Origins Spectral Interpretation Resource Identification Security-Regolith Explorer (OSIRIS-REx) Project

ANOMALOUS SAMPLING ATTEMPT CONTINGENCY PLAN

Associated with the Design Reference Mission (DRM)

OSIRIS-REx-PLAN-0054

Revision -

April 30, 2015

Goddard Space Flight Center
Greenbelt, Maryland

CM FOREWORD

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In this document, a requirement is identified by "shall," a good practice by "should," permission by "may" or "can," expectation by "will," and descriptive material by "is."

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DOCUMENT CHANGE RECORD

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LIST OF TBDs/TBRs

Item No.	Location	Summary	Ind./Org.	Due Date
1	Section 1.4	`TBD - OSIRIS-REx Data Dictionary document number	Name/ Code	07/15
2	Section 1.4	`TBD - OSIRIS-REx Science Team TAG Reconstruct Plan document number	Name/ Code	07/15
3	Section 2.3.1.2	The scope and capability of these resources is under review (TBR).	Lorenz/ 433	03/15

1.0 Introduction

1.1 Overview

The mission's first attempt to collect a sample will be the first time the flight system will experience the asteroid's gravity field below 25m, and the first time it will interact with the surface. The environment at contact is highly uncertain – the properties and behavior of the regolith in micro-gravity, the behavior of the flight system when the TAGSAM is in contact with the surface and the collection gas fired, and the behavior of the fluidized regolith bed and its interaction with the collection gas. Given this uncertainty, there is a possibility that > 60g of bulk sample will not be collected on the first attempt, so a contingency plan and associated decision-making process are needed to describe how the science and mission operations teams will respond to a variety of plausible scenarios.

1.2 Scenario Description

This contingency plan will define several plausible scenarios that include as common elements 1) the decision to attempt sample collection (i.e. go beyond the termination point of the Matchpoint Rehearsal), and 2) potential flight system interaction with the surface, including surface contact of the TAGSAM head, release of the collection gas after the Matchpoint maneuver, firing the backaway thrusters after the Matchpoint maneuver, and combinations of these.

1.3 Scope

The contingency plan for the TAG sampling attempt will include decision pathways based on scenarios with the common elements described above, and the flight and ground system activities associated with those pathways. This set of decision pathways will also include the scenarios that lead from the threshold Level 1 requirement to return more than 60g of bulk regolith to the mission success criterion to return any amount of sample to Earth based on the answers to the following questions: Was any sample collected? Is the risk of attempting another sample collection unacceptable (due to a problem with the health of the flight system, the environment created by the first sampling attempt, or the exceedance/near-exceedance of flight system safety limits during the first attempt)?

The flight and ground system activities associated with the decision pathways may include processing and analysis of flight system telemetry and remote sensing data to reconstruct the sampling event, collecting additional remote sensing data of the sampled site to characterize the "divot", and ground analysis and testing to reproduce the cause(s) of failure and develop corrective actions for the next attempt. This plan will also lay out the flight operations necessary to set up for a second sampling attempt, including navigation and maneuver design activities to

return the flight system to safe home orbit, observations to conduct a search for new orbiting satellites that may have been liberated by the previous sampling attempt, and repeat of TAG rehearsal and sample collection activities for a different site.

1.4 Applicable Documents

Document Number	**Title**
PLA-OSIRIS-REx-REF-0012	Appendix F to the New Frontiers Program Plan: Program Level Requirements for the OSIRIS-REx Project – Level 1 Requirements
PLA-OSIRIS-REx-RQMT-0001	OSIRIS-REx Mission Requirements Document
PLA-OSIRIS-REx-OPS-0001	Design Reference Mission
PLA-OSIRIS-REx- NFP3-RQ-12-SE-3	OSIRIS-REx Fault Protection Design Document (FPDD)
ORX-SCT-CP-001 to -015	Flight System Contingency Plans
OSIRIS-REx-PLAN-0055	No Viable Sample Sites Contingency Plan
OSIRIS-REx-PLAN-0056	Detection of a Natural Satellite Contingency Plan
OSIRIS-REx-PLAN-0057	Detection of a Dust Plume Contingency Plan
TBD	OSIRIS-REx Data Dictionary
TBD	Science Team TAG Reconstruct Plan

2.0 Actions

2.1 Overview

Figures 1 – 3 below show the sequence of steps and decisions the ground team will step through in response to a contingency for the sampling attempt. The key question after the first sampling attempt is "was sample collected?" Returning any amount of sample to Earth achieves mission success, so in the event that some quantity of sample is successfully collected, the team needs to carefully weigh the risks of returning to the surface to collect more and potentially losing the sample already in hand. This risk assessment will involve assessing the health of the spacecraft to safely perform a second attempt and return the sample to Earth, the dynamics and performance of the spacecraft during the first attempt, and the dust and/or satellite environment created by that attempt that could put a return to orbit at risk. Table 2-1 provides the success criteria and explanation for each decision point in the subsequent flow charts.

If no sample was collected on the first attempt, then the team will both initiate the operations to return the spacecraft to the asteroid and work to understand what went wrong the first time and what needs to be done differently the second time. A key question in this decision path is "did the spacecraft interact with the surface?" If not, then the team focuses on the spacecraft performance/behavior as the cause and can initiate a repeat attempt at the prime sample site. If some kind of interaction did occur – TAGSAM surface contact, GN_2 release, backaway thruster plume impingement – then the team needs to understand the properties and behavior of the surface from remote sensing data and spacecraft telemetry to a) determine why sampling was not successful, b) determine what will be done differently the second time, and c) estimate the contamination of the prime site to decide whether or not the second attempt needs to be at the backup site.

