MRD-411

Primary Co-I: Emery

Science Working Group:  Thermal Analysis

411 Produce, within 7 days of final downlink of applicable data, a predicted temperature map of each candidate sampling ellipse for the estimated dates and Bennu times of day for TAG with ≤ 5m spatial resolution and accurate to +/-10K (Site-specific temperature maps (at the time of sampling)

~~~~~~~~~~~~~~~~~~~~~~~~~~

Summary of Requirement

The requirement is to compute predicted temperatures at the time of sampling using the Site-Specific Thermal Inertia Maps and the asteroid thermal model (FTPM)

Verification of this requirement includes

Establishing that the system can produce the Site-Specific Thermal Inertia Maps with the temporal and spatial requirements specified.

Demonstrating that the software required has been provided and tested

Prediction of temperatures using thermal inertia maps -- TAWG

Establishing that the SPOC data storage and dissemination plan enables ready transfer of necessary data products

Data Products Required

Compute Site Specific Temperature Prediction Map (TA-006) from Site Specific Thermal Inertia Maps (TA-005) using the asteroid thermal model (FTPM).

Inputs

Site-Specific Thermal Inertia Maps (TA-005)

Bolometric Bond Albedo Map (SA-37)  -- can move forward with estimate if not available

Site-Specific DTM (ALT-17) and Site-Specific DTM ancillary template (ALT-31)

RMS tilt map (ALT-25) -- can move forward with estimate if not available

Resolution Mapping Ancillary File (ALT-29)

Bennu Spin State (ALT-35)

Heliocentric ecliptic coordinates of spin pole

Rotation period

Time of TAG
~~~~~~~~~~~~~~~~~~~~~~~~~~

Outputs

Site-Specific Temperature Prediction Maps (TA-006)

No other dependencies exist for this product

Ability/Availability of the System to Generate Sufficient Observations

Computation of temperatures with stated accuracy traces back to derivation of absolute flux to 3% accuracy, which depends on the OTES instrument meeting its performance requirements, which has been demonstrated/documented elsewhere (see below). In other words, the requirements in MRD-540 must be met in order for the requirements on the temperature prediction to be met.

The current DRM contains the required observations to meet the coverage, spatial resolution, time of day, and data return requirements.

Minimum Success Criteria

To enable OTES to collect the required data, operations during the Orbit-B and/or Reconnaissance phases must, at a minimum, meet the surface coverage and spatial resolution requirements listed in MRD-540.

Dependencies by Mission Phase

Orbit-B and/or Recon: As detailed in MRD-540, the spacecraft must meet the range-to-Bennu requirement specified by the DRM in each of the for each potential sample site OTES observing campaign in order to ensure that OTES collects spectra with the required spatial resolution. Data must be returned and processed prior to exiting Reconnaissance phase.

The input data listed above must be available before computation of Site-Specific Temperature Prediction map can begin.

Adequacy of the DRM

The mission profile described by DRM Rev. C currently enables the required data to be collected.

Data Products per Mission Phase

Orbit-B and/or Recon: Production of these science products can begin immediately after the Site Specific Thermal Inertia Maps are available and the time of TAG has been determined.

