OSIRIS REx SPOC
Engineering Peer Review

OSIRIS-REx™
ASTEROID SAMPLE RETURN MISSION

Safety Map

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Agenda

- Overview
- Safety drivers to input products
- Safety Map Requirements
- Map production process and flow
- Status
- Minimal mission scenario
- Contingency considerations
- Summary & work to go

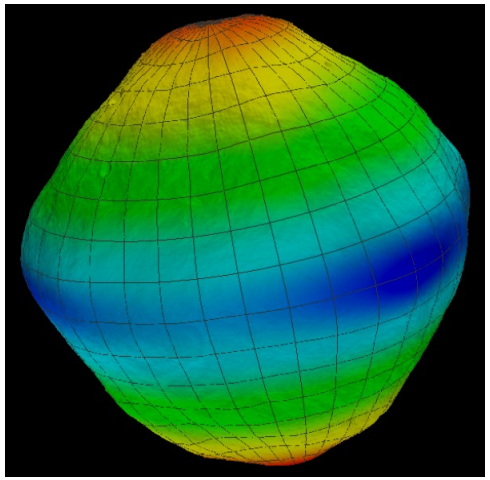
Driving Requirements

- **MRD-570:** OSIRIS-REx shall select a sample site that satisfies the following criteria:
  a. >99% probability of ensuring the safety of the flight system during sampling
  b. …

- The Safety Maps are required to certify the safety of candidate sites against the performance constraints of the flight system to ensure the collected sample can be successfully returned to Earth and that additional sampling attempts will be possible (if necessary).

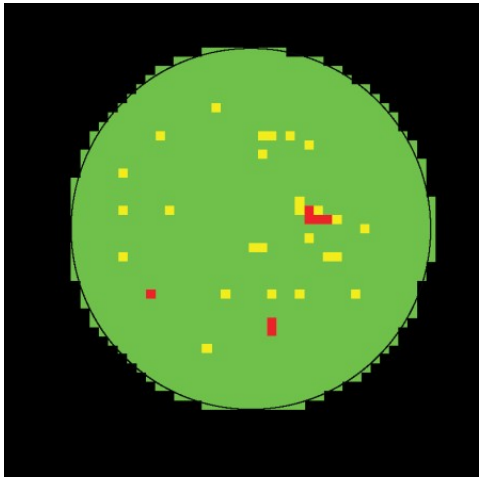
What are the Safety Maps?

Global



Global shape model with facets colored per color code below

Site-specific

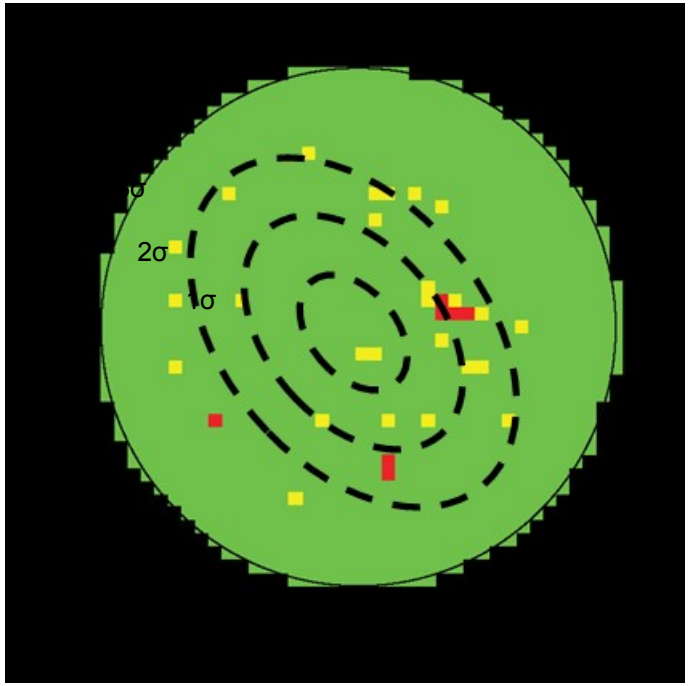


50m diameter area shape model with facets colored per color code below

- **Green** = map element meets all safety requirements
- **Yellow** = one or more individual parameters exceeds safety requirement but values remain below analyzed spacecraft capability
- **Red** = one or more individual parameters exceeds known capabilities
- **Black** = no data for one or more individual parameters