At several places in the decision tree other contingency plans are invoked to turn a "no" into a "yes" outcome. For example, if an orbiting satellite is produced by the first TAG attempt, the Natural Satellite Detection contingency plan will be used to plan and execute the operations needed to determine the satellite's orbit and plan the spacecraft trajectories to avoid it.

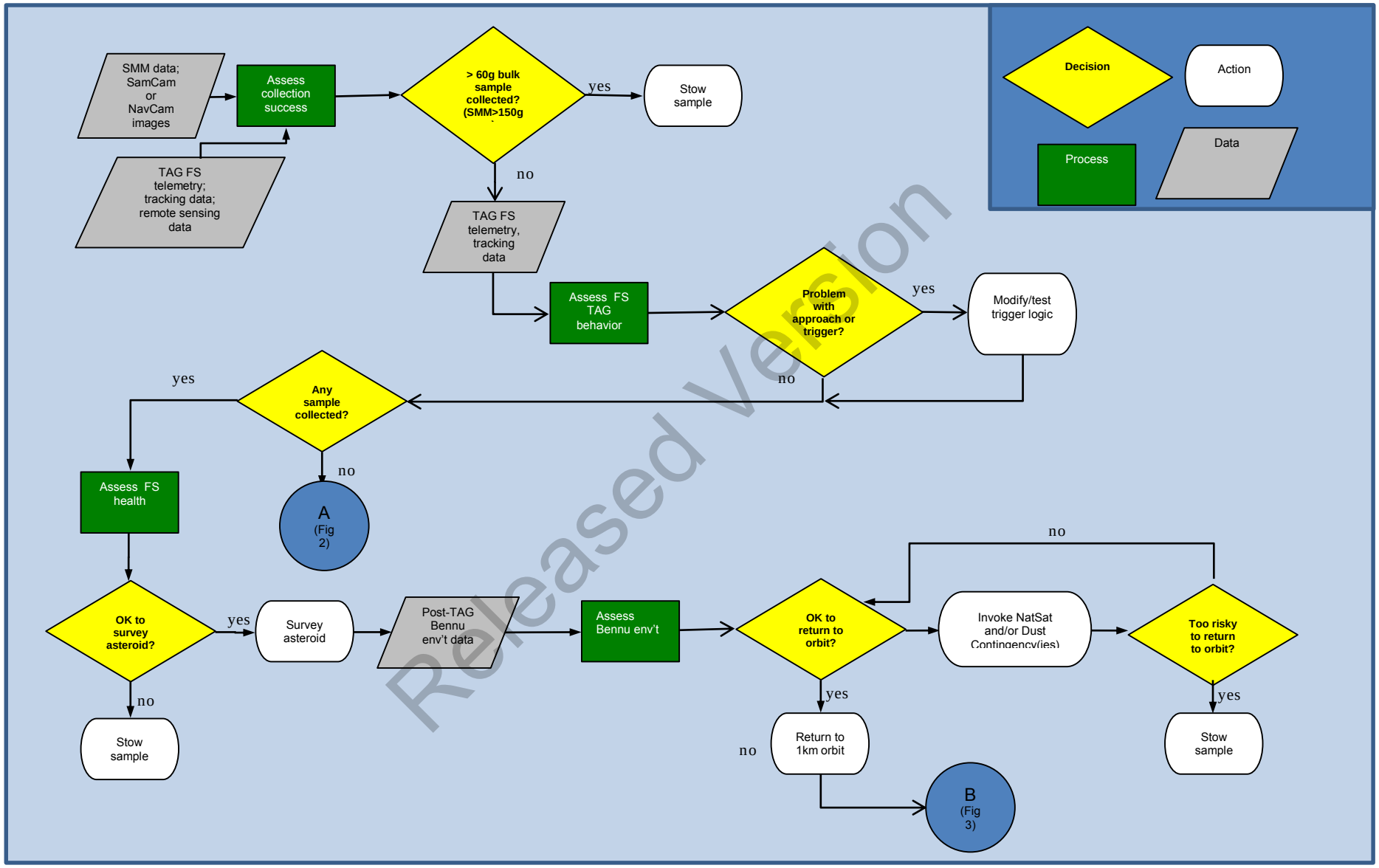

Figure 1: Decision Tree < 60g sample collected

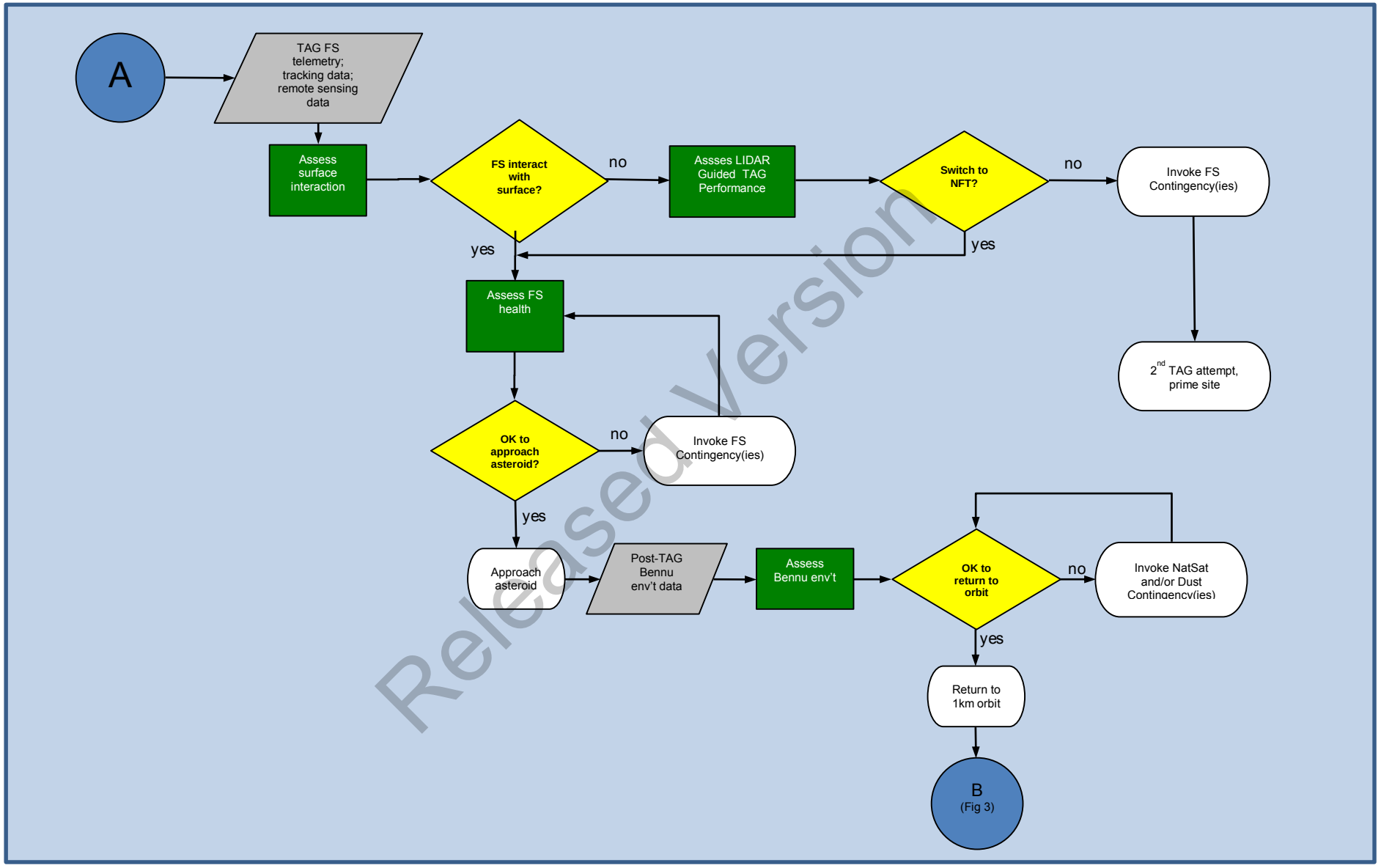

Figure 2: Decision Tree -- no detectable sample

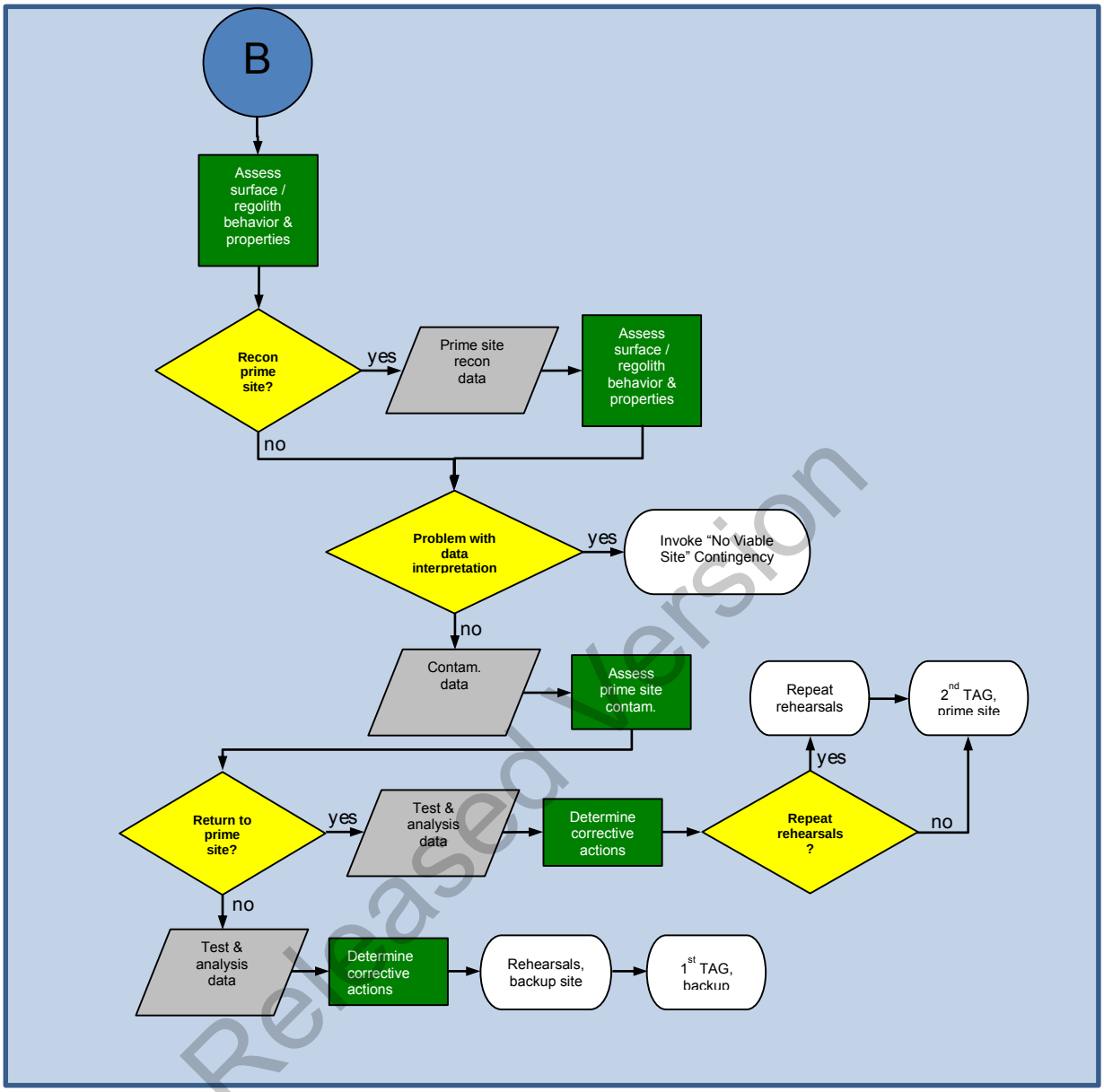

Figure 3: Decision Tree – Return to Prime Site or go to backup

Decision Point	Criteria	Comment
> 60g bulk sample collected?	Sample Mass Measurement indicates that collected mass minus the measurement uncertainty is greater than 60g	Per CDR analysis, the CBE of SMM performance shows we must measure greater than 84g collected to be confident we have met the 60g mission requirement with measurement uncertainty accounted for.

Decision Point	Criteria	Comment
Problem with Approach or Trigger	Determine if the inability to retrieve sufficient sample was caused by: 1. Contact with asteroid before TOT window 2. TOT window closed before contact 3. Failure of contact triggers 4. Trigger latency too long or too short	There are a number of very low probability issues that could cause a sampling anomaly due to sampling logic or HW failure. Reconstruction of the event should reveal a solution to the problem and the logic can be properly 're-tuned'.
