Handling late changes to Titan science

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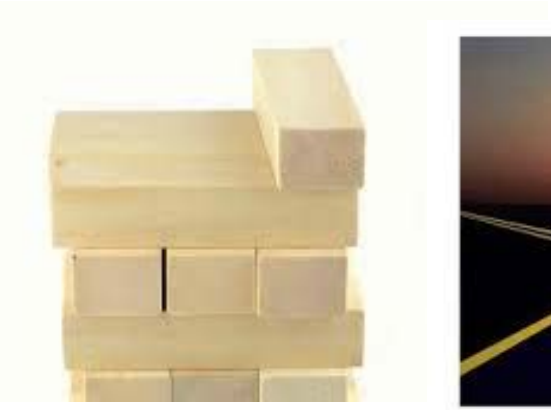
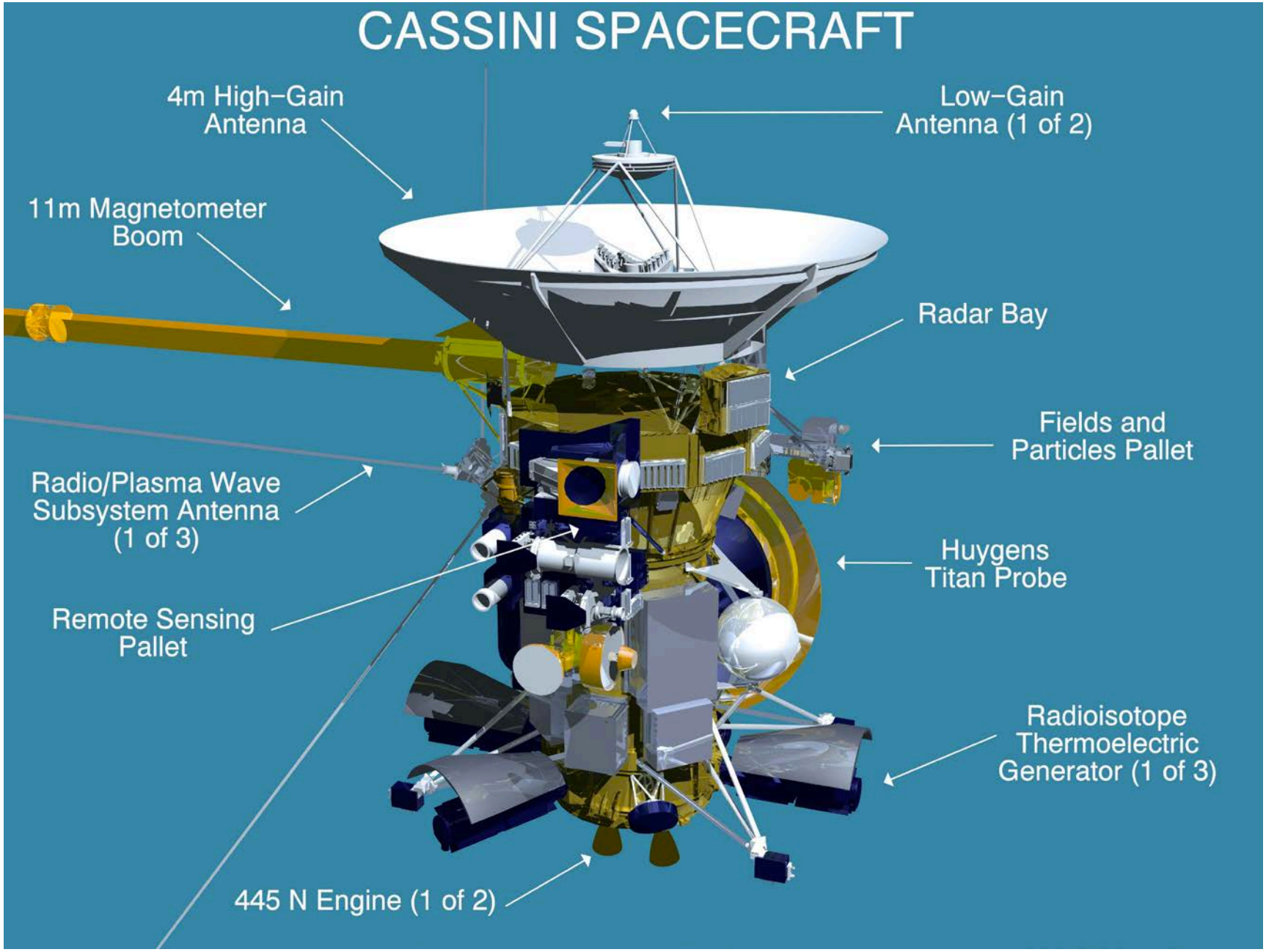
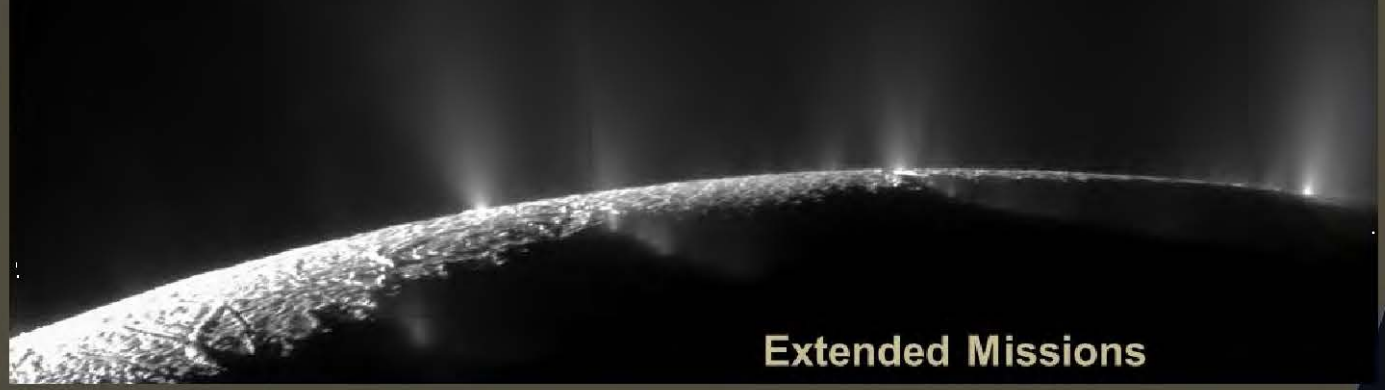
Cassini/Jet Propulsion Laboratory