Probability of Contacting Safe Terrain

- Combining each site-specific Safety Map with its corresponding Deliverability Map yields the probability of contacting safe terrain
  - Sum of probabilities of delivery to green (or green + yellow) facets
  - Probability will also be calculated for individual safety parameters



Global and Site-specific Maps Needed

Safety Driver	Spacecraft Subsystem	Surface parameters	Global Map?	Site-specific Map?
Monitor the range/ range-rate corridor (avoid early, unexpected contact)	GN&C, LIDAR	Tilt @ 1m, reflectance at 1064nm	Yes	Yes
Estimate Time of Touch • Sets window for contact detection • Prevents TAGSAM arm from sinking in below elbow	GN&C, LIDAR	Tilt @ 1m, reflectance at 1064nm	Yes	Yes
Maintain a comm link (MRD-41)	Telecomm	Tilt @ 50m	Yes	No
Don't overheat the spacecraft	Thermal	Temperature	Yes	Yes
Don't tip the spacecraft over and contact the surface (MRD-573)	Mechanical	Tilt @ 1m	Yes	Yes
Don't bend or break the TAGSAM arm or head	Mechanical	Tilt @ 1m	Yes	Yes
Avoid dust/gas plumes (May be removed)	Mechanical and GN&C	Dust/gas plume	Yes	No
Prefer smoother sampling surface	Mechanical	Tilt @ 1m	No	Yes

Safety Map Requirements

Number	Requirement	Rationale
SM.GMAP.01	SPOC shall compute the global probability of safety for each facet of the GSM. The probability shall be a value between 0 (0% safe) and 100 (100% safe)	This requirement specifies the need to generate a probability (i.e. uncertainty) of safety for each facet of the GSM. The resolution is dictated by the GSM resolution and follows the distribution of error (eg Gaussian or Poisson…).
SM.GMAP.02	SPOC shall generate a global safety map by visualizing the probability values on the GSM	Builds on the previous requirement. Once the probability is computed per each facet, it can be visualized
SM.GMAP.03	SPOC shall compute the global safety probability map by convolving the safety probability with deliverability at the GSM resolution. The probability of mission safety shall be a value between 0 (0% mission success) and 100 (100% mission success)	This requirement specifies the need to convolve the safety map with the deliverability and to compute the overall mission safety. The probability will be generated for each facet within the contact area based on the probability of contact (ie deliverability) and whether any mission safety factors are exceeded at that facet. The probability of contact for each facet will be determined by either: 1) The Global Deliverability Map 2) A deliverability error ellipse
SM.GMAP.04	The global safety map shall be generated within 5 days of SPOC receipt of the input parameter maps.	Define time constraints for generating the global safety map
SM.GMAP.05	The global safety map shall have the spatial resolution equivalent to that of the GSM.	Defines the resolution of the global safety map to be equivalent to the global shape model

Safety Map Requirements

Number	Requirement	Rationale
SM.SSMAP.01	SPOC shall compute the site-specific probability of safety at the resolution of the DTM. The probability shall be a value between 0 (0% safe) and 100 (100% safe)	This requirement specifies the need to generate a probability (ie uncertainty) of safety for each DTM element at the potential TAG site. The resolution is dictated by the resolution of the DTM and follows the distribution of error (eg Gaussian or Poisson…)
SM.SSMAP.02	SPOC shall generate a site-specific safety map by visualizing the probability values for each pixel in the TAG ellipse at the resolution of the DTM.	Builds on the previous requirement. Once the probability is computed per each pixel in the TAG ellipse, it can be visualized
SM.SSMAP.03	SPOC shall compute the site specific mission safety probability by convolving the safety probability with deliverability at the DTM resolution. The probability of safety shall be a value between 0 (0% mission success) and 100 (100% mission success)	This requirement specifies the need to convolve the safety map with deliverability map to compute the overall mission safety. The probability will be generated for each facet within the contact area based on the probability of contact (ie deliverability) and whether any mission safety factors are exceeded. . The probability of contact for each site will be determined by either: 1) The Site specific deliverability map A deliverability error ellipse
SM.SSMAP.04	The Site-specific safety probability map (SSMAP.03) shall be compatible with the OSIRIS-REx data visualization tool.	Compatibility means the data product can be ingested by, visualized by, and have all the functionality of the visualization tool applied to the input maps. The output formats for the safety map shall include at least two versions: (i) one version in the shape model format, (ii) one version in the Project-defined map-projection format.
SM.SSMAP.05	The Site-specific safety map shall be generated within 5 days of SPOC receipt of the input parameter maps.	Define time constraints for generating the site-specific safety map
SM.SSMAP.06	The global safety map shall have the spatial resolution equivalent to that of the GSM.	Defines the resolution of the global safety map to be equivalent to the global shape model