Any Sample collected	SMM indicates greater than uncertainty collected OR SAMCAM pictures indicate sample collected in SAMCAM head or on sample pads. OR NAVCAM/SAMCAM indicates TAGSAM head made contact with asteroid	
OK to Survey Asteroid	No -critical hardware (both prime and redundant) damaged by first TAG attempt AND Flight system did not exceed design cases during contact AND One lidar or one NavCam performs within specification	
OK to return to orbit (two places)	Thermal and physical hazards (dust plumes and natural satellites) do not present risk to spacecraft at 1km orbit	New hazards may have been generated as a result of the spacecraft interacting with the asteroid by either direct physical contact or thruster plumes
Too risky to return to orbit	Review of Natural Satellite and Dust Plume Contingency plans indicate that it is too risky to return to orbit	Clear indication should be provided from existing contingency plans. These should also have been invoked prior to the initial sampling attempt.
FS interact with asteroid	NAVCAM indicates TAGSAM head made contact with asteroid	Clear indication of physical contact must be observed. False activation of TAG triggers is not sufficient.

Decision Point	Criteria	Comment
Switch to NFT	Performance analysis indicates that LIDAR guided TAG SW or HW is responsible for the lack of asteroid interaction AND The problem with LIDAR guided TAG cannot be reliably corrected	
OK to approach asteroid	Are there any obstacles to approaching the asteroid that have developed: - Natural satellites - Dust Plumes	New hazards may have been generated as a result of the spacecraft interacting with the asteroid by either direct physical contact or thruster plumes.
Recon Prime site	Does the Post processed data indicate that the prime site may have been disturbed during the anomalous sampling attempt	Keep in mind that if the rehearsals are to be repeated, the CP rehearsal may serve the same purpose as recon.
Problem with data interpretation	Is there an incompatibility between the data obtained during prox ops and the actual surface properties of the asteroid as determined from the sampling attempt? - Does not contain unexpected hazards - Surface contains sampleable material	
Return to prime site	Does TAG reconstruction data and/or recon data indicate that the prime site was not contaminated by anomalous TAG attempt	Review image data for signs of severe scouring or disturbance by thrusters
Repeat rehearsals	Is it necessary to repeat rehearsals: - Switching to NFT guidance - Change of approach corridor - Change of sensor configuration	

Table 2-1 Decision Criteria

2.2 Sampling Event Reconstruction

2.2.1 Available Reconstruction Data

- Remote sensing data for FDS to perform trajectory reconstruction and science team to understand regolith response (Figure 4):

