OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

OSIRIS-REx PI Lessons Learned

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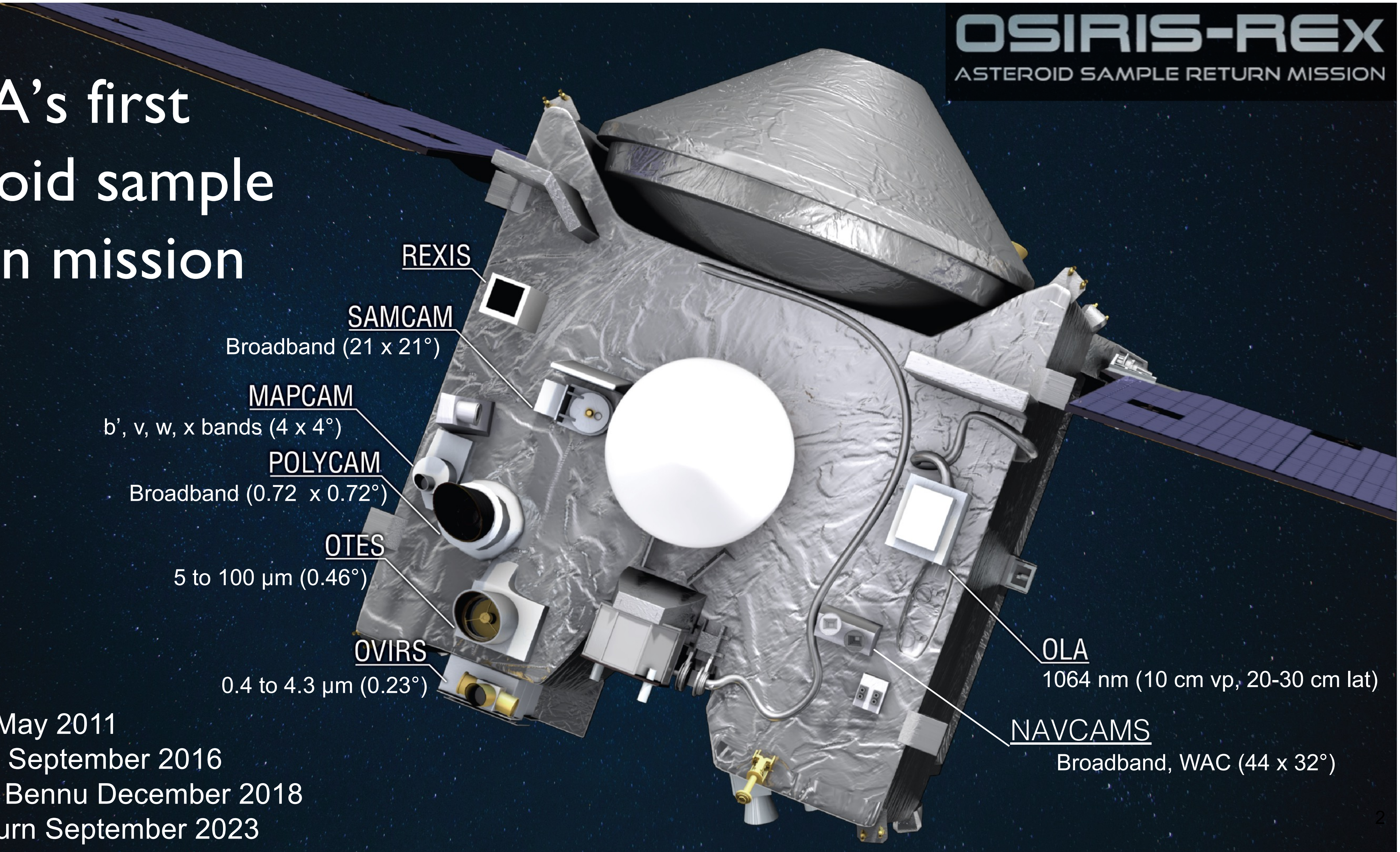
OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

NASA’s first asteroid sample return mission



REXIS

SAMCAM
Broadband (21 x 21°)

MAPCAM
b’, v, w, x bands (4 x 4°)

POLYCAM
Broadband (0.72 x 0.72°)

OTES
5 to 100 µm (0.46°)

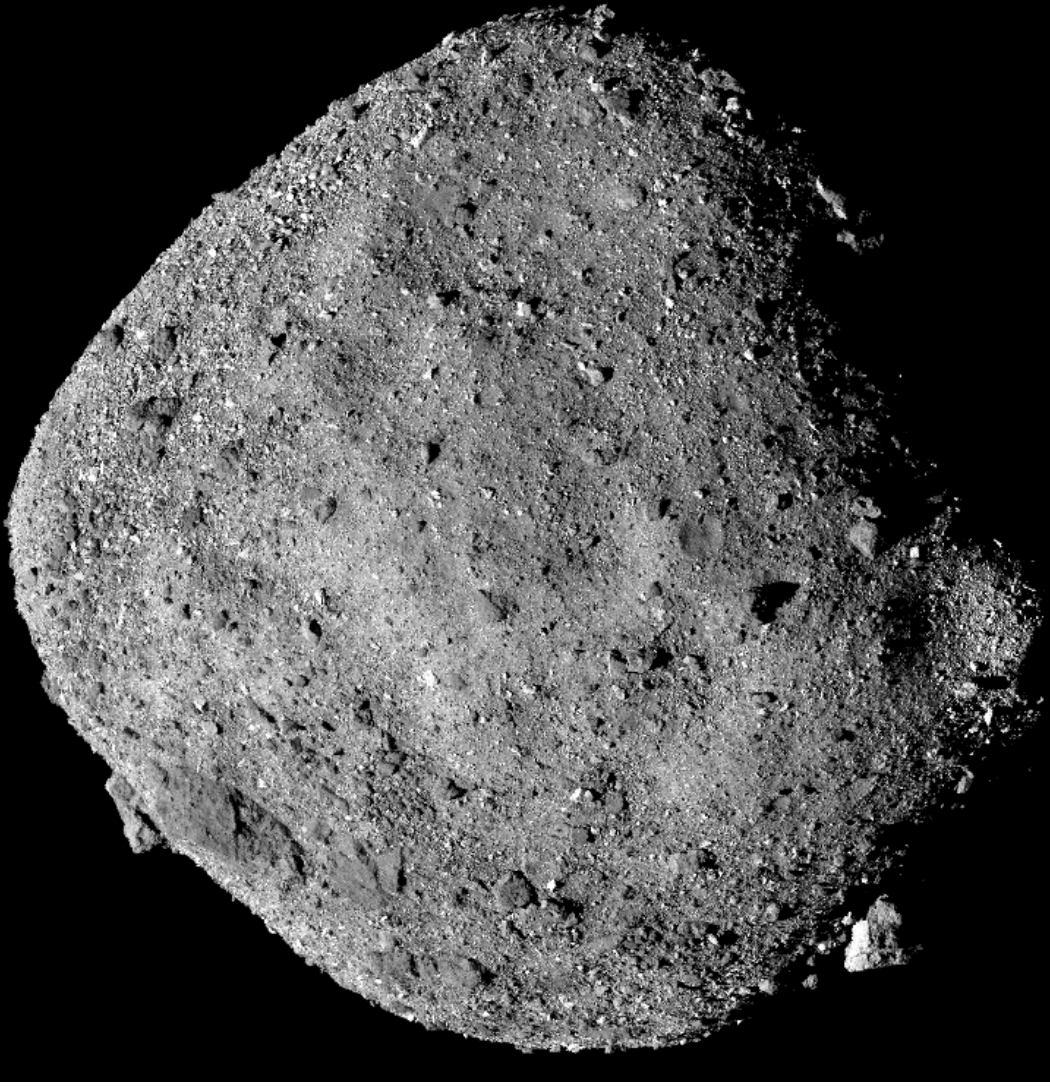
OVIRS
0.4 to 4.3 µm (0.23°)

OLA
1064 nm (10 cm vp, 20-30 cm lat)