Input Data Products

Input Product	From:	Global map spatial resolution	Data collection mission phase	Site-specific map spatial resolution	Data collection mission phase	Green	Yellow	Red
Shape Model (Tilt @ 50m)	Altimetry	21 cm	Detailed Survey, BBD	N/A	N/A	TBD (latitude and date dependent)	TBD	TBD
Shape Model (Tilt @ 1m)	Altimetry	21 cm	Detailed Survey, BBD	5 cm	Orbital B	< 14 deg	TBD	TBD
Temperature Predict Map	Thermal Analysis	50 m	Detailed Survey, Equatorial	8 m	Orbital B	< 350 K	TBD	TBD
Dust/gas Plume Map	Regolith Development	2m	Detailed Survey, Equatorial	N/A	N/A	No dust plumes observed within 25m of sample site	No yellow limit	Dust plume observed within 25m of sample site
Reflectance at 1064 nm Map	SAWG/ IPWG	2m	Detailed Survey, Equatorial	50cm	Recon*	Incidence angle < 40°: 0.015 - 0.069 Incidence angle < 70°: 0.023 - 0.069	TBD	TBD

*provides confirmation only

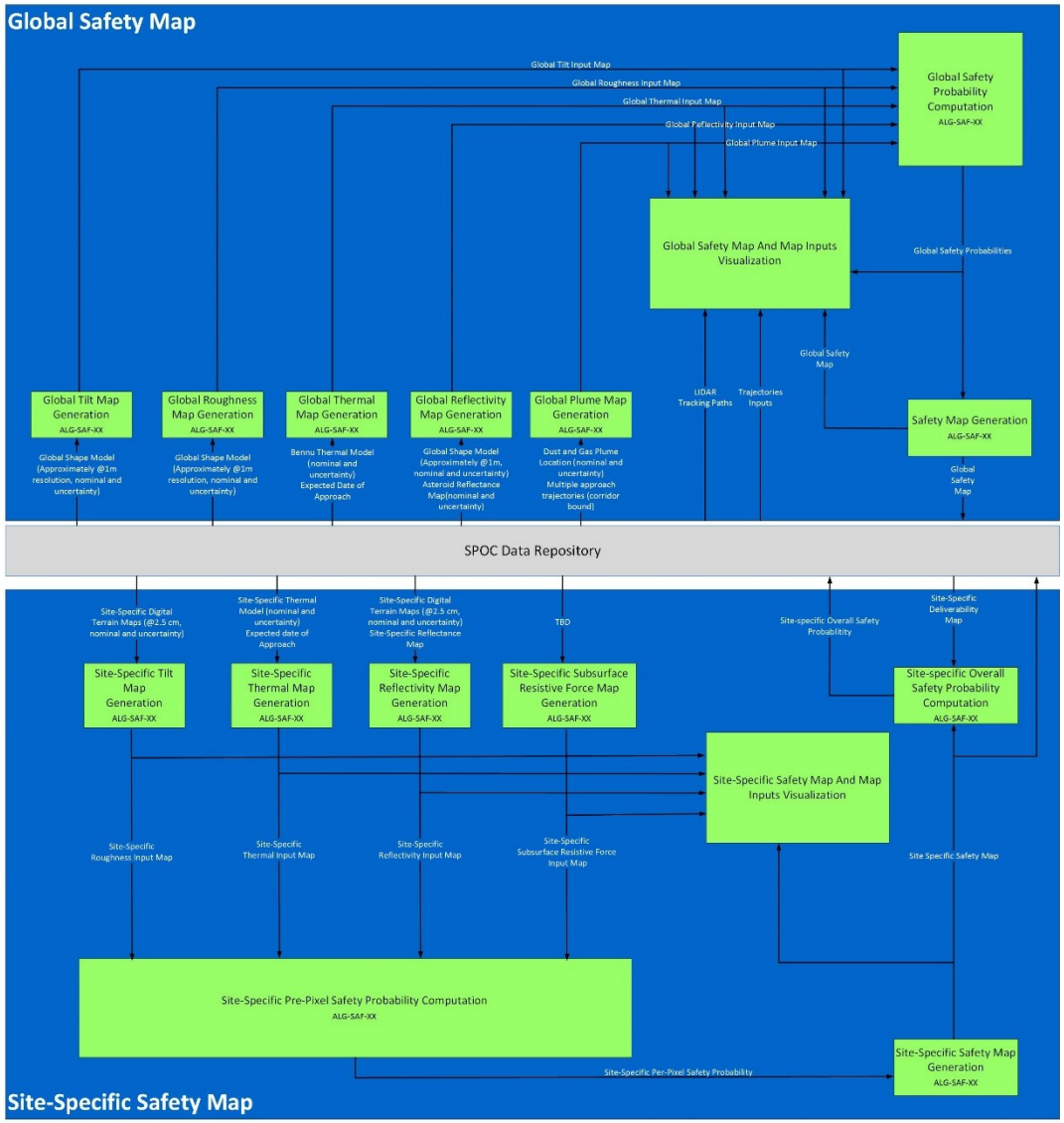
Safety Map Algorithms – Global Inputs

Number	Requirement	Rationale
SM.ALG.01	SPOC shall generate a global tilt input map of Bennu. The global tilt scale map will provide the average tilt of the expected sampling area (nominally 50m diameter) for each facet within the GSM. The assigned location for the tilt will be the geometric center of the facet.	This requirement ensures continuous communications from final approach to first surface contact. The tilt at the scale of the sampling ellipse defines the spacecraft attitude during the final approach to surface contact. Tilt in this context represents the angle of the surface normal relative to zenith and the surface normal vector (ACF) should be obtained