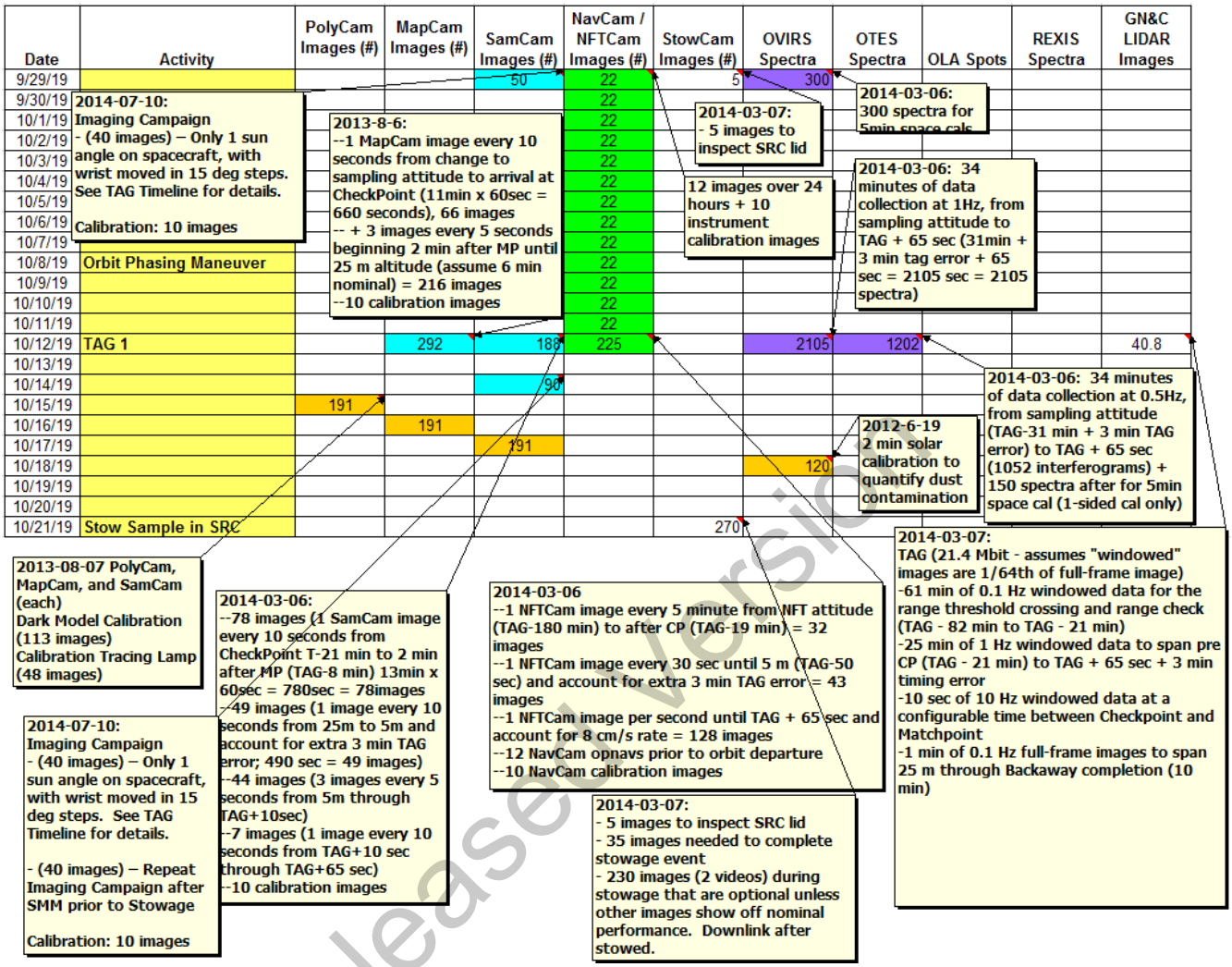

Figure 4: Observations during the Sample Collection phase include MapCam and SamCam (blue) imaging of the sampling event and the TAGSAM Head post-sampling, NavCam optical navigation imaging (green) and OVIRS and OTES spectral data (purple); OVIRS, OCAMS solar calibration (orange), and GN&C lidar data (no color)

- GN&C subsystem telemetry:
  - 200Hz IMU data (gyro & accelerometers)
  - S/C filtered attitude
  - S/C filtered angular rates
  - S/C filtered translational accelerations
  - ACS Thruster accumulated on-times
  - Reaction wheel telemetry
  - LIDAR images
  - Range measurements going into GN&C algorithms (i.e. single range value based on subwindows)

    - Processed range/rate estimate from GN&C
    - Time of touch estimate(s) from GN&C
- REPM telemetry (Fault Protection subsystem):
    - Pogo trigger info
    - Accelerometer trigger info
    - Trigger logic outputs
- Temperature sensor data
- Potentiometer angles (TAGSAM, SATAG)
- All subsystem health data (Prop, Comm, GN&C, EPS, Thermal, FSW, etc.)
- EVRs, Fault History Table (see FPDD) and command history
- Doppler / Ranging data from DSN
- Pressure data from GN_2 bottles
- Sample Mass Measurement & TAGSAM head imaging data (SamCam)

More detailed descriptions of individual data types can be found in the OSIRIS-REx Data Dictionary document. (A non-controlled description of the data can be found in "Spacecraft Telemetry Stream for Touch and Go (TAG)", Rev. 1 (11-14-2013), available on the Science Team Wiki.)

2.2.2 Surface / Regolith Behavior and Properties

The science team will use data processed through the SPOC to constrain the surface response to the spacecraft. It will rely on post-TAG data products derived from the following: (1) TAG Telemetry Report from the TAG event that include data from TAGSAM, IMU, & Telecom. (2) Imagery/Movie from SamCam, (3) Trajectory Reconstruction based on the NFTCam imagery and the radio tracking data, (4) Sample Mass Measurement Report, (5) Post-TAG NFTCam and GNC LIDAR Imaging Report.

The science team TAG reconstruction effort will also use a prepared atlas of modeling results, both numerical and laboratory TAG sampling tests. Numerical modeling will be calibrated to the TAGSAM Testbed Campaign, and then provide explorations of a larger parameter space, including significant tests in Bennu-gravity. This modeling atlas compared with the post-TAG data products will be used to reconstruct the specific behavior of the asteroid during its interaction with the spacecraft, as well as directly inspect the behavior of the TAG site on the asteroid. Due to the short turnaround for the Science Team TAG Reconstruct Report, most of the numerical and laboratory modeling will be done in advance.

