Cassini
Mission Planning

The Last Orbit: Planning Cassini's Plummet into Saturn

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Overview

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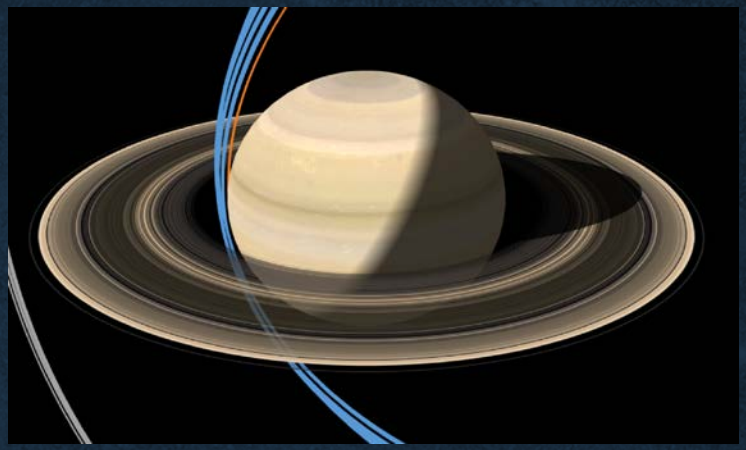

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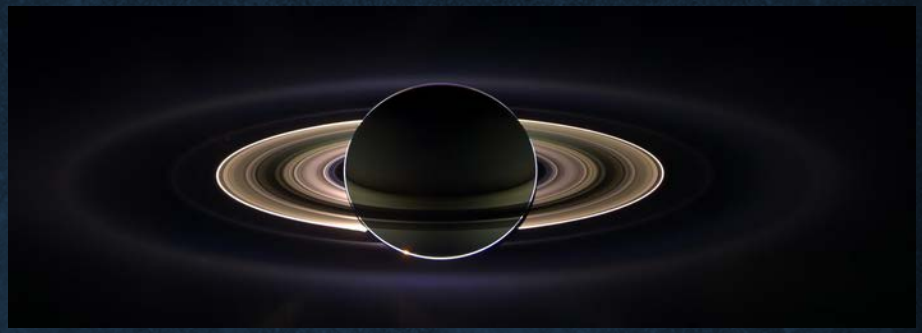
Some of Cassini's Great Finds

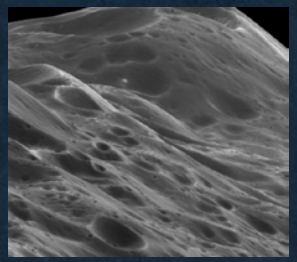
2005 - Huygens probe makes first landing on a moon in outer solar system

2005 - Discovery of active, icy plumes on moon Enceladus

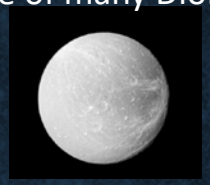
2006 – Backlit Saturn reveals faint rings



2007 – Mountains on Iapetus

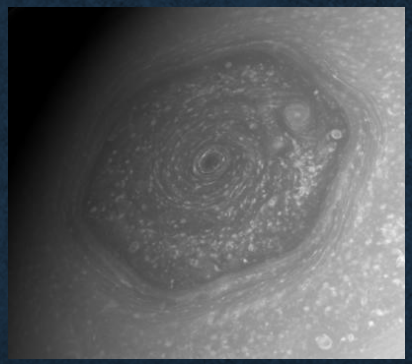


2010 – One of many Dione flybys



2011 – Saturn's largest storm

2013 – Saturn's north pole, a hexagonal hurricane



2014 – 100th Titan flyby

2015 – Cassini's flyby through Enceladus' plumes

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Cassini Mission Overview

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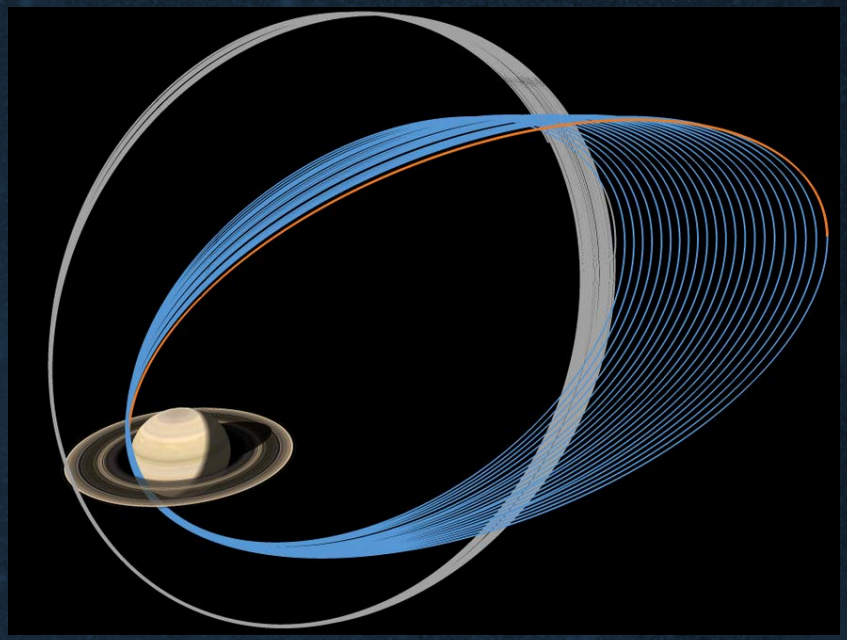
Introduction to the End