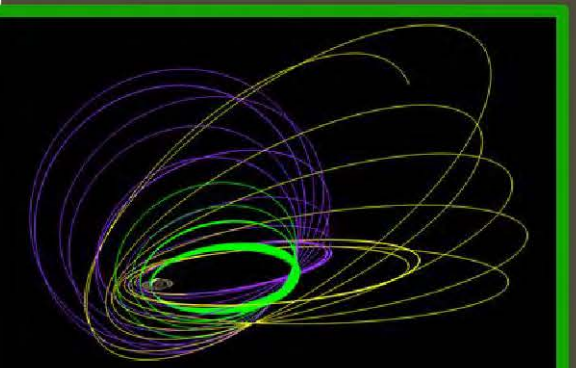
- The spacecraft, the mission
- How Titan science gets planned
- Four examples of late additions/changes
  - What can be done to make this kind of change as easy to implement as possible? What lessons did we learn?




CASSINI SPACECRAFT
4m High-Gain Antenna
Low-Gain Antenna (1 of 2)
11m Magnetometer Boom
Radar Bay
Fields and Particles Pallet
Radio/Plasma Wave Subsystem Antenna (1 of 3)
Huygens Titan Probe
Remote Sensing Pallet
Radioisotope Thermoelectric Generator (1 of 3)
445 N Engine (1 of 2)



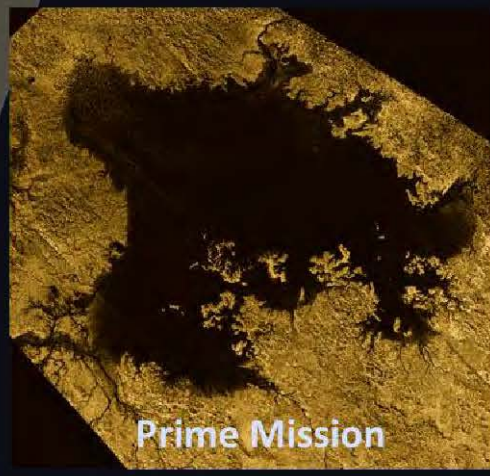
Extended Missions



Northern Summer Mission

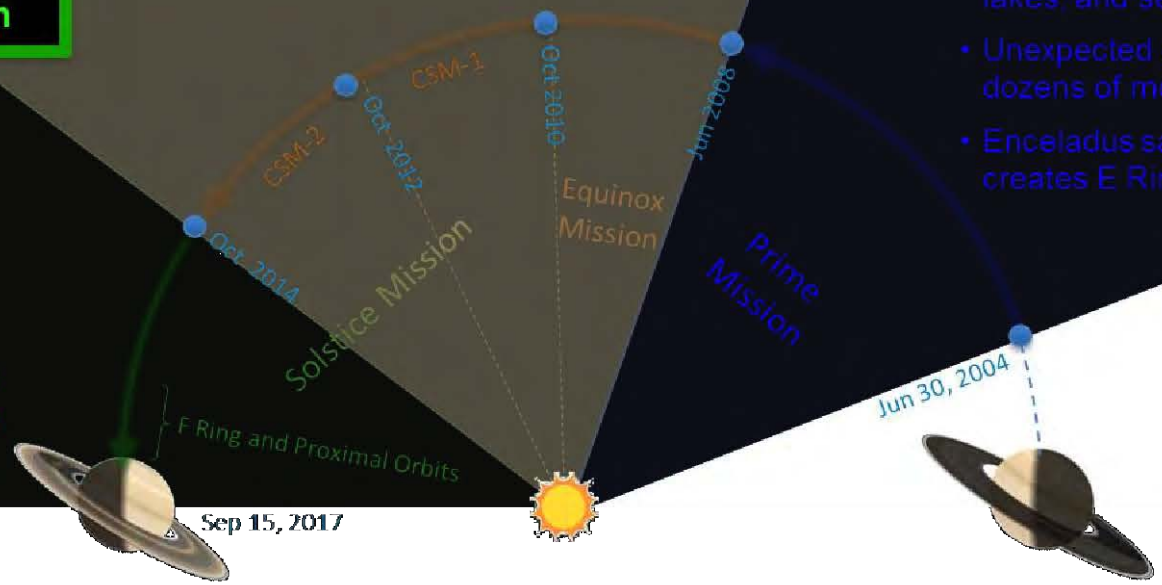
- Saturn's rotation rate
- Total mass of main rings
- Ring structures in 3D at high resolution
- Saturn gravity field sufficient to constrain formation theories
- Direct sampling of ring particles and Saturn's upper atmosphere

- Main rings only 10m thick, with complex km-scale vertical structures
- Gravity binds ring particles into ephemeral streamers
- Titan has methane weather, subsurface water ocean
- Rare, Earth-sized storm wrapped around Saturn
- Saturn oscillations revealed by ring spiral waves
- Enceladus has subsurface water ocean; orbital tidal stress controls plume volume