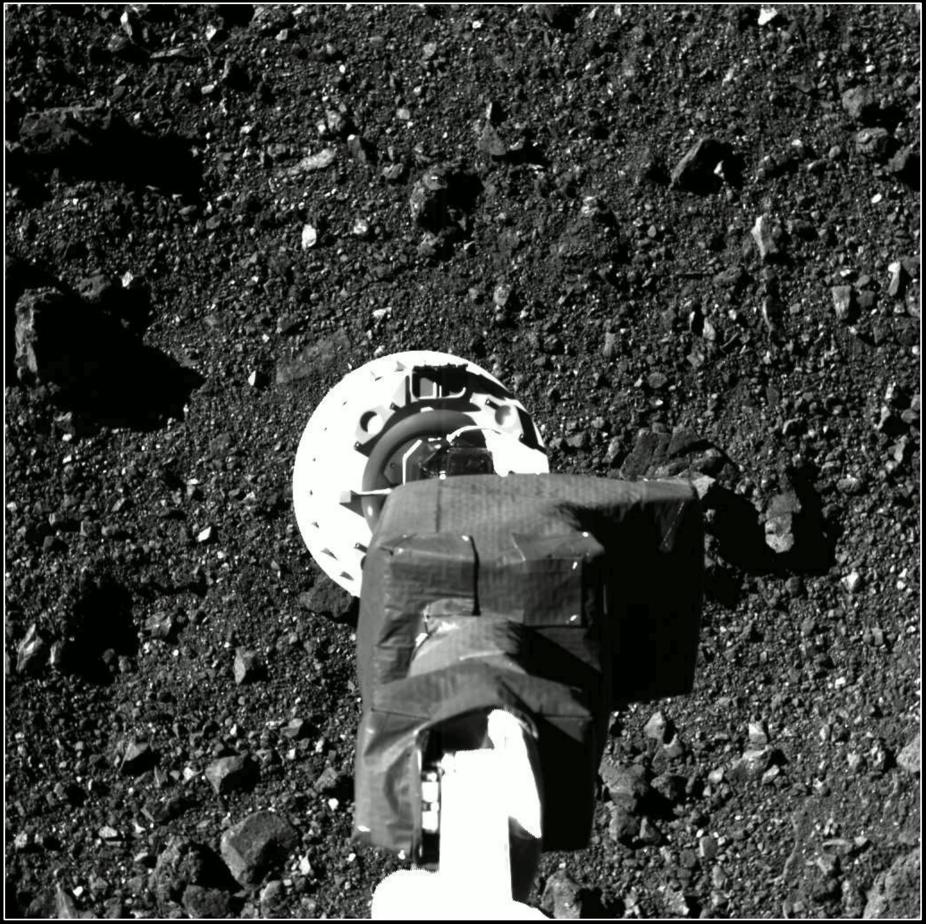
NAVCAMS
Broadband, WAC (44 x 32°)

Selected May 2011
Launched September 2016
Arrived at Bennu December 2018
Earth Return September 2023

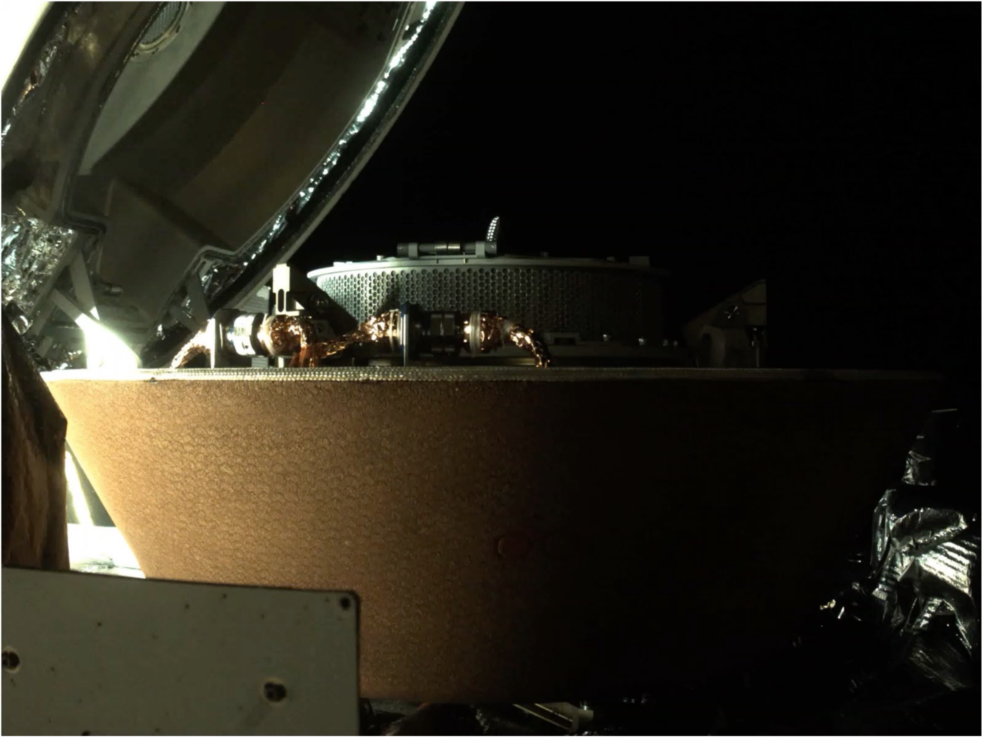
Meeting Bennu with
OSIRIS-REx in 2018

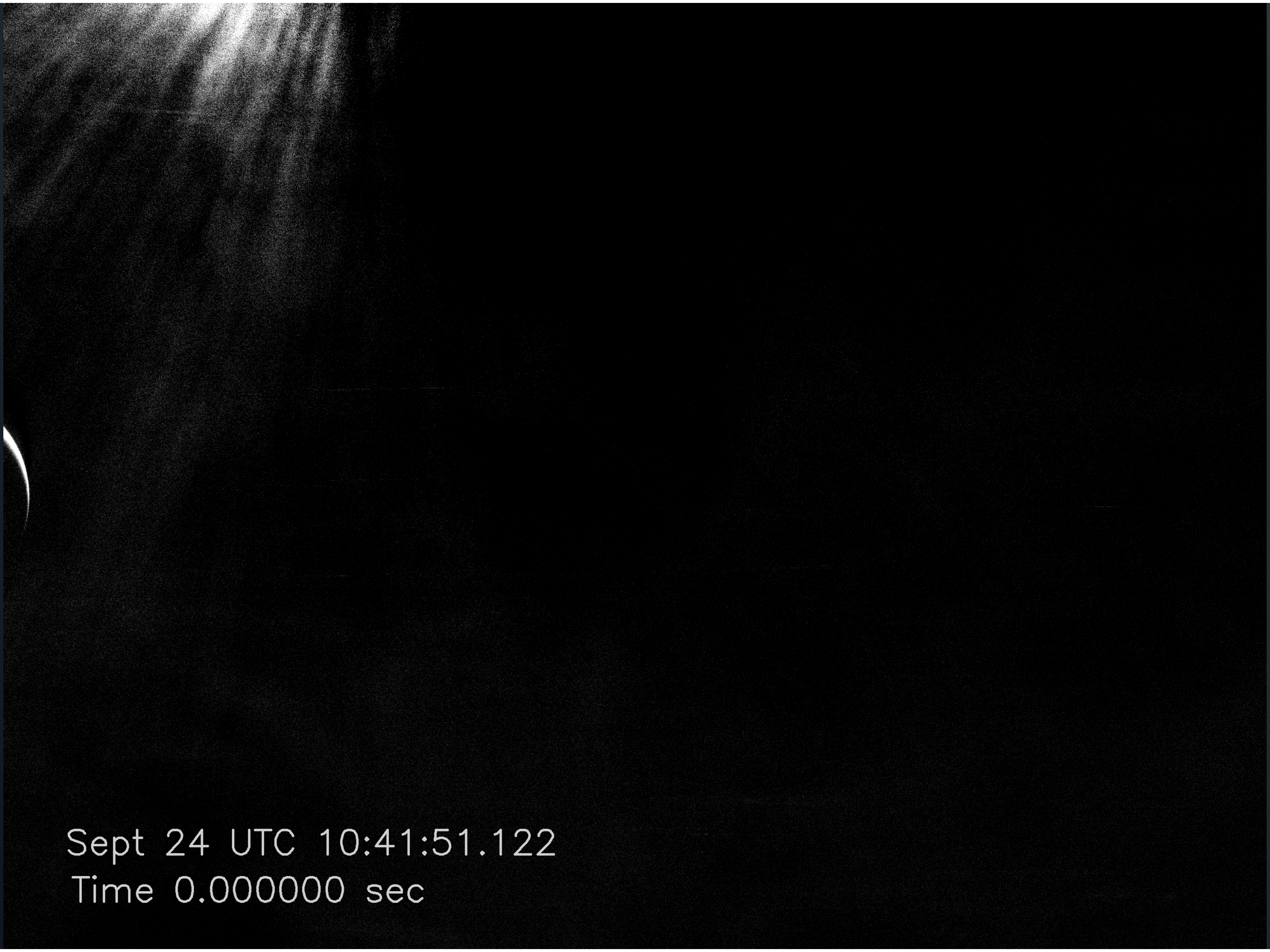


Sampling asteroid Bennu



Stowing the sample away





Sept 24 UTC 10:41:51.122
Time 0.000000 sec

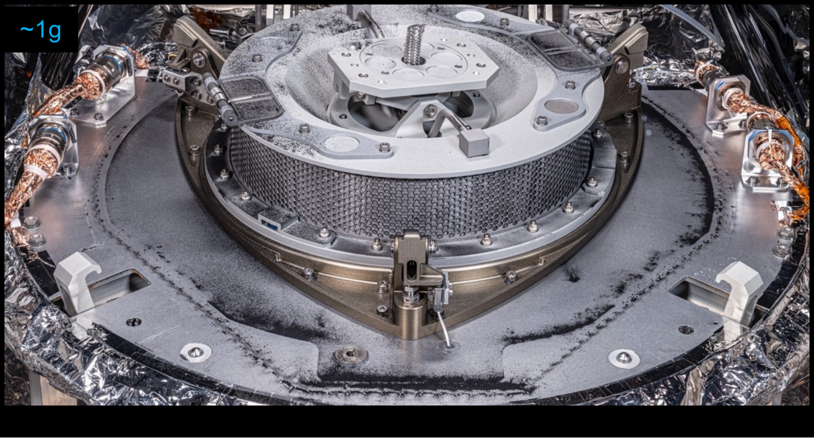
121.6g of sample

Requirement: Collect and return 60g from asteroid Bennu

~50g

~70g

~1g



Erika Blumenfeld – Joseph Aebersold JSC

Risk Areas – What Keeps the PI Up-At-Night?