SM.ALG.02	SPOC shall generate a global roughness input map for each facet in the GSM. The roughness parameter (TBD) will indicate how smooth (or rough) the sampling area is centered on each of the facets in the GSM.	Determining an appropriate sampling site is based on the overall orientation of the sampling site but also on whether there are significant deviations from the average. When convolved with the deliverability map, it will provide the probability of contacting a facet that exceeds the tilt capability of the spacecraft (approximately 14 deg).
SM.ALG.03	SPOC shall generate a global thermal input map of Bennu indicating the temperature for each element in the thermal map. The global temperature map (~40m resolution) shall be calculated for the predicted local time-of-TAG and solar range for the expected TAG date	During approach of the sampling site, it would be unsafe for OSIRIS-REx to approach a portion of the asteroid that exceeds the spacecraft capability. SPOC already has a requirement to generate global thermal and temperature predictions for various local times.
SM.ALG.04	SPOC shall generate a global reflectivity input map of Bennu indicating the reflectivity at 1064nm for each element of the GSM	Ensures that the surface that will be measured to determine range is within the range of reflectance values in which the LIDAR is designed to operate. Predictions of the variation in intensity are also important to enabling avoidance of excessively high variations in reflectance that could affect LIDAR ranging performance
SM.ALG.05	SPOC shall generate a global plume input map of Bennu.	During approach of the sampling site following orbit departure, it would be unsafe for OSIRIS-REx to fly through a plume of dust or gas being expelled from the asteroid.