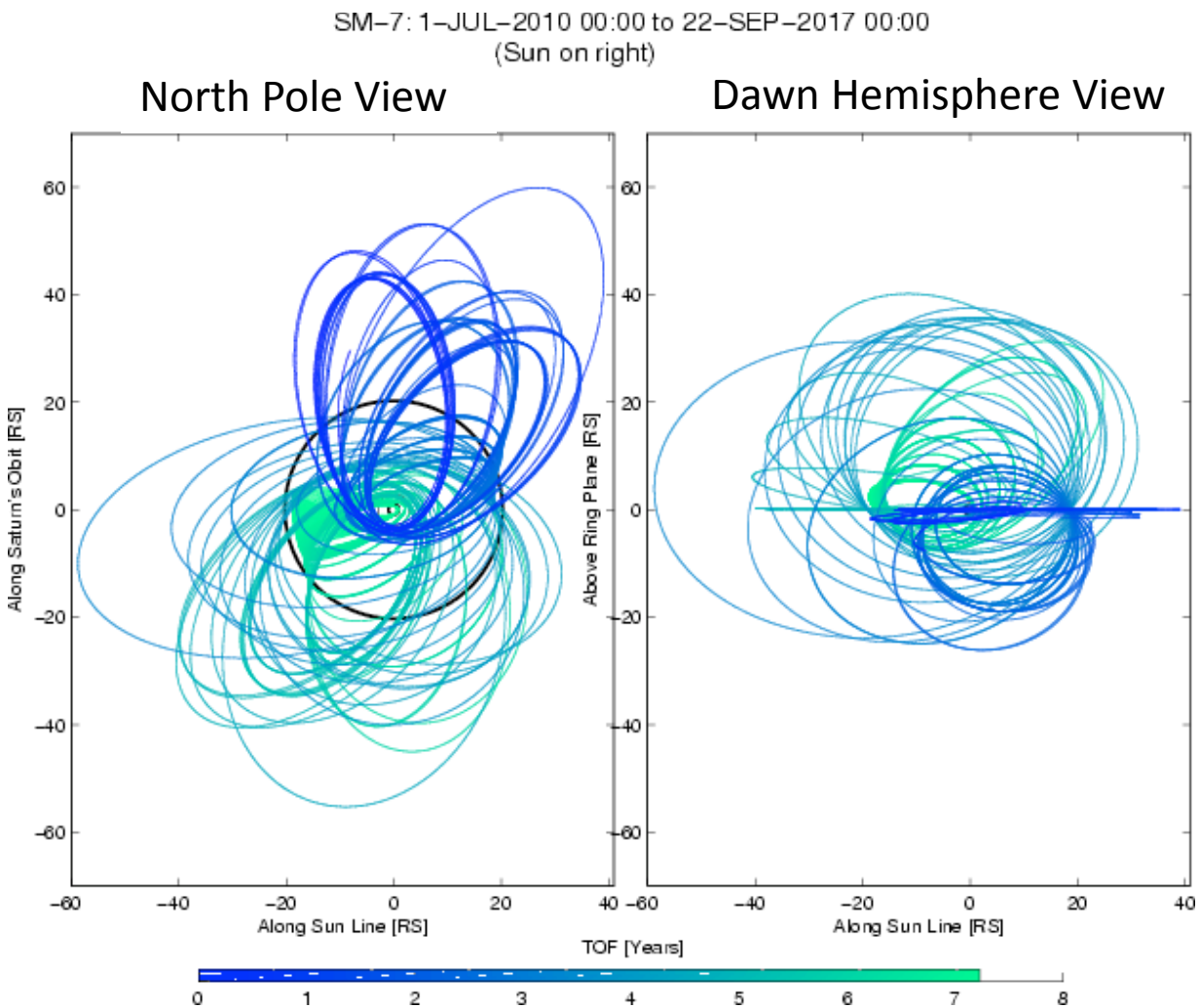


Prime Mission

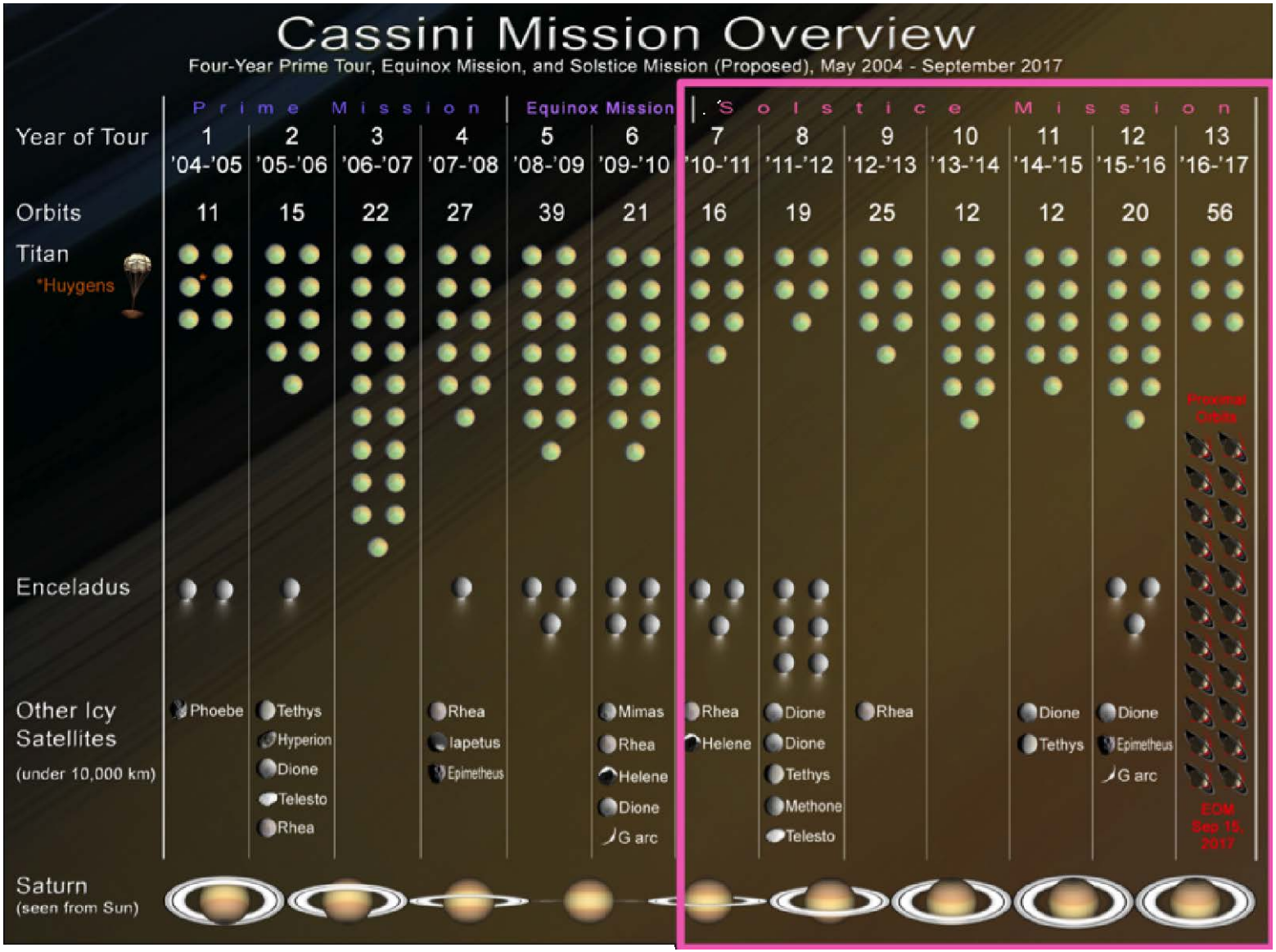
- European partnership for first outer-planet moon landing
- Methane clouds, rain, rivers, lakes, and seas on Titan
- Unexpected diversity among dozens of moons
- Enceladus salt-water plume creates E Ring