Risk Area
Unique Aspects of a Sample Return Mission
Preventing Mission Requirements Creep
Long-Term Continuity of Expertise

Unique Aspects of a Sample Return Mission

Small Body Technical Challenges

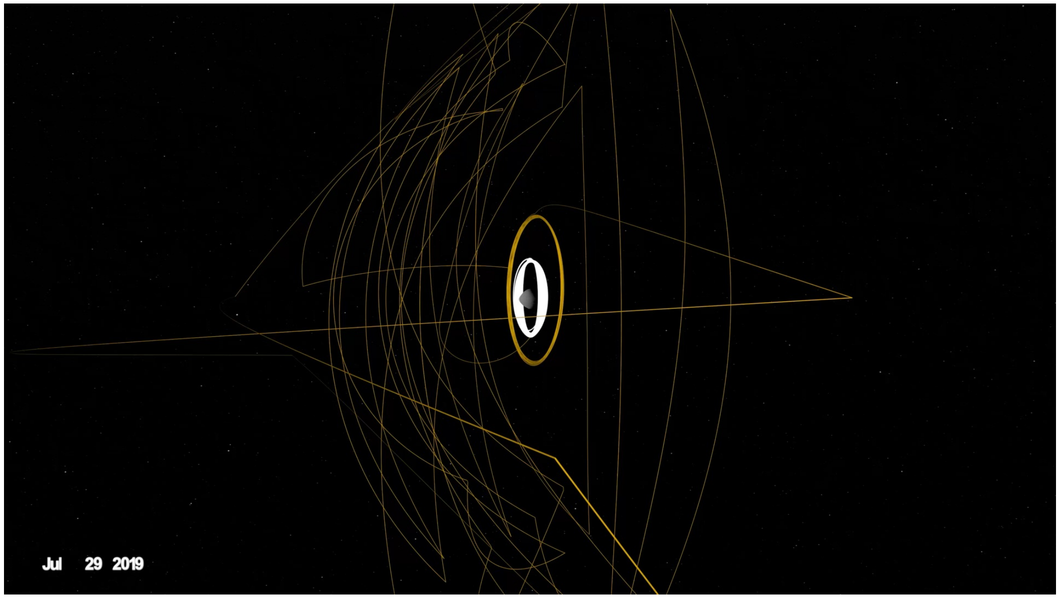
Established World Class Navigation Team

- Recognized challenge of operating in microgravity environment

And yet

- Navigation effort underscoped at beginning of development (rectified post-PDR)
  - Solar radiation pressure and S/C thermal re-radiation significantly contribute to trajectory propagation errors.
  - Drove requirement for operationally complex 24-hour ground in the loop target ephemeris updates
- Science planning/operations effort underscoped
  - Challenges with accounting for navigation uncertainty in observation design
  - Implemented observation sensitivity analysis
- Targeting complexity led to development of FSW patch in Phase E
- Current best estimate navigation performance and updated thermal constraints to meet tight constraints – reassess and release margin

World records: smallest object orbited by a spacecraft, closest orbit of an asteroid, and highest resolution satellite map of any planetary body.



Small Body Technical Challenges

Developed detailed Design Reference Mission to guide the execution of asteroid operations and sample collection

- Documented the spacecraft trajectory, science observations, downlink schedule, and required science data products

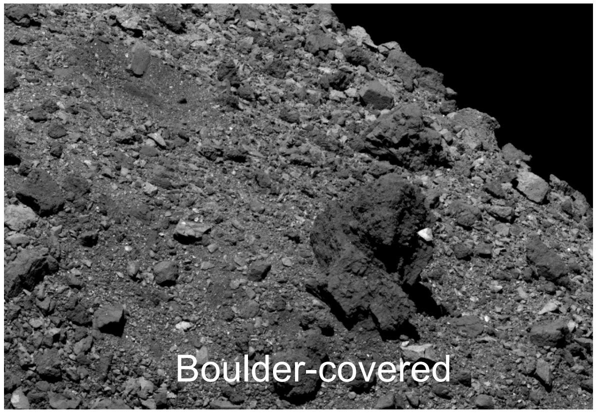
Design Reference Asteroid was essential to design the mission

- Contained the best pre-encounter estimates for parameters spanning orbital, bulk, rotation, radar scattering, photometric, spectroscopic, thermal, surface analog, and operational environmental properties

And yet

- Observation requirements and mission plan refined after launch
- Bennu surprises required Recon phases to be redesigned and caused switch to backup navigation technique for sample collection
- Reassessed conservatism in safety calculations for sample collection when confronted with Bennu challenges

Executed all planned mission phases and collected twice the required sample



Proactive risk and strategic reserve management crucial for addressing challenges

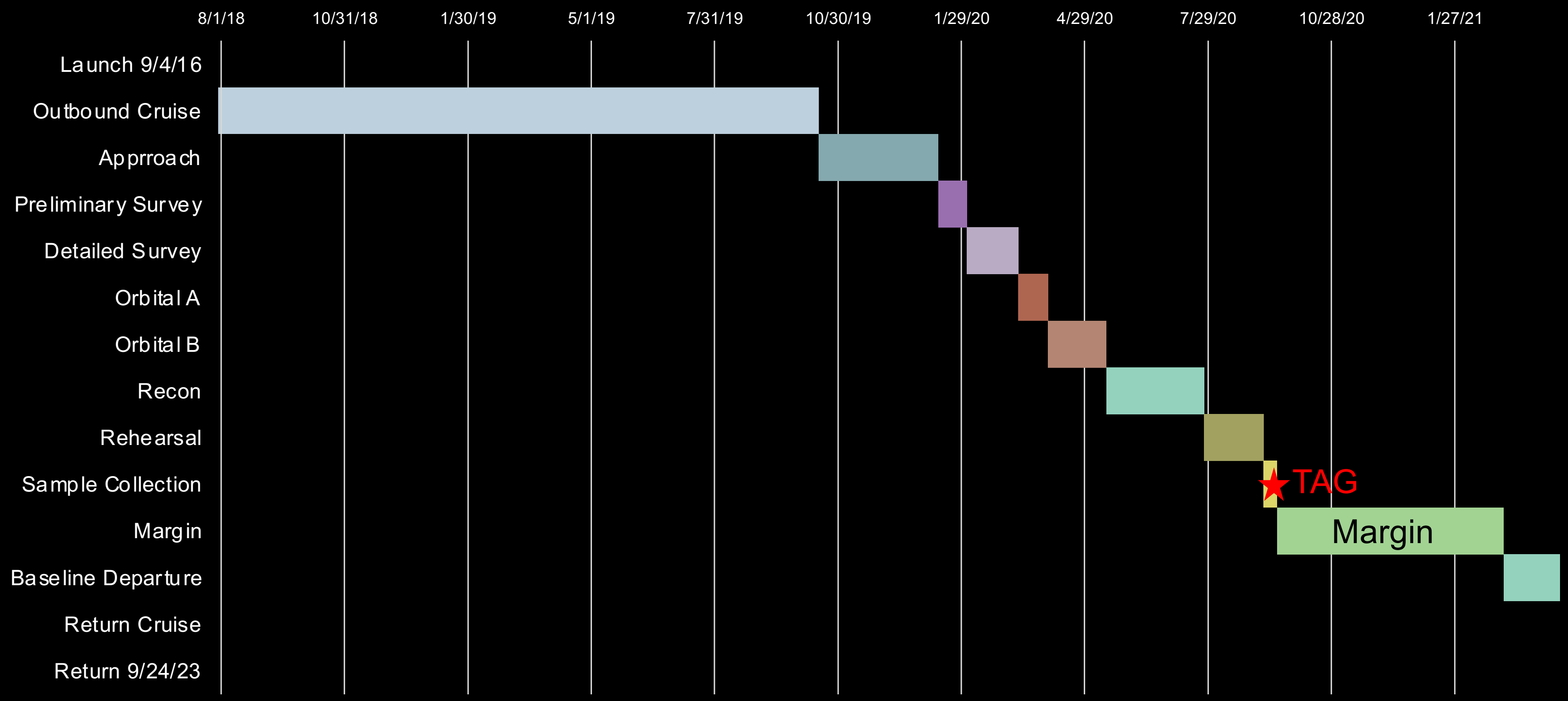
- Proactive planning for major risks and possible descopes
- Avoid analysis paralysis and be willing to make difficult decisions
  - Phase A descope of instrument due to growing costs
  - Almost descoped another instrument because of late funding start and delay in authority to proceed
  - Added backup navigation technique for sample collection (Natural Feature Tracking) in Phase C
    - Backup navigation technique was critical for dealing with the Bennu challenges
    - Addition of NavCam essential for OpNav conops and for particle ejection observing