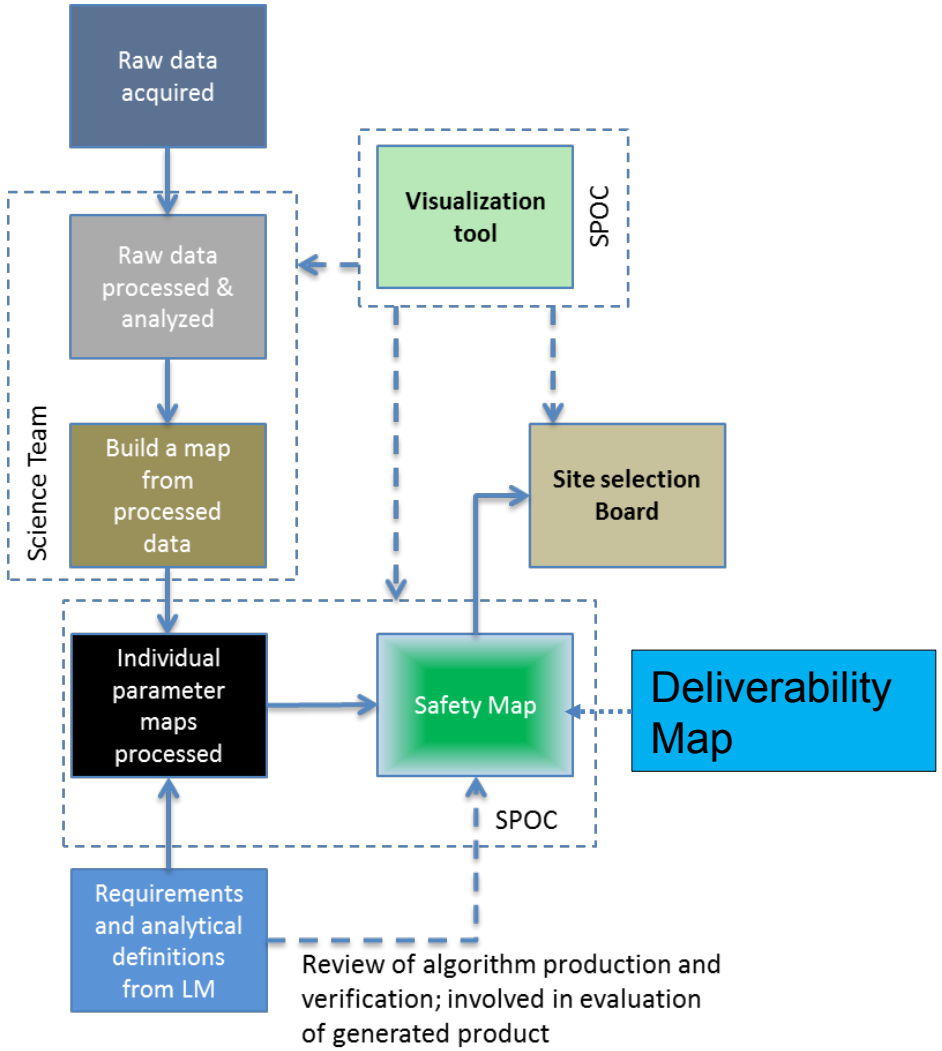
Safety Map Algorithms– Site Specific Inputs

Number	Requirement	Rationale
SM.ALG.06	SPOC shall generate a site specific tilt input map for each potential sampling sites. The site specific tilt scale map will provide a map for a targeted sampling site. The local tilt map will provide the average tilt of all facets within the contact area for every facet in the DTM. The contact area is a parameterized value and will be approximately at the scale of the TAGSAM head (TBR).	Spacecraft safety is dependent on the contact dynamics of the TAG event, which is partially determined by surface tilt. The spacecraft is capable of safely contacting the surface if the tilt of the actual contact surface does not exceed 14 deg (required) or TBD degrees (expected spacecraft performance).
SM.ALG.08	SPOC shall generate a site-specific thermal map of Bennu indicating the temperature for each element in the thermal map for the projected TAG time (local time). The site-specific temperature map (8 m) shall include temperatures for both the local TAG site and approach corridor at the predicted local time-of-TAG and solar range for the TAG date.	During approach of the sampling site, it would be unsafe for OSIRIS-REx to approach a portion of the asteroid that exceeds the spacecraft capability. SPOC already has a requirement to generate global thermal and temperature predictions for various local times.
SM.ALG.09	SPOC shall generate a site-specific reflectivity input map of Bennu indicating the reflectivity at 1064nm for each of the candidate sampling sites at the resolution of the site specific DTM.	The Safety Map WG needs to know the reflectance of the asteroid at 1064nm to ensure that the surface that will be measured to determine range is within the range of reflectance values in which the LIDAR is designed to operate. Predictions of the variation in intensity are also important to enabling avoidance of excessively high variations in reflectance that could affect LIDAR ranging performance