- 2010-2017: Solstice Mission
  - Equatorial Orbits
  - Inclined Orbits
  - F-ring & “proximal orbits”
- Mission ends on September 15th, 2017 with spacecraft disposal into Saturn



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- Key Topic: the last orbit of the mission & the data return strategy during the final descent into Saturn
- Goal: get the last bits possible deep in Saturn’s atmosphere before LOS (loss of signal)
  - Important scientific opportunity to explore the deepest regions of Saturn yet

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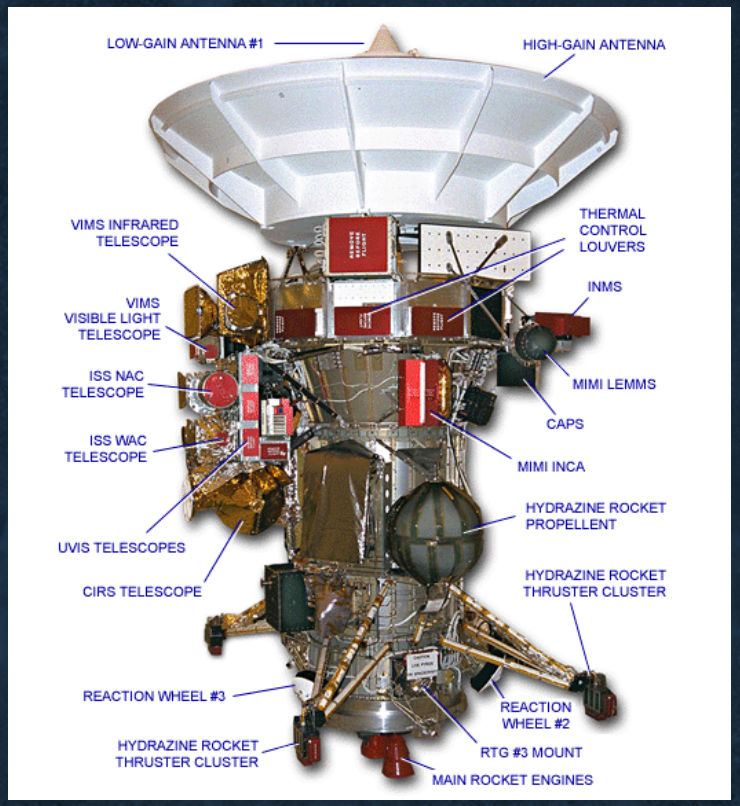
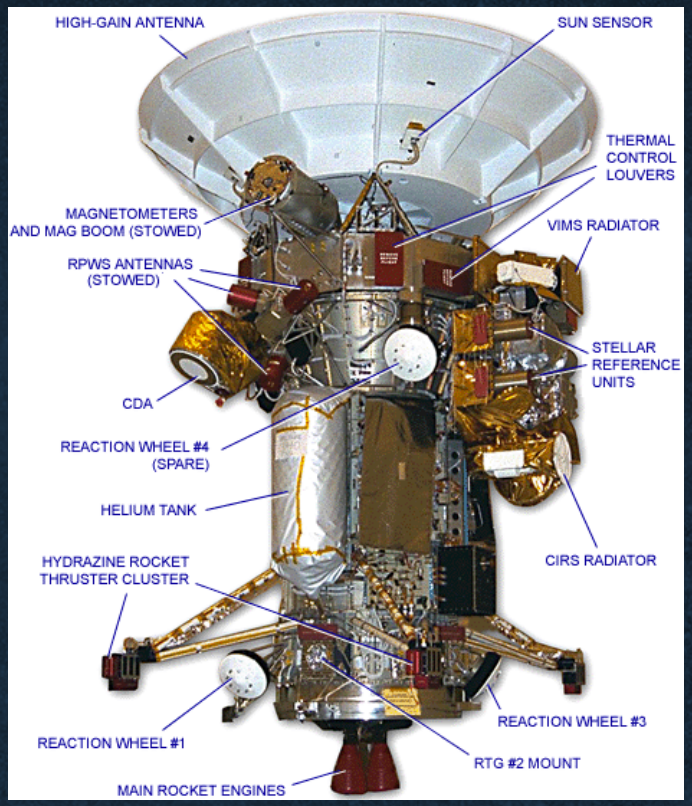
Spacecraft Description