Proactive risk and strategic reserve management crucial for addressing challenges

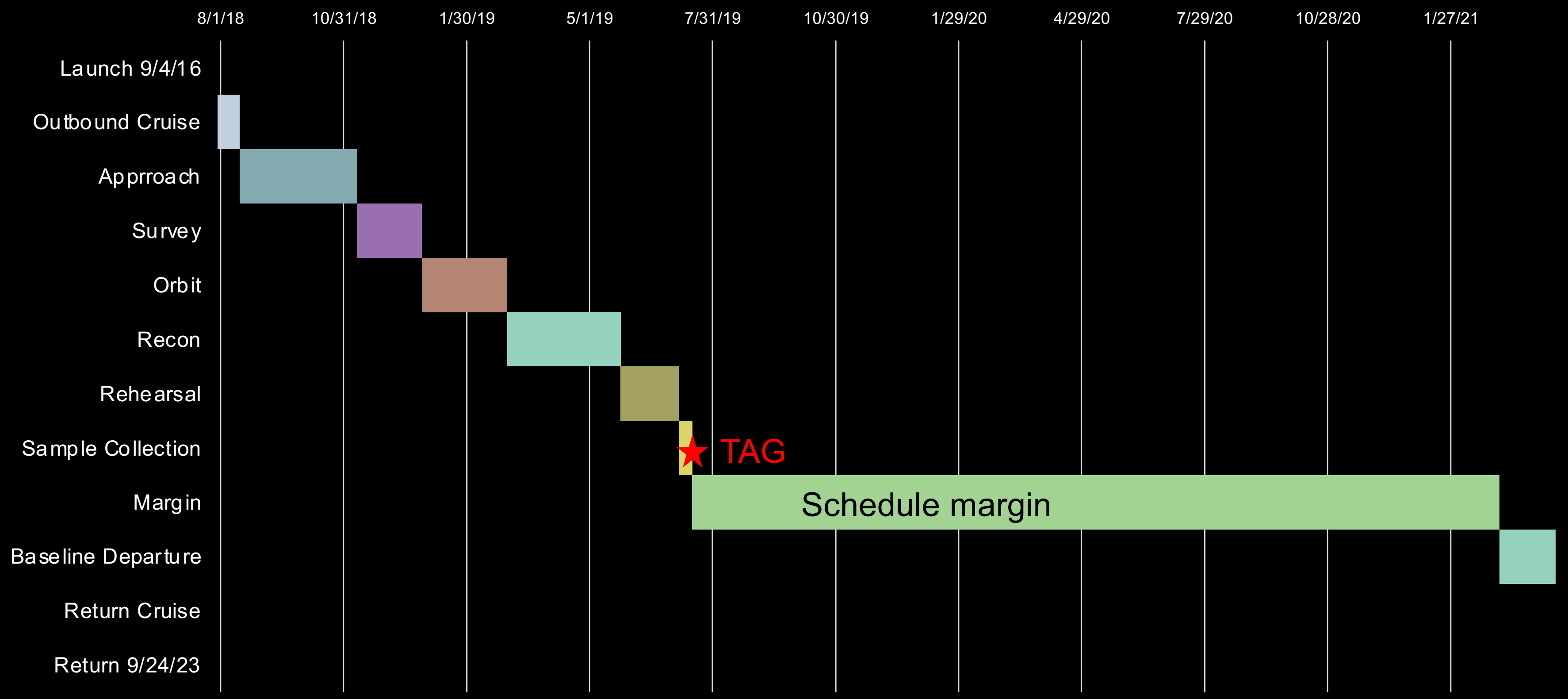
- Mass and schedule margin are key indicators of how the design and build are progressing
  - Strategic management of margin
  - Example of allocation of Proximity Operations schedule margin (following slides)

