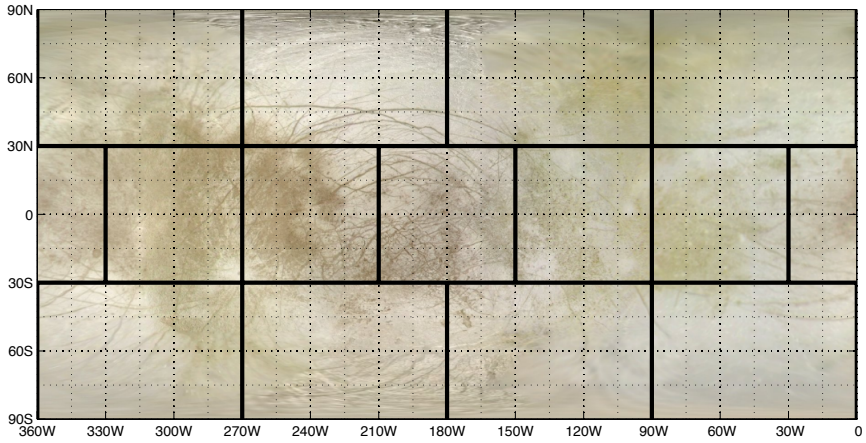
13F7-A21 Phase: Pump Down

Key:
- Pump Down







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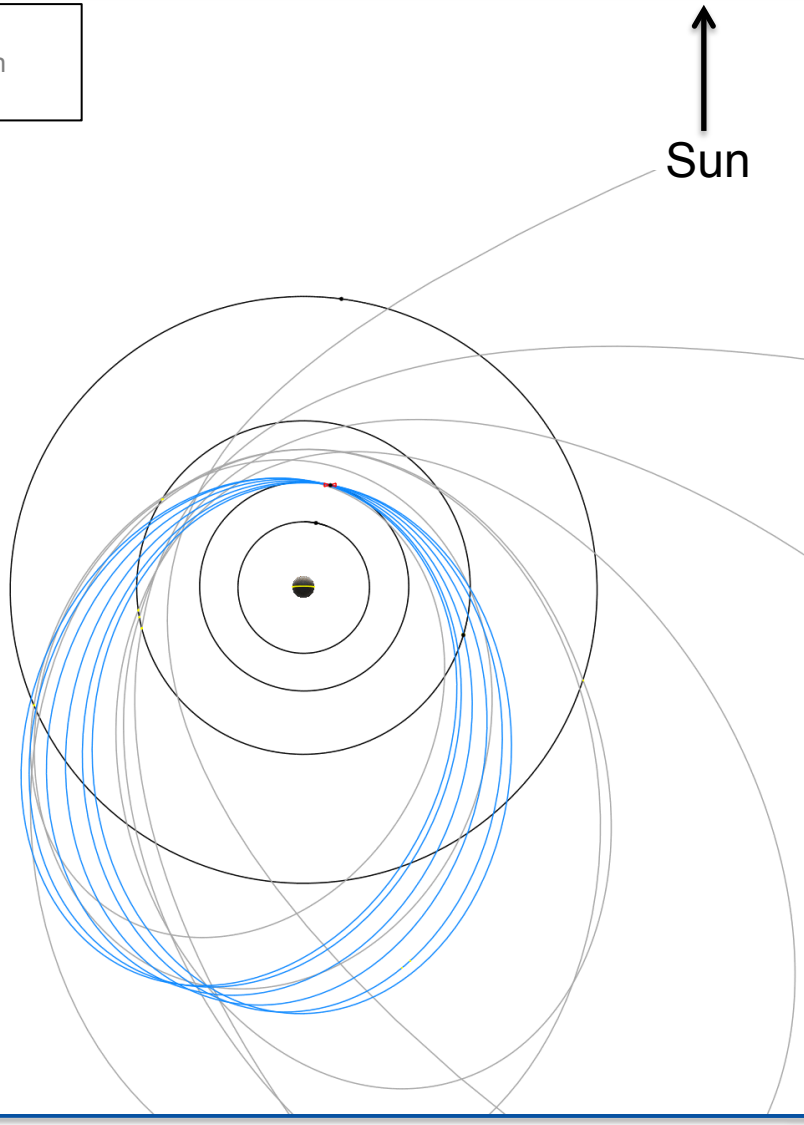
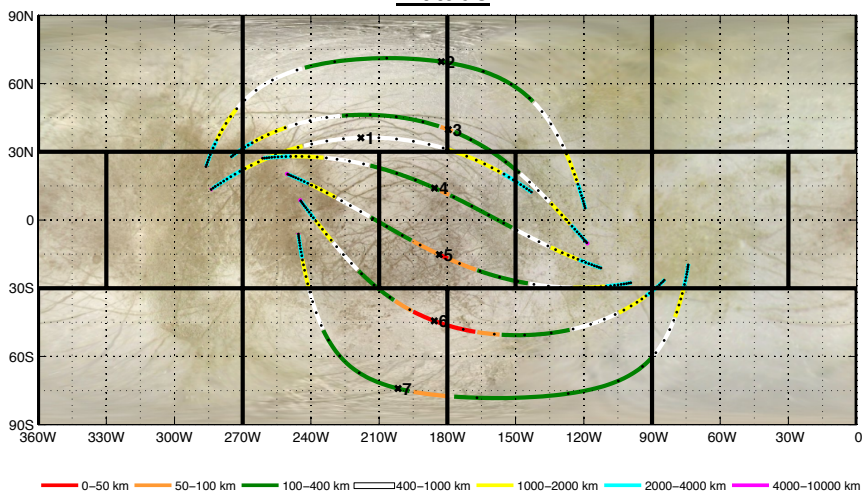
13F7-A21 Phases: COT-1

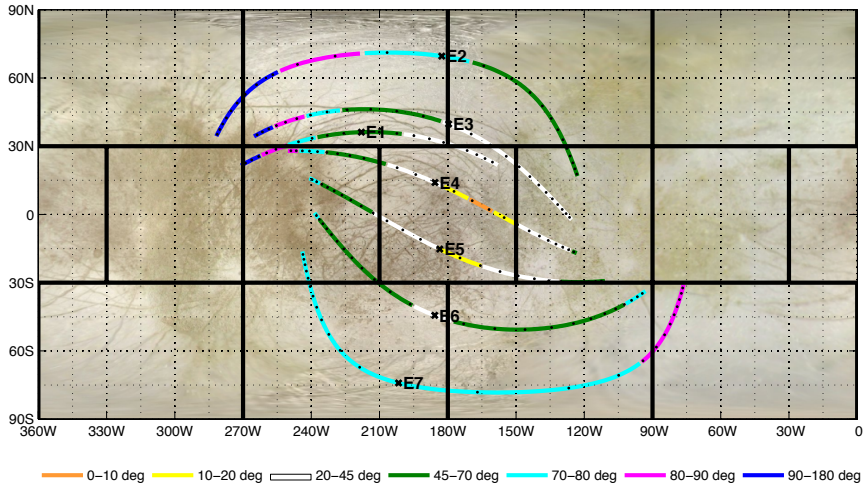
Key:
- Pump Down
- COT-1



Altitude



Solar Phase



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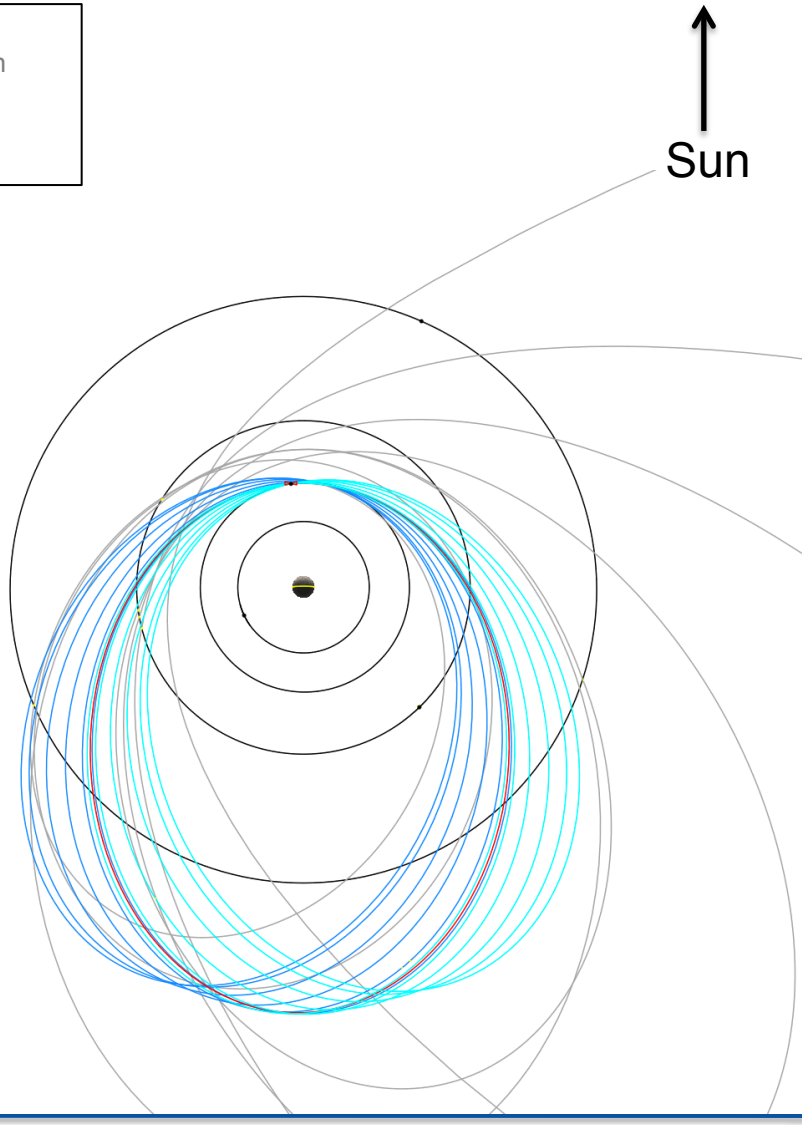
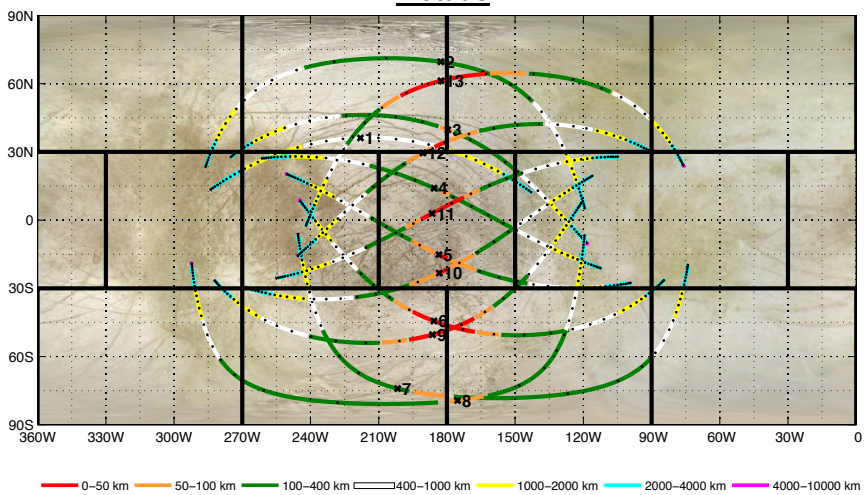
13F7-A21 Phases: COT-2

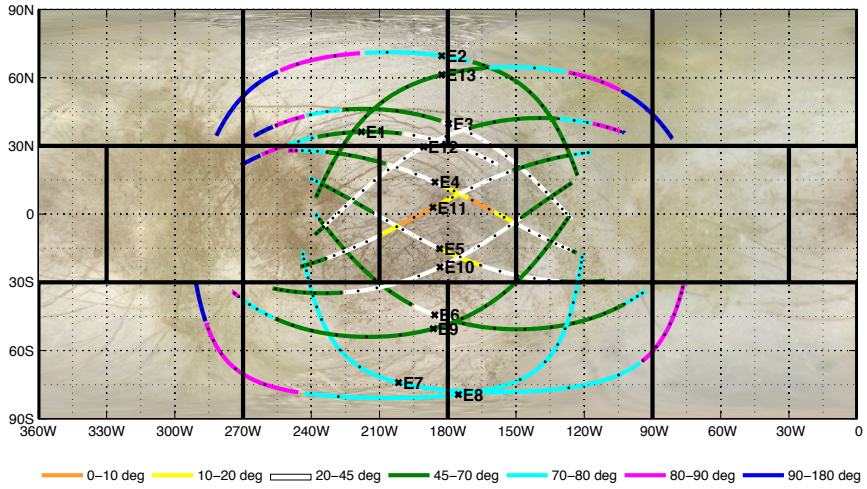
Key:
- Pump Down
- COT-1
- Non-Res
- COT-2



Altitude



Solar Phase



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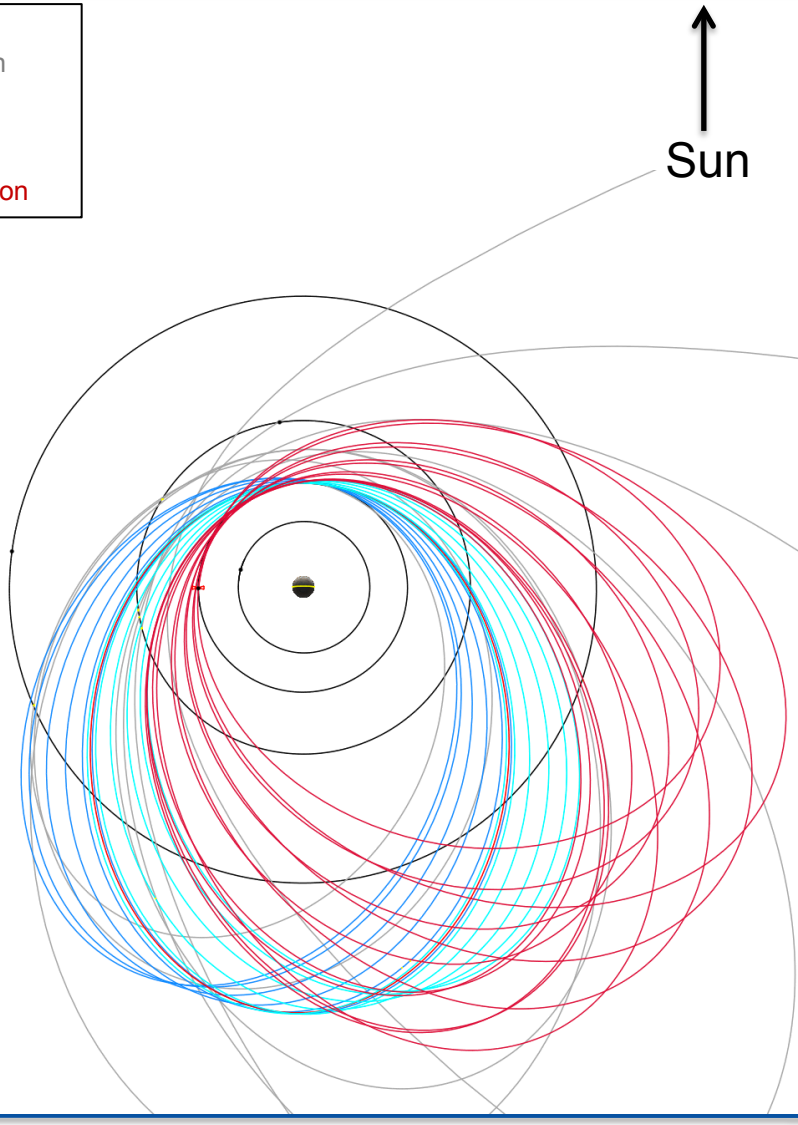
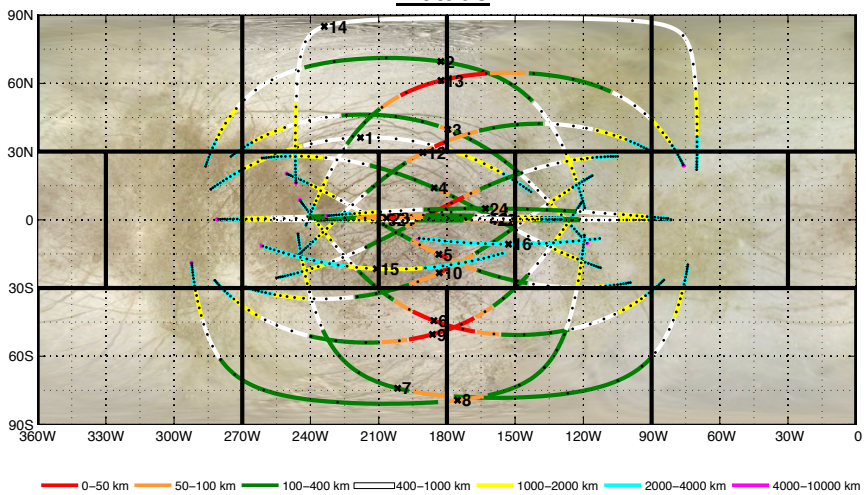
13F7-A21 Phases: Petal Rotation

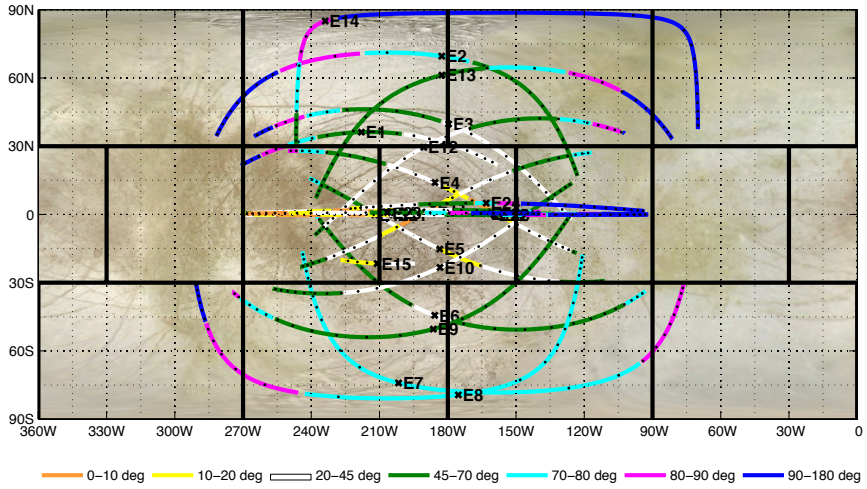
Key:
- Pump Down
- COT-1
- Non-Res
- COT-2
- Petal Rotation



Altitude



Solar Phase



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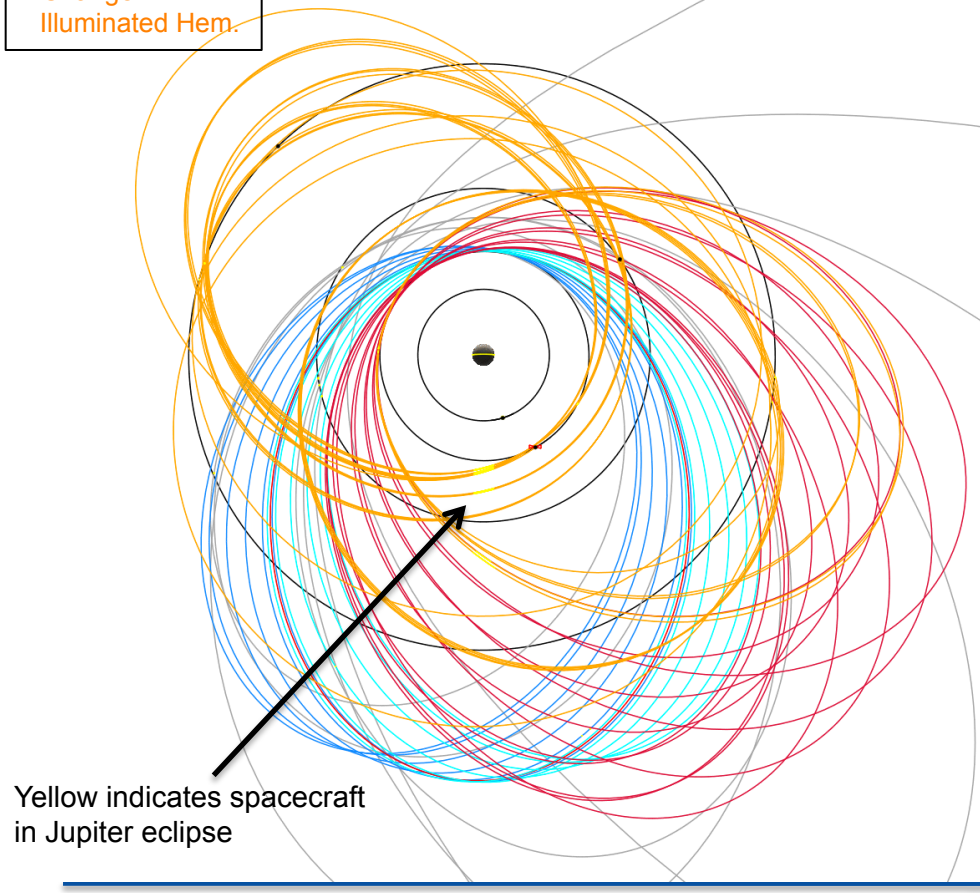
13F7-A21 Phases: Change Illuminated Hem.