Image credits: http://www.jpl.nasa.gov/infographics/





- **12 science instruments:** standard science observation periods during last orbit prior to final descent; only select instruments ON during final descent
- **7 engineering subsystems:** certain modes and activities for EOM

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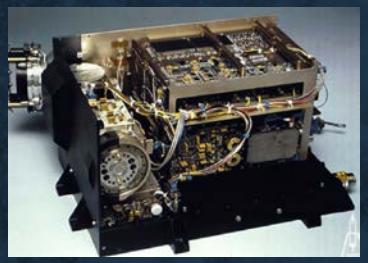
Spacecraft Description: 12 Science Instruments

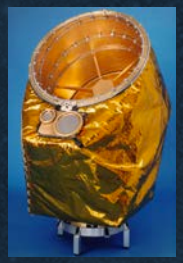
ON

Ion & Neutral Mass Spectrometer (INMS): determines chemical, elemental and isotopic composition



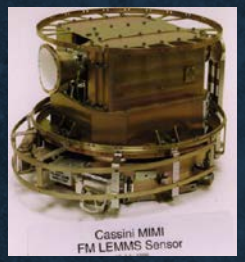
Ultraviolet Imaging Spectrograph (UVIS): box of four telescopes that see UV light

Cosmic Dust Analyzer (CDA): directly measure chemical composition of dust particles

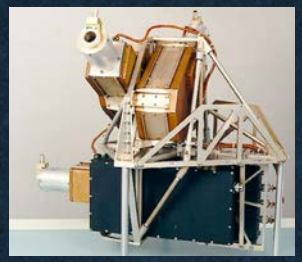


Composite Infrared Spectrometer(CIRS): searches for heat & discerns an object's composition

Magnetospheric Imaging Instrument (MIMI): measure composition, charge state & energy distribution



Radio & Plasma Wave Science (RPWS): receives and measures the radio signals coming from Saturn



Magnetometer (MAG): measures the strength and direction of the magnetic field

Image credits: see References slide 21

OFF (or sleep)

Imaging Science Subsystem (ISS)

Radio Detection & Ranging (RADAR)

Visible & Infrared Mapping Spectrometer (VIMS)

Cassini Plasma Spectrometer (CAPS)

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Spacecraft Description: 7 Engineering Subsystems

System Fault Protection (SFP)

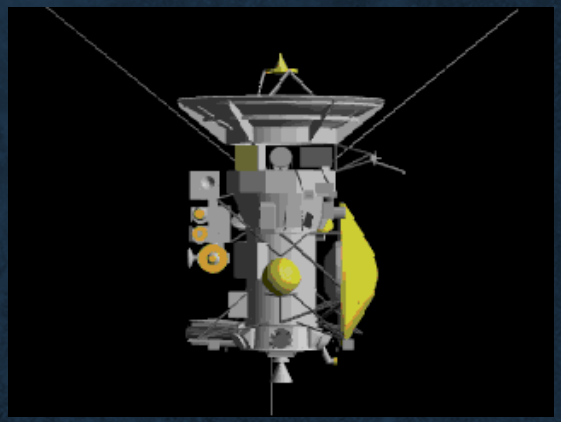
Monitors/devices to respond to faults or call safing if needed

Radio Frequency Subsystem (RFS)

DST-A and TWT-B cross-strapped for polarization, HGA for comm; LGA in anomalies as needed

Thermal Devices Subsystem (Thermal)

Insulation blankets, heaters, etc. for thermal control



Command & Data Subsystem (CDS)

Redundant Computers & SSRs; CDS-B prime with CDS-A in hot backup; SSR-B currently prime

Power & Pyrotechnics Subsystem (PPS)

Powered by 3 RTGs & distributed to spacecraft (pyros for LV separation, etc.)