Margin is the project currency

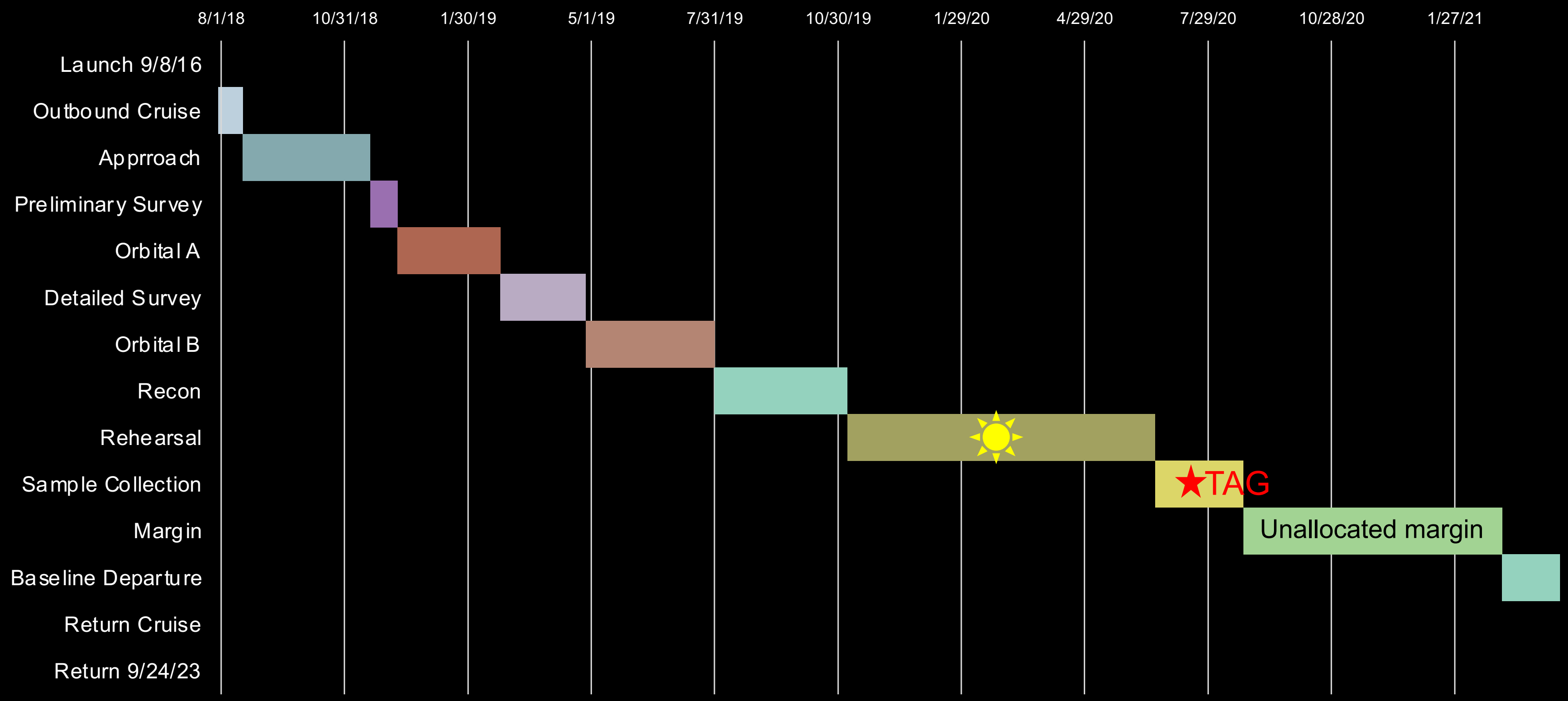
Plan at Proposal, 2011



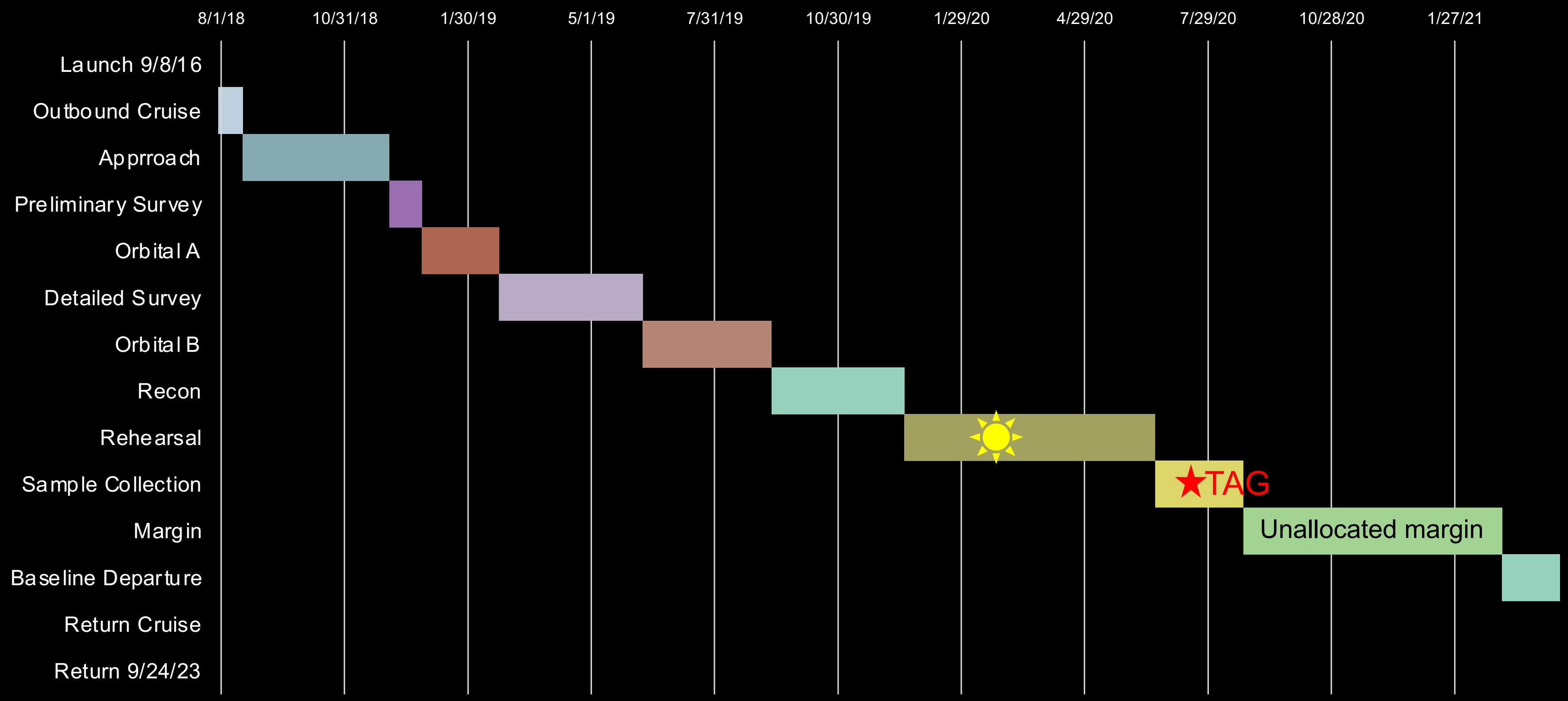
OSIRIS-REx Plan in 2012



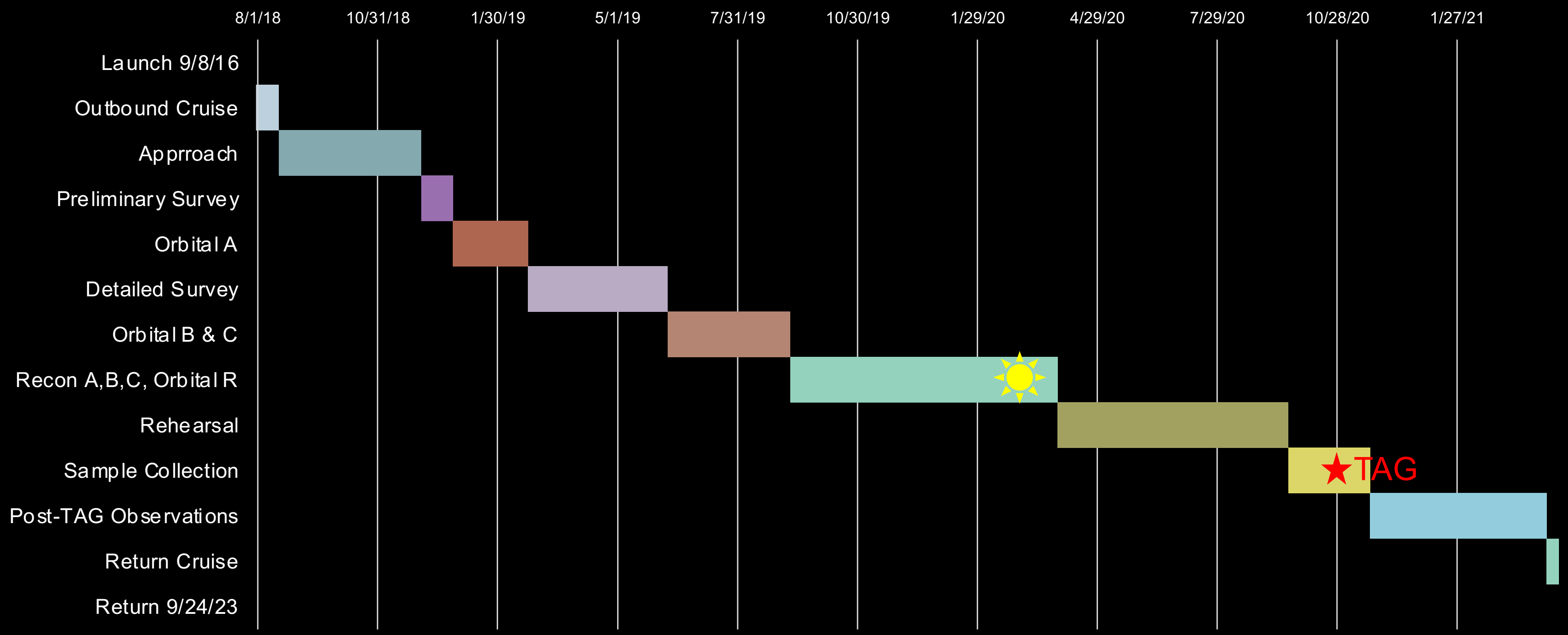
Plan at Launch 2016
Allocation of Margin



Plan at Arrival 2018
Allocation of Margin



Actual


8/1/18
10/31/18
1/30/19
5/1/19
7/31/19
10/30/19
1/29/20
4/29/20
7/29/20
10/28/20
1/27/21
Launch 9/8/16
Outbound Cruise
Apprroach
Preliminary Survey
Orbital A
Detailed Survey
Orbital B & C
Recon A,B,C, Orbital R
Rehearsal
Sample Collection
Post-TAG Observations
Return Cruise
Return 9/24/23
★TAG

Preventing Mission Requirements Creep

Systems Engineering Built into the Project Culture

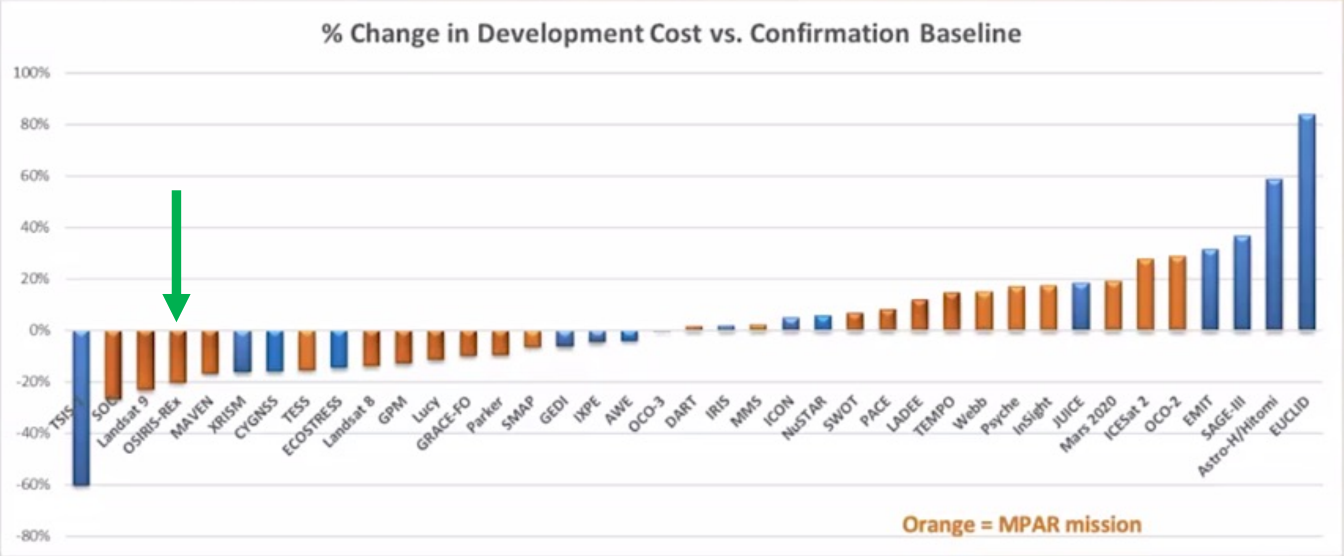
- **Well understood and stable requirements**
  - Focus was on sample collection and return (mission success)
  - Guided development and decision-making throughout project lifecycle
    - All operational mission phases/observations directly tied to science requirements
- Systems engineering during Phase E because of high mission complexity and large number of interfaces (GSFC, UA, LM, Instrument Teams, Nav)
  - Mission Systems Engineer – GSFC
  - Mission Implementation Systems Engineer – UA
- Systems engineering in Phase F – interfacing with all stakeholders (Curation, Mission Sample Scientist, Sample Analysis Team)
  - Not originally in the plan but needed for managing sample analysis test plan, developing sample processing and allocation processes, and interfaces

Thorough cost estimate developed and independently validated

- Clear understanding of the scope of work
- Work Breakdown Structure
- Methods and rationale used for cost estimates
  - Basis of Estimates
  - List of quotes received
  - List and description of analogs
    - Quantify cost savings from heritage
  - Model assumptions & results
- Clear link to the project schedule
  - Identify interdependence
  - Identify margins
- Clearly identify cost risks & mitigations
- Adequate reserves

Independent evaluation increases confidence in cost estimate

Recent Development Cost Performance



Since the establishment of the 70% JCL requirement for major missions in 2009, SMD has confirmed and launched 39 missions

- Including Webb, these missions have overrun their Phase C/D commitments by a net 4.5%
- Excluding Webb, these missions have underrun their Phase C/D budget commitments by a net 0.5%
- 19 of these missions completed development under their cost commitment
- Recently launched missions now included: TEMPO, EUCLID, JUICE, XRISM, Psyche, AWE, PACE

SMD continues to refine its ability to execute missions within cost commitments by implementing improved management techniques (particularly on large strategic missions) and the use of independent review boards and cost estimates, including joint cost and schedule (JCL) estimates.