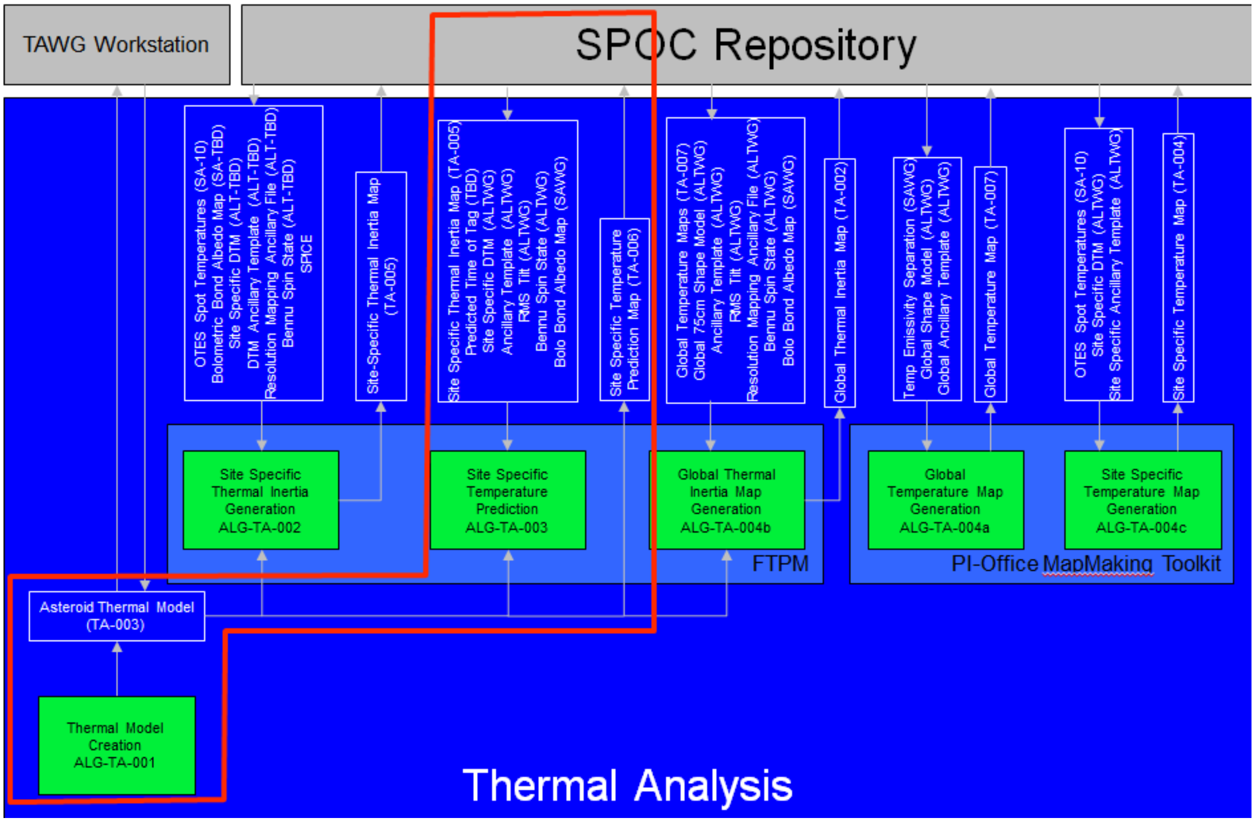
It will take approximately 2 days to create and validate each temperature prediction map, once the thermal inertia maps are available.

Overview of Processing

Software required to satisfy MRD-411:

The Site Specific Temperature Prediction Map is derived using the TAWG thermal model algorithm (FTPM - fast thermophysical model) (ALG-TA-001).

FTPM has been delivered to the SPOC.




Provenance of Algorithms, Software and Techniques

The general form of the thermal model algorithm used is a standard energy balance algorithm that includes the effects of heat conduction and storage. The process will be to run a thermophysical model with parameters appropriate to the observation in order to reproduce OTES-derived Temperature Maps. For the Approach Phase data, thermal inertia will be varied to match the measured disk-integrated flux. For the Survey phase data, thermal inertia will be varied to match the temperatures derived from OTES as a function of time-of-day. For the Reconnaissance Phase data, thermal inertia will be varied to reproduce the temperature measured by OTES of the sample site.

The thermal model to be used at Bennu (FTPM) is a direct outgrowth of the thermal model developed by Ben Rozitis during his PhD dissertation research, and is informed by more than 10 years of asteroid thermal model research by the science member co-I responsible for this data product (see references below). Ben Rozitis was employed as a post-doc by OSIRIS-REx to modify his thermal model for use by the mission, and he is now a collaborator who is very active in TAWG activities. The numerical approach is described in a few publications (see references below). During development of the thermal model, Ben Rozitis and Josh Emery tested and refined their thermal model for Bennu in collaboration with thermal engineers and with Dr. Marco Delbo of the Observatory of Nice.

Primary references

Rozitis, B. and S.F. Green 2011. Directional characteristics of thermal-infrared beaming from atmosphereless planetary bodies - a new thermophysical model. MNRAS 415, 2042-2062.