Planning starts when a trajectory is chosen



Titan flybys occur every 1-2 months



All Titan flybys planned in advance (jumpstart)

TIMING — REFERENCE TRAJECTORY 09XXXX

RANGE (KM) ------> 290k 200k 140k 81k 81k 140k 200k 290k

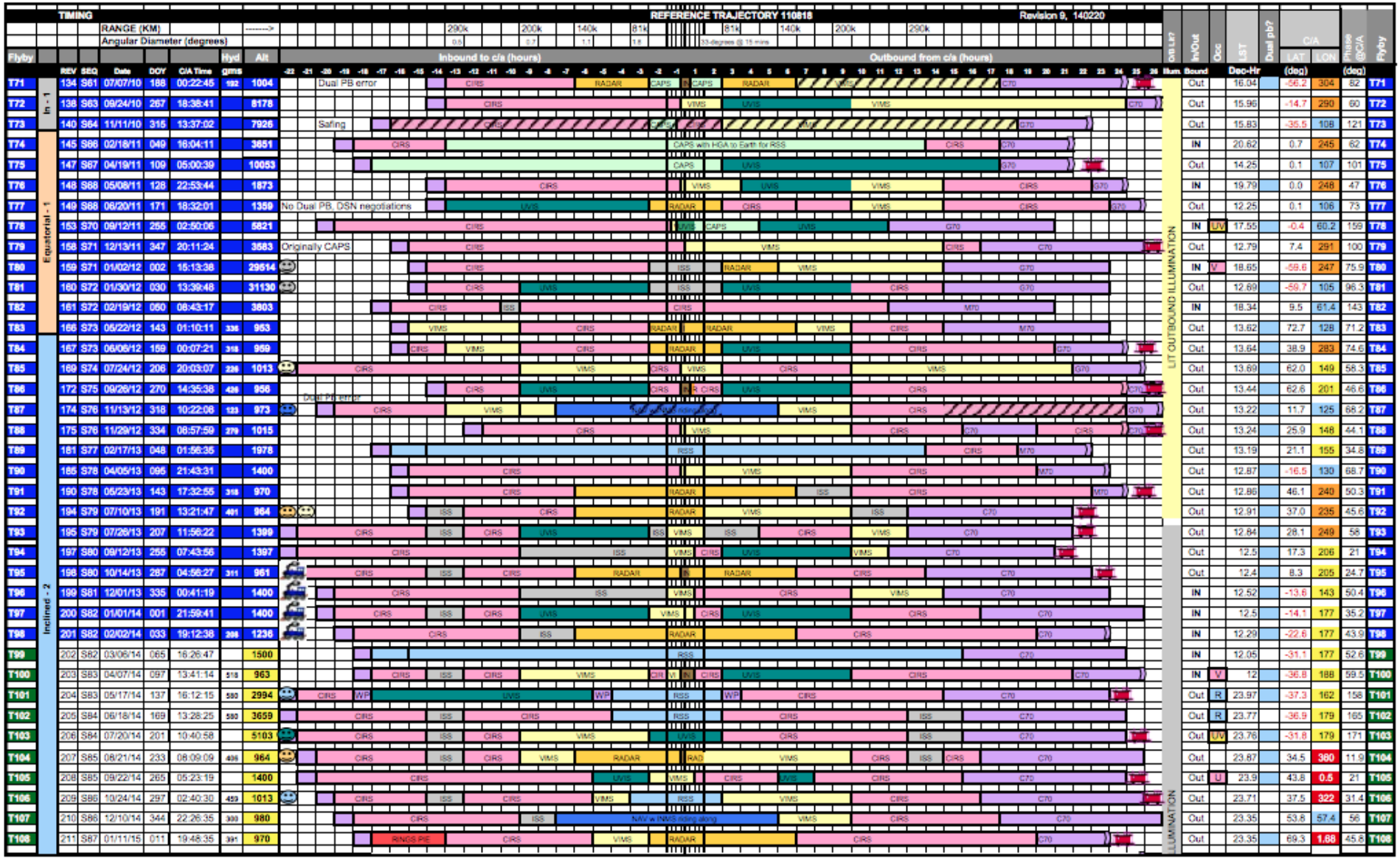
Angular Diameter (degrees) 05 07 11 18 33-degrees @ 15mins