PI Support Office and Science Team

- **Established PI Support Office**
  - Finances - *Project Planning and Control Officer*
    - Provide insight and oversight to the planning and execution of all OSIRIS-REx project resources
    - Essential for maintaining cost control
  - *Science* - *Mission Instrument Scientist and Science Team Chief*
    - Science observation ConOps, development of Design Reference Mission, evaluate payload capabilities against science requirements
  - *Operations/Systems Engineering* - *Mission Implementation Systems Engineer (Phase E)*
  - Publications - *Chief Editor (Phase E)*
- **Detailed Statements of Work for Science Team**
  - Well understood roles and responsibilities
  - Interdependence between science and engineering required effective communication and interfaces between elements
    - Science provided input to mission design and produced operational products

Long-Term Continuity of Expertise

Team Continuity and a Multi-Generational Team

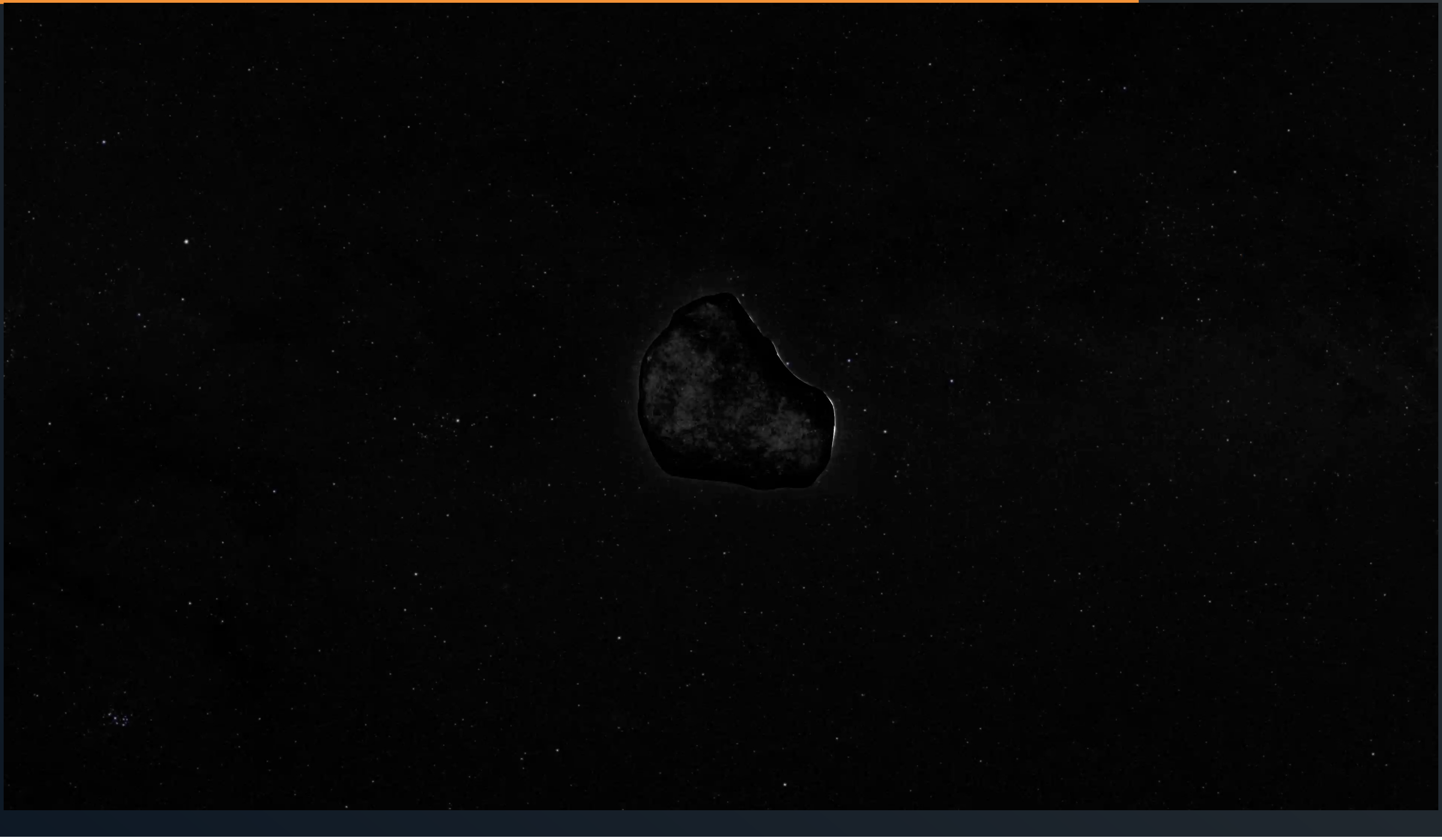
- **Team continuity throughout the mission lifecycle (13+ years)**
  - Phase A into development, with continuity into operations
  - Brought operations team on during ATLO
- **Development of a multi-generational team**
  - Succession plans for critical personnel, even for the PI
  - Example of OSIRIS-APEX PI
- Team dynamics and culture extremely important – PI influence on culture
  - Bringing people together from across multiple institutions and cultures – cultivate project identity
  - Informal team building activities
- In-person time is essential to develop relationships, establish trust, and ensure good communication across the team
  - PI spent significant time at GSFC and HQ in development to facilitate communication with PM and NASA stakeholders
  - Colocation of Navigation and Spacecraft team during operations – effective communication and transfer of information

Summary

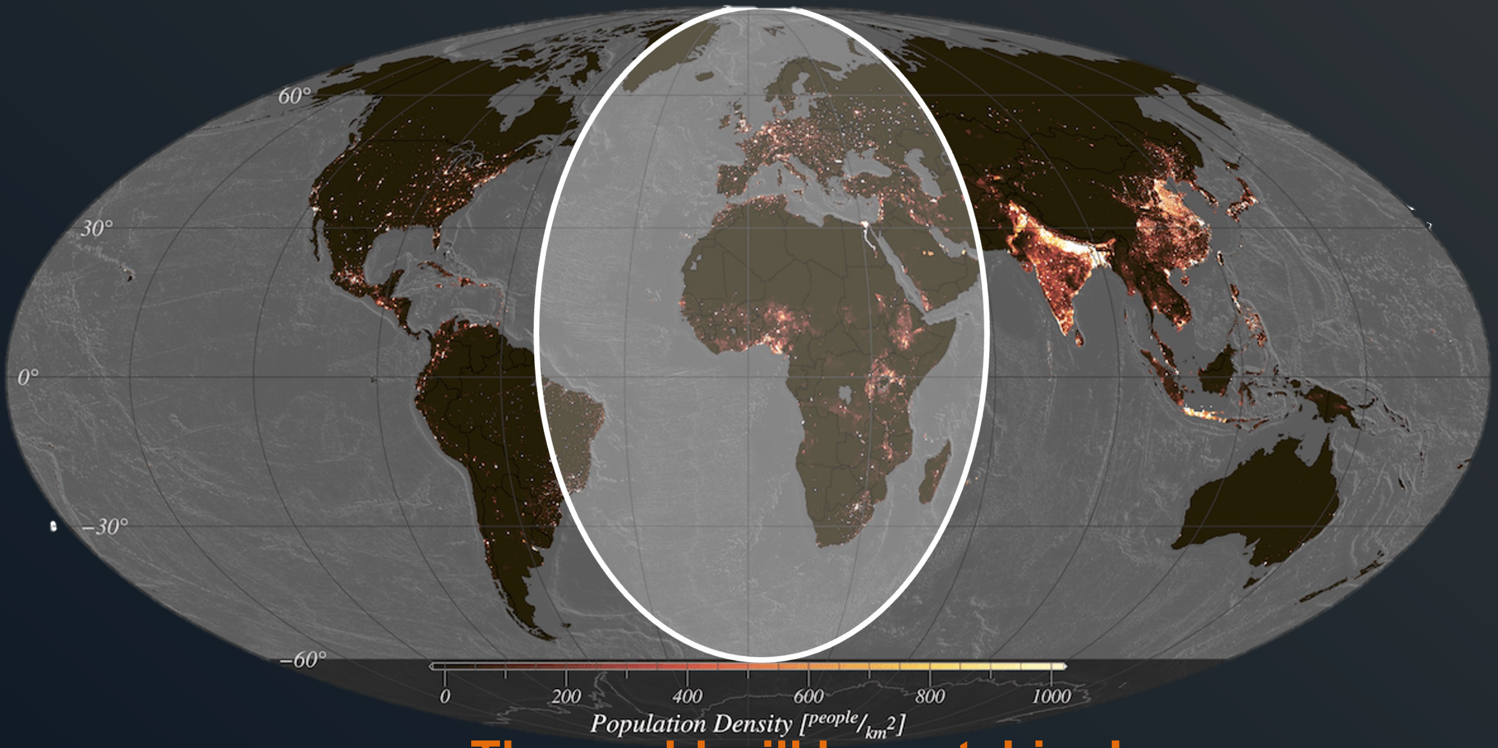
Risk Area	Mitigations
Unique Aspects of a Sample Return Mission	• **Established World Class Navigation Team** • **Developed detailed Design Reference Mission which guides the execution of careful & methodical asteroid operations and sample collection** • Earth-return enveloped by Stardust Capsule and Entry
Preventing Mission Requirements Creep	• Detailed Phase A study completed • **Well understood and stable requirements** • **Thorough cost estimate developed and independently validated** • Incorporating lessons learned into baseline plan • **Established PI Support Office** • **Established detailed SOW's for Science Team** • PI & Management team are committed to deliver
Long-Term Continuity of Expertise	• Organization is optimized for success • Partner organizations are assigned responsibilities aligned with corporate strengths • **Development of a multi-generational team** • **Phase A team provides continuity into Phase B**