Rozitis, B. and S.F. Green 2012. The influence of rough surface thermal-infrared beaming on the Yarkovsky and YORP effects. MNRAS 423, 367-388.

Rozitis, B. 2011. "Physical and Dynamical Characterisation of Near Earth Asteroids via Thermophysical Modeling." Open University PhD Dissertation, advisor: Dr. Simon Green.

Supporting references

Emery, J. P., D. P. Cruikshank, and J. Van Cleve (2006) Thermal emission spectroscopy (5.2 - 38 µm) of three Trojan asteroids with the Spitzer Space Telescope: Detection of fine-grained silicates, Icarus, 182, 496-512.

Emery, J.P., et al. 2014. Thermal infrared observations and thermophysical characterization of OSIRIS-REx target asteroid (101955) Bennu. Icarus 234, 17-35.

Kieffer, H. H. (2012) Thermal model for analysis of Mars infrared mapping, JGR-in press, doi:10.1029/2012JE004164. (Despite the title of the paper, this is a generalized thermal model applicable airless bodies as well as Mars.)

Delbó, M. and Tanga (2009) Thermal inertia of main belt asteroids smaller than 100 km from IRAS data. Planetary and Space Science, 57, 259.

Delbó, M. et al. (2007) Thermal inertia of near-Earth asteroids and implications for the magnitude of the Yarkovsky effect.Icarus, 190, 236.

Expected/Simulated Data

The asteroid thermal model (FTPM) has been tested by verifying that it can:

Compute surface temperatures on Bennu using the existing radar shape model.

Derive thermal inertia from simulated temperature maps (again, using the existing radar shape model).

These tests are documented in ppt slides for TAWG telecons, during which the results of the tests were presented to the TAWG. (Thermal Analysis Working Group Scratch Page)

Analysis & Verification Methods

For thermal model performance, see the discussion under Expected/Simulated Data above.

The core of the thermal model for OSIRIS-REx was developed by Ben Rozitis during his PhD dissertation and a subsequent post-doc at the Open University. The Rozitis et al. publications listed above describe the development of the model and testing against results produced by other models.

The OSIRIS-REx thermal model was tested against two other published thermal model, those of M. Delbo and J. Emery. The model by J. Emery is the one that was used to derive the thermal inertia of Bennu from Spitzer space telescope observations. The OSIRIS-REx thermal model ran significantly faster than the other two (by virtue of running on GPUs) and produced results (computed temperatures and fluxes) that agreed with the other two models to less than 1%.

The OSIRIS-REx thermal model and J. Emery's thermal model were both used to estimate the thermal inertia of Itokawa from unpublished Spitzer space telescope data. Both models gave results of 700 +/- 200 SI units for the thermal inertia of Itokawa. The large uncertainty is due to calibration issues with the data, and we decided not to publish these results because they do not improve on previous estimates and we are not confident in the calibration of the data.

Two versions of the OSIRIS-REx thermal model were built and delivered to the SPOC. The Advanced ThermoPhysical Model (ATPM) is the more sophisticated model, in that it considers facet-to-facet shape-shadowing and self-heating calculations. These calculations are computationally expensive, so the Fast ThermoPhysicalModel (FTPM) was developed and delivered. The FTPM neglects facet-to-facet shape-shadowing and self-heating, so runs significantly faster. Temperatures computed with the FTPM match those from the ATPM to within a few K, except in the case of low thermal inertias near the equator. The accuracies of the ATPM and FTPM thermal inertia retrievals were tested by computing temperatures on the radar shape model using the ATPM, adding 1 K Gaussian random noise to those temperatures to represent measurement uncertainties, then retrieving thermal inertias using both the ATPM and the FTPM. The ATPM retrieval was within 2 to 3 percent of the input thermal inertia everywhere. The FTPM retrieval was within 20% of the input thermal inertia everywhere. The ATPM was used to determine that the requirement of predicting temperatures to withing +/- 10K levies a requirement on thermal inertia of 20%, so the both versions of the OSIRIS-REx thermal model satisfy the necessary requirements. The FTPM will be the baseline model, to ensure that the production timeline is met. The ATPM will be run concurrently to provide verification of the results of the FTPM.

Existing or Potential Liens

There are currently no known liens on the DRM, OTES instrument, or spacecraft system that would degrade the solution or preclude success.