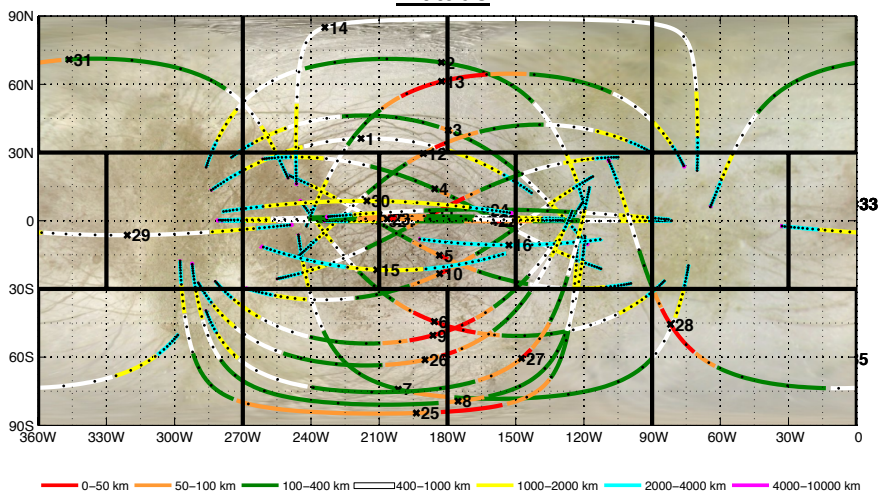
Key:
- Pump Down
- COT-1
- Non-Res
- COT-2
- Petal Rotation
- Change Illuminated Hem.

Sun

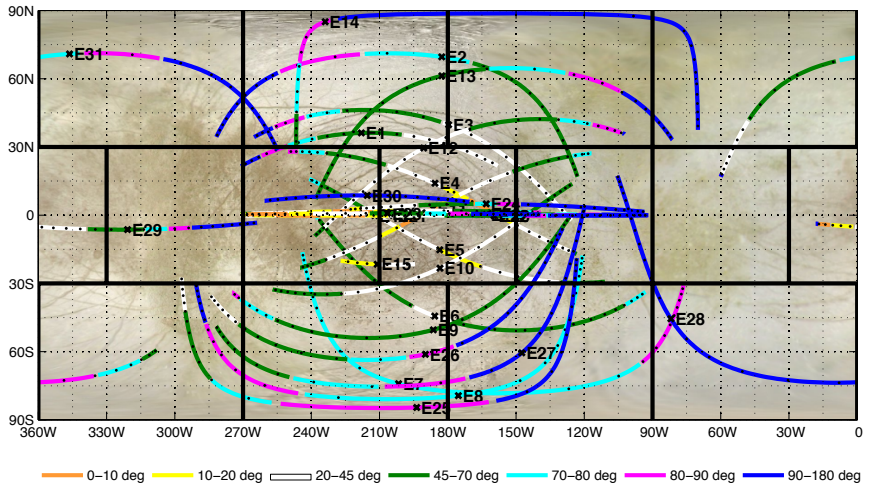


Yellow indicates spacecraft in Jupiter eclipse

Altitude



Solar Phase



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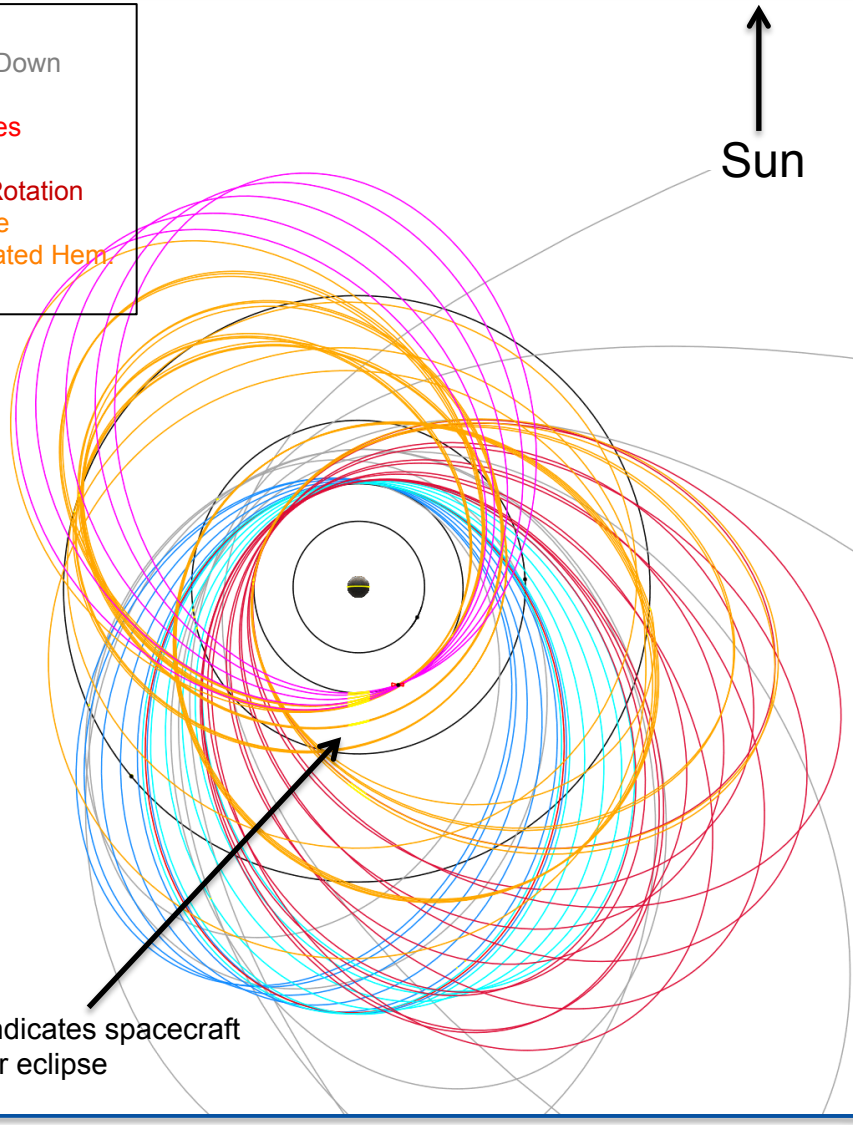
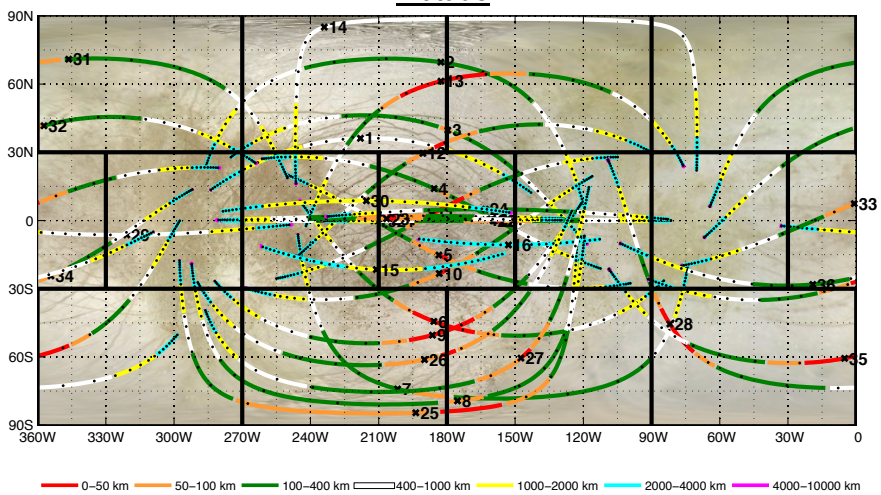
13F7-A21 Phases: COT-3

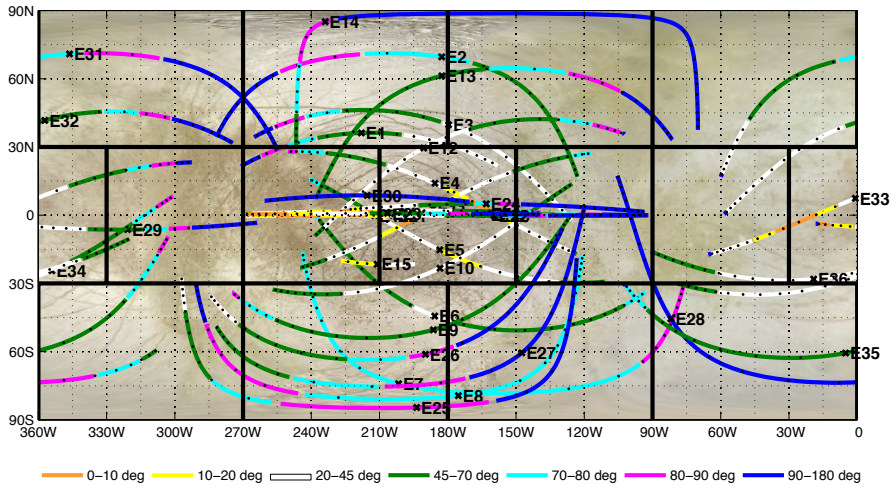
Key:
- Pump Down
- COT-1
- Non-Res
- COT-2
- Petal Rotation
- Change Illuminated Hem
- COT-3



Altitude



Solar Phase



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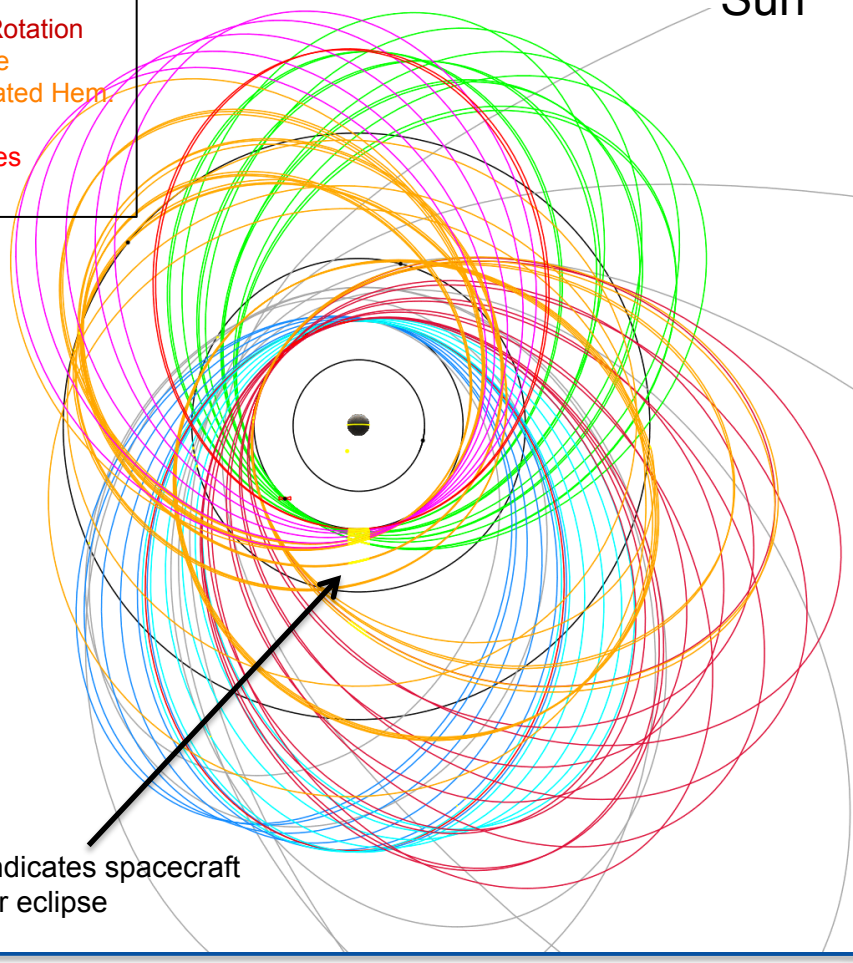
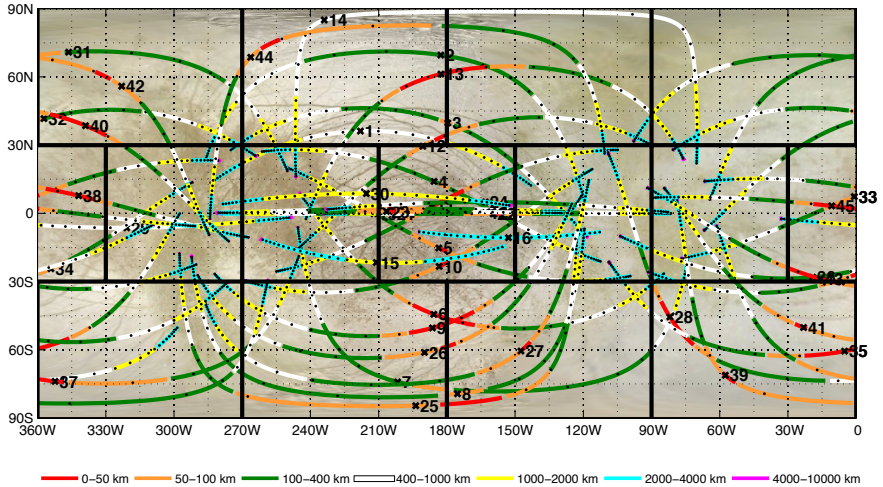
13F7-A21 Phases: COT-4

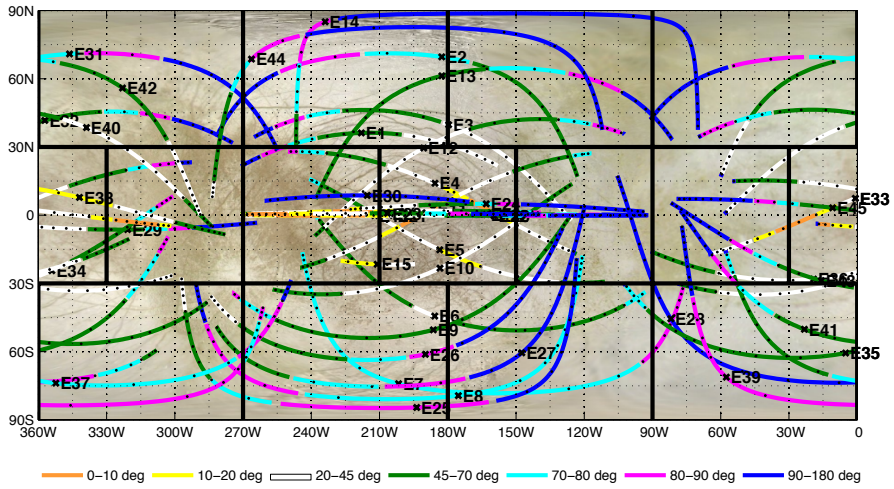
Key:
- Pump Down
- COT-1
- Non-Res
- COT-2
- Petal Rotation
- Change Illuminated Hem
- COT-3
- Non-Res
- COT-4



Altitude



Solar Phase



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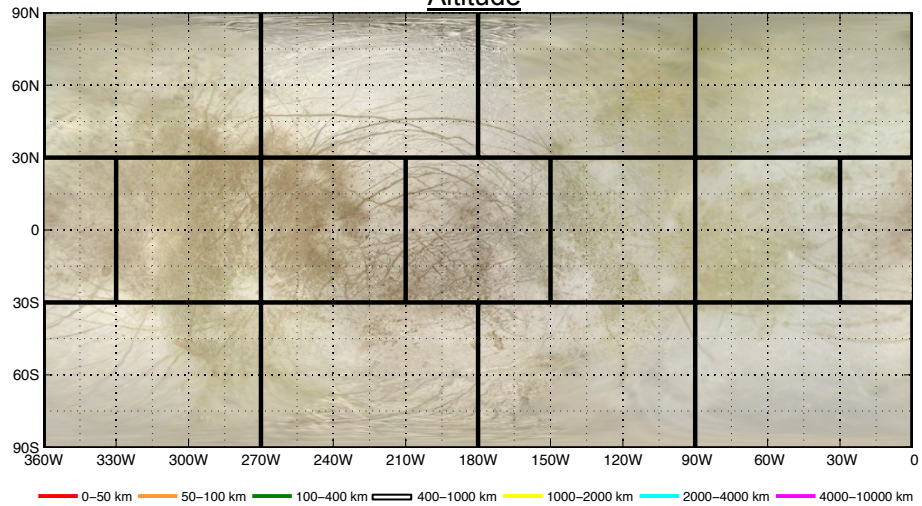
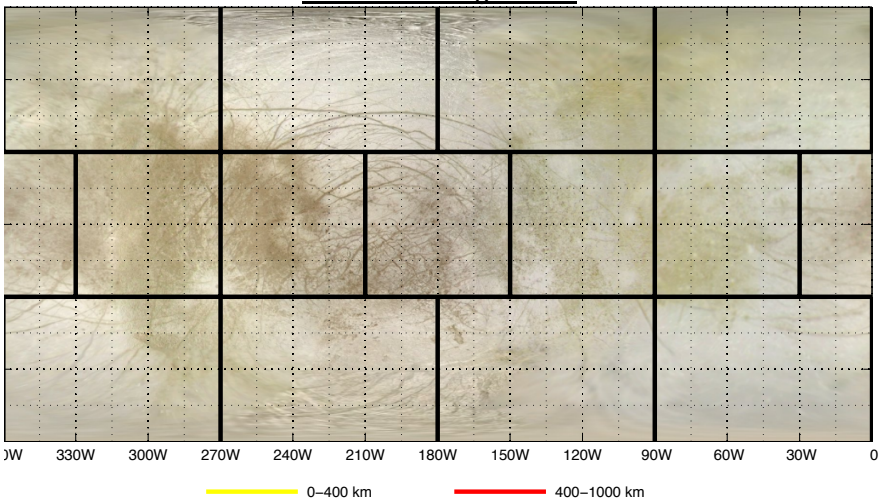
13F7 Select Instrument Coverage