Propulsion Management Subsystem (PMS)

2x Main Engines (redundant) for large maneuvers; 16 (4x4) RCS thrusters for small maneuvers & attitude control

Attitude & Articulation Control Subsystem (AACS)

Attitude determination with IRUs, SRU
Attitude control with RWAs (1,2,4 currently) & RCS thrusters

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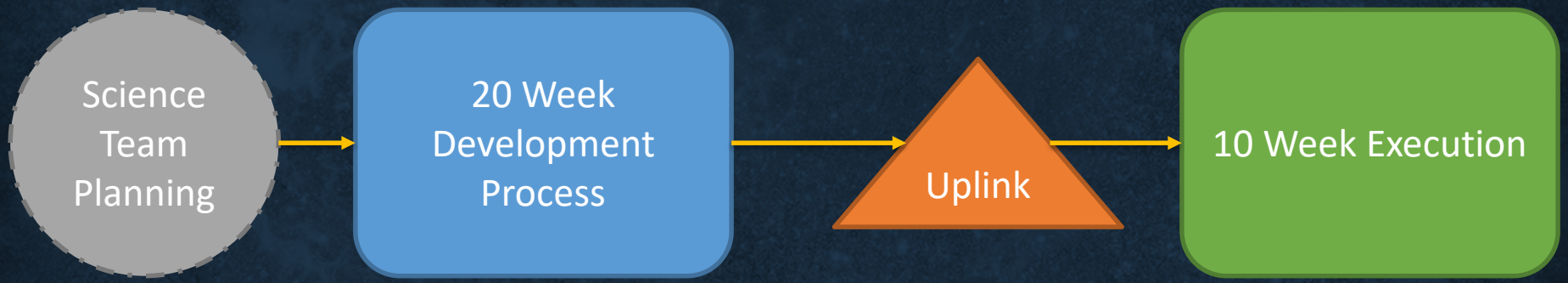
Normal Spacecraft Operations: Background Sequence

- Cassini operates on lengthy background sequences and shorter, more rapidly designed "real-time" activities
- BG Sequence: command file that contains 10 weeks worth of pre-planned science and engineering activities



- Long-term planning of observations & activities

- Refinement of science observations
- Placement of engineering activities
- Flight rule & constraint checks

- Uplinked multiple days prior to execution
- May be split into multiple files as needed

- Spacecraft steps through execution of commands in time order
- Has "slots" for planned R/T commands as needed

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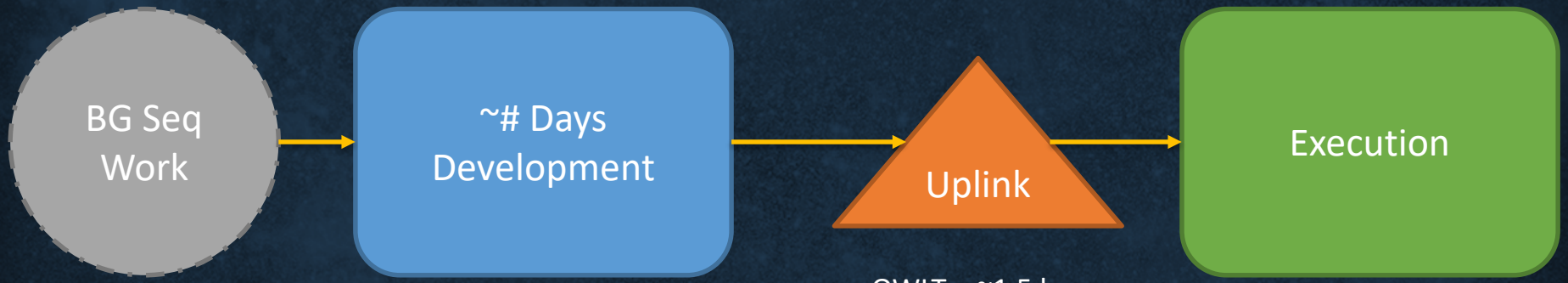
Normal Spacecraft Operations: "Real-time" Activities

- Background sequence includes placement for *planned* "real-time" activities
- Background sequence may be interrupted or stopped completely for *unplanned* real-time commands (i.e. anomalies or safing)
- "Real-time" activities: Smaller development time much closer to execution to use latest data available
- Examples of *planned* R/T activities: OTMs, live updates to pointing for tightly controlled flybys, FSW uploads



- Contains "slots" with necessary opmodes, etc. for *planned* R/T activities

- Development work is done on the order of a day to a ~week
- Latest data is used

- OWLT = ~1.5 hrs
- RTLT = ~3 hrs
- Uplink on execution DSN pass or ~days before

- Usually occurs over a DSN pass
- Multiple hours on one pass or possibly stretched out over 2+ passes

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Normal Spacecraft Operations: Science Data Collection & Transmission

- Background sequence includes science observation commands and commands to return data over a DSN pass

Science Observation

Store data on SSRs

Turn to Earth for DSN Pass

Transmit data to DSN antenna on scheduled pass

- Science instrument commands for measurements, images, etc.
- Spacecraft commands for pointing, power
- Pointing corresponds to what is best for observation

Image credits: http://saturn.jpl.nasa.gov/photos/imagedetails/index.cfm?imageId=4626
http://solarviews.com/eng/earth.htm
http://www.nasa.gov/topics/technology/features/dsn20100308.html