The output of this data product will be an estimate of the asteroid's response to the spacecraft delivered via estimates for the area of asteroid contacted, the volume of the surface mobilized, the near-surface properties of the contacted regolith (compliance/compression, cohesion, surface induration), as well as modeled trajectories and size distribution for backscattered objects. The output will be simple ASCII data files output in standard CGS units to describe various properties of the asteroid surface properties (cohesion, surface induration, sub-surface large

particles) and estimated outcomes of the TAG event (total surface area contacted, total volume mobilized, estimated collected sample mass).

2.2.3 Flight System Behavior / Changes

Each spacecraft subsystem will plot data showing performance and also compare to previous trending to show areas of interest or anomalies. For example, if a drop of telecom gain is noticed after TAG, it may be an indication that dust accumulated or damage occurred on the antenna. The subsystem analyses are a routine event to determine how the spacecraft performed during any event of interest, and no special tools are procedures are needed. Other key subsystems to note that will be analyzed include:

- Thermal: temperature sensor evaluations
- Power: battery state-of-charge; solar array current (*Note: need to understand errors from potentiometers locating the positions of the solar arrays before / after TAG)*
- GN&C: attitude, rates, accelerations, LIDAR ranges, time-of-touch estimate, etc
- Fault Protection: Rendezvous Performance Monitor (REPM) status of triggers
- FSW: Diagnostics, EVRs, FHT, command history
- Mechanisms: potentiometers (*Note: need to understand errors from potentiometers locating the positions of the solar arrays before / after TAG*)
- Number of Pogo microswitch contact indications
- Propulsion: gas bottle pressure

In addition to evaluating the overall spacecraft health and safety post-TAG the reconstructed spacecraft orbit & attitude will be loaded into STK to visualize the TAG event. FDS will perform orbit reconstruction using NavCam imagery (and possibly LIDAR images, MapCam, and SamCam data as well). (*Note: It may take several days after TAG before NavCam data will be available.*) High rate IMU data will be recorded during the contact event and available for downlink. GN&C can perform attitude reconstruction based on telemetry. Images from all sensors will be played back, and can be viewed alongside an STK video to provide situational awareness for the images. The above reconstruction activities should be in a mature enough state to start making path forward decisions within three days after TAG.

From this reconstruction, the flight team will look for any anomalous situations that may have caused an anomalous TAG (such as IMU acceleration spikes when not expected, or discovering from images and STK that a large rock potentially caused an early trigger before TAGSAM was fully seated on the surface). There are numerous possibilities for what could have caused a anomalous TAG, so gathering the analysis and looking for obvious culprits would be performed quickly. A more extensive root-cause analysis may be necessary to completely define the reconstruction and determine what caused the anomalous TAG.

Before proceeding with a second TAG, a full spacecraft assessment will be necessary to determine the risk of a second TAG as well as the risk of being able to perform Sample Return. The steps to be performed are as follows:

1. Assess any hardware degradation due to TAG #1, with the main concern related to

dust/regolith during contact. If hardware was impacted at all during TAG #1, the project would need to determine if additional impact from TAG #2 could cause more severe damage and prevent sample return.
    - Power: Solar arrays
    - Telecomm: antennas (signal strength)
    - GN&C/attitude knowledge: Star Trackers, Sun Sensors
    - GN&C/thrusters: possible thrust level test to see if performance is degraded
    - Thermal: blankets, radiators, temperature sensor overall checkout
    - Images: StowCam images of payload deck, especially SRC. SamCam images of sampler head to see if any damage or jamming of the pogo.
2. Assess any secondary hardware that could be required for sample return that was not evaluated in step 1.
    - Star Tracker #2 – if this was damaged due to TAG #1, the project may decide to skip TAG #2
3. Assess science instruments used during TAG to determine if they can be used for TAG #2. If a sensor is not working, a full understanding of what happened to it should be performed to assess the risk of TAG #2 and potential impacts to other hardware critical for sample return.
4. If primary hardware for TAG is in good condition, the project can go forward with planning TAG #2. Evaluate backup sensors specific for TAG to know if any damage from the first TAG attempt was sustained. This provides information about the environment and the likelihood of sustaining damage on try #2.
    - LIDAR #2
    - NavCams for NFT

The above assessment provides the flight team with knowledge of the ability and risk to perform a second TAG.

2.3 Impact to Operations

2.3.1 Determining Corrective Actions

Upon confirmation the spacecraft is healthy and safe; the focus will be to determine the reason for the anomalous sample attempt. A Tiger Team will be stood-up with the Project's TAG Phase Lead as the chairperson. This person will assemble the necessary expertise from on-project staff as well as reaching out to non-project resources.

The Tiger Team will perform a "fish-bone" analysis to provide further direction into finding the root cause. The TAG Fault Tree will be an excellent starting for the "fish-bone" analysis.

Once the Tiger Team has determined the reason, or most plausible reason, the operations will then take the necessary actions to incorporate the finding into the next attempt.

2.3.1.1 TAG Parameters Adjustable in Flight

- Trigger detection settings
    - accelerometer threshold & persistence

  - pogo persistence
  - window for time-of-touch enable
- Sequence timing for GN_2 release & back-away burn
- GN&C LIDAR gain settings for better time-of-touch prediction
- GN&C controller parameters
- Contact velocity

2.3.1.2 Ground Analyses and Tests

Science Processing & Operations Center (SPOC)

The science team will use the modeling tools prepared for the Science Team TAG Reconstruct effort in order to inform corrective actions for the 2nd TAG attempt. These tools rely on the numerical modeling of the asteroid's surface response to the Spacecraft combined with the data collected by the science payloads and spacecraft telemetry during the 1st TAG attempt. The details and algorithms guiding these efforts will be explained in the Science Team TAG Reconstruct Plan, under the supervision of the Regolith Development Working Group.