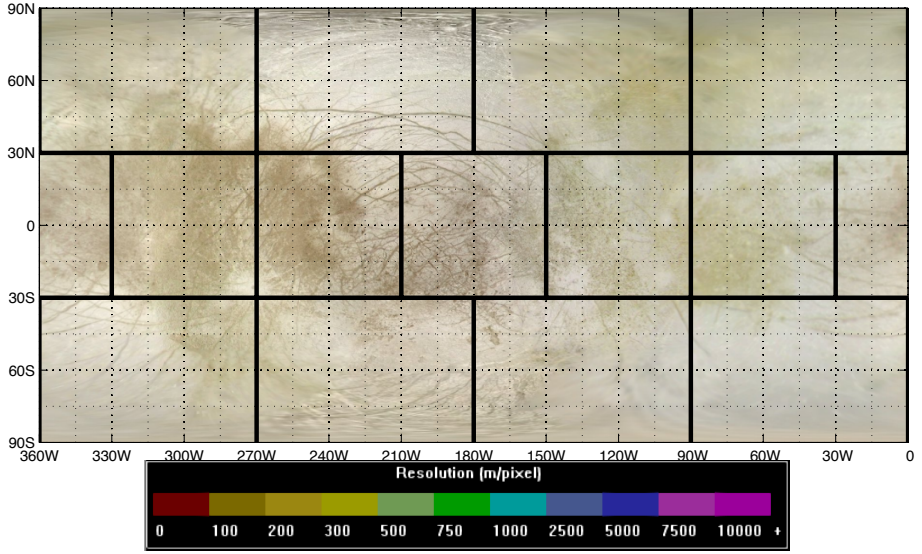
Altitude



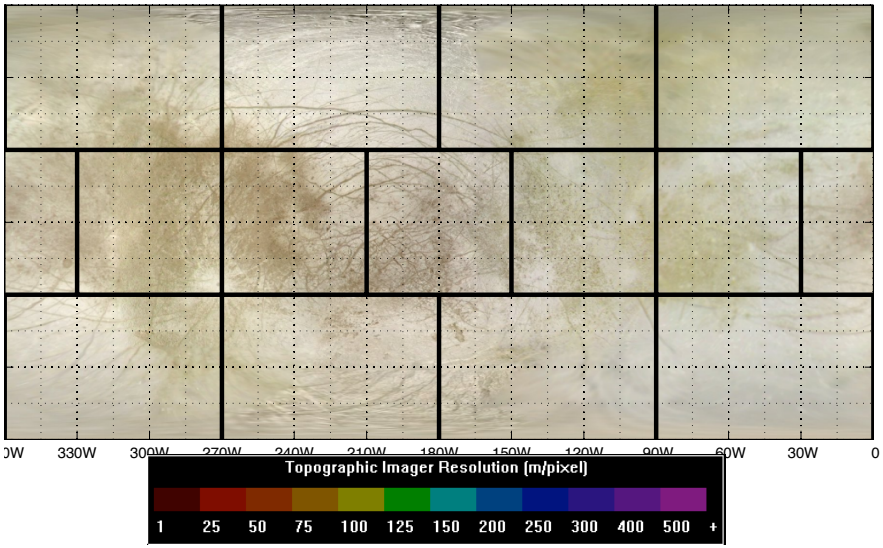
Ice Penetrating Radar



SWIRS



Topographic Imaging



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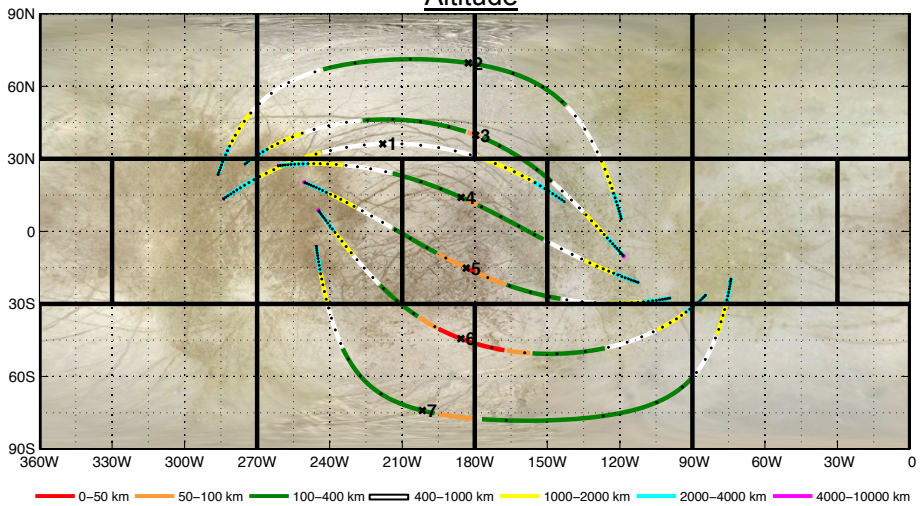
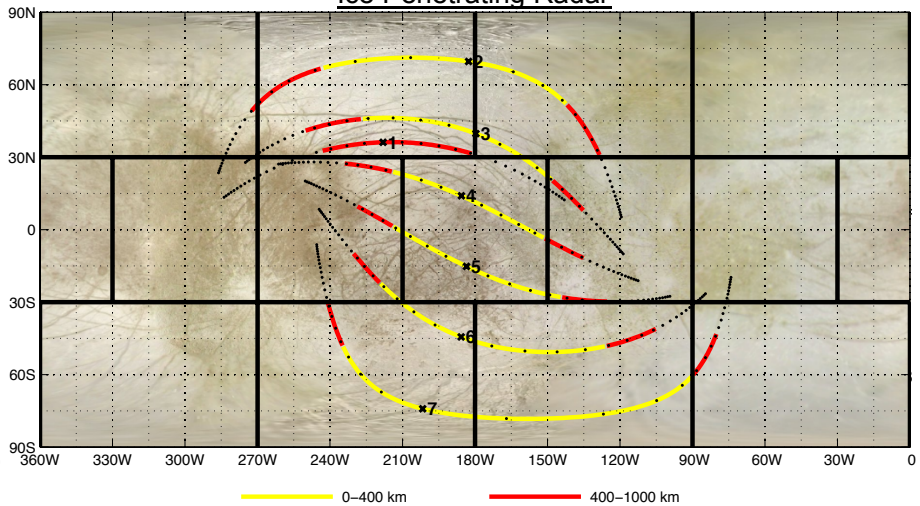
13F7 Select Instrument Coverage
COT-1

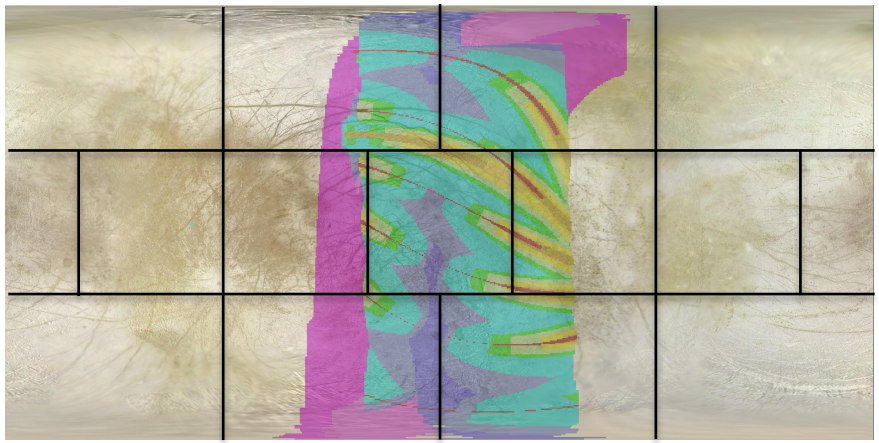
Altitude

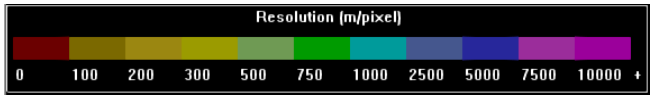


Ice Penetrating Radar

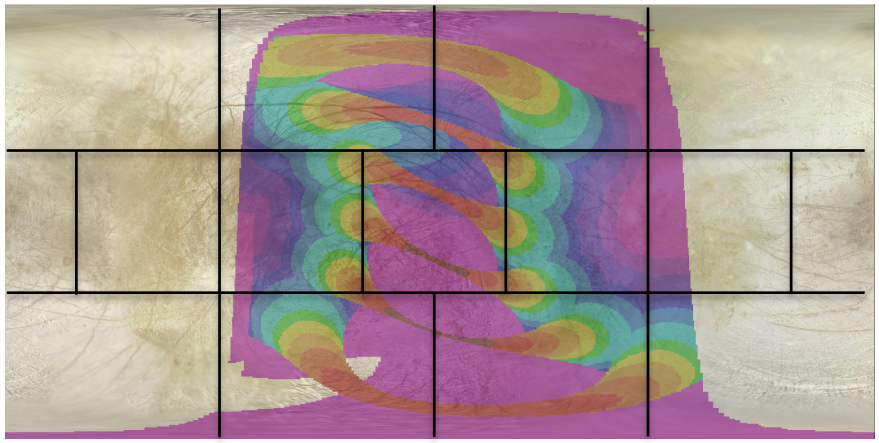


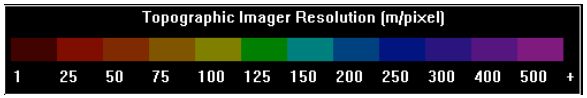
SWIRS





Topographic Imaging





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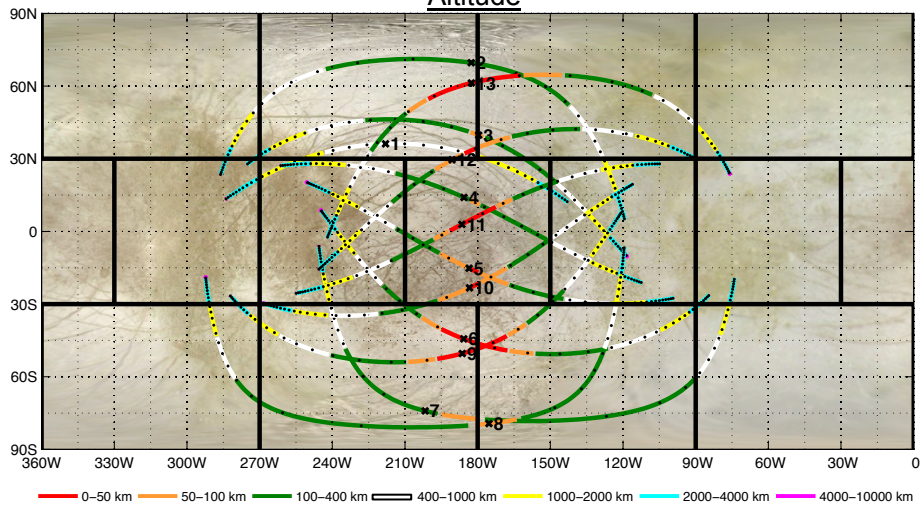
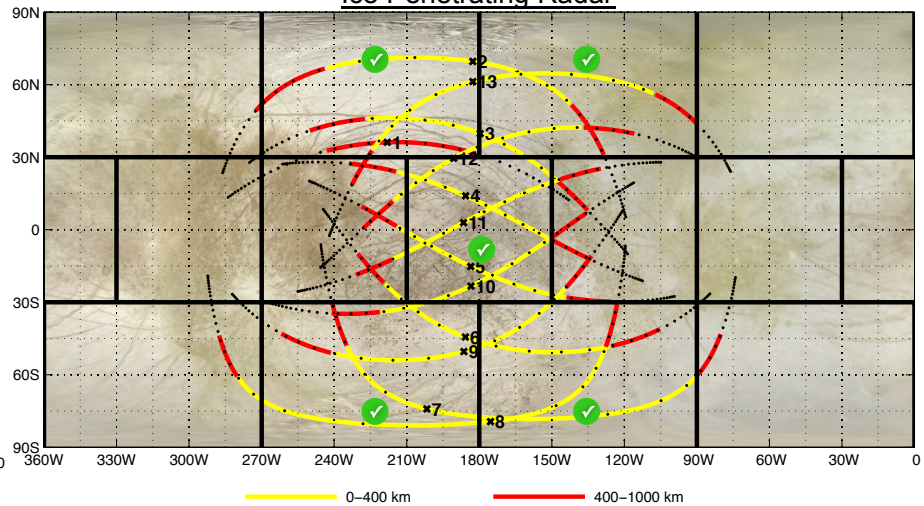
13F7 Select Instrument Coverage
COT-2

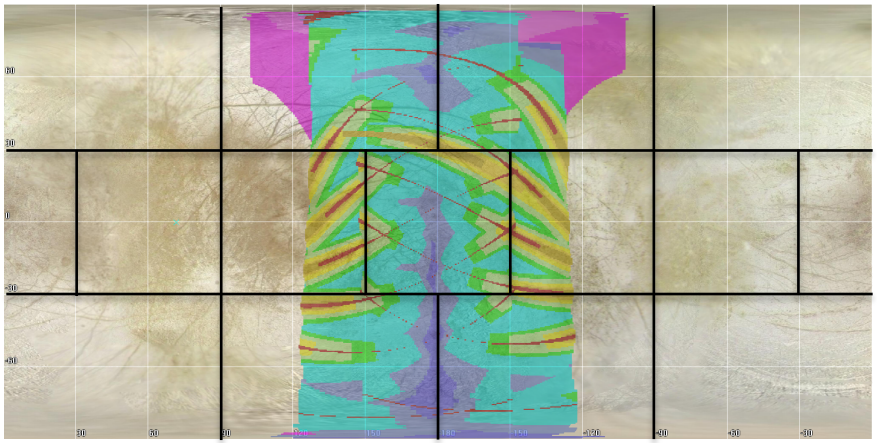
Altitude



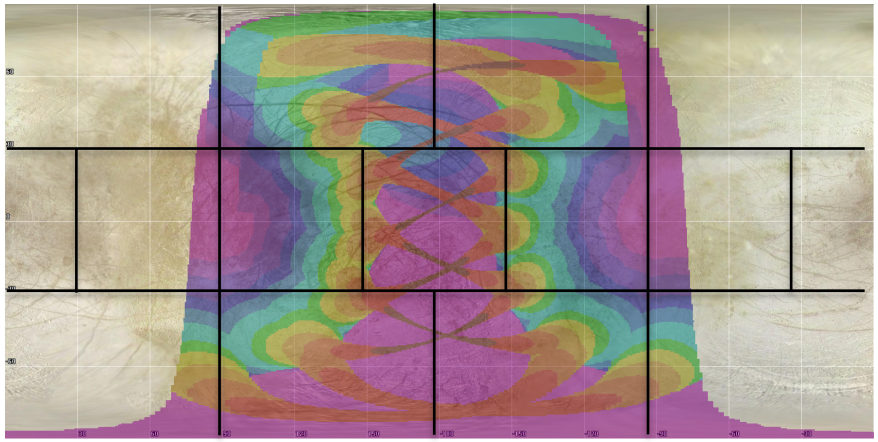
Ice Penetrating Radar

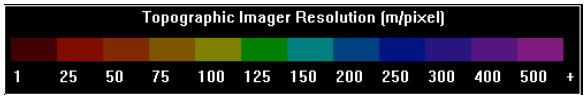


SWIRS



Topographic Imaging





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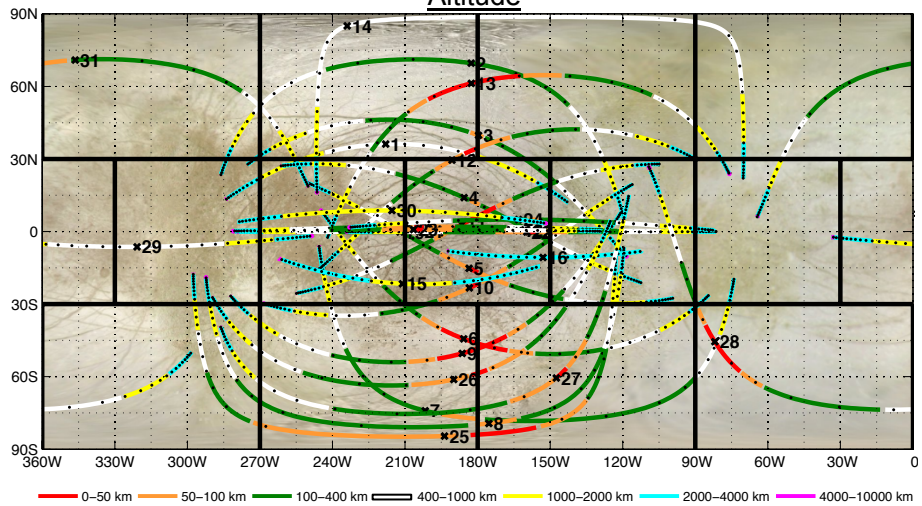
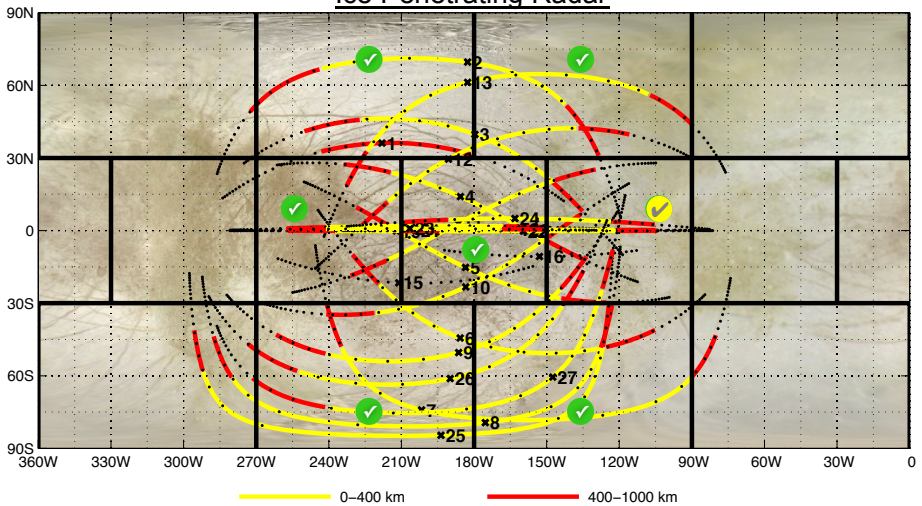
13F7 Select Instrument Coverage

Petal Rot., Change Illuminated Hem.

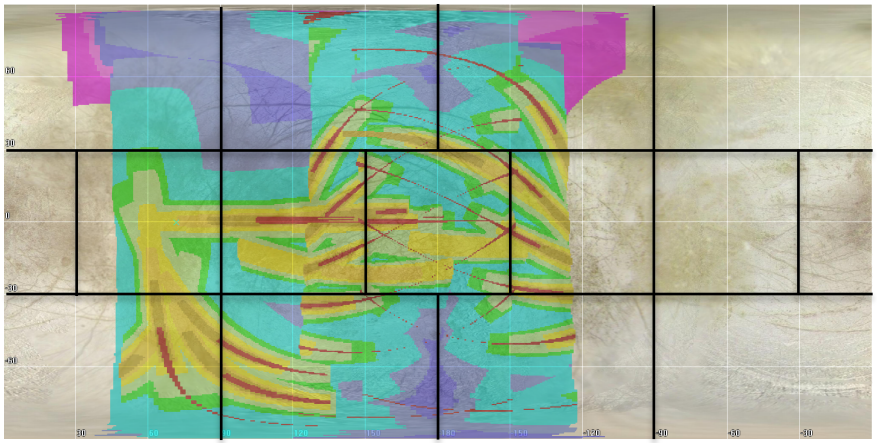
Altitude



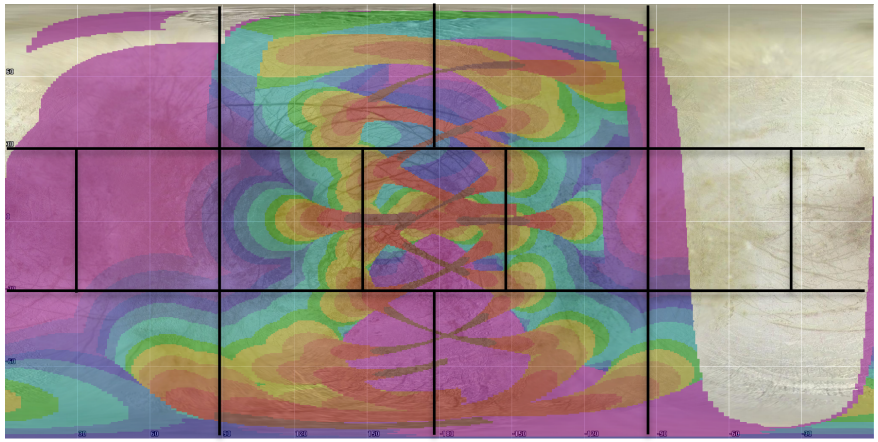
Ice Penetrating Radar

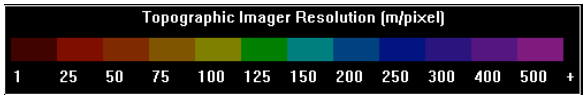


SWIRS



Topographic Imaging





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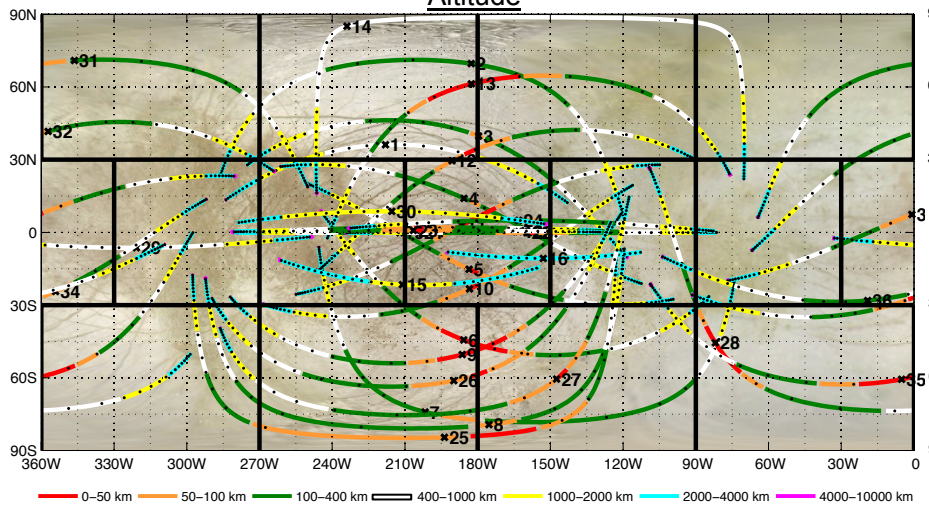
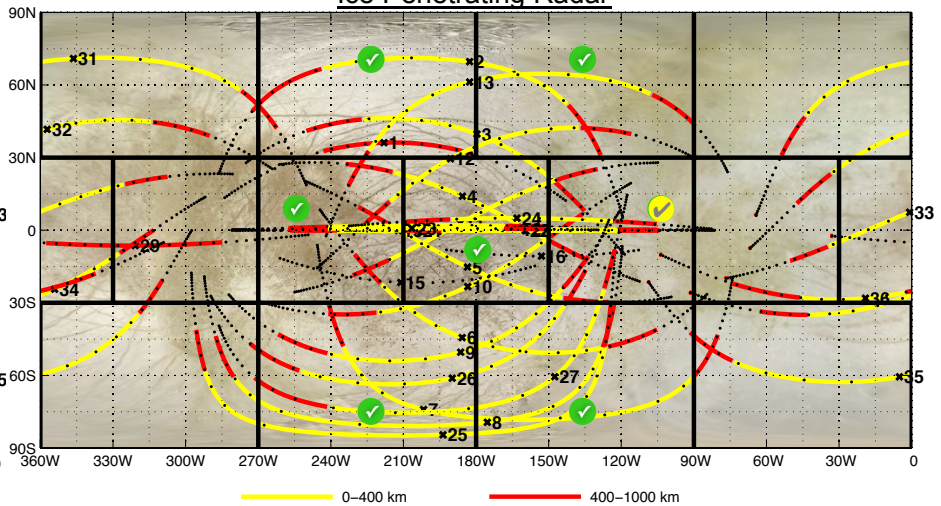
13F7 Select Instrument Coverage
COT-3