Products from MRD-540 are used as inputs here, so liens on MRD-540 must be cleared before the inputs are available for the temperature predictions.

SPOC Requirements

SPOC is providing several Windows workstations with GPUs to run the thermal model.

SPOC must provide access to all of the inputs listed above.

The SPOC-Thermal Analysis ICD is in draft and will be linked here when it is available.

External Interfaces

There are no external interfaces for derivation of OTES spot temperature.

The thermal model (FTPM) runs on Windows workstations that the SPOC will provide. No other external interfaces are required.

~~~~~~~~~~~ Below obsolete, can be used above if useful ~~~~~~~~~~~~

Data Products

Description: Site-specific temperature maps (at the time of sampling) (MRD-411)

Sample-Site Temperature Maps. The OTES Spot Temperature data from individual Reconnaissance Phase overflights of each candidate sample site will be mapped at TBD projection to produce temperature maps of each site. The local time will vary across each sample site (~30 minutes for a 50-m diameter equatorial site). This time-of-day effect will not be removed from the temperature data product. In addition to the temperature maps from the Reconnaissance Phase data, maps can be made of each site using data acquired during other mission phases for comparison with other instrument data and derived data products. In addition to the temperature maps, two ancillary maps will be produced that give: 1) the number of OTES spectra included in each element of the map; and 2) the average local time of the OTES data used in each map element.

Process Overview

The temperature maps will be constructed from individual OTES Spot Temperature data. These maps will be used as inputs to the thermal inertia data products and as the initial indicator of the temperature environment of the asteroid that the spacecraft will experience. This data product is needed because temperature is an indicator of surface physical properties and these maps provide the initial, model-independent evidence for spatial variation in physical properties across the surface of RQ36. These maps will also be used as one of the inputs to the thermal inertia data products. The data are in units of Kelvin.

Expected Data Return by Mission Phase

Reconnaissance Phase -

Availability of Input Data Products

All of the temperature maps require:

1) The OTES Spot Temperature data

2) The latitude, longitude, and local time of the OTES Spot Temperature

3) User inputs for the constraints (quality, local time, etc) used to create a specific map

Data Processing Tasks
~~~~~~~~~~~

The maps will be constructed from the OTES Spot Temperature data using straightforward binning tools that incorporate weighted averaging and data quality constraints. The algorithm assumes that the latitude, longitude, and local time are known for each individual OTES spot observation. The mapping software will be written in the open source Davinci software program that is available at: http://davinci.asu.edu/ . Preliminary versions of these algorithms have been developed and used to map temperature data from the Mars Global Surveyor TES instrument. The maps will be produced in a TBD projection, which can be reprojected to any desired projection using the ISIS software tools.

## Time-frame for Data Processing

The production of the maps will be very rapid – several seconds to tens of seconds per map.

If the maps were produced that the nominal OTES resolution, the global maps would have a resolution of 40 m, resulting in an approximately 50x50 pixel map of floating point data and a data volume of approximately 20 Kbytes per map. The sample site maps will have an OTES nominal resolution of 4 m and cover an area approximately TBD x TBD, resulting in an approximately TBDxTBD pixel map of floating point data, or a data volume of approximately TBD per map.

## Analysis and verification methods

Validation of the temperature maps will assume that the individual OTES Spot Temperature data used as inputs to the maps have already been validated. Validating the map will require that a person examine the map and observe for obvious data striping, which would indicate that data from differing times of day were incorrectly merged into the map or that there were issues with the latitude, longitude, or local time information. If the maps are valid, then the temperatures should be a smoothly varying function of latitude and longitude. The maps will also be examined by a person to observe any data gores, which could indicate missing data or unexpected exclusion of data through incorrect or overly limiting constraints.

## Software

Davinci (see above) is the software package/programming language for which the OTES data processing software is written. The binning, averaging, data quality constraining mapping software will be written in davinci. This software runs on Linux, Windows, and MacOS and will be installed on the SPOC system for use on all OTES data processing. Any reprojection of the maps to specific geometric projections will be done using the ISIS software package.

## References

Similar global temperature maps for Mars derived from the Mars Global Surveyor TES instrument have been submitted to the PDS as special products