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Definition of EOM Scenario

- **End of Mission (EOM) Scenario:** How project plans to secure science data collection during last orbit and, in particular, the final descent in Saturn's atmosphere

Requirement

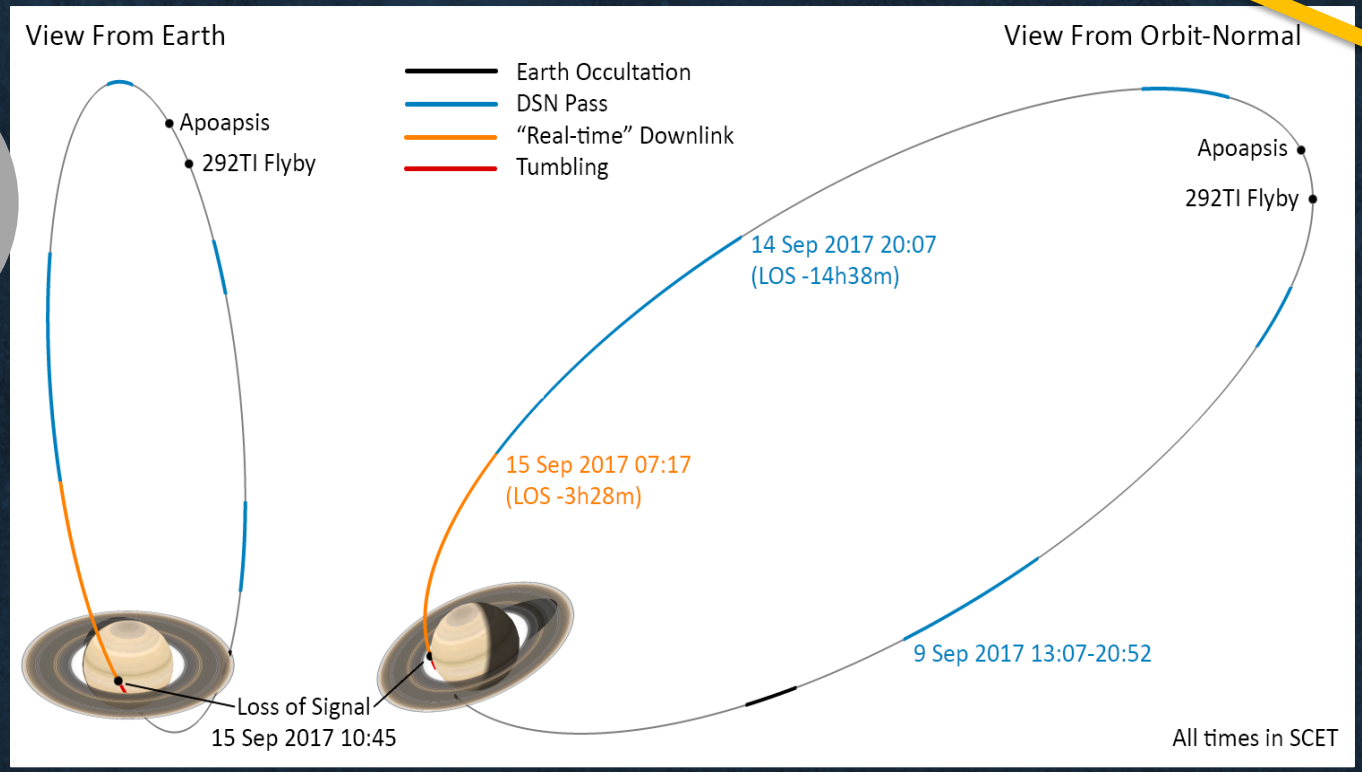
Spacecraft disposal for planetary protection; T126 – the last targeted flyby of Titan on April 22nd 2017 (before the last orbit) sets up the ballistic trajectory into Saturn

Objective

Successful collection of unique EOM data, especially last bits possible before LOS

JPL/Cassini Planetary Protection Plan addresses this

This is the key point!



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SCET = Spacecraft Event Time

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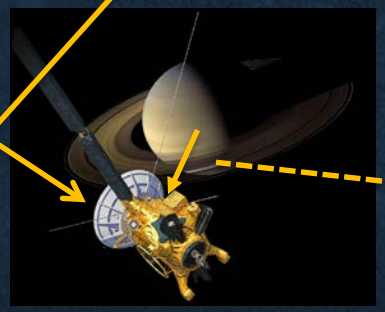
Guiding Principles

- Assumptions & Constraints
  - 150901 reference trajectory & June '15 atmospheric model
  - Spacecraft will be operating nominally (See risks for possible off-nominal operations)
  - Sequence "S101" will be designed & implemented following the normal sequence development schedule
  - No new flight software
- Operability Considerations
  - Near **"real-time" data transmission**: data is transmitted at nearly same rate it is collected