Safety Map Architecture



Map Production Flow



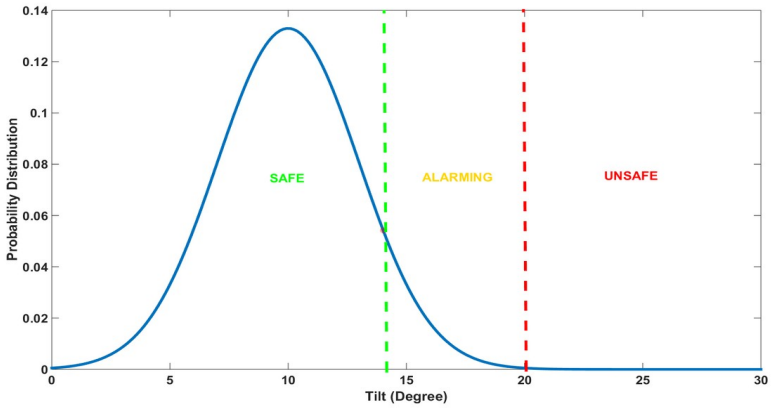
- Parameter maps will be generated by the science team as the data are made available
- Data for some of the maps is not available until very late
- Expected that preliminary safety maps will be made generated and used to eliminate possible TAG sites
- The safety maps will be convolved with the deliverability maps (FDS) to provide global and site specific probability of meeting safety requirements

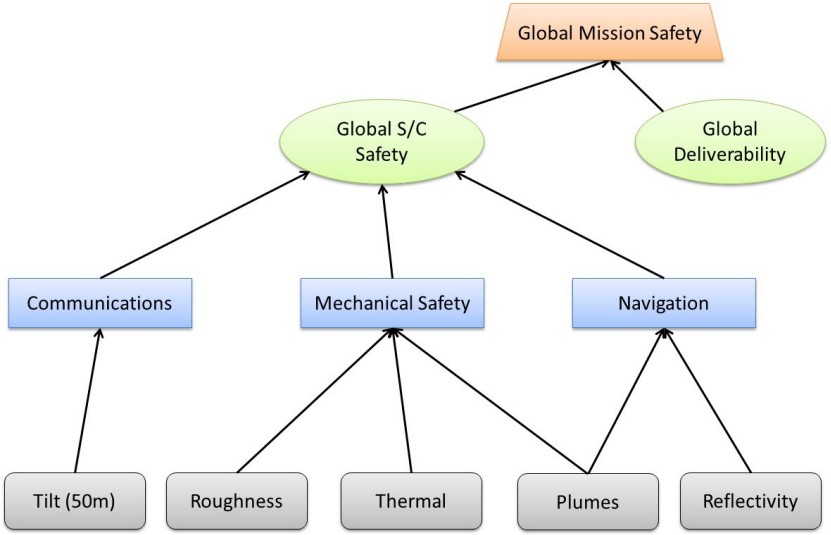
Status of Algorithm Development

- All algorithms associated with the input maps (global and site specific) have been delivered to the SPOC
  - Plume map is TBD
  - Roughness map is placeholder
- Requirements on Science Wiki at
  - https://sciwik.lpl.arizona.edu/wiki/pages/s3X2x2k8/Safety_Maps_MRD570a.html
- Algorithm Descriptions on Science Wiki at
  - https://sciwik.lpl.arizona.edu/wiki/pages/31S8n0t5/Algorithm_Descriptions.html

Safety Map BBN Algorithm Development Status

- A Bayesian Belief Network (BBN) approach has been considered for computing the probability of S/C safety to support global and site selection
- Development status
  - A preliminary version of the Bayesian network has been defined and implemented
    - Implemented using the NETICA ® platform and interfaced with MATLAB
    - Currently under evaluation to understand performance and tuning of the parameters