Flyby		REV	SEQ	Date	DOY	C/A Time	Hyd gms	Alt	Inbound to c/a (hours) -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1	Outbound from c/a (hours) 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24	Illum.	In/Out Bound	Occ	LST Dec-Hr	Recover?	C/A LAT (deg)	C/A LON (deg)	Phase @C/A (deg)	Flyby
T71	In - 0	134		07/07/10	188	00:26:43	xxx	1005			LIT OUTBOUND ILLUMINATION	Out		16.04		-56.1	304	82	T71
T72		138		09/24/10	267	18:45:26		8124				Out		15.96		-15.9	291	60	T72
T73		140		11/11/10	315	13:45:51		7921				Out		15.84		-35.4	108	121	T73
T74	Equatorial - 1	145		02/18/11	049	16:04:10		3640				IN		20.62		0.4	244	62	T74
T75		147		04/19/11	109	05:10:03		9996				Out		14.26		0.0	107	101	T75
T76		148		05/08/11	128	22:52:20		1862				IN		19.79		0.0	247	47	T76
T77		149		06/20/11	171	18:40:32		1383				Out		12.26		0.1	106	73	T77
T78		153		09/12/11	255	02:49:32		5941				IN		17.55		-0.3	60.2	159	T78
T79		158		12/13/11	347	20:07:38		3763				Out		12.78		8.0	291	100	T79
T80		159		01/02/12	002	14:51:40		29331				IN		18.63		-58.7	247	75	T80
T81		160		01/30/12	030	13:30:12		31172				Out		12.68		-58.7	105	96	T81
T82		161		02/19/12	050	08:16:10		3844				IN		18.31		9.7	61.4	143	T82
T83		166		05/22/12	143	00:54:06	xxx	990				Out		13.61		72.3	127	71	T83
T84		167		06/06/12	158	23:51:22	xxx	990				Out		13.64		38.3	283	75	T84
T85		169		07/24/12	206	19:47:16	xxx	990				Out		13.68		61.9	149	58	T85
T86		172		09/26/12	270	14:20:40	xxx	990				Out		13.41		62.8	201	47	T86
T87		174		11/13/12	318	10:07:16	xxx	990				Out		13.22		11.3	124	68	T87
T88		175		11/29/12	334	08:42:07	xxx	1164				Out		13.25		25.2	147	45	T88
T89		181		02/17/13	048	01:42:39		1500				Out		13.16		23.2	157	33	T89
T90		185		04/05/13	095	21:28:41		1302				Out		12.84		-14.9	132	66	T90
T91		190		05/23/13	143	17:18:27	xxx	990				Out		12.86		45.8	239	50	T91
T92		194		07/10/13	191	13:07:29	xxx	990				Out		12.89		36.7	235	46	T92

Maximize Titan science return by balancing science objectives across the entire set of flybys

Major resource to be allocated: pointing control

The formerly blank slate:



Detailed integration work starts with rough timeline…

138TI_T72	8175	Lit Outbound

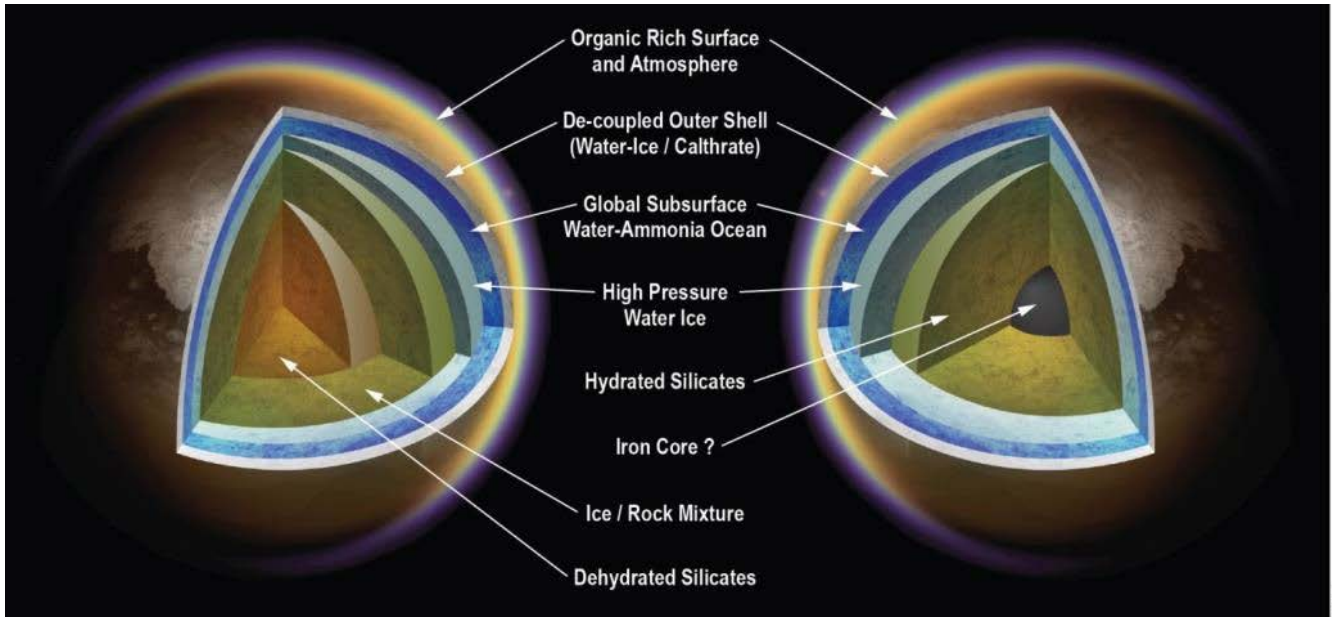
Start Time	End Time	Prime Activity	Obs. Detail	Op Mode	TLM Mode	Comments
2010-267T05:17:00	2010-267T05:57:00	SP Turn to WP				
2010-267T05:57:00	C/A - 12:26:00	OD Uncertainty Dead Time				
C/A -12:26:00	-09:00	CIRS	N			
-09:00	-05:00	CIRS	R			
-05:00	-02:15	CIRS	T			
begin custom period						
-02:15	**-00:15**	**CIRS**	**CIRS will turn to VIMS attitude**			FIRLMB at 87S and 60N; FIRLMBAER and INT
-00:15	**0**	**VIMS**				
2010-267T18:38:41		**CLOSEST APPROACH**	**NEG_Y to Titan,**			
0	**+02:15**	**VIMS**				NT2 5km/pixel equat
end custom period						
+02:15	+05:00	UVIS	X			
+05:00	+09:00	UVIS	X			
+09:00	+14:00	VIMS	V ISS riding along			
+14:00	+22:28	VIMS	B ISS riding along			
C/A + 22:28:19	**2010-268T17:22:00**	OD Uncertainty Dead Time				
2010-268T:17:22:00	**2010-268T18:02:00**	SP Turn to Earth for downlink				
2010-268T18:02:00	2010-268T19:32:00	Y-Bias window				
2010-268T19:32:00	**2010-269T06:17:00**	Canberra 70M Array		DFPW Normal		

…Finished product contains more-detailed pointing

138TI_T72	8175	Lit Outbound

Start Time	End Time	Prime Activity	Obs. Detail	Op Mode	TLM Mode	Comments
2010-267T05:17:00	2010-267T05:57:00	SP Turn to WP	NEG_Y to Titan, NEG_X to NTP	DFPW Normal	S_N_ER_3	
2010-267T05:57:00	C/A - 12:26:00	OD Uncertainty Dead Time		DFPW Normal	S_N_ER_3	
C/A -12:26:00	-09:00	CIRS	N	DFPW Normal	S_N_ER_3	
-09:00	-05:00	CIRS	R	DFPW Normal	S_N_ER_3	
-05:00	-02:15	CIRS	T	DFPW Normal	S_N_ER_3	
begin custom period				DFPW Normal	S_N_ER_3	
-02:15	-00:15	CIRS	CIRS will turn to VIMS attitude	DFPW Normal	S_N_ER_3	FIRLMB at 87S and 60N; FIRLMBAER and INT
-00:15	0	VIMS		DFPW Normal	S_N_ER_3	
2010-267T18:38:41		CLOSEST APPROACH	NEG_Y to Titan, (Tc2a)	DFPW Normal	S_N_ER_3	
0	+02:15	VIMS		DFPW Normal	S_N_ER_3	NT2 5km/pixel equat
end custom period				DFPW Normal	S_N_ER_3	
+02:15	+05:00	UVIS	X	DFPW Normal	S_N_ER_3	
+05:00	+09:00	UVIS	X	DFPW Normal	S_N_ER_3	
+09:00	+14:00	VIMS	V ISS riding along	DFPW Normal	S_N_ER_3	
+14:00	+22:25	VIMS	B ISS riding along	DFPW Normal	S_N_ER_3	
C/A + 22:25:00	2010-268T17:22:00	OD Uncertainty Dead Time		DFPW Normal	S_N_ER_3	
2010-268T17:22:00	2010-268T18:02:00	SP Turn to Earth for downlink		DFPW Normal	S_N_ER_3	
2010-268T18:02:00	2010-268T19:32:00	90 min Y-bias window		DFPW Normal	S_N_ER_3	
2010-268T19:32:00	2010-269T06:17:00	Canberra 70M Array		DFPW Normal	RTE_N_SPB	

Stacking new science on top of old (Radio Science using Low Gain Antenna)



Only three Radio Science gravity passes of Titan during Cassini's final seven years
RSS wants more, but pointing for all Titan flybys was already allocated
Could any useful science be done using the low gain antenna?
Could this actually be implemented?