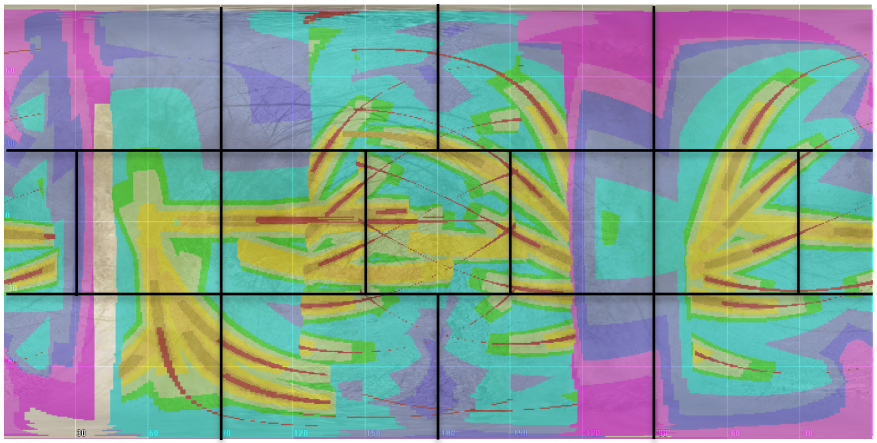
Altitude

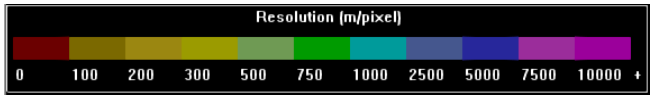


Ice Penetrating Radar

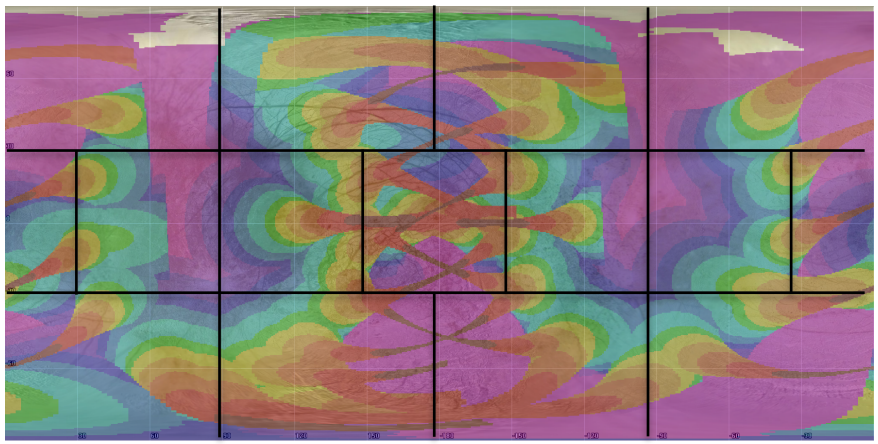


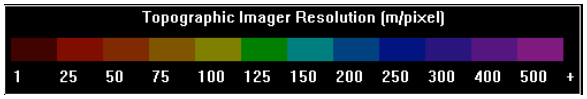
SWIRS





Topographic Imaging





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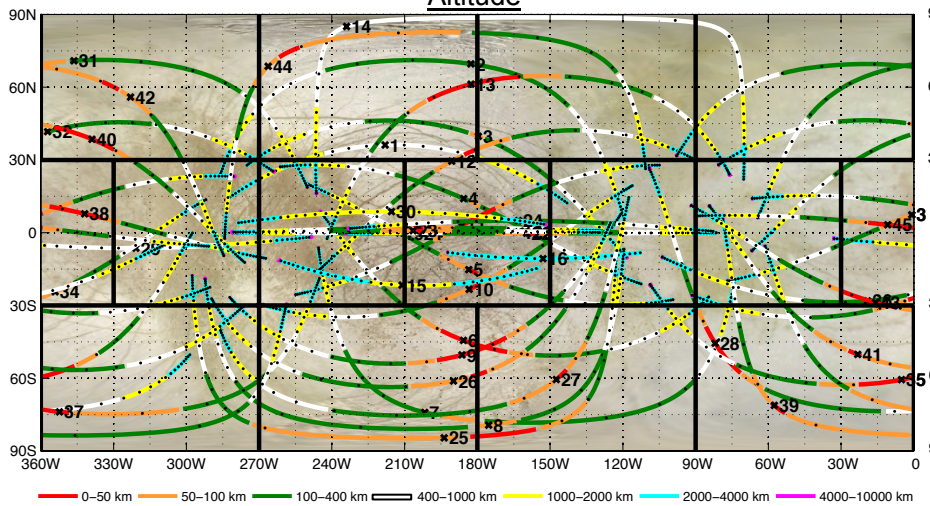
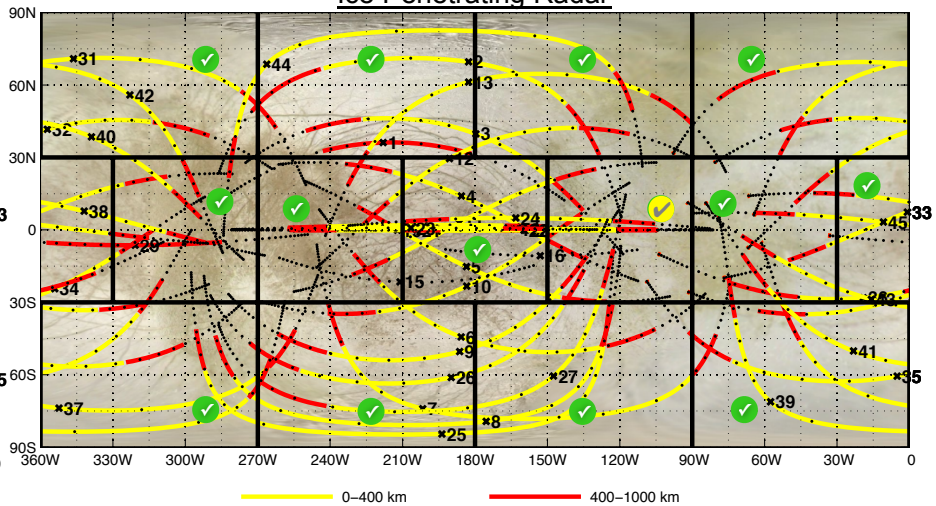
13F7 Select Instrument Coverage
COT-4

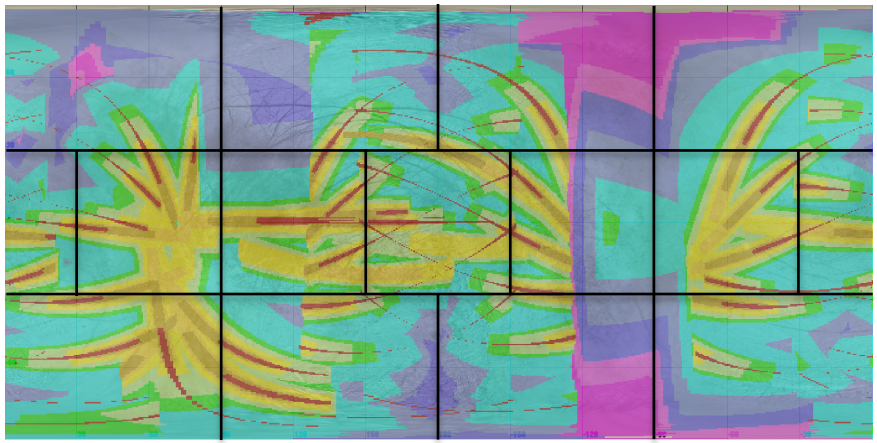
Altitude

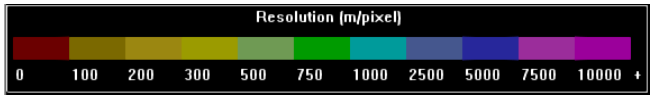


Ice Penetrating Radar

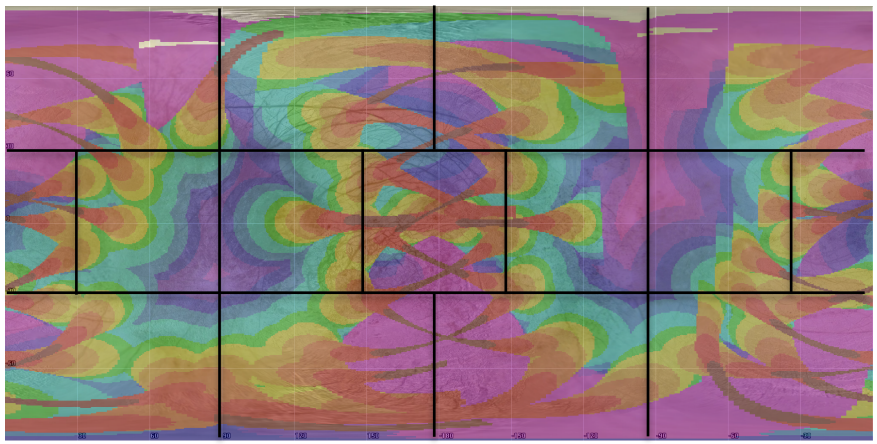


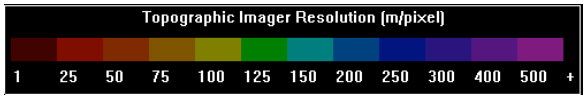
SWIRS





Topographic Imaging





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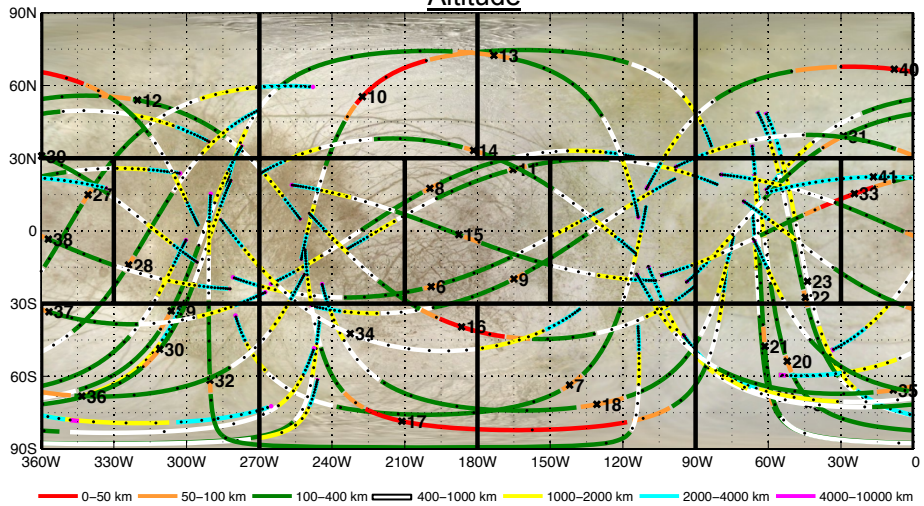
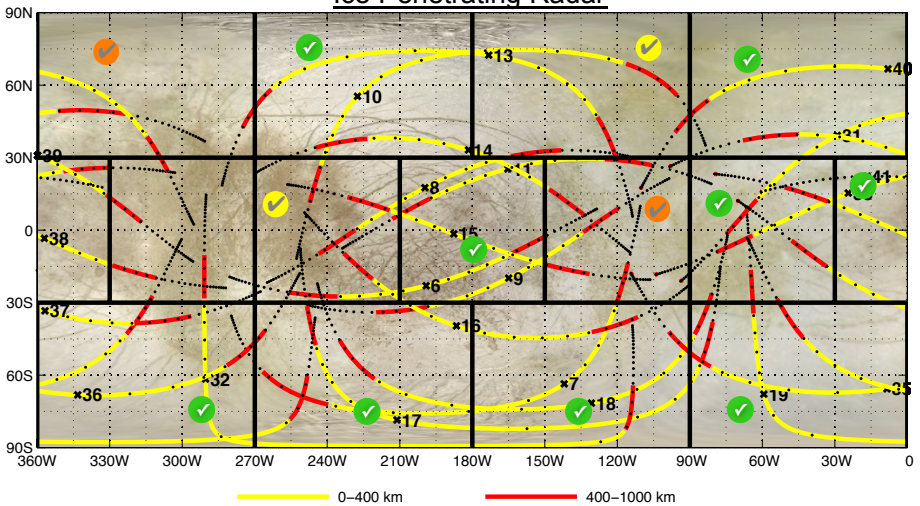
11F5 Instrument Coverage
(Previous Trajectory)

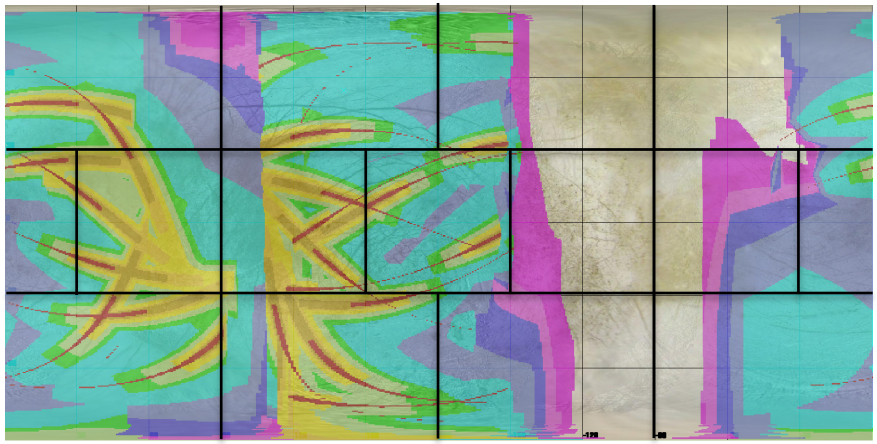
Altitude

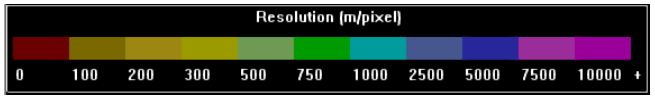


Ice Penetrating Radar

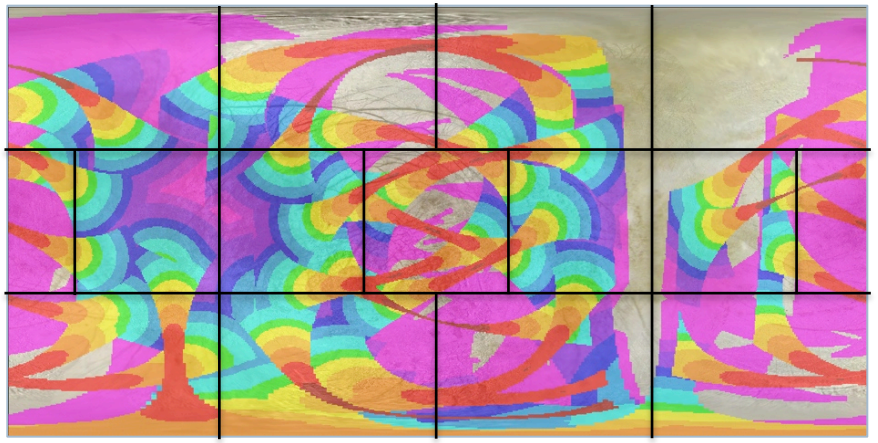


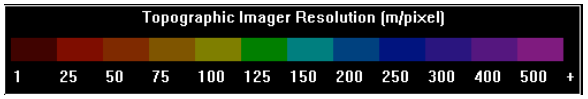
SWIRS





Topographic Imaging





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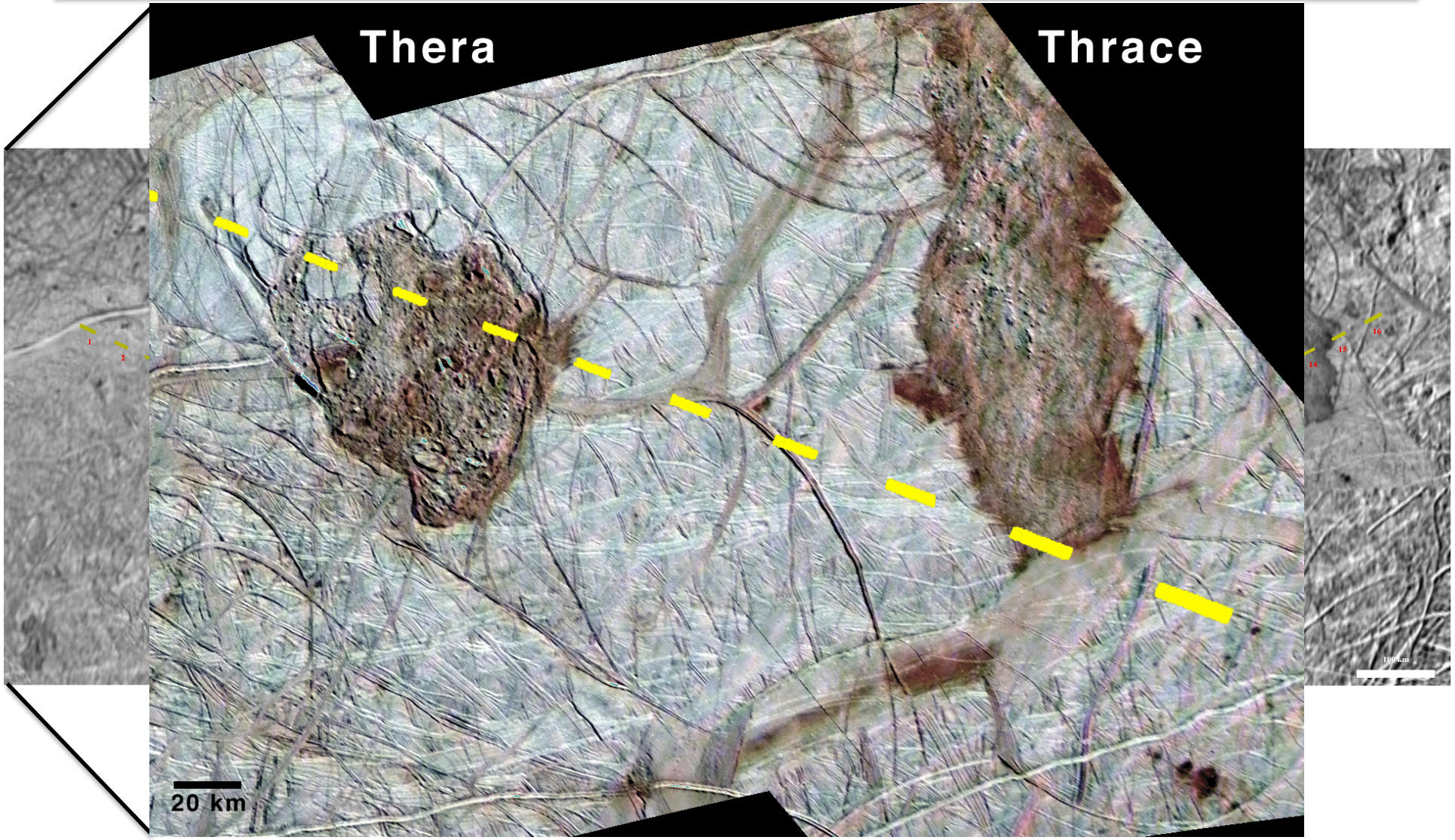
13F7-A21 Reconnaissance