If the spacecraft behaved nominally and the asteroid responded outside of nominal expectations as derived by the Science Team's map products (Safety, Deliverability, Sampleability and Science Value), then the tools developed for the Science Team TAG Reconstruct Plan will be used to determine the flaw in the map products. The data collected during the TAG Rehearsal and 1st TAG attempt will provide the detailed description of the asteroid surface properties that will be used to re-calibrate the original map products. These map products will then be re-processed for the entire asteroid by the Science Team, and the sample site selection process can be re-started. The numerical modeling tools and laboratory characterization testbeds will be mobilized to explore new modeling parameter space, or to re-examine conditions with new understandings of asteroid behavior. These efforts can likely explore 10's of test cases under the proposed schedules for the 2nd TAG attempt.

Mission Support Area (MSA)

In Phase E, the spacecraft command sequences will be tested using SoftSim terminals and Spacecraft Test Lab (STL) racks. There will be two STLs for OSIRIS-REx, which are scheduled to be on-line by September 2014. The STLs include flight-like C&DH electronics and software models for all other spacecraft components. During Phase E, one STL will be used for command stack testing, but the second STL will be available for anomaly resolution and TAG sequence testing in case of a anomalous sampling attempt. In addition, there will be several SoftSim terminals available in Phase E for command stack testing. The ADAMS dynamics analysis tool is also planned to be available in Phase E to support TAG analysis. This model can be updated to better understand the surface contact dynamics based on reconstruction data in the event of an anomalous sampling attempt. The model has a relatively long run time (each individual contact simulation takes approximately 10 minutes or more to run), and as such the number of simulations this tool can perform is limited.

All verification analyses and reports performed during Phase C/D will also be available during Phase E. These analyses will be re-visited prior to the first sampling attempt to ensure their

validity when compared to the current spacecraft performance. Flight-like versions of TAG related hardware such as the TAGSAM and LIDAR will be available in Phase E for further testing if necessary. If these components are suspected as the cause of the anomalous sampling attempt, they can be interfaced to the STL for testing with a flight-like C&DH. The scope and capability of these resources is under review (TBR).

Freespace (GSFC)

The Freespace is a high-performance simulation environment that enables modeling and analysis of the interaction of extra-terrestrial objects (e.g. spacecraft). It has a computationally efficient numeric engine, which enables high-resolution graphical interface. Due to its ability to capture complex multi-body dynamics, it has been used on GPM, MMS, LRO, RESTOR, and many others. With every mission, Freespace has been expanded to accommodate needed dynamics (ie slosh, wire dynamics, rate tracing…). For the OSIRIS-Rex mission, contact dynamics, sliders mechanism dynamics and several others are being added to the modeling capabilities of Freespace.

The OSIRIS-Rex Freespace simulation provides an independent assessment of the TAG maneuver. Freespace, a multi-body, orbit/attitude dynamics simulator with slosh interface, will bridge the gap between the ACS Simulink rigid body attitude dynamics and the Adams multi-body dynamics to provide an integrated analysis. These attributes also allow for high-fidelity contingency analysis. In the event of an anomalous TAG maneuver, the engineers will utilize the data from this anomaly to recreate the maneuver in Freespace to determine the root cause and the appropriate mitigation strategies. These strategies can be verified over a wide range of initial conditions and configurations using the Monte Carlo component of Freespace. The visualization component of Freespace can also be utilized to aid engineers in checking instrument FOV and phase angle during the TAG approach and evaluate the NFT performance. The visualization tool can also be used to observe unintuitive dynamics during TAG.

In summary, Freespace can be used to model the TAG attempt, verify mitigation scenarios and test new TAG maneuvers quickly and accurately, while providing scientist and systems engineers with a visual understanding of the maneuver. This visualization can be used in the safety assessment and decision to make another TAG attempt.

2.3.2 Operations Concept for a Second Attempt

The timeline below represents one scenario for performing a second TAG, involving a repeat of a subset of asteroid operations leading up to TAG #1:

- 14 days: Re-acquire Bennu from > 20km; orbit determination and maneuver design process
- 7 days: Approach Bennu; characterize operations environment (dust, satellites)
- 13 days: Return to 1km Safe Home Orbit
- 14 days: Characterize "divot" at 1st TAG site with a Recon-like flyover (if needed)
- 42 days: Repeat TAG Rehearsal Phase (if needed for second TAG site)
- 23 days: Repeat Sample Collection Phase

Figure 5 shows how nominal and 2nd TAG timelines overlap.

Note that the TAG reconstruction and corrective action determination activities described above occur in parallel with the activities in this timeline. If these troubleshooting activities are not completed at some point during the repeat of the TAG rehearsals, additional time will be needed to complete the TAG #2 timeline.

