MRD-540

MRD-540 2.4.8 For ≥80% of a 2-sigma TAG delivery error ellipse around each of up to 12 candidate sampling sites, measure the absolute flux of thermally emitted radiation with 3% accuracy and use it to derive and map thermal inertia at a spatial resolution ≤8 m

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Summary of Requirement

The requirement is to measure thermal flux from potential sample sites in order to map temperatures and compute thermal inertia.

Verification of this requirement includes

Establishing that OTES can measure the thermally emitted flux with the required accuracy

Establishing that the mission profile enables observations to meet the temporal and spatial requirements

Demonstrating that the software required for the three processing steps has been provided and tested

Derivation of brightness temperature from L2 OTES calibrated radiance -- SAWG

Mapping of spot temperatures -- SPOC-provided mapping tools

Derivation of thermal inertia from the 7 temperature maps -- TAWG

Establishing that the SPOC data storage and dissemination plan enables ready transfer of necessary data products across the different processing steps

Data Products Required

Step 1: The first processing step is to derive brightness temperature from the OTES L2 calibrated radiance spectra.

Input

OTES L2 calibrated radiance spectra from Orbit-B and/or Recon phase

Output

Best-fit derived brightness temperature (SA-10), including uncertainties and wavelength of brightness temperature calculation, and emissivity spectrum (SA-11) for each OTES spot measurement. (1) Radiometric uncertainties are associated with each spectral channel of each OTES radiance spectra, and these are propagated through the brightness temperature calculation during the emissivity-temperature separation. This is only one component of the final temperature uncertainty. (2) A larger component of the kinetic temperature uncertainty is the judgement of wavelength and emissivity at that wavelength to use.

No other dependencies exist for this product
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Step 2: The second processing step is to produce temperature maps (one for each sample site observation). The outcome of this step is production of Site Specific Temperature Maps (TA-004).

Inputs

OTES spot brightness temperatures (SA-10)

Site-Specific DTM (ALT-17)

Site-Specific DTM ancillary template (ALT-31)

Output

Site Specific Temperature Maps (TA-004)

includes for each facet: rotation phase at time of temperature measurement, orbit true anomaly at time of temperature measurement, emission vector, wavelength of brightness temperature measruement, temperature uncertainty

This product depends on the software called MAKE_MAPS that is currently in production at the PI office.

Step 3: The third processing step is to compute thermal inertias at each map facet from the Site-Specific Temperature Maps to produce Site Specific Thermal Inertia Maps (TA-005)

Inputs

Site-Specific Temperature Maps (TA-004)

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

Outputs

Site-Specific Thermal Inertia Maps (TA-005)

No other dependencies exist for this product

Ability/Availability of the System to Generate Sufficient Observations

Derivation of absolute flux to 3% accuracy depends on the OTES instrument meeting its performance requirements, which has been demonstrated/documented elsewhere (see below).

The current DRM contains the required observations to meet the global 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.

The observations should avoid mid-morning (~10am local time) and mid-afternoon (~3pm local time), as the temperatures at these times are degenerate for a wide range of thermal inertias.

Dependencies by Mission Phase

Orbit-B and/or Recon: 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 ≤8 m spatial resolution. Data must be returned and processed prior to exiting Reconnaissance phase.

Input data to step 3 must be available before derivation of Site-Specific Thermal Inertia 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 begins immediately after the completion of OTES instrument pipeline processing resulting in L2 (calibrated radiance) products.

Calculation of temperature is rapid (<1 sec/spectrum).

It will take approximately 2 days to create and validate each map, once the temperature data area available from each potential sample site.

It will take approximately 2 days to produce and validate each of the site-specific thermal inertia maps, once all of the required inputs are available.

Overview of Processing

Software required to satisfy MRD-540:

Derived temperature from OTES L2 calibrated radiance spectra is obtained using a SAWG script referred to as the emissivity-temperature separation algorithm (emissivity.dvrc); this script runs in the Davinci environment.