“Can we do this?” issues

- Science Team determined criteria for successful Low Gain Antenna science
  - On-board test: Could LGA gather “adequately precise” Doppler tracking? YES
- S/C Engineering office assessed risk from switching between the HGA and LGA
  - DSN tracking
- Test concept on board spacecraft

Integration and Command/Sequence Generation

- “Favorable to the LGA” pointing is the major issue
  - RSS rider cannot compel prime instrument to change pointing
  - Integration: see if specifying NEG_Z to Earth for (less constrained) secondary axis compatible with prime observation
  - Implementation: RSS uses delivered c-kernel pointing file to evaluate if RSS LGA criteria are met
- Most LGA opportunities to date have not met all the required criteria at this point

Final Project Review Involves Nav and Engineering

- Project manager wants to see unique/worthwhile science return in exchange for risk and additional workload

Flyby	C/A Date	Sequence	OK in Integration?	Pointing Design Compatible?	Project Review Decision
T82	Feb 19 2012	S72	Yes	No	n/a
T94	Sept 12 2013	S80	Yes	No	n/a
T97	Jan 1 2014	S82	Yes	Yes	No go
T105	Sept. 22 2014	S85	Yes	TBD	–
T110	Mar 16 2015	S88	TBD		
T111	May 7 2015	S89	TBD		
T115	Jan 16 2016	S92	TBD		
T116	Feb 1 2016	S92	TBD		
T123	Sept 27 2016	S96	TBD		

- **Bottom line:** piggybacking additional science adds additional workload, time, and coordination. Allow plenty of time when adding new capability during flight ops.

Accommodating a damaged instrument: dual timelines

- Two “10 pointer” flybys claimed by each instrument during jumpstart planning for most unique/important science
- Cassini Plasma Spectrometer (CAPS) turned off six months before CAPS Dec 2011 10-pointer
  - Sequence in implementation phase
    - Final approval in four months (Nov 8, 2011)
- Limited options:
  - Gamble that CAPS would be operational by Titan flyby

    OR
  - Quickly swap in another instrument for CAPS

Gee, it would be great if we could postpone this decision…why not create and develop two possible timelines to buy some time?

ENGR_158SC_KPTYBIAS347_PRIME
SP_158NA_OBSERV347_NA
CDA_158OT_RATE010005_RIDER
CAPS_158SA_SURVEY002_PRIME
INMS_158SA_SURVEYSEG002_INMS
MAG_158OT_SURVEY005_PRIME
MIMI_158CO_SURVEY003_MAPS
SP_158NA_TOSTSEG347_NA
SP_158TI_DEADTIME347_PRIME
CAPS_158TI_T79PTG001_PRIME
CIRS_158TI_T79PTG001_CAPS
CAPS_158TI_T79INBND001_PRIME
RPWS_158SA_OUTSURVEY002_PRIME
INMS_158TI_T79INBND001_INMS
RPWS_158TI_TIINTRMED001_PRIME
MAG_158TI_MAGTITAN001_PRIME
MIMI_158TI_TITINOV001_RIDER
CAPS_158TI_T79CLOSE001_PRIME
INMS_158TI_TITAN79001_INMS
MIMI_158TI_TITCAOV001_RIDER
RPWS_158TI_TICA001_PRIME
MP_158TI_FLYBYT079_NA

Observations only in original timeline

Delete (repeatedly!)

New observations for alternative timeline

Alternative Naming Scheme

ENGR_158SC_DFPW347_PPS
ENGR_158SC_KPTYBIAS347_PRIME
CDA_158OT_RATE010005_RIDER
INMS_158SA_SURVEYSEG002_INMS
MAG_158OT_SURVEY005_PRIME
MIMI_158CO_SURVEY003_MAPS
SP_158NA_TOSTSEG347_NA
SP_158TI_DEADTIME347_PRIME
CIRS_158TI_FIRNADCMP501_PRIME
ISS_158TI_FIRNADCMP501_CIRS
UVIS_158TI_FIRNADCMP501_CIRS
RPWS_158SA_OUTSURVEY002_PRIME
INMS_158TI_T79INBND001_INMS
CIRS_158TI_MIRLMBINT501_PRIME
ISS_158TI_MIRLMBINT501_CIRS
UVIS_158TI_MIRLMBINT501_CIRS
CIRS_158TI_FIRNADMAP501_PRIME
ISS_158TI_FIRNADMAP501_CIRS
UVIS_158TI_FIRNADMAP501_CIRS
MAG_158TI_MAGTITAN001_PRIME
CIRS_158TI_FIRLMBINT501_PRIME
ISS_158TI_FIRLMBINT501_CIRS
UVIS_158TI_FIRLMBINT501_CIRS
MIMI_158TI_TITINOV001_RIDER
RPWS_158TI_TIINTRMED501_PRIME
CIRS_158TI_FIRLMBAER501_PRIME
ISS_158TI_FIRLMBAER501_CIRS
INMS_158TI_TITAN79001_INMS
MIMI_158TI_TITCAOV001_RIDER
RPWS_158TI_TICA001_PRIME
CIRS_158TI_FIRLMBT501_PRIME
ISS_158TI_FIRLMBT501_CIRS
CIRS_158TI_GLOBMAP501_VIMS
ISS_158TI_CLOSAPP500_VIMS
MP_158TI_FLYBYT079_NA

More issues: epochs, inputs

- Different epoch types offered tradeoffs in flexibility and workload
  - Ground moveable block (no changes possible after sequence is radiated); *or*
  - Live moveable block
    - Changes possible until shortly before execution **but**
    - Two LMB epochs, real time commanding and many more ports for sequence file delivery add complexity
  - Given existing workload, choose simplicity