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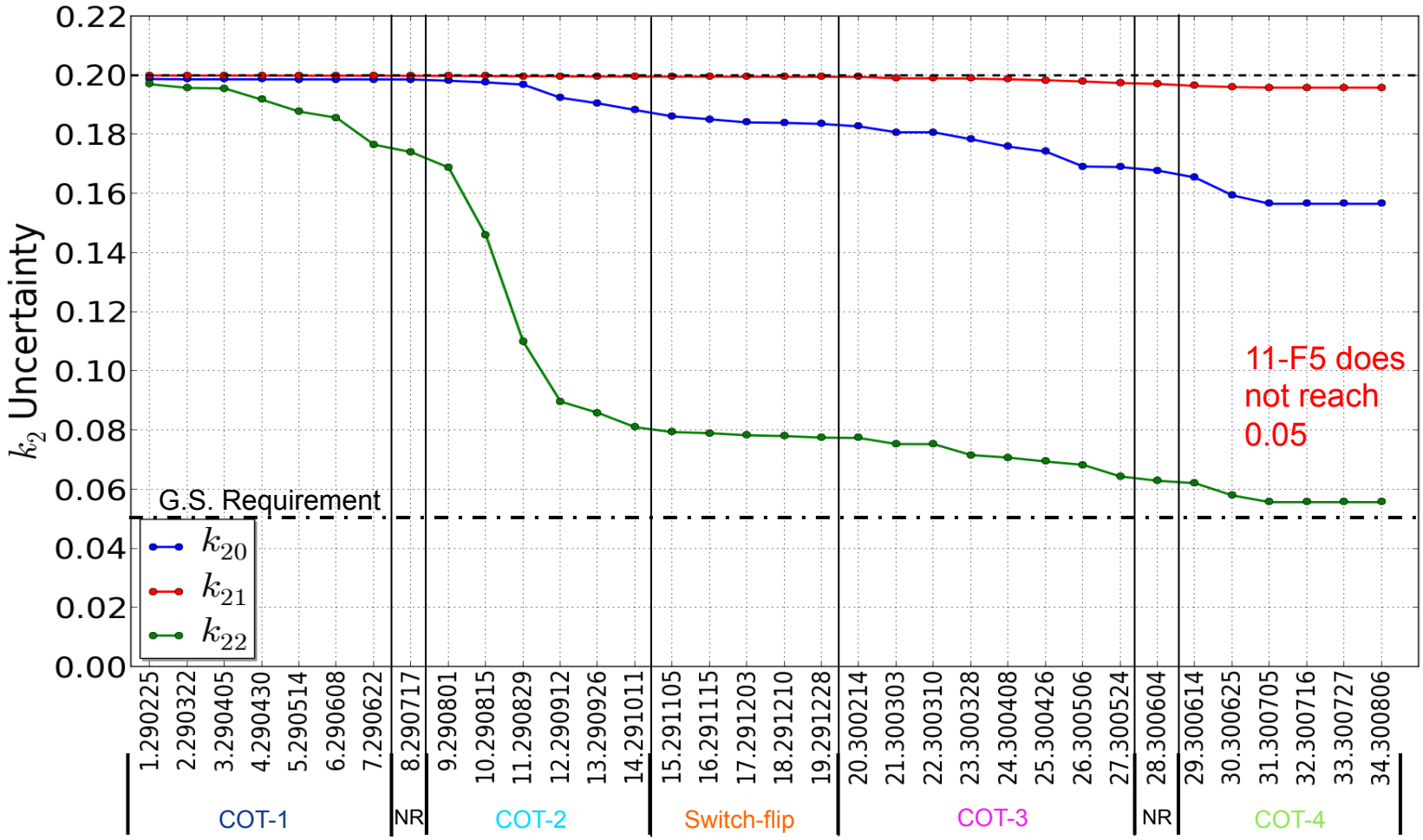
11-F5 Gravity Science

Doppler Error (1σ): 0.07 mm/s; s/c with obscurations



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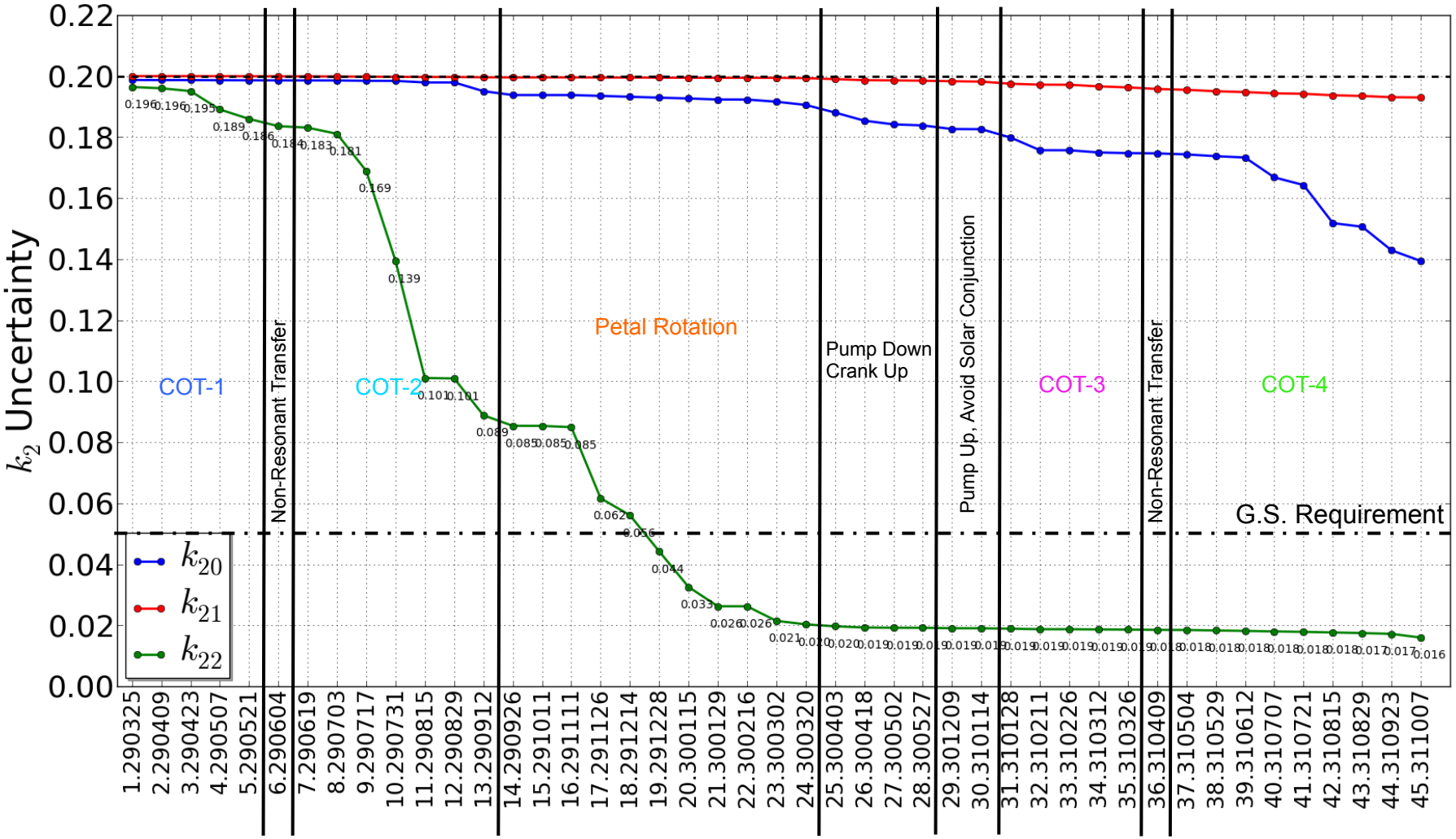
13F7-A21 Gravity Science

Doppler Error (1σ): 0.07 mm/s



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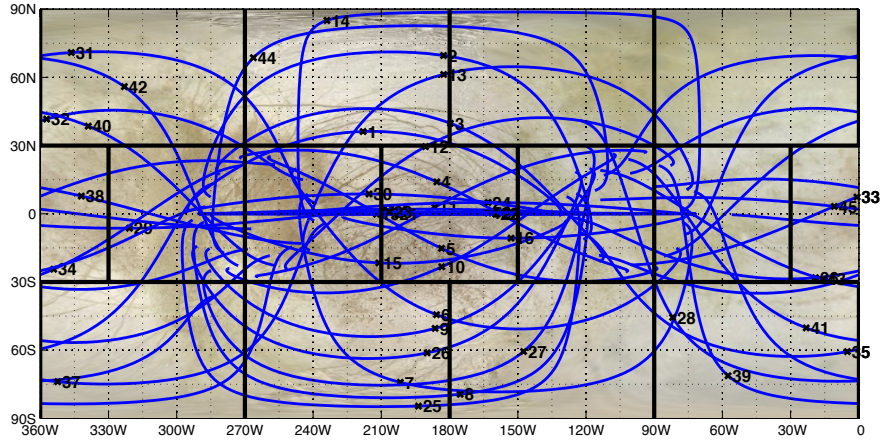
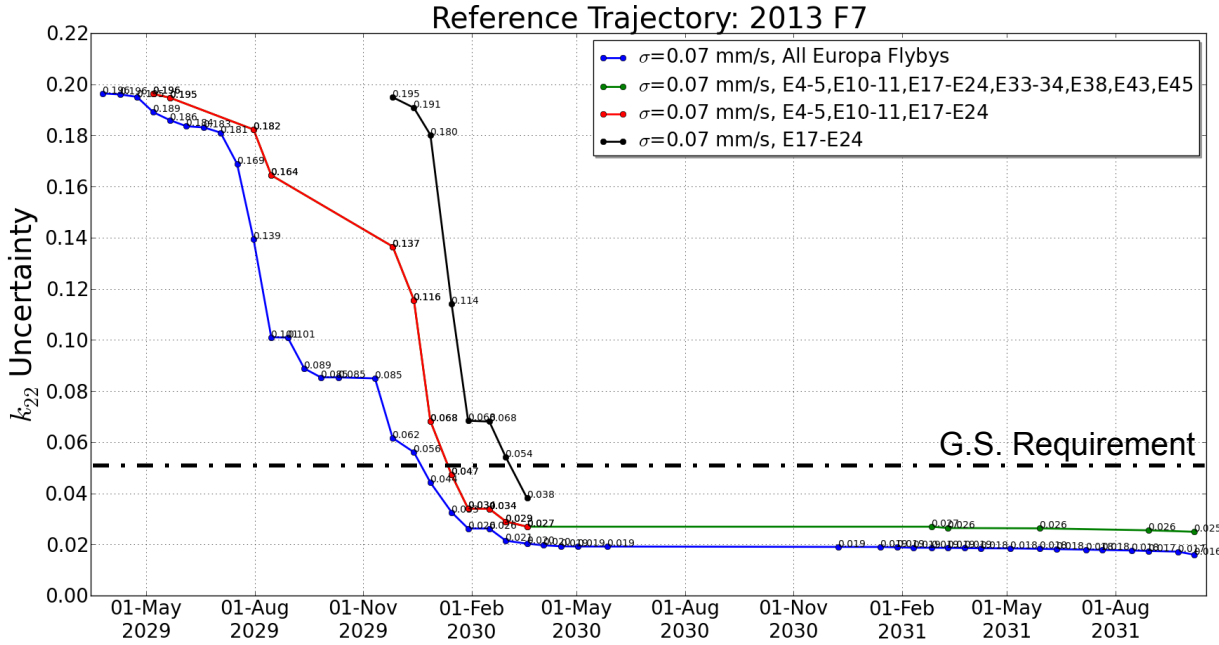
13F7-A21 G.S.: Select Flybys





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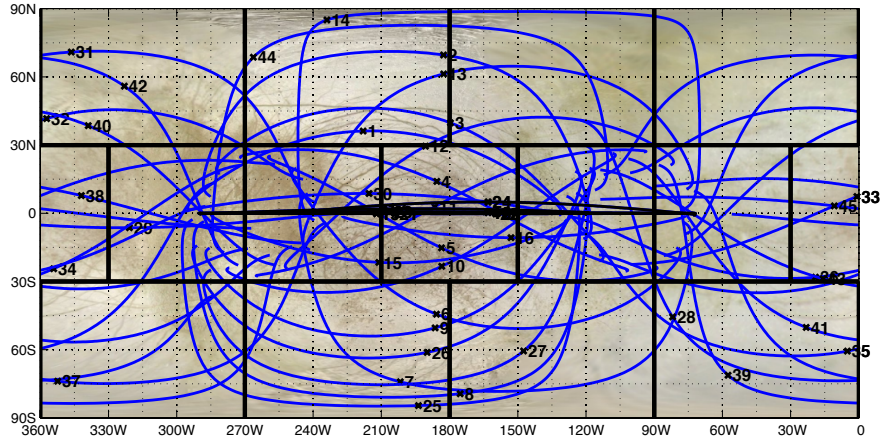
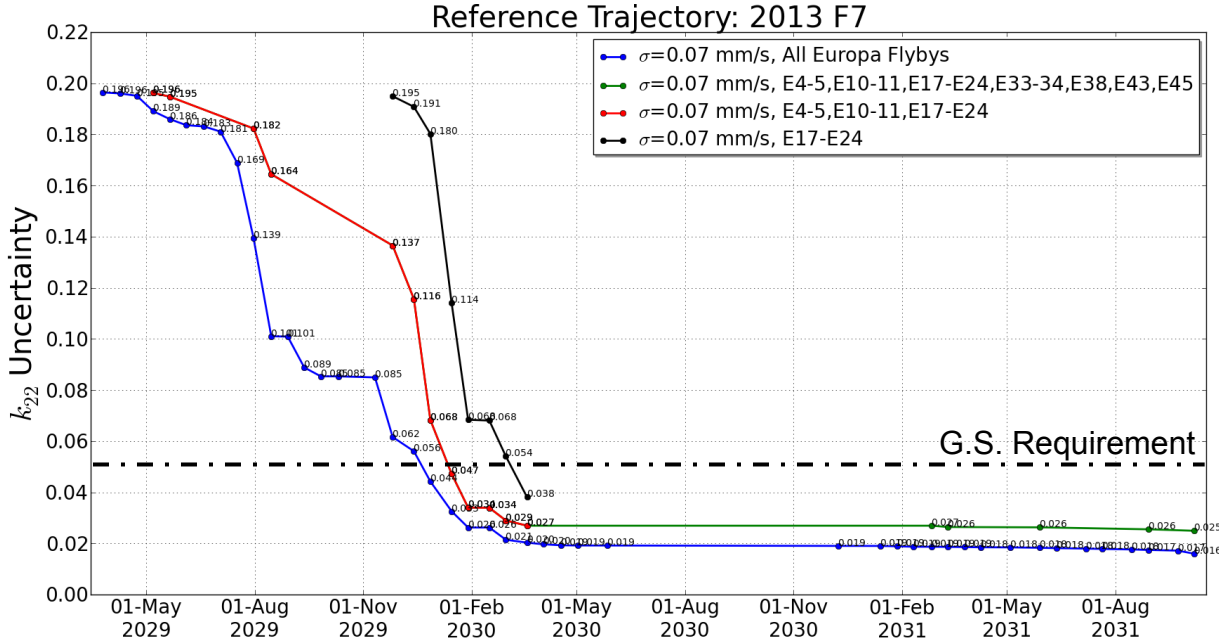
13F7-A21 G.S.: Select Flybys





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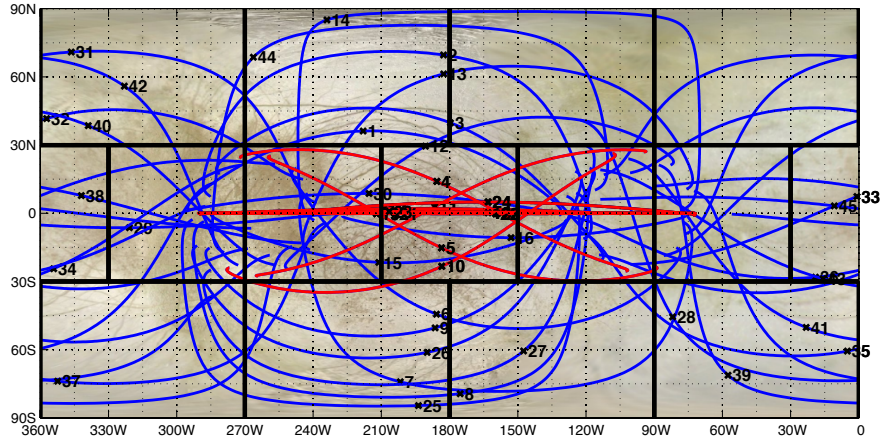
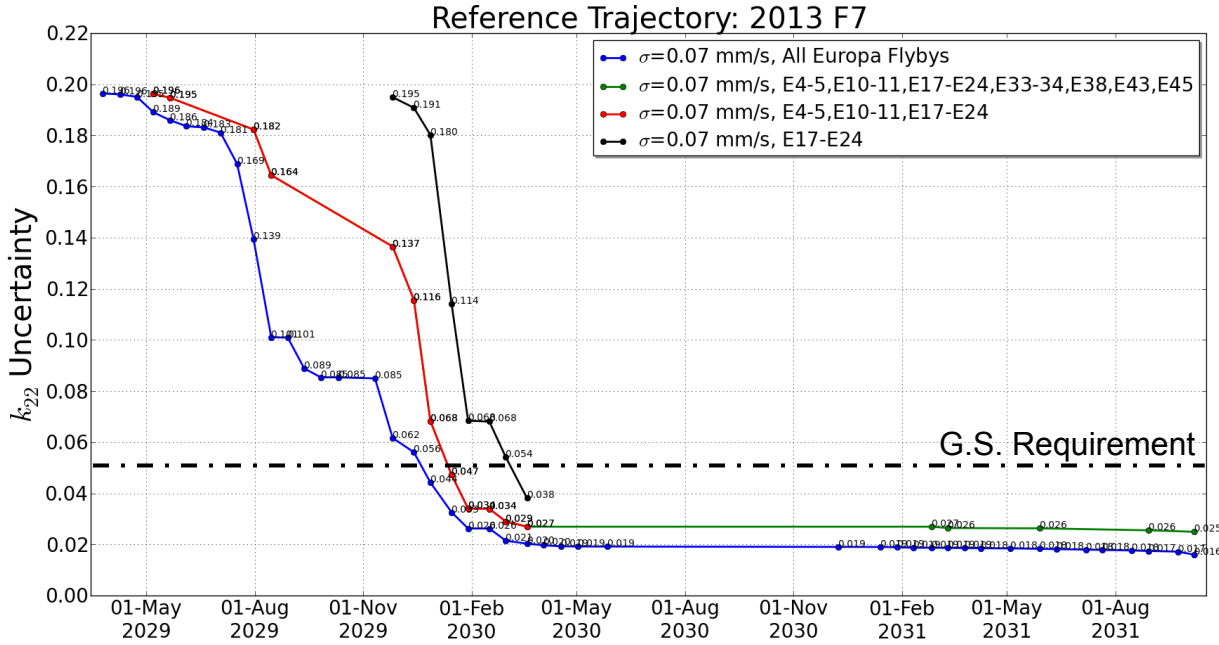
13F7-A21 G.S.: Select Flybys