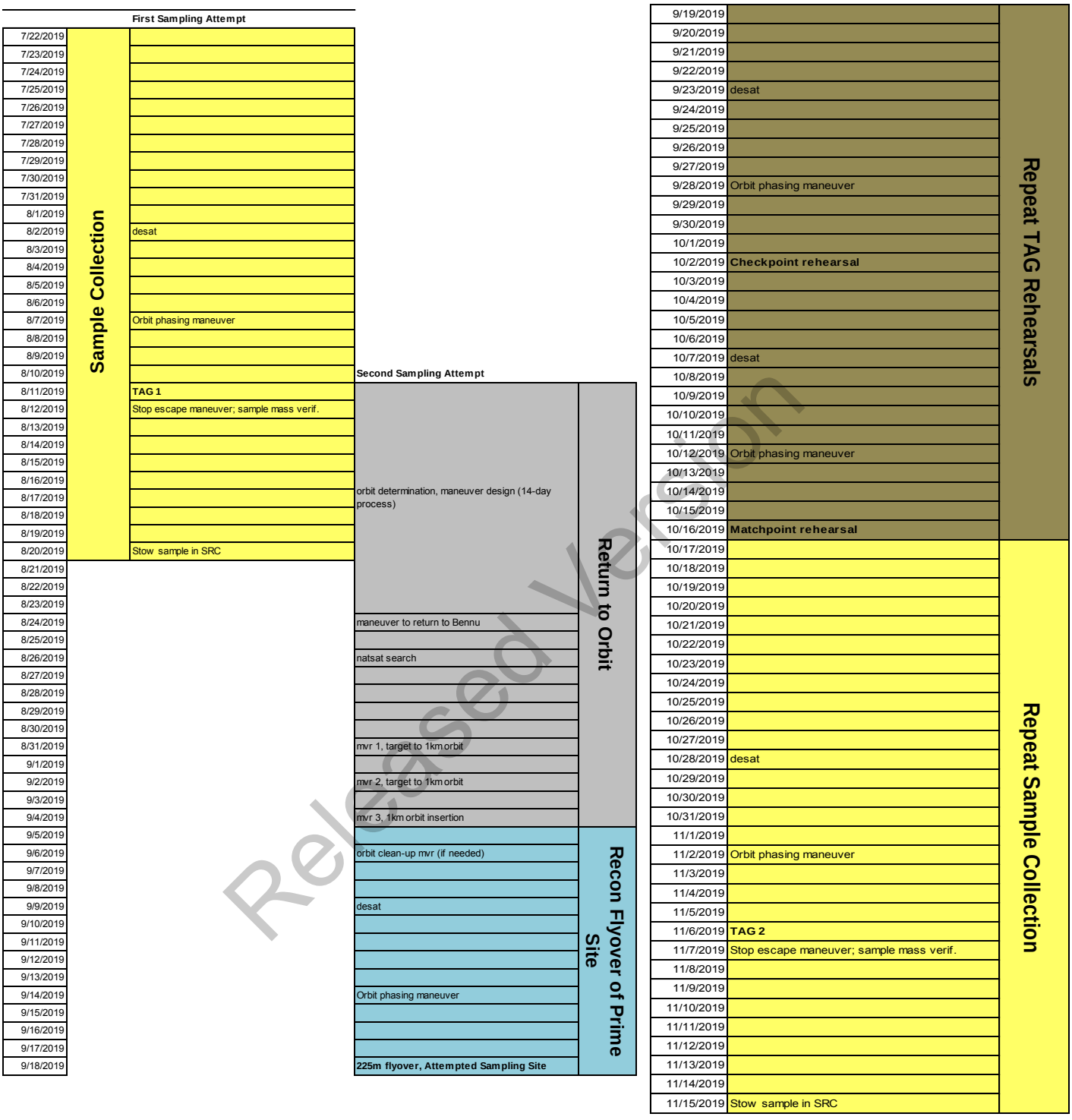

Figure 5: Second sampling timeline (includes time for optional rehearsals)

APPENDIX A: ACRONYMS

ACS – Attitude Control System

ADAMS – Automatic Dynamic Analysis of Mechanical Systems

C&DH – Command & Data Handling

CCM – Camera Control Module

CGS – Centimeter/Gram/Seconds

CM – Configuration Management

CMO - Configuration Management Office

DRM - Design Reference Mission

DSN – Deep Space Network

DVR – Digital Video Recorder

EPS – Electrical Power System

FDS – Flight Dynamics

FHT – Fault History Table

FPDD – Fault Protection Design Document

FS – Flight Segment

FSW - Flight SoftWare

GN2 – gaseous nitrogen

GN&C – Guidance, Navigation, and Control

GSFC – Goddard Space Flight Center

GPM – Global Precipitation Measurement

HGA – High Gain Antenna

Hz - Hertz

ICD – Interface Control Document

IMU – Inertial Measurement Unit

LGA – Low Gain Antenna

LIDAR – Light Detection and Ranging

LM – Lockheed Martin

LRO – Lunar Reconnaissance Orbiter

LTR – Low Thrust REA (REA – Rocket Engine Assembly)

MGA – Medium Gain Antenna

MMS – Magnetic Multi-Scale project

MOI – Moment of Inertia

MSA – Mission Support Area

NASA – National Aeronautics and Space Administration

NFT – Natural Feature Tracking

NPD – NASA Policy Directive

NPR – NASA Procedural Requirement

OCAMS – OSIRIS-REx Camera Suite

OLA – OSIRIS REx Laser Altimeter

OSIRIS-REx – Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer

OTES – OSIRIS REx Thermal Emission Spectrometer

OVIRS – OSIRIS REx Visible and Infrared Spectrometer

PI – Principal Investigator

REPM – REndezvous Performance Monitor

RESTOR – Reusable Earth Synchronous Tele-Operated Refueler

REXIS – Regolith X-Ray Imaging Spectrometer

RWA – Reaction Wheel Assembly

SATAG – Solar Array Two Axis Gimbal

SMM – Sample Mass Measurement

SPE – Sun-Probe-Earth

SPOC – Science Processing and Operations Center

SRC – Sample Return Capsule

STK – Satellite Tool Kit

STL – Spacecraft Test Lab

TAG – Touch-and-Go

TAGSAM – Touch and Go Sample Acquisition Mechanism

TBD – To Be Determined

TBR – To Be Reviewed

TCM – Trajectory Correction Maneuver

UA – University of Arizona