Dual Timeline Bottom line

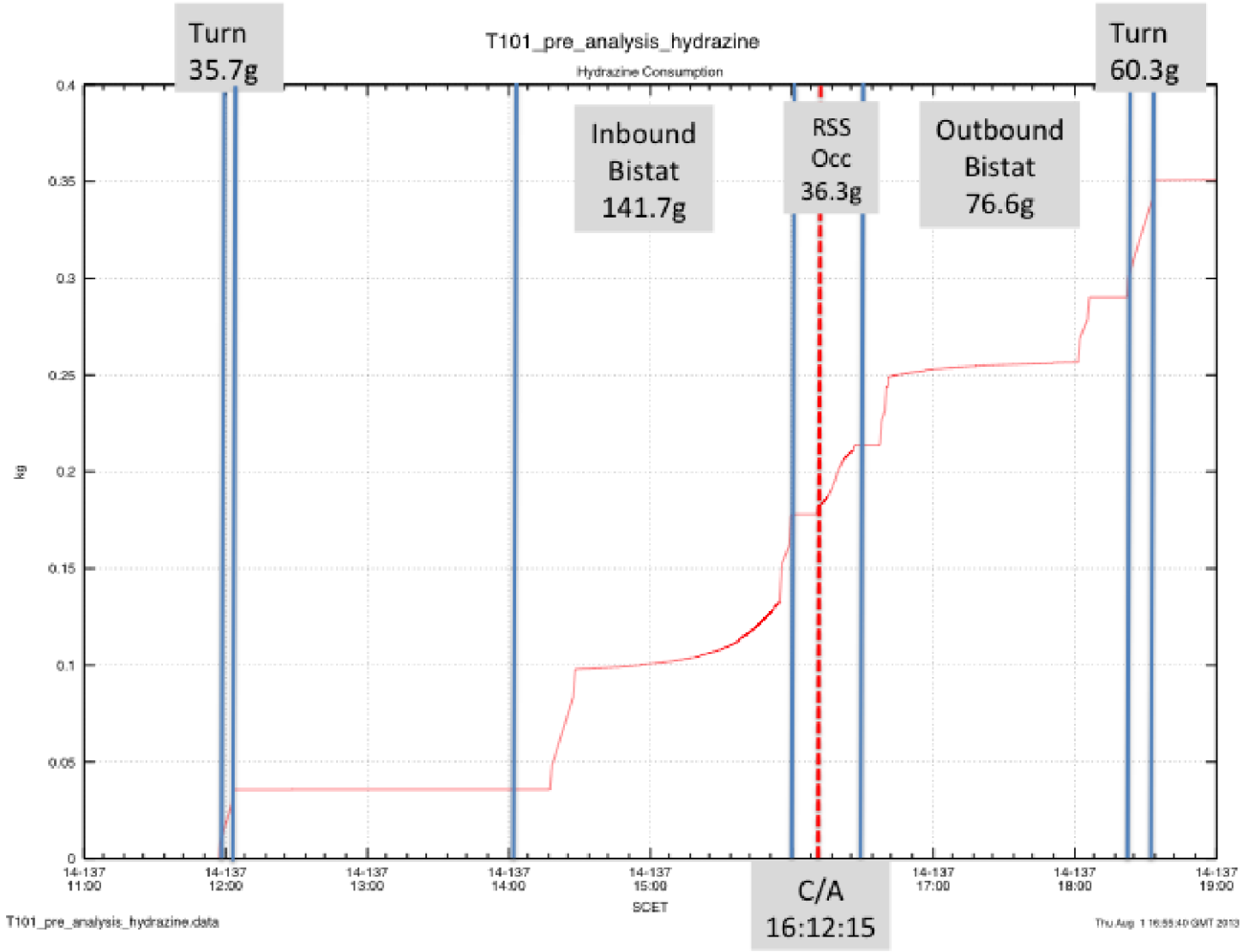
- Dual (or more!) timeline development is complicated and work-intensive
- Building a software scheduling database that can accommodate dual (or more!) timelines will be expensive
- If you anticipate losing capability, strongly consider paying upfront to develop a more robust operations integration scheduling tool

Consumables: a growing concern for an extended mission

- Is science using too much hydrazine?
  - Early (jumpstart) estimate based on historical trends
  - Detailed (implementation) estimate based on actual pointing commands
    - Using too much? Only option is to yank the observation
    - Too late to make smart science choices, no time to redesign

Solution: Move analysis earlier in the process

- Instrument teams asked to develop and deliver detailed pointing designs during early integration phase
- AACS team agrees to run early analysis of hydrazine use
- Science planning annotates graph of hydrazine use, showing cost of each pointing command



- Proposed plan too expensive? Modify design or give time to another instrument

Consumables Analysis Bottom line

- At the cost of some up-front work:
  - Instruments get best shot at keeping their observations from being cut;
  - Titan science doesn’t lose observing opportunities;
  - Decisions based on science trades
  - Project knows consumables are managed effectively

Whose science is higher priority?

- RADAR “10-pointer” observation would heat Visual and Infrared Mapping Spectrometer, impacting its observations
  - Not enough time for VIMS to cool down
  - VIMS heating model underpredicting heating by 2-3 degrees K (expected heating of 6 degrees K)
  - VIMS wanted to protect its science, asked RADAR to redesign to avoid heating

RADAR vs VIMS

- RADAR developed alternative observing strategies
  - Presentation described science enabled by each strategy and resulting heating
  - ALL teams welcome to comment
- Final decision at “core” meeting
  - One representative per instrument
  - Chosen design significantly heats VIMS but enables some VIMS science
  - VIMS found similar observation opportunity later in the mission with no heating issues

RADAR vs VIMS Bottom line

- Instrument teams worked together to find best science balance

If you want to make late changes:

- “Piggybacking” science opportunities on existing science for an in-flight mission is possible, but complex. If the science opportunities are of high enough priority, the work investment may be worthwhile, but doesn’t guarantee success and will take longer than expected.

- Database/software capability to handle multiple timelines will be expensive but adds flexibility in last-minute decision making. Missions that anticipate a greater likelihood of loss of capability leading to a need to replan science should consider this option.

- Tracking consumable use at higher fidelity early on is a wise investment of time.

- An experienced and tightly knit team, intimately familiar with each others’ instruments, can make the best possible decisions when science trades must be made.