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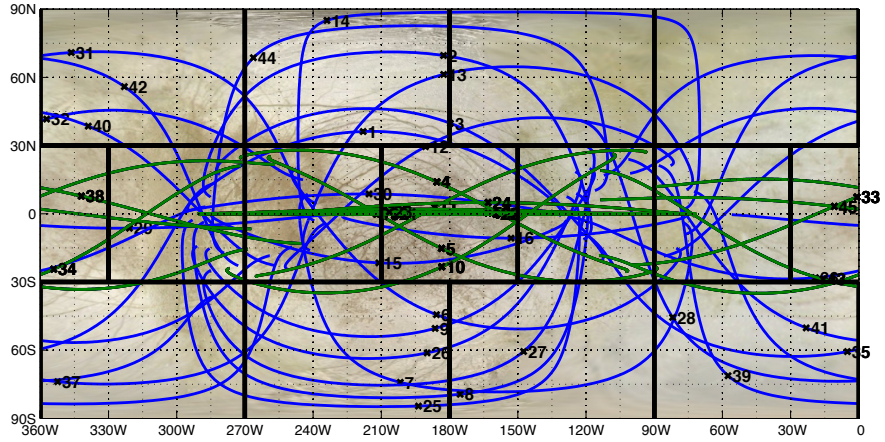
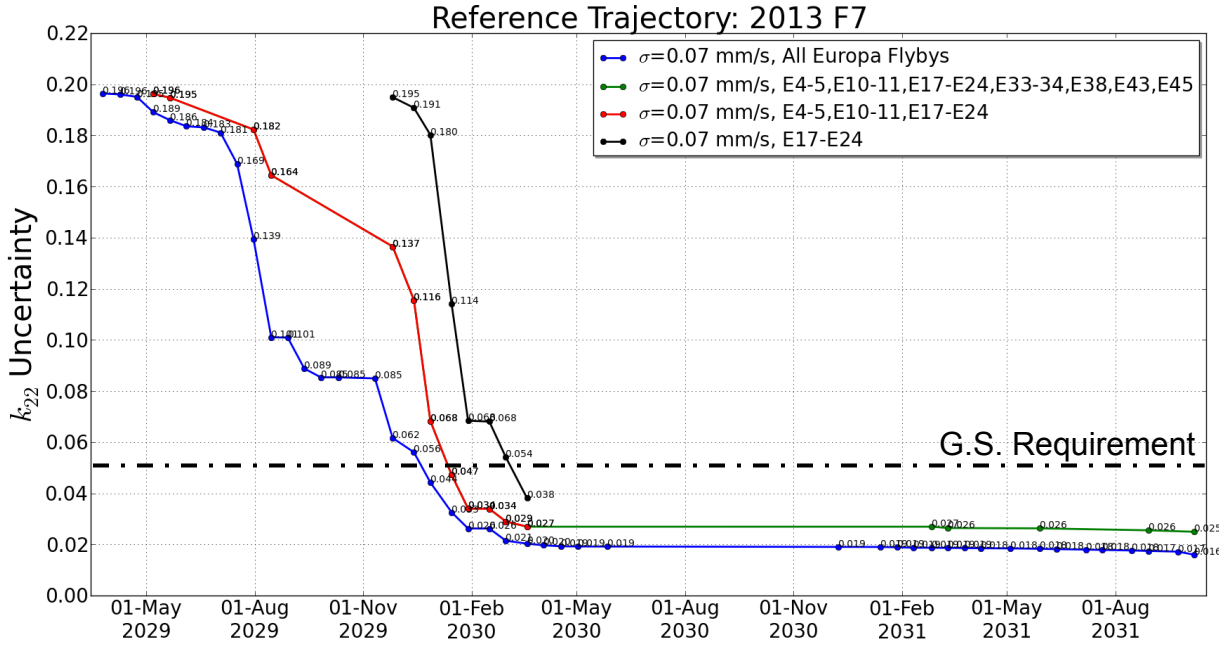
13F7-A21 G.S.: Select Flybys





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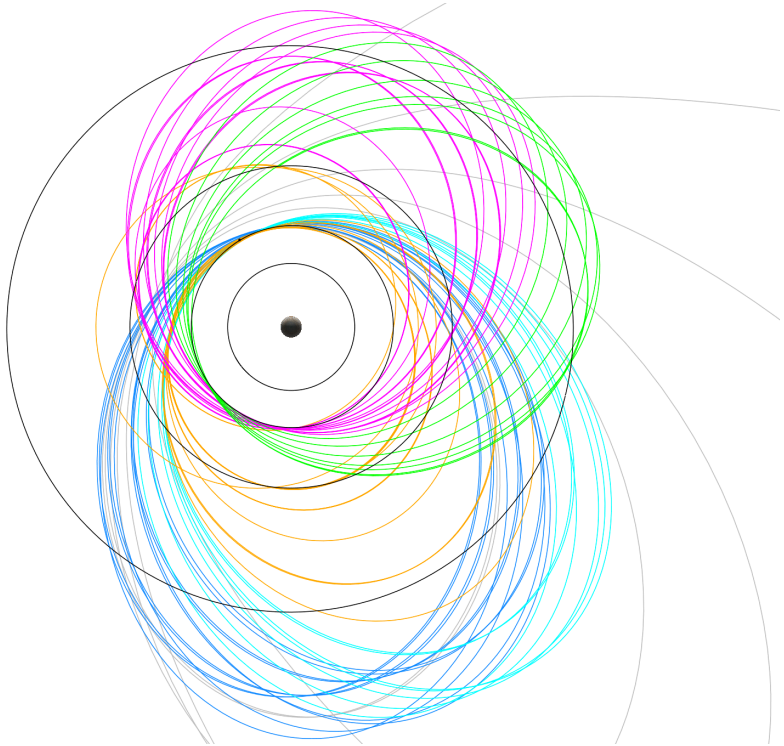
13F7 / 11F5 Petal Plot Comparison

11F5-A21



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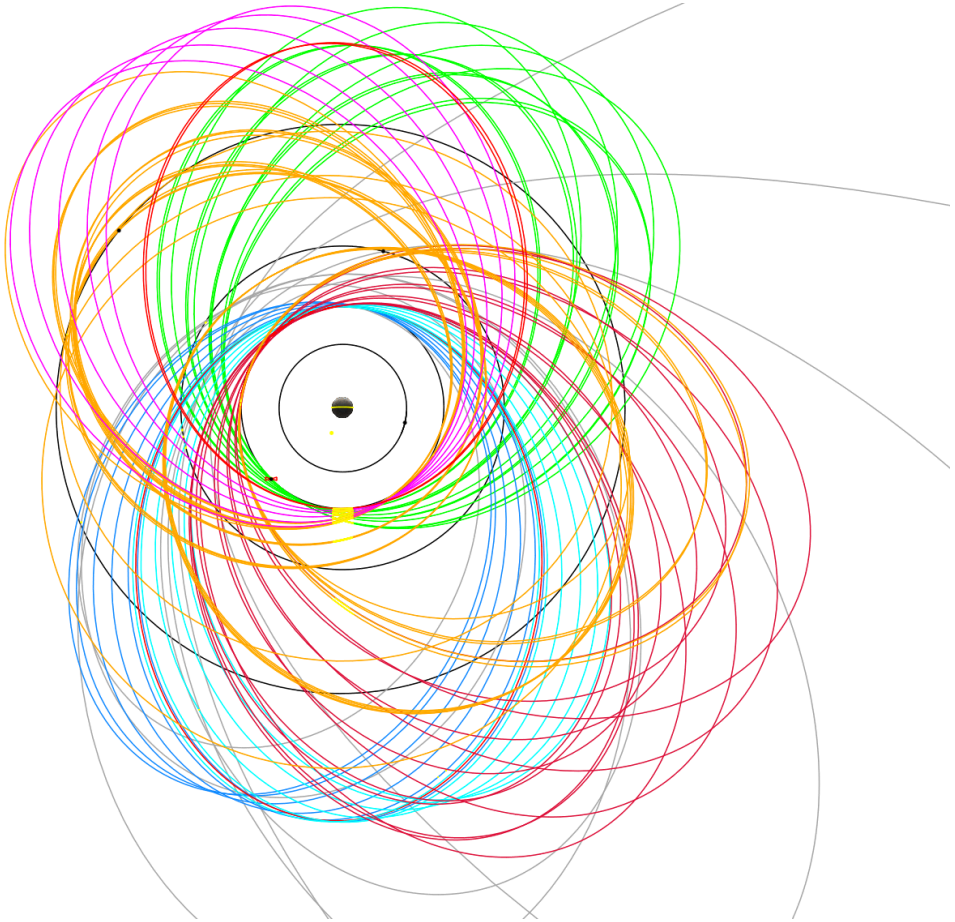

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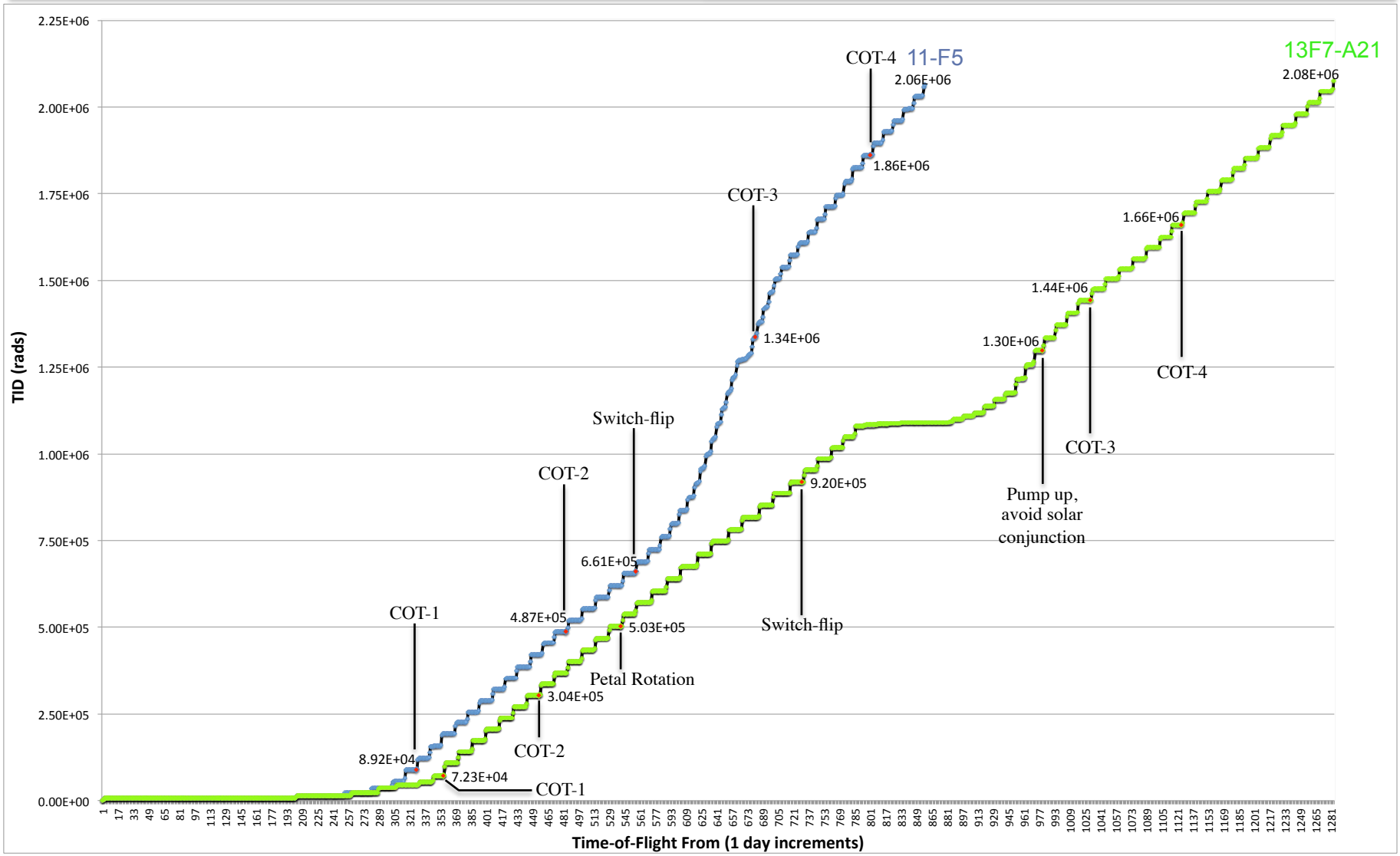
TID Comparison

[GIRE; Si behind 100 mil Al spherical shell]



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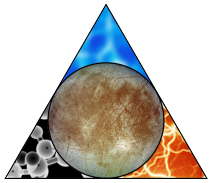


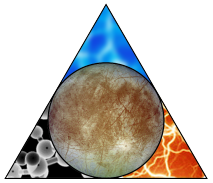
Europa Clipper Mission Concept Simulated Observations

13F7-A21 Trajectory

Andy McGovern, APL

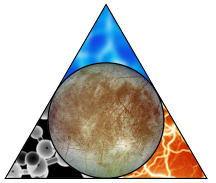
September 30, 2013

Simulation Overview



- 1st order simulations of operational concepts to determine coverage extents of science products.
- So far IPR, Recon Camera, SWIRS, and Thermal Imager have been simulated based on instrument fact sheets.
- Instruments are perfectly mounted and aligned
- Moving parts move. SWIRS scan mirror, Recon flip mirror.
- Coverage is plotted on a global map (passive optical instrument coverage is color coded for solar incidence angle).
  - Black means surface is too dark (incidence angle > 80°)
  - White means surface is saturated (incidence angle < 20°)

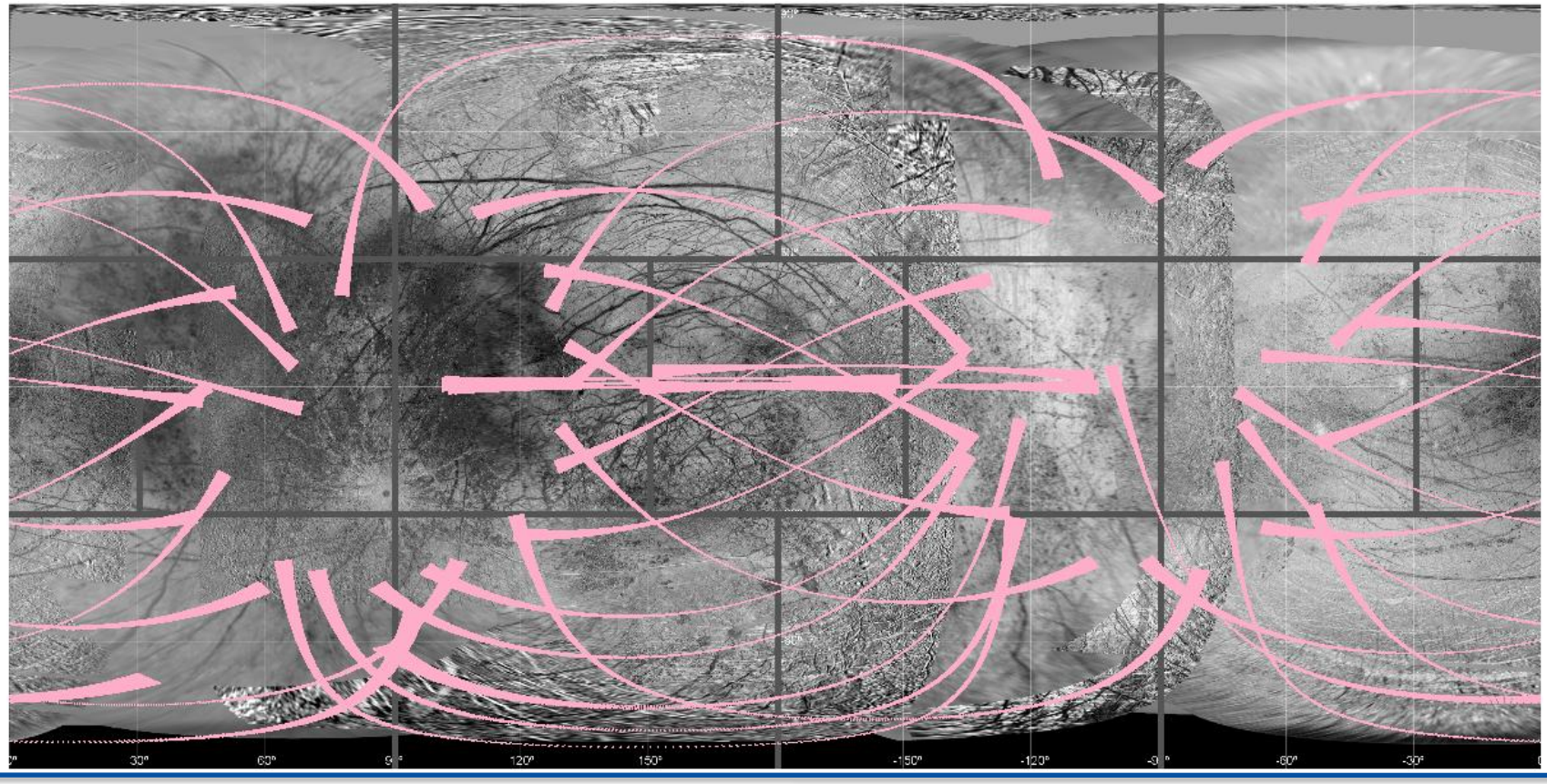
From IPR Fact Sheet



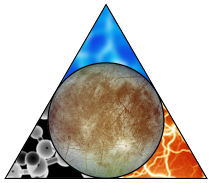
- For each Europa flyby with closest approach ≤100 km altitude, obtain continuous dual-frequency, nadir-pointed radar soundings and altimetry whenever the S/C altitude is ≤1000 km (approximately E±8 min).
- IPR does internal processing of the data (range compression, pre-summing, Doppler filtering, data averaging, and resampling).
- Processed data are then transferred to the S/C CDH at a rate of 25.2 Mb/s for storage, and later downlinking.
- A total of 24.2 Gb of data will be generated per flyby. Simultaneous Topographic Imager stereo coverage is required of the IPR ground track.

IPR

- Orbits that have a closest approach below 105 km
- IPR crossovers in 14 / 14 tiles



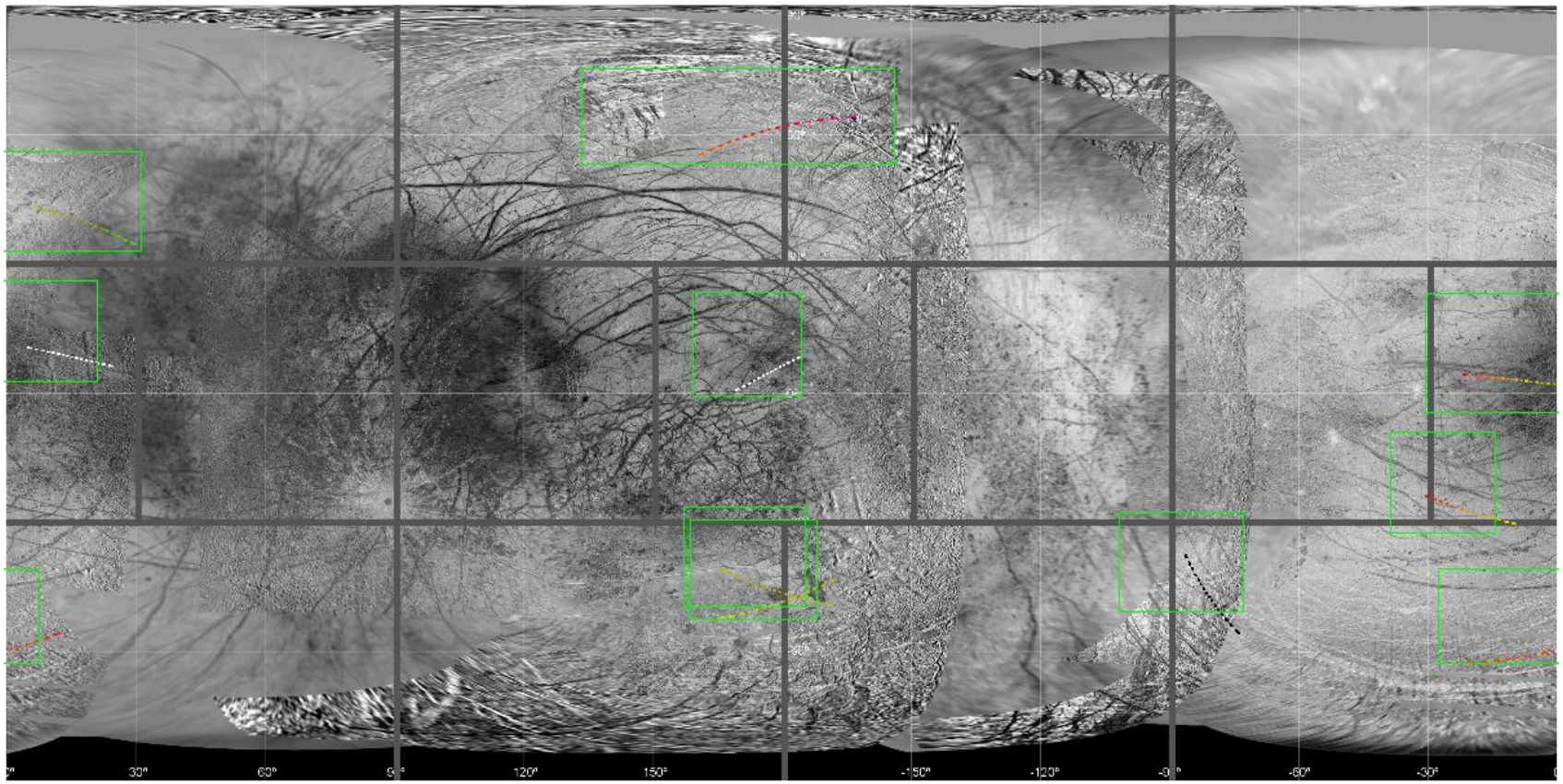
From Recon Camera Fact Sheet



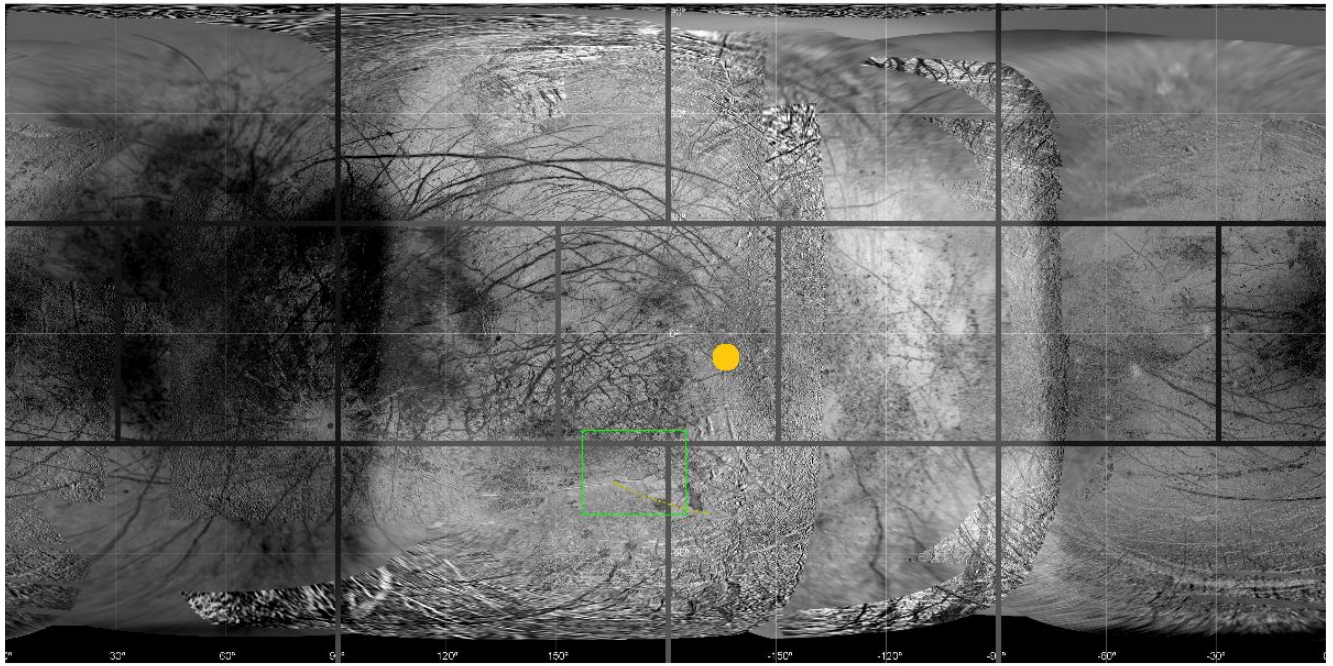
- For each Europa flyby at ≤50 km altitude, obtain stereo pushbroom coverage of selected target areas along the ground track when at altitudes of ≤50 km (within CA ±60s).
- A flip mirror is used to view first up track 15° forward from nadir for a period of ~2s (≥10 km swath length) and then flipped to view backward 15° from nadir to view the same swath in stereo for another ~2s.