APOPHIS AND OSIRIS-APEX FLY BY EARTH
APRIL 13, 2029

OSIRIS-APEX
APOPHIS EXPLORATION MISSION



OSIRIS-APEX
APOPHIS EXPLORATION MISSION

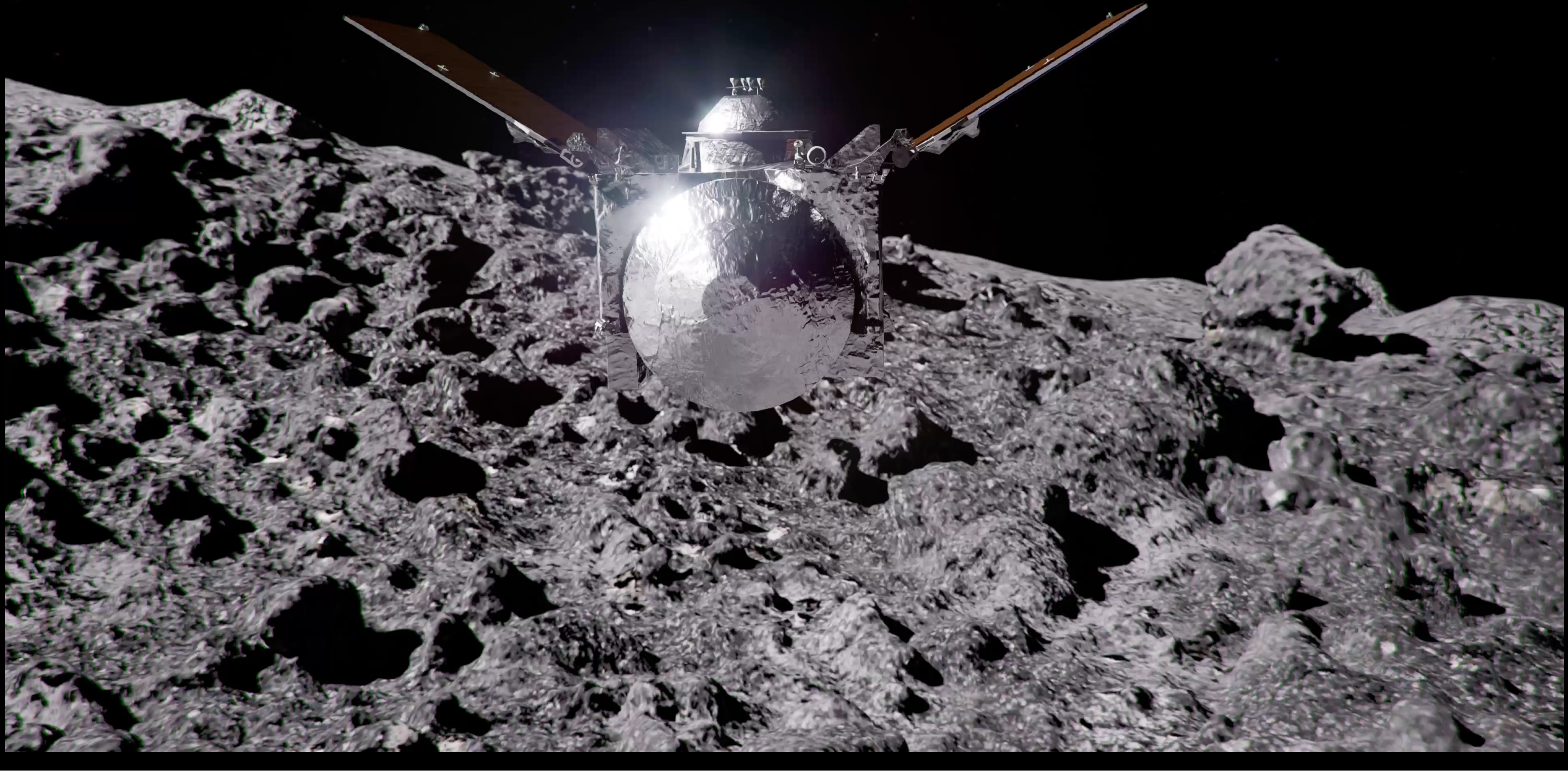


The world will be watching!

Naked-eye visibility: 2 billion people

STIR MANEUVER TO EXCAVATE SURFACE MATERIAL

OSIRIS-APEX
APOPHIS EXPLORATION MISSION



LESSONS LEARNED FROM OSIRIS-REX AS APPLIED TO OSIRIS-APEX

OSIRIS-APEX
APOPHIS EXPLORATION MISSION

- OSIRIS-APEX using lessons learned from operations at Bennu in mission planning
  - Mission phase design for more relaxed operational cadence
  - More autonomy
  - Simplification and streamlining of processes
  - Modular observations for operational flexibility
- Experienced team
  - More thorough understanding of S/C constraints, observation requirements, and navigation performance
  - Considering operations concepts, cadence, and human factors early in design cycle
  - Closely coordinating the navigation, S/C operations, and science planning teams

Conclusions

- OSIRIS-REx was highly successful despite challenges and complexity of the mission. Launched on time and under budget, collected twice the required sample on first attempt, and delivered sample safely to Earth.

- Healthy margins and reserves as well as a rigorous risk management process crucial for addressing challenges

- Remarkable team across all mission elements that was invested in mission success

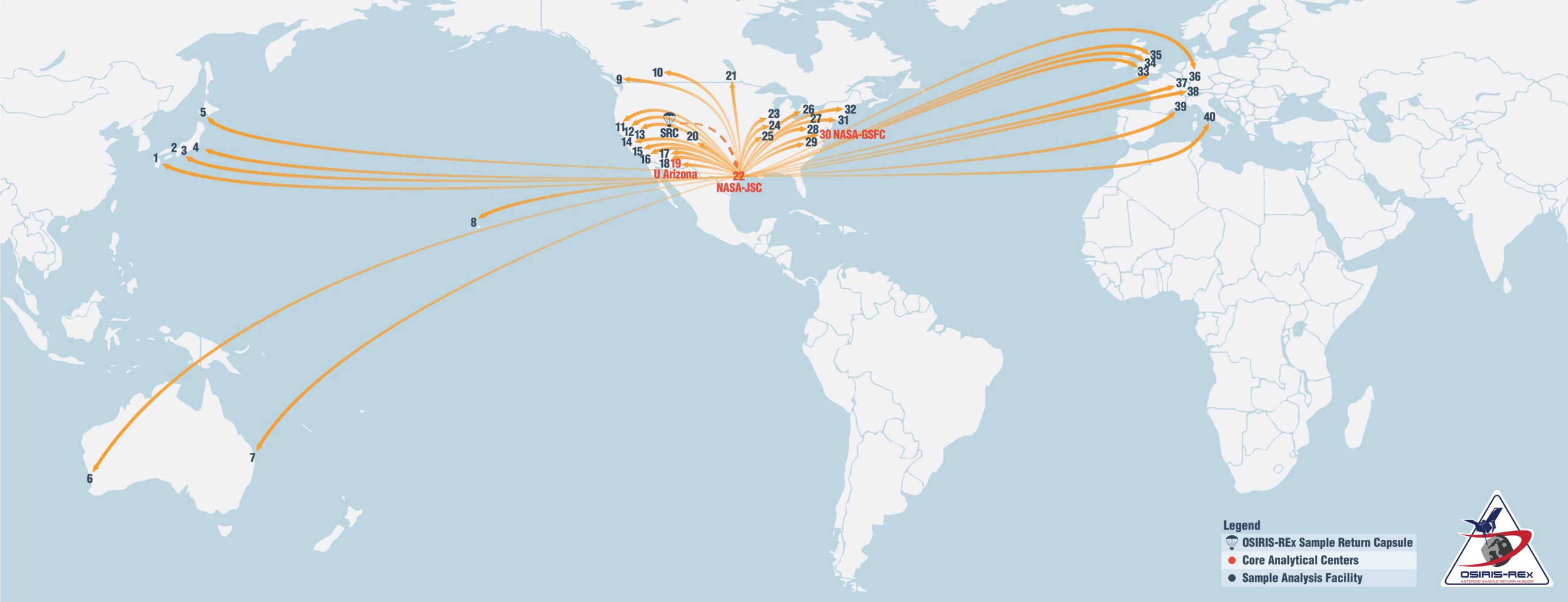
Expect the Unexpected

- Challenges during build and test: The death of the first PI, a Canadian austerity movement, federal shutdown, a fire that destroyed an instrument housing, a blizzard that delayed building a different instrument, a train wreck that destroyed a part of that instrument being delivered, quality control issues with detectors, an explosion next to the rocket and spacecraft

- Challenges during operations: US internet outage that cut off the DSN from S/C operations center prior to orbit insertion, an unexpectedly rocky surface, another federal shutdown, particle ejections, a bomb cyclone, a crucial missed DSN pass, and a global pandemic.