Science Observation While on Earth point

"Store" data on SSRs



Specific instrument data collection rates to closely match Tx rate

Transmit data just after it is collected

Image credits: see slide 11

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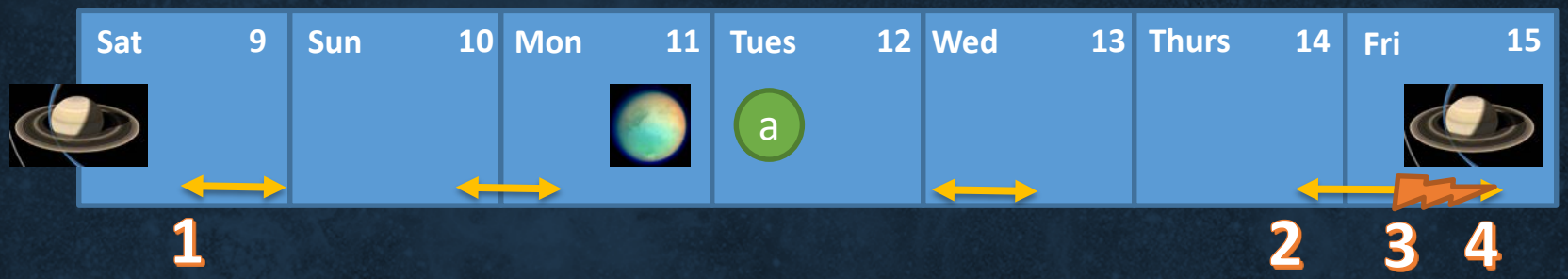
Boundary Definitions

Last week of the mission in Earth Receive Time (ERT/UTC)



- Boundary Definitions of Key Points:

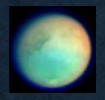
1. **Scenario Start:** first post-periapsis pass of Rev 292 – establish health and safety of spacecraft after Rev 292 transit; RWA control; other operations/sequencing per normal operations
2. **Start of Continuous Coverage:** 14.5* hours prior to LOS – assume SSRs are completely full, RWA-to-RCS control transition (exact timing not yet determined)
3. **"Real-time" Tx:** 3.5* hours prior to LOS – SSRs completely cleared, specific instrument data collection rates (slide 11), Tx rate at 27 kbps (34m antenna), RCS control
4. **Scenario End:** LOS due to loss of RCS control authority in atmosphere

* Subject to change

Saturn atmospheric transit/ final descent

a Apoapsis

Real-time downlink


Final non-targeted Titan flyby

DSN pass (current schedule subject to change)

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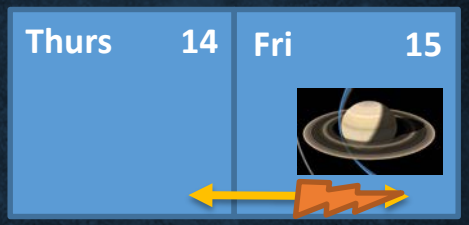
Timeline of Events

- The sequence of activities shown contribute to the success of the EOM objective—the collection of the unique science data

Absolute Time (SCET)	Absolute Time (ERT/UTC)	Time Relative to LOS	Activity
2017-251T23:04	9/9/17 0:26	-006T11:40	Transition to RCS Control
2017-252T01:25	9/9/17 2:47	-006T09:19	Transition to RWA Control
2017-252T06:52	9/9/17 8:14	-006T03:52	Earth occultation by Rings
2017-252T08:38	9/9/17 10:00	-006T02:06	End Earth occultation by Rings
2017-252T13:07	9/9/17 14:29	-005T21:37	Beginning of EOM scenario on DSS-63 pass
2017-254T19:03	9/11/17 20:25	-003T15:41	Final non-targeted Titan flyby (292Ti)
TBD	TBD	TBD	Transition to RCS control for final plunge
2017-257T20:14:31	9/14/17 21:37	-14:30:00	Start of continuous coverage
2017-257T20:14:31	9/14/17 21:37	-14:30:00	Turn to Earth & Begin final downlink
2017-258T07:14:31	9/15/17 8:37	-03:30:00	SSRs cleared (latest possible time)
2017-258T07:14:31	9/15/17 8:37	-03:30:00	Start of real-time transmission period
2017-258T10:43:31	9/15/17 12:06	-00:01:00	RCS @ 10% duty cycle
2017-258T10:44:13	9/15/17 12:07	-00:00:18	RCS @ 50% duty cycle
2017-258T10:44:28	9/15/17 12:07	-00:00:03	RCS @ 90% duty cycle
2017-258T10:44:31	9/15/17 12:07	-00:00:00	Loss of signal (RCS @ 100% duty cycle)
2017-258T10:44:31	9/15/17 12:07	-00:00:00	End of scenario