Recon Camera

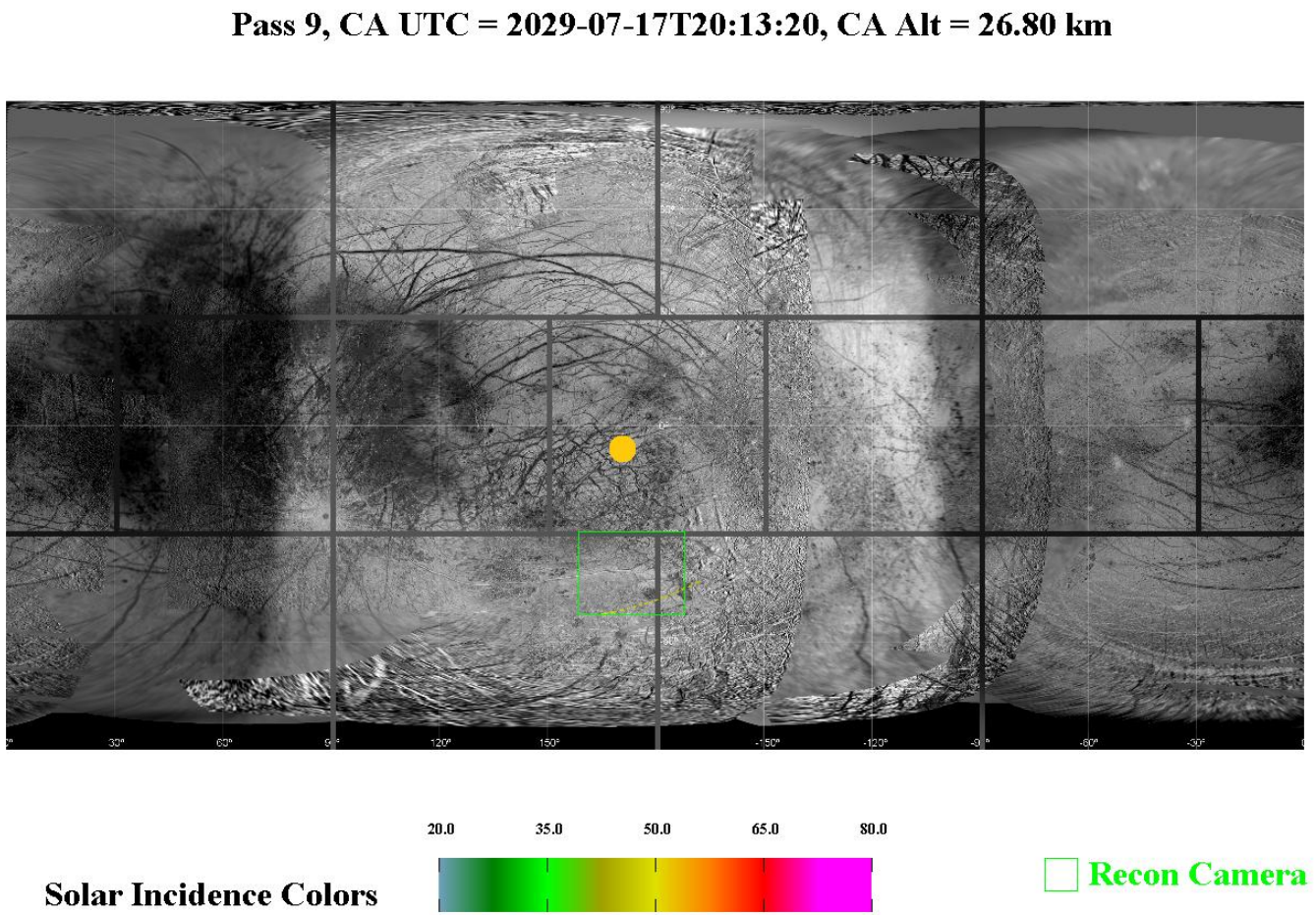
- Closest approach below 50 km (6, 9, 11, 13, 28, 35, 38, 40, 43, 45)
- IPR crossovers in 5 / 14 tiles



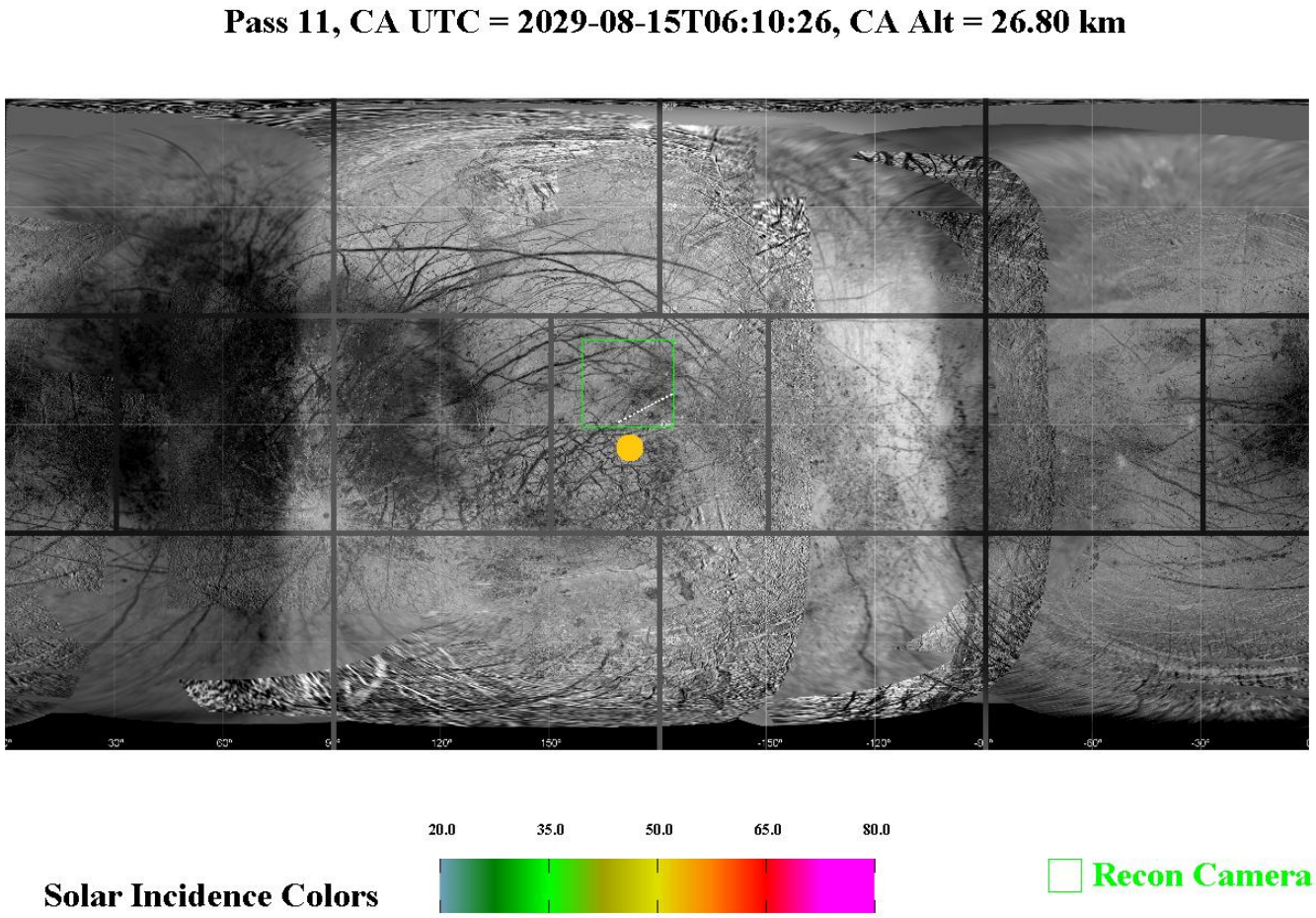
Recon Camera Pass 6



Recon Camera Pass 9

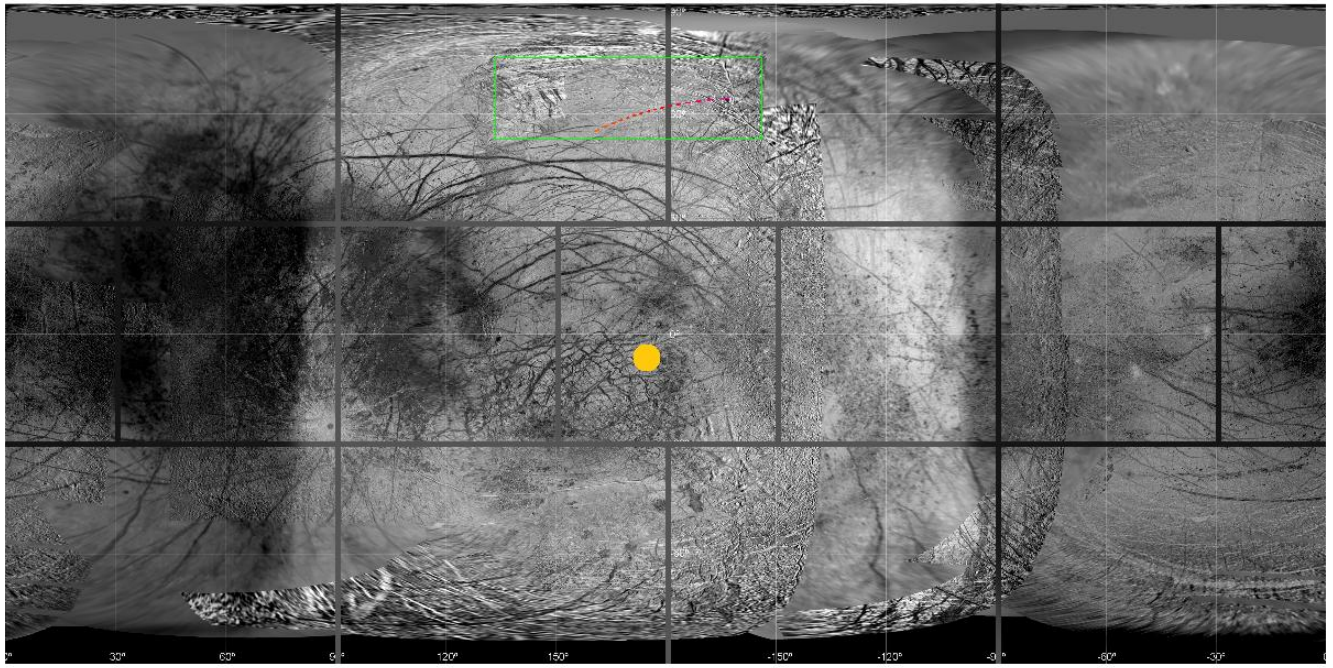


Recon Camera Pass 11 (Sun Overhead)