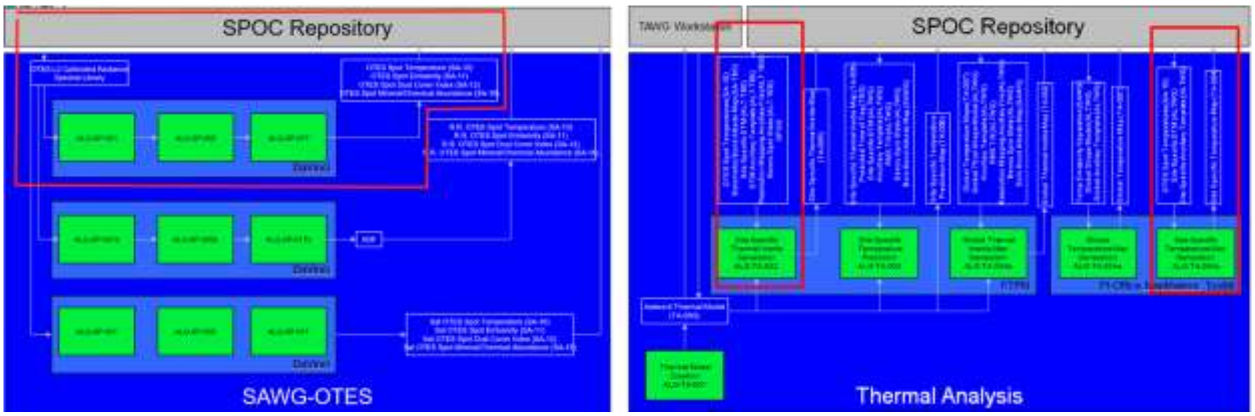
emissivity.dvrc has been delivered to the SPOC.

Site Specific Temperature Maps are made using the SPOC-supplied GetSpots and MakeMaps routines

These scripts are currently (30 Apr 2016) in development.

TheSite Specific Thermal Inertia 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 performance of the OTES instrument (including calibration data showing that the 3% absolute flux requirement is met) is detailed in the OTES instrument manuscript at this link: https://sciwik.lpl.arizona.edu/wiki/pages/U3B5r7/Space_Science_Reviews__Special_Issue.html

The temperature-emissivity separation algorithm has been used for similar data by several different spacecraft missions (e.g., TES on Mars Global Suveyor, Mini-TES on the Mars Exploration Rovers).

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 OTES instrument performance, reference the above-linked manuscript.

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

Existing or Potential Liens

Lien-SPEC-2 has closed. The database search, input, and output currently implemented in the JSON database at the SPOC for meeting the MRD Requirements on spectral data processing(MRD-118, MRD-140, MRD-143, MRD-147, MRD-154, MRD-159 and MRD-540), are ready for operations. These database uses have been completed, validated, verified and used successfully by SAWG and TAWG scientists during the first Science Operations Proficiency Integrated Exercise (SOPIE-1). The SAWG and TAWG teams demonstrated that the database

IO is complete -- by correctly using it to create data products during the SOPIE-1 exercise. Only minimal support was required from Sanford Selznick (Director of Science Data Processing) and his staff to use the database structure to download datasets and upload higher level data products. The software and database structures for extracting L2 OTES and OVIRS data from the database, and handing them off to the various data processing algorithms, then returning them to the database, has been completed (i.e., science database tables have been implemented), and Lien-SPEC-2 can be closed.

Closure on Lien-SPEC-2: Lien on the SPOC: The second lien on successfully meeting this requirement is the implementation of needed database access and data processing linkages at the SPOC. SAWG has delivered individual algorithms for conducting the required analyses, but there is currently no defined procedure for SAWG to extract L2 OTES and OVIRS data from the database, and hand it off to the various algorithms, then return it to the database (i.e., science database tables have not been implemented). Removing this lien will require work on both the part of the SPOC and the SAWG to generate algorithms and update existing algorithms once a process is defined.

Lien-SPEC-3 has closed. The software that has been delivered to the SPOC for meeting the MRD Requirements on mapping (MRD-118, MRD-140, MRD-154, and MRD-540), namely GETSPOTS, and MAKEMAPS are ready for operations. This software suite has been completed, validated, verified and used successfully by SAWG and TAWG scientists during the first Science Operations Proficiency Integrated Exercise (SOPIE-1). The SAWG and TAWG teams demonstrated that the user's manual for this software suite is complete and accurate -- by correctly using it to map test data and reproduce known spectral data patterns that were inserted into the SOPIE-1 test data sets made by Beth Ellen Clark (OVIRS), and Phil Christensen (OTES), respectively. During the SOPIE-1 exercise, only minimal support was required from Luke Hawley (author of MAKEMAPS) and Sanford Selznick (Director of Science Data Processing) to create the necessary spectral map data products required by the exercise designers (Mike Nolan, Mathilde Westermann, and Anjani Polit). The software for mapping calculated spot values onto the Bennu Shape model is ready for operations, and Lien-SPEC-3 can be closed.