2 3 4

Last <~day

Exact times not yet finalized

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Description of Key Events

Instrument	Proposed rate (bps)
CAPS	0
CDA	4192
CIRS	1600
INMS	1498
ISS	0
MAG	1976
MIMI	2200
RADAR	0
RPWS	6865
UVIS	1801
VIMS	0

- **Data collection and transmission:**
  - 14.5 → 3.5 hours before LOS:
    - Used to clear SSRs (takes about 11 hours for full SSRs)
  - "Real-time" Tx at 3.5 hours prior to LOS
    - Data will be collected while on Earth-point
    - Data is transmitted at nearly the same rate it is collected
    - Tx: 27 kbps (for the backup 34m antennas, and it works on primary 70m antennas)
    - Rx: Instrument rates in table to closely match Tx rate

- **Loss of Signal:** LOS predicted to occur on 9/15/17 at 12:07 ERT/UTC (2017-258T10:44:31 SCET)
  - AACS ran simulations to predict atmospheric torque on spacecraft
  - Simulation includes model for RCS thrusters
  - LOS occurs when spacecraft loses RCS control authority (cannot hold itself on Earth-point)
  - LOS predicted to occur at density = $9*10^{-11}$ kg/m^3 (radius = 61,321 km)

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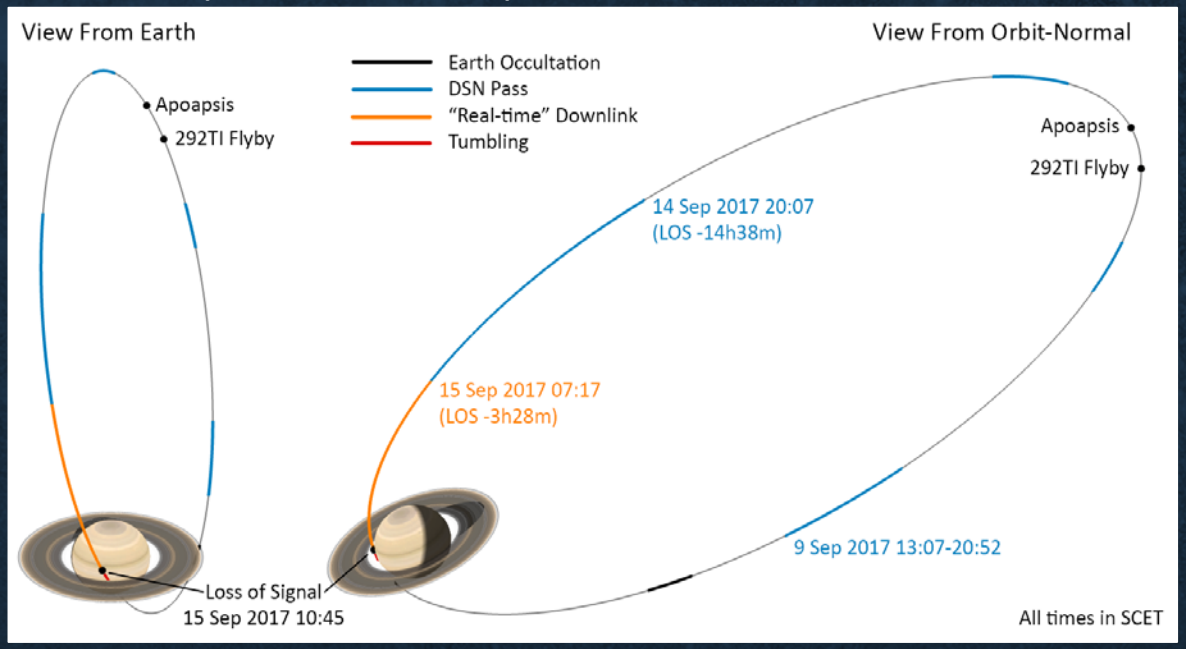
Decisions, Trades & Analyses

1. Transmission rates from spacecraft to Earth for the "real-time" transmission
   - 34m rates, 27kbps - finalized
2. DSN coverage for last orbit
   - As shown in figure below
3. Type of station coverage for the period of continuous coverage & length
   - 70m + 34m – dual coverage; 14.5 hours
4. When to start the "real-time" transmission period
   - Currently 3.5 hours before loss of signal: gives us time to see data come back and correct certain aspects with R/T uplink