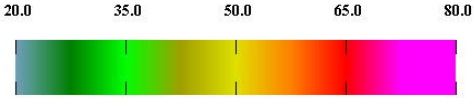


Recon Camera Pass 13

Pass 13, CA UTC = 2029-09-12T15:59:50, CA Alt = 26.80 km

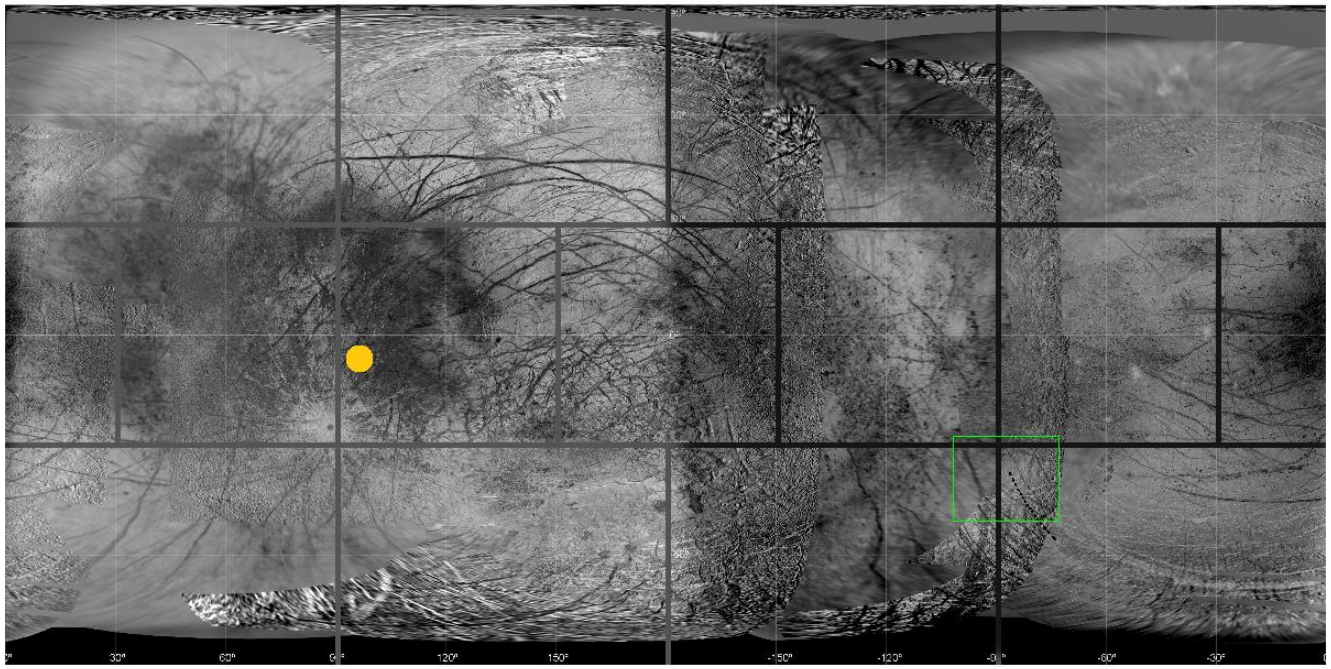


Solar Incidence Colors

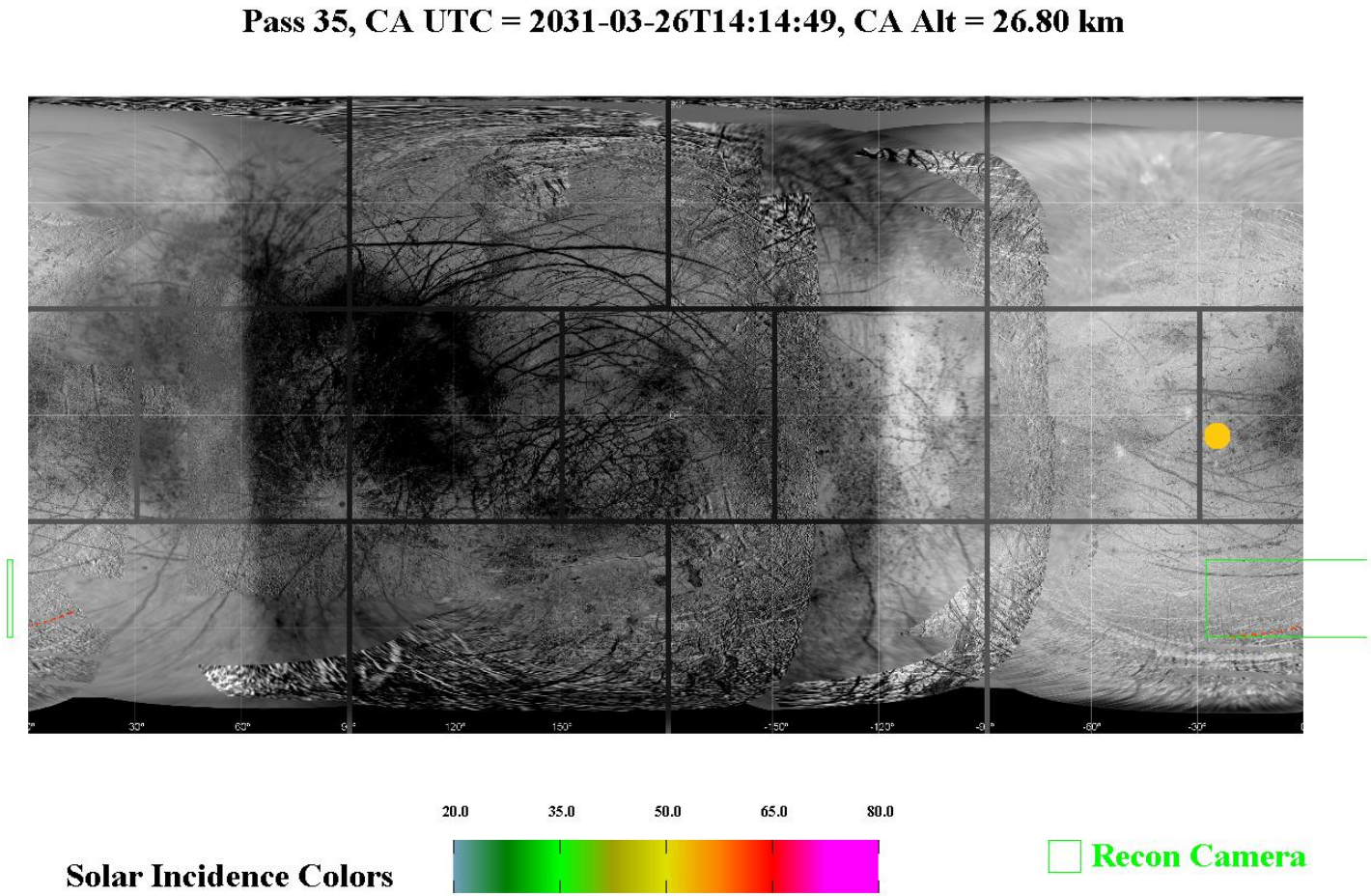


Recon Camera

Recon Camera Pass 28

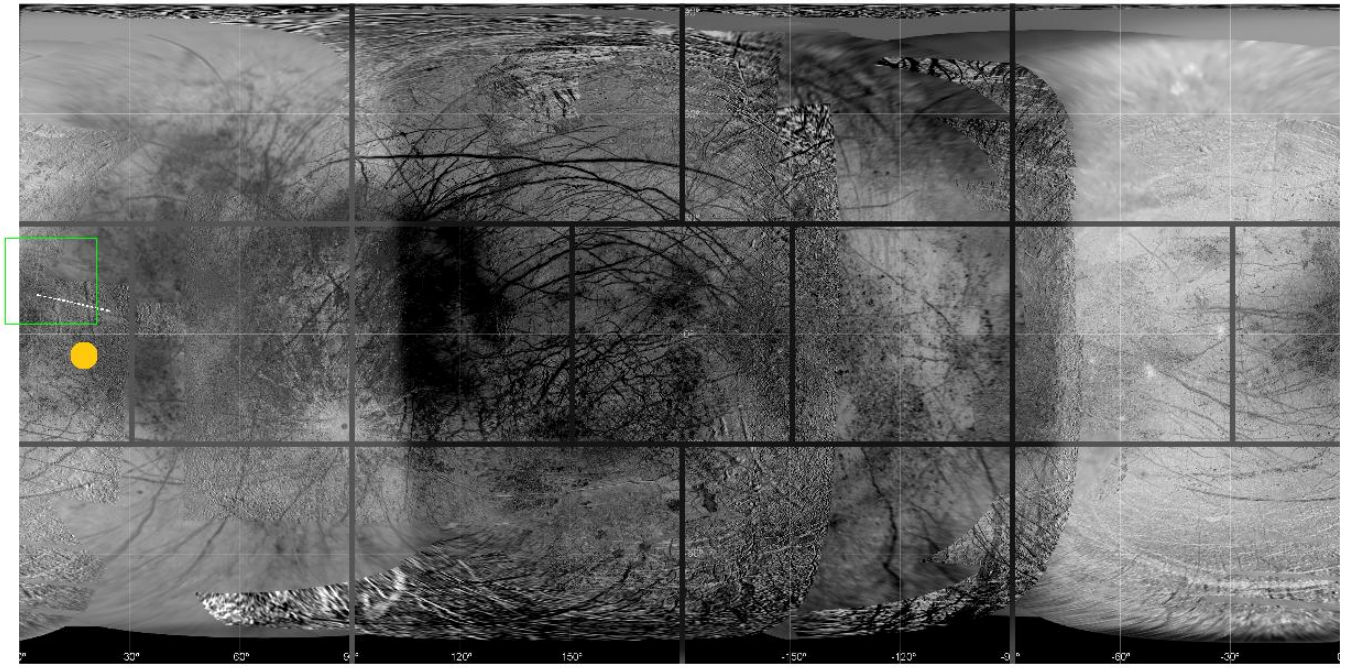


Recon Camera Pass 35



Recon Camera Pass 38

Pass 38, CA UTC = 2031-05-29T03:36:15, CA Alt = 26.80 km

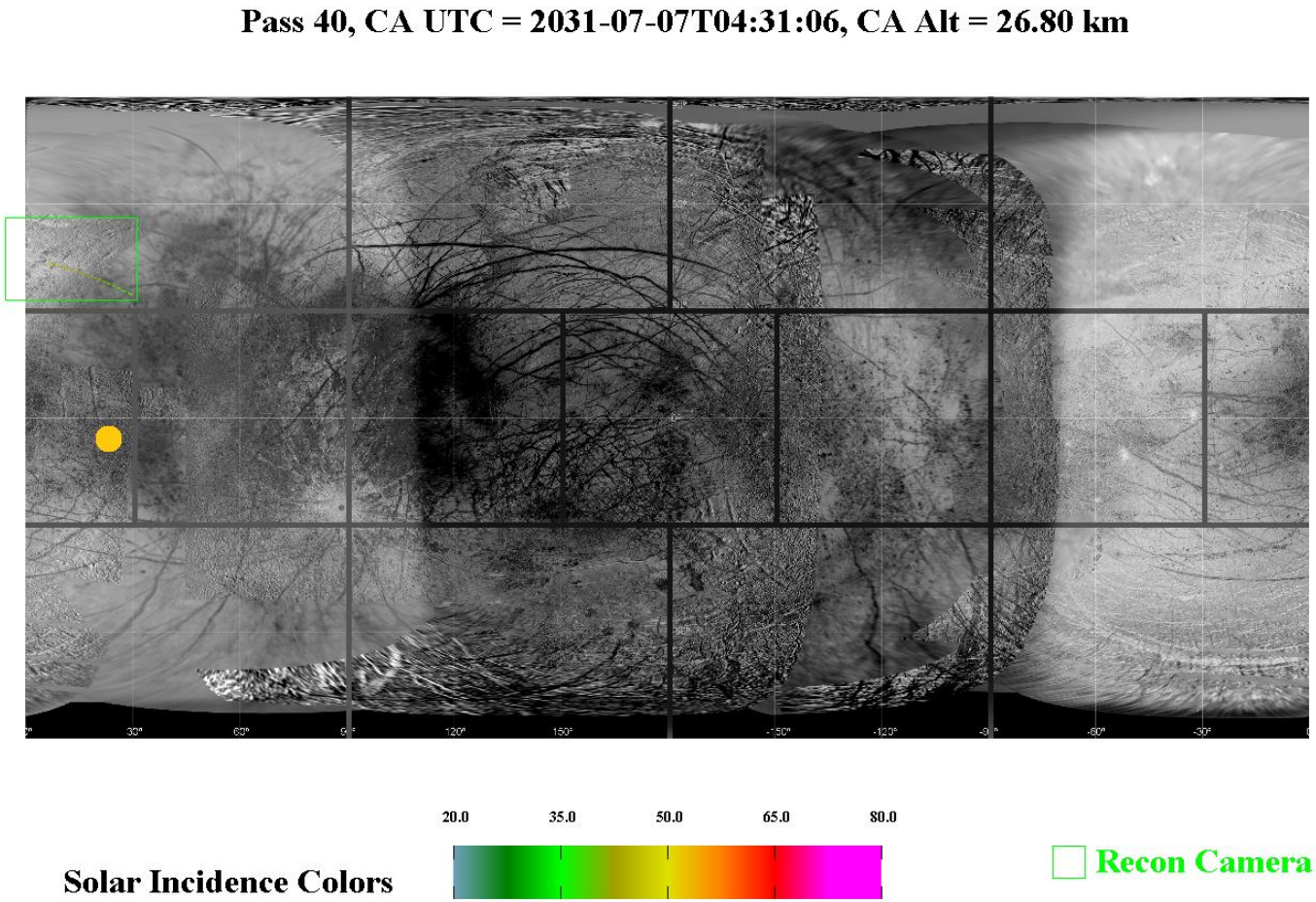


Solar Incidence Colors

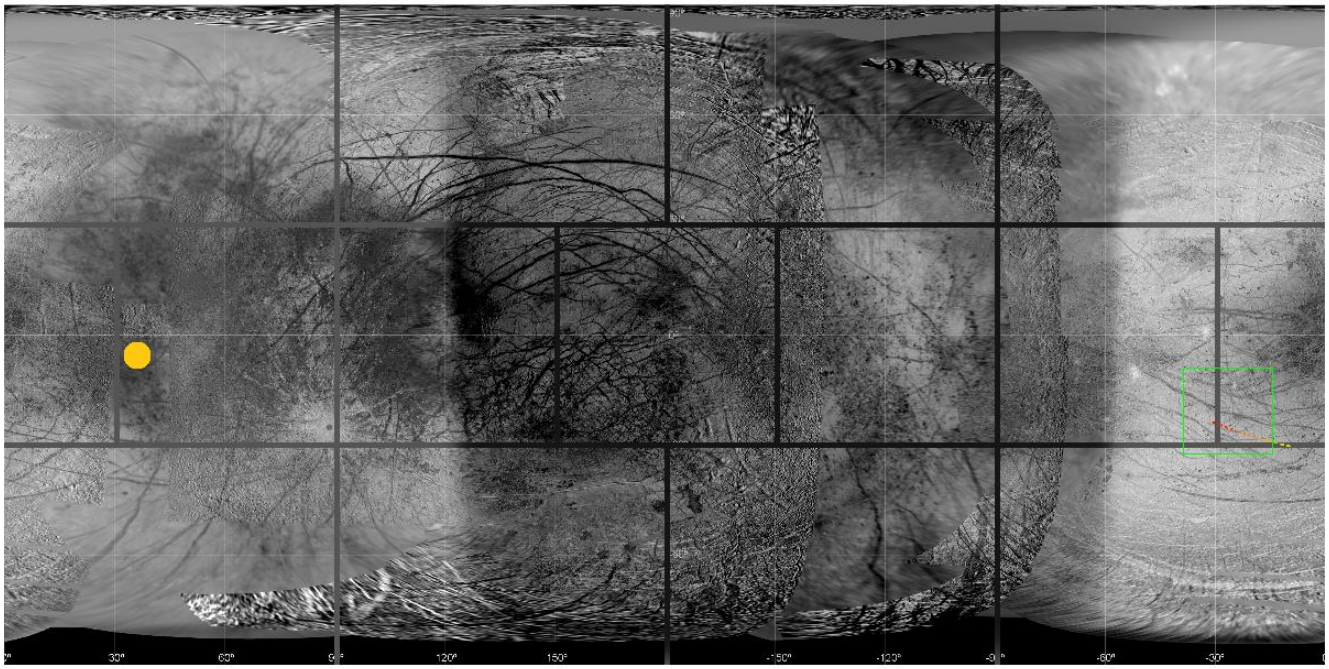
20.0 35.0 50.0 65.0 80.0

Recon Camera

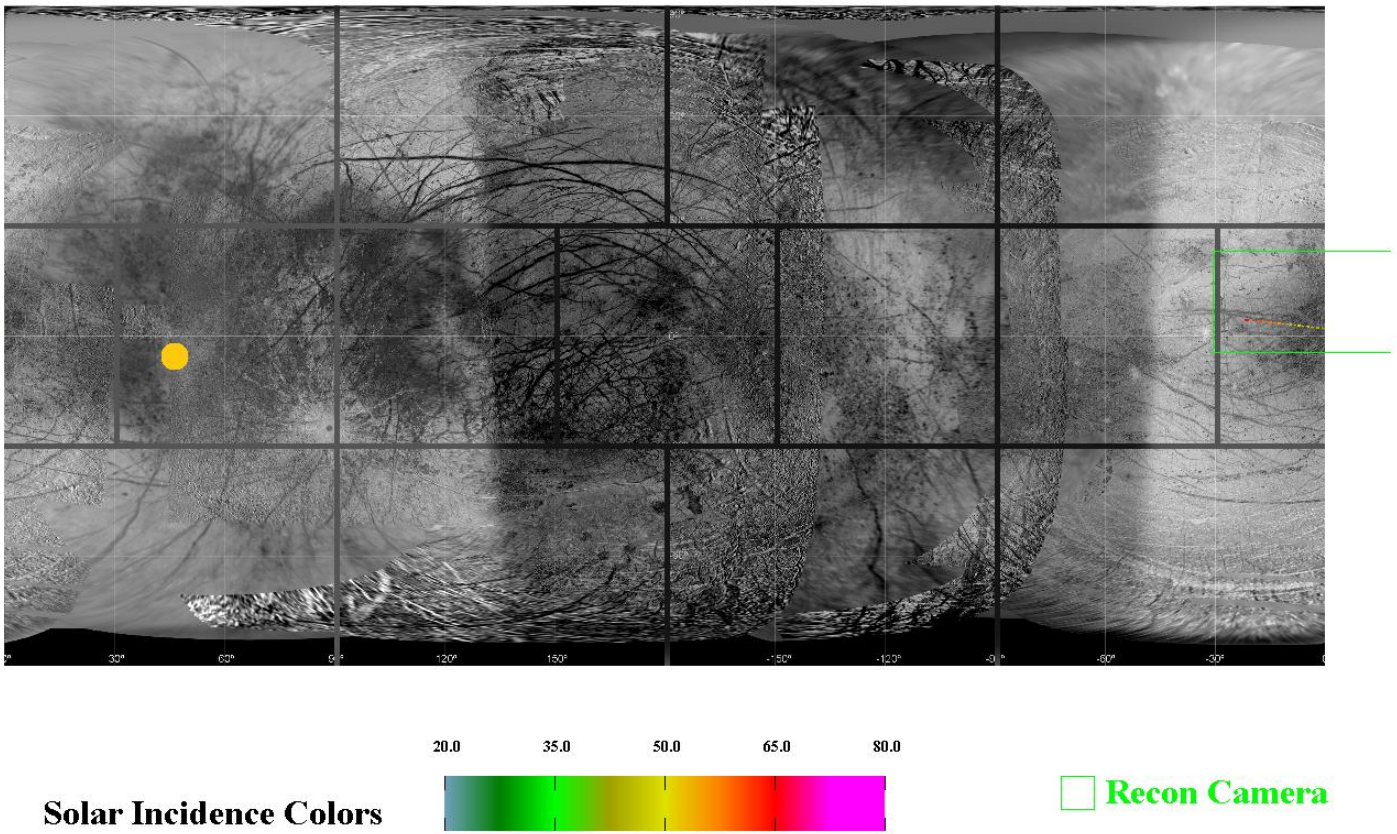
Recon Camera Pass 40



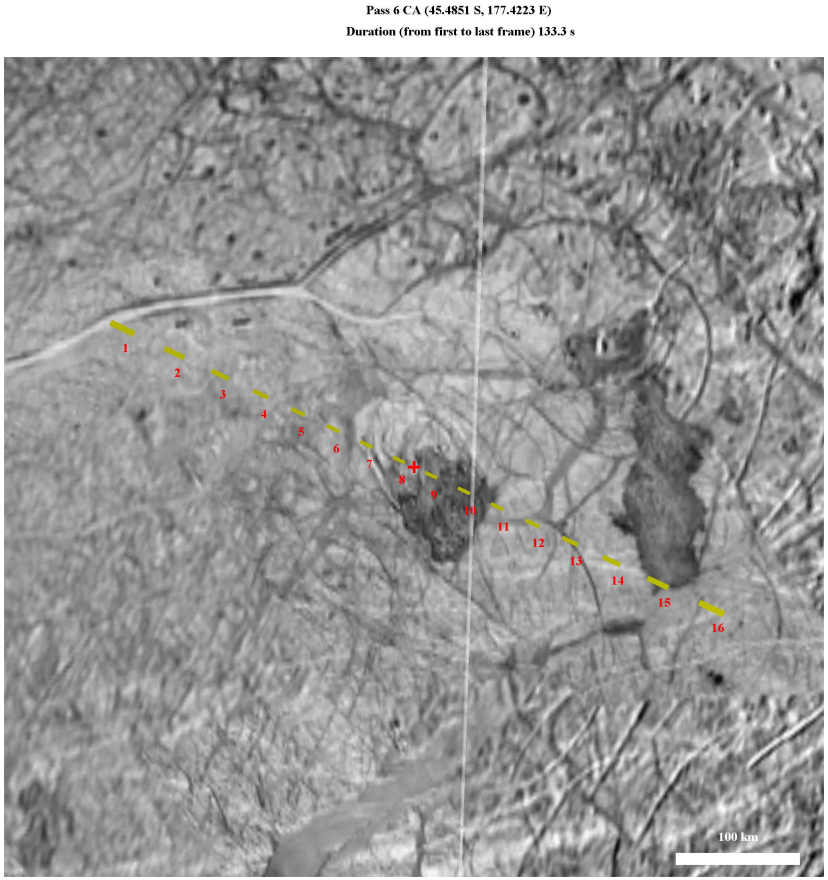
Recon Camera Pass 43

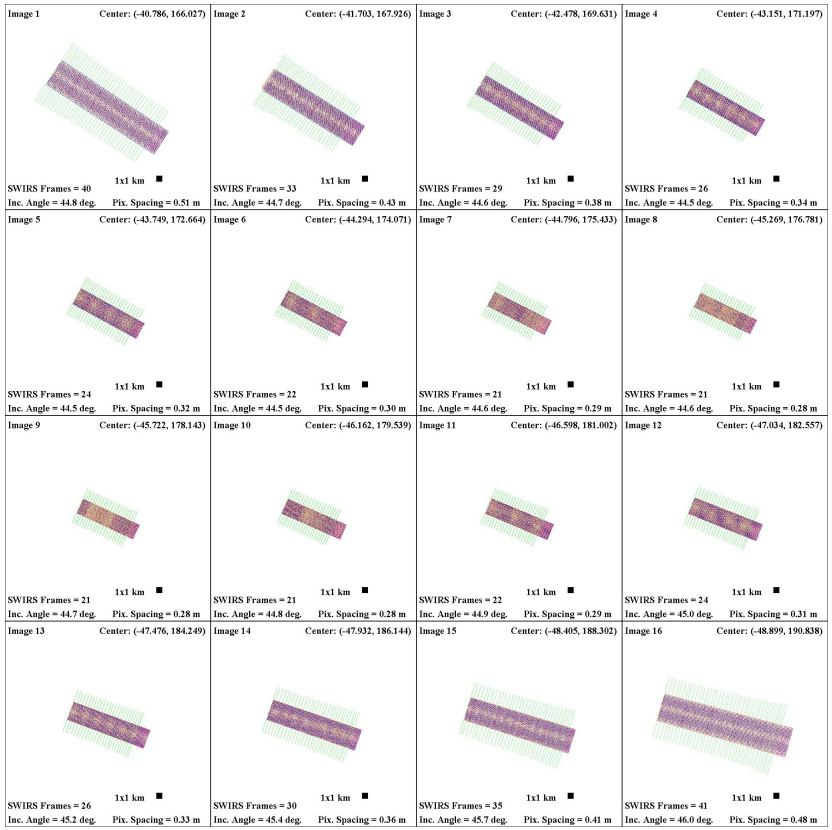
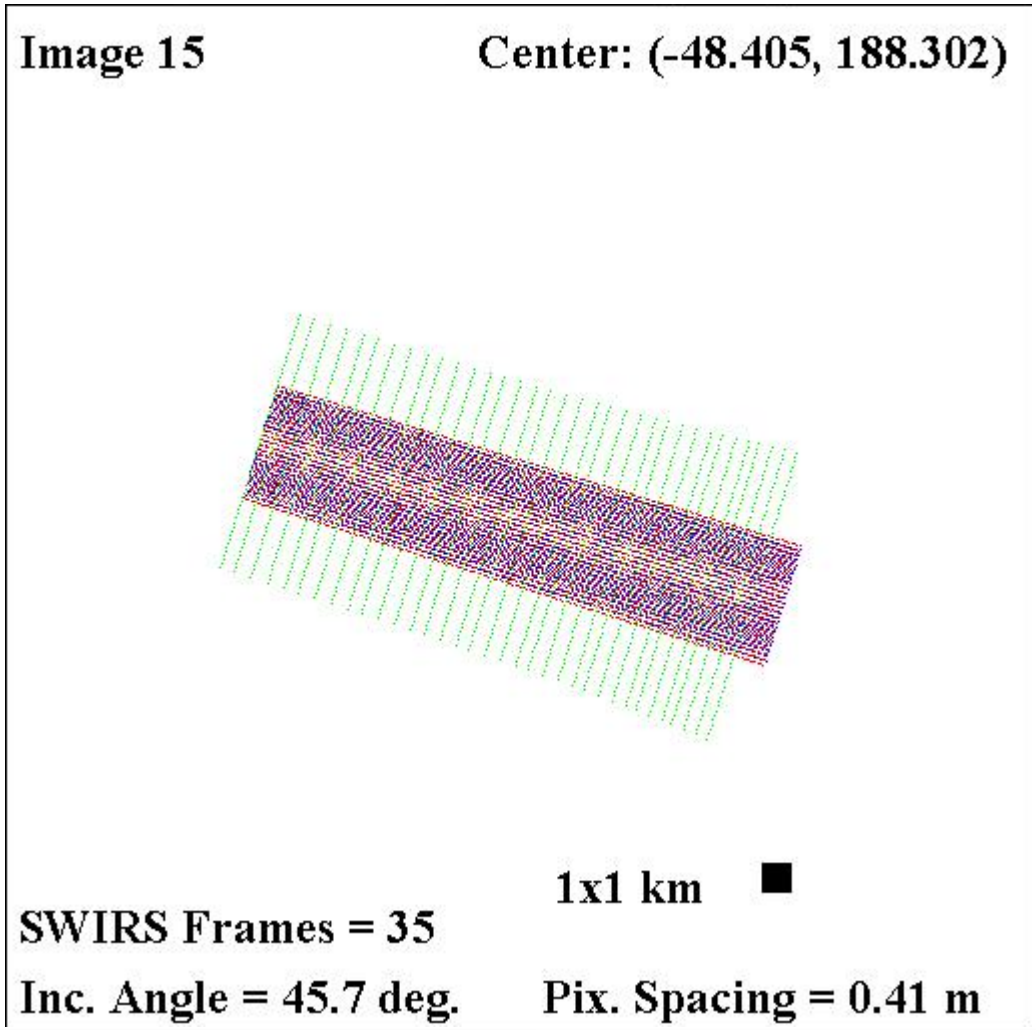


Recon Camera Pass 45



Recon Camera Pass 6 Details





Recon Camera Pass 6 Details