BACKUPS

Locations of Sample Analysis Facilities for the OSIRIS-REx Mission



1 Kyushu University
2 Ritsumeikan University
3 Nagoya University
4 U of Tokyo / JAMSTEC
5 Hokkaido University
6 Curtin University
7 University of Queensland
8 University of Hawaiʻi
9 University of British Columbia
10 University of Calgary
11 Stanford University
12 University of California
13 Lawrence Livermore National Lab
14 NASA-AMES
15 Caltech/JPL
16 University Auxilary and Research Services Corporation
17 Arizona State University
18 Planetary Science Institute
19 University of Arizona
20 Southwest Research Institute
21 University of Winnipeg
22 NASA-JSC
23 Field Museum
24 Purdue University
25 Washington University
26 York University
27 Pennsylvania State University
28 NMNH / CI
29 University of Virginia
30 NASA GSFC
31 Brown University
32 Boston College
33 University of Oxford
34 Natural History Museum
35 Open University
36 Goethe University
37 CRPG
38 ETH Zürich
39 Côte d'Azur Observatory
40 Vatican Observatory

LESSONS LEARNED FROM OSIRIS-REX

- Navigation effort underscoped at beginning of development
  - Solar radiation pressure and S/C thermal re-radiation significantly contribute to trajectory propagation errors
  - Drove requirement for performing operationally complex 24 hour ground in the loop target ephemeris updates
- Targeting complexity led to development of Bennu relative and time relative targeting
  - Flight software patch absolutely critical – eliminated third shift for late updates
- Observation requirements not fully defined during development of the Design Reference Mission
  - Observation constraints and mission plan refined after launch
  - Crucial to use current best estimate navigation performance and update thermal constraints to meet tight constraints
- Addition of NavCam, which was essential for OpNav conops and for particle ejection observing
  - Stellar and landmark OpNav
  - Ability to reuse OpNav target files was critical

LESSONS LEARNED FROM OSIRIS-REX

OSIRIS-APEX
APOPHIS EXPLORATION MISSION

- Science planning/operations effort underscoped
  - Challenges with accounting for navigation uncertainty in observation design
  - Implemented extensive observation sensitivity analysis to test for coverage, observation constraint compliance, operational safe zone, and adequate slew margin.
  - Margin was critical – image overlap, slews, settle time, between sequences.
- Complexity of mission plan, tight operational timeline, and difficulty of recovering missed observation required development of rigorous planning and implementation process and tools to catch issues early in the process
  - Each phase had unique science and operational objectives and had its own operational challenges
  - Implementation of templates and observation envelope for each phase
- Interdependence between science and engineering required effective communication and interfaces between elements
  - Science helped mission design
  - Operational products produced by science team
- Colocation of navigation and S/C team critical to success – effective communication and transfer of information

LESSONS LEARNED AS APPLIED TO APEX

OSIRIS-APEX
APOPHIS EXPLORATION MISSION

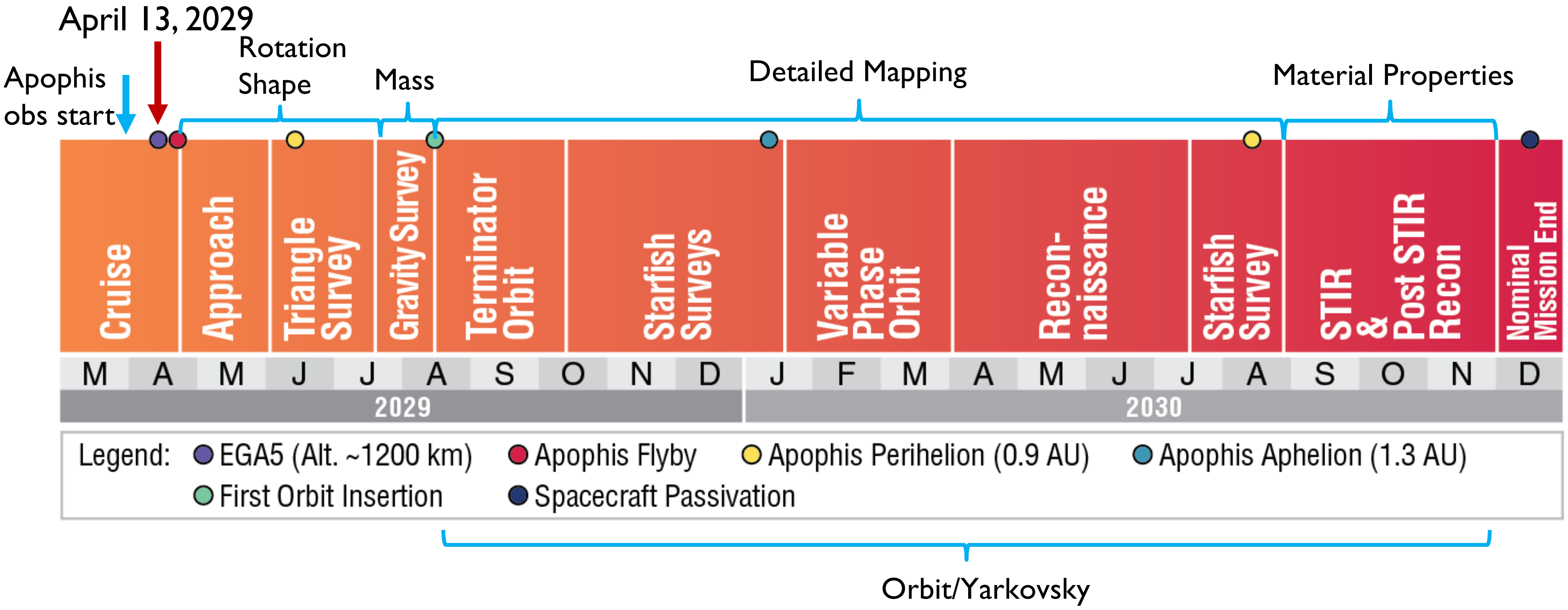
- Experienced team
  - More thorough understanding of S/C constraints, observation requirements, and navigation performance
  - Considering operations concepts, cadence, and human factors early in design cycle
  - Closely coordinating the navigation, S/C operations, and science planning teams
- Trajectories designed to allow more relaxed operational cadence than at Bennu with 1 maneuver per week versus 3-4
- Allocated more time for Approach and initial flybys before orbit insertion for easier cadence of operations and more observations of complex rotational behavior
- Streamlining observation planning and implementation and improved tools
  - Incorporate more of the science planning and spacecraft constraint checking in the trajectory design and optimization software so less iteration required
- Addition of autonomous onboard ephemeris update capability to update instrument targeting for observations
  - Flight software patch will reduce number of two-shift operations

OPERATIONAL FLEXIBILITY FOR APEX

OSIRIS-APEX
APOPHIS EXPLORATION MISSION

- Modular observing modes instead of individually customized observations
  - Non-principal axis rotation and longer period require different strategy
  - APEX will observe at regular intervals every few hours as S/C slowly moves through multiple observing geometries and builds up coverage as Apophis rotates and precesses
    - Similar to OpNav conops at Bennu
- For an object that is not well characterized, be prepared for significant changes to plans
  - Unknowns in how Apophis rotation state will change after Earth encounter
  - The more repetitive and modular the better for fast responses to new information after arrival
  - Close coordination and streamlined processes allow for flexibility to respond to surprises

Proximity Operations Timeline



April 13, 2029

Apophis obs start

Rotation
Shape

Mass

Detailed Mapping

Material Properties

Cruise | Approach | Triangle Survey | Gravity Survey | Terminator Orbit | Starfish Surveys | Variable Phase Orbit | Recon-naissance | Starfish Survey | STIR & Post STIR Recon | Nominal Mission End

M A M J J A S O N D (2029) J F M A M J J A S O N D (2030)

Legend: ● EGA5 (Alt. ~1200 km) ● Apophis Flyby ● Apophis Perihelion (0.9 AU) ● Apophis Aphelion (1.3 AU)
● First Orbit Insertion ● Spacecraft Passivation

Orbit/Yarkovsky