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Risks & Mitigations

- DSN antenna failure/loss
  - Mitigation: Dual coverage (34m and 70m) for last 14.5 hours (potentially longer, not yet finalized)
- Spacecraft anomalies that call safing
  - Mitigation: Detailed safing strategy for last orbit
  - Safe state: The safe state objectives are to regain attitude control and to point the spacecraft to Earth for telecommunications. Safing immediately powers the instruments off and stops science data collection and transmission.
  - Anomalies that call safing: loss of attitude control (due to RWA or thruster faults), loss of attitude knowledge, a computer or sequencing error, power undervoltage or excessive power draw, and loss of telecom downlink capability (due to transponder or TWTA faults)

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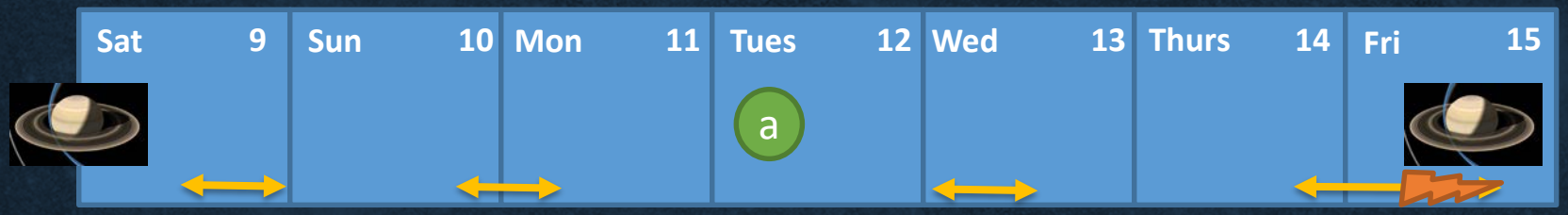
Safing Strategy

- Safing will not be disabled for this scenario
- Rationale: the spacecraft will command a predictable state if safing is called (as opposed to letting the fault propagate to an unknown state)
- If the spacecraft enters safing, 1 of 3 paths will be followed depending on **timing** and **criticality** of fault:

1. Restart the entire S101 background sequence on the spacecraft: includes all of S101 w/ final descent
2. Uplink a pre-constructed mini-sequence, containing only the final descent: contains the instrument data collection rates during real-time Tx period and other necessary commands
3. No response: the objective for unique EOM science data objective will be lost (requirement for planetary protection is still met)



**timing is notional; actual timeline will depend on finalized DSN passes, the anomaly that tripped safing, and other factors*

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Conclusion

- Cassini's EOM scenario has been developed to secure the last bits of data as the spacecraft takes its mission-ending plunge into Saturn.
  - ✓ Important assumptions/constraints/considerations
  - ✓ Overall timeline of events with boundary definitions
  - ✓ Detailed timeline in place (with some potential changes)
  - ✓ Real-time Tx strategy solidified
  - ✓ Instrument data collection rates accepted and tested
  - ✓ Simulations for LOS timing
  - ✓ Framework for safing strategy in place (based on existing safing procedures)
- Work to go:
  - ❑ Finalize time in "real-time" transmission: currently 3.5 hours before LOS
  - ❑ Finalize DSN passes, particularly length of time for continuous coverage: currently 14.5 hours
  - ❑ Detailed safing timeline and safing strategy
  - ❑ Other timing such as RCS opmode transition before final descent

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References

- Manor-Chapman, Emily, “Cassini Solstice Mission Overview and Science Results”, 2013 IEEE Aerospace Conference, Big Sky, MT, 2013.
- Buffington, B., “Proposed End-of-Mission for the Cassini Spacecraft: Inner D Ring Ballistic Saturn Impact”, Paper IAC-10-C1.9.2, 61st International Astronautical Congress, Prague, CZ. 2010.
- Doody, Dave, “The Cassini Saturn-Orbiter Spacecraft,” Basics of Space Flight, Chapter 11, URL: http://solarsystem.nasa.gov/basics/cassini/index.php [cited 8 March 2016].
- Yam, C., Davis, D., Longuski, J., Howell, K., and Buffington, B., “Saturn Impact Trajectories for Cassini End-of-Mission”, Journal of Spacecraft and Rockets, Vol. 46, No. 2, 2009, pp. 353-364, March-April, 2009.
- Burk, Thomas A., “Cassini at Saturn Proximal Orbits – Attitude Control Challenges”, 2013 AIAA Guidance, Navigation, and Control Conference, Boston, MA, 2013.
- Slide 7 Images
  - CIRS: http://saturn.jpl.nasa.gov/multimedia/products/pdfs/20080930_CHARM_CIRS.pdf
  - UVIS: http://lasp.colorado.edu/home/cassini/instrument/
  - MAG: http://www.jpl.nasa.gov/missions/cassini-huygens/
  - INMS, CDA, MIMI, RPWS: http://saturn.jpl.nasa.gov/spacecraft/cassiniorbiterinstruments/

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Questions?

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