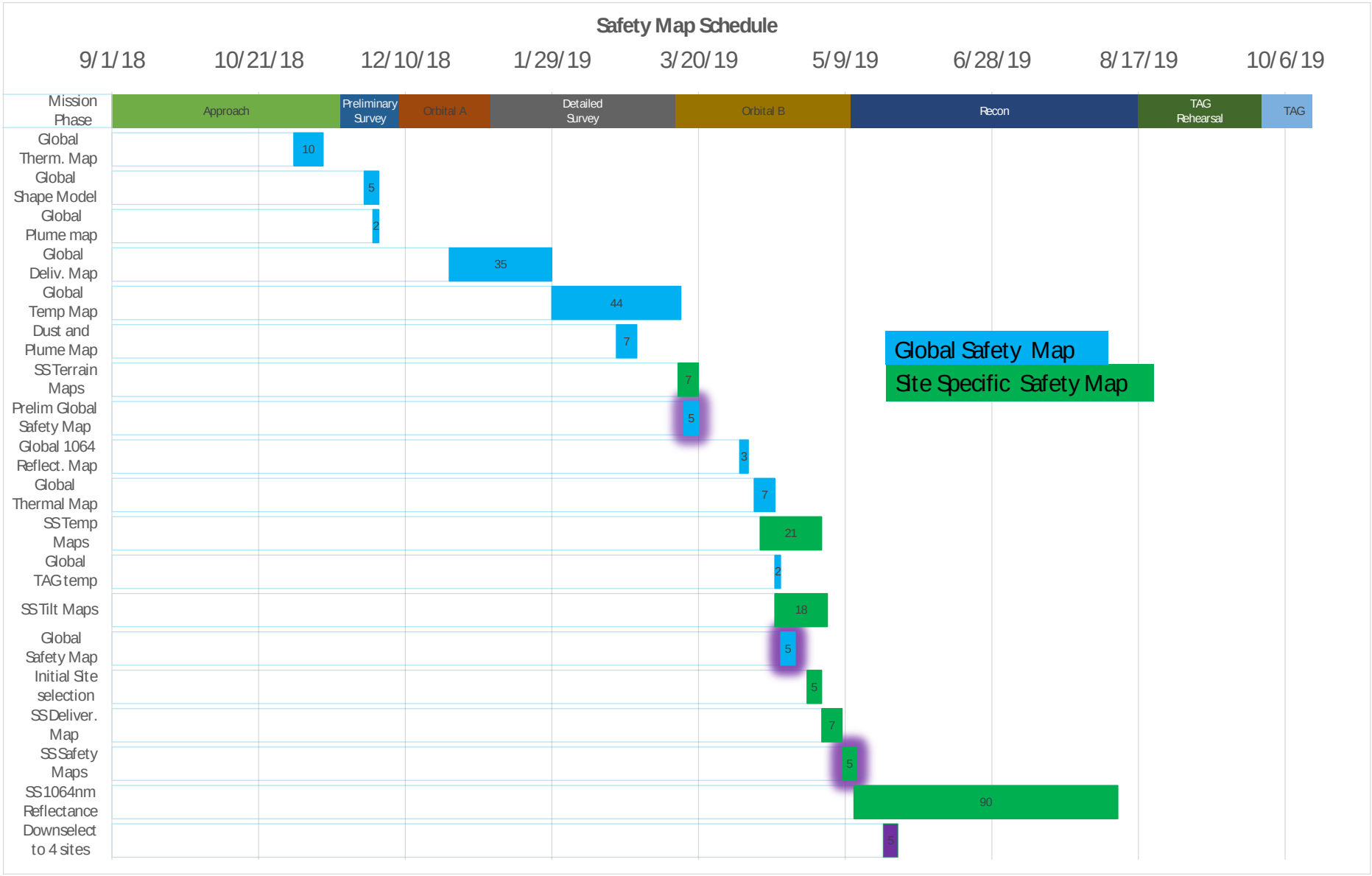




Relevant Schedule and Inputs

- Observations for product begin:
  - Global - 10/2018 during Approach
  - Site Specific – 2/2019 during Detailed Survey
- All observations for product in to SPOC:
  - Global - 3/2019 during Detailed Survey
  - Site Specific – 5/2019 (8/2019 for reflectance) during Recon
- Safety Maps available:
  - Global – 4/17/2019
  - Site Specific – 5/8/2019 with update for reflectance at 8/15/2019
- Processing begins on
  - Global: 4/12/2019
  - Site Specific: 5/3/2019
- Data product lead: Dave Lorenz
- Backup data product lead: Ron Mink

Safety Map Schedule

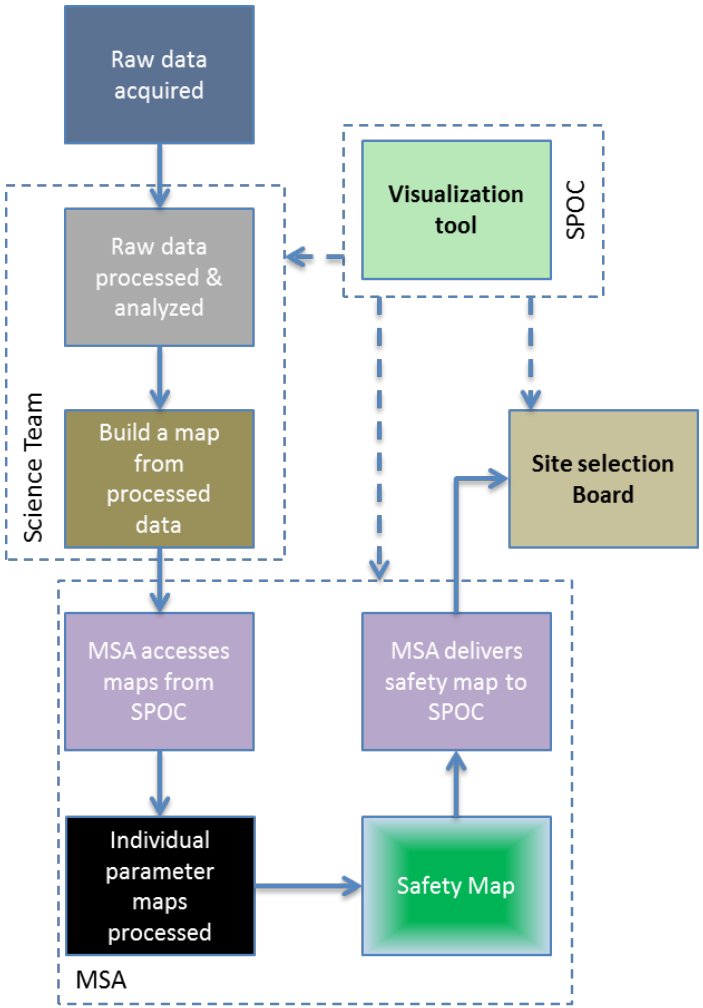


Minimal Mission Scenario

- How will the minimal mission scenario affect your product?
  - Safety Map is produced in minimum mission success plan
  - Temperature maps come from direct measurements of surface temperature rather than thermal models

Contingency Considerations

- Scenario – no sample site meets all safety requirements
  - Map production flow per figure at right
  - Individual parameter maps are incorporated into subsequent “coupled” analyses (e.g. the shape model, in conjunction with a dynamical model of the spacecraft, is analyzed in ADAMS), the results of which define the Safety Map
  - Map parameters can be modified (eg size of TAG ellipse, approach vector etc)
- Scenario – surface contact is made during sampling, but insufficient (or no) sample is collected
  - “Surface response” maps generated that relate information about surface properties and behavior from remote sensing data and spacecraft telemetry collected during TAG to the pre-TAG characteristics of the site determined from remote sensing only



Work to go

- Develop Bayesian network
  - Understand how to develop Bayesian network
  - Develop rules
  - Understand uncertainties on each parameter
- Understand Plume impingement hazards
- Roughness - not a safety issue but possible discriminator
- Statistical distribution of facets – Gaussian?
- Process flow – how are maps constructed
  - Pending requirements and algorithm review and sign off with SPOC team
  - What “knobs” are needed to control the process?
- Production and test of safety map software
- Contingencies – how to identify low hanging fruit in the event that there are no viable sites
  - Generate and prioritize contingencies

Summary

- Safety Maps provide likelihood of the spacecraft safely encountering Bennu terrain during TAG
- Science observation plan in the DRM provides the required data
- Roles and responsibilities for map development are well understood
- Documentation baselined (Data Product Description & Requirements Report)

Back Up

Tilt Map Algorithms

- All maps calculations can be weighted by using the probability of expected contact as provided by the FDS deliverability map or a deliverability ellipse
- Global Maps, Tilt @ 50m/1m
    - For each facet in the global shape model within the 50m diameter circle:
        1. Compute surface normal or each facet of interest
        2. Compute ‘weighted’ average of surface normal – this determines approach vector for TAG
        3. Color code per green/yellow/red limits based on comm

- Site-specific Map, Tilt @ 1m – same steps applied to higher resolution shape model within 50m diameter area
    - Compare tilt of each facet to the average tilt of the entire TAG site
    - Color code facets to red/yellow/green
    - Combine with deliverability map to calculate probability of meeting system requirements

Temperature, Plume, and Reflectance at 1064nm Algorithms

- Temperature
  - Global
    - For each facet in the global shape model
      1. Assign the nominal predicted temp for each facet (@ 65 degree solar phase angle), for the estimated date of TAG
      2. Color code per green/yellow/red limits
  - Site-specific - same steps applied to higher resolution shape model within 50m diameter area
- Dust/gas plumes, global map only
  - Color code each facet in the global shape model per green/red limits
- Reflectance at 1064nm
  - Global Map
    - For each facet in the global shape model
      1. Assign the nominal value of reflectance at 1064nm
      2. Color code per green/yellow/red limits
  - Site-specific Maps – same steps applied to higher resolution shape model within 50m diameter area