Closure on Lien-SPEC-3: Lien on the PI-Office: The third lien on successfully meeting this requirement is the completion of software for mapping calculated spot values onto the Bennu shape model. Removing this lien requires the completion of the requisite software, which is not a SAWG deliverable.

Lien-THERMAL-1 has closed with the agreement between SAWG and TAWG on the correct approach.

Lien-THERMAL-1: Lien on the SAWG - there is currently no agreed-upon way to estimate the derived temperature uncertainty. The SAWG-TAWG teams must agree on how to estimate the temperature uncertainty and write and deliver the software to make the calculation.

Update: At the OTES Calibration Review telecon on 16 June 2016, Phil Christensen provided more information on uncertainties. Phil Christensen took an action to create a Temperature (K) vs Temperature-Uncertainty (K) look-up-table using Monte Carlo simulations of combined errors, using lab emissivity data of different materials. This will essentially create a new version of slide 40 from the OTES Calibration Review that will be more appropriate for OSIRIS-REx. The due date on this is 1 Sept 2016. The SAWG will then modify the "Temperature-Emissivity Separation" algorithm and software int he OTES Science Pipeline to use this look-up-table.

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

SPOC Requirements

SPOC must produce OTES instrument L2 calibrated radiance spectra, enable these to be fed to the SAWG algorithm for emissivity-temperature separation, ingest derived temperature to the database for retrieval by TAWG algorithms. Geometric information is not required for derivation of spot temperature, but will be needed for the production of temperature maps and thermal inertia maps.

SPOC is currently developing mapping software (GetSpots and MakeMaps) that will be used for creating temperature maps.

The SPOC-Thermal Analysis ICD is posted on ODOCS: \OSIRIS-REx Ground Systems\9.4 SPOC\9.4.2 Systems Eng\ICDs\WG ICDs\

External Interfaces

There are no external interfaces for derivation of 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

Data Product Description: Site-specific thermal inertia map (MRD-540)

Site-specific Thermal inertia maps: these will assist in the determination of the physical properties (including mean particle size) of the surface of RQ36, and in particular, for each potential sampling ellipse.

Process Overview

Thermal inertia is determined by observing the response of the surface to changes in energy input – primarily solar insolation. During the different mission phases, this thermal response will manifest itself in different ways with respect to the data obtained by OTES and the other instruments.

Site-Specific Thermal Inertia Maps will be derived from data from the Reconnaissance (and TAG rehearsal?) phase. Thermal inertia will be derived for each OTES spot measurement. The results will be reported as a single value (with appropriate uncertainty) for each OTES spot. The process for determining thermal inertia of the sample site will depend on the scenario finally
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chosen for the observations during Reconnaissance phase. If multiple overflights/observations of the sample site are performed (i.e., radiance/temperature at multiple times of day is measured), the procedure will closely follow that described above for the Global Thermal Inertia Maps. If a single overflight/observation of the sample site is performed (i.e., radiance/temperature is measured at a single time of day), then a single temperature point will be fit to the diurnal temperature curve and the thermal inertia varied to find the best match. This latter procedure is somewhat degenerate, particularly in the morning (6am to 10am local time) and afternoon (3pm to 7pm local time). If the single overflight is chosen, effort should therefore be made to avoid these times of day.

An important application of the site-specific thermal inertia maps (and to a lesser extent the Global thermal inertia maps) is to help constrain the effective mean particle grain sizes of the regolith. The procedure for reliably estimating average grain size from thermal inertia has not been fully developed. The brief description below is meant to give an overview of factors to consider in the interpretation of thermal inertia, and these issues will be developed more fully in Phase C/D.

Ambiguity is possible when attempting to constrain particle grain size based on thermal inertia, depending on the thermal inertia range measured. However, there are several ranges of thermal inertia values for which interpretation is not ambiguous. Even in the nonambiguous cases, we do not have a precise way to map a given thermal inertia value to a specific grain size. Rather, thermal inertia can be used to constrain the effective mean particle size of the surface measured. For Mars, empirical laboratory calibration is used. OSIRIS-REx may also benefit from empirical laboratory studies, and much lower atmospheric pressure conditions would be most relevant. Otherwise, determining grain size distributions from thermal inertia will be qualitative (or not well-constrained). The following list explores several possibilities:

1) NOT AMBIGUOUS: Small thermal inertia values (<200 or 300) unambiguously imply an abundance of very fine (< ~few hundred micron sized) grains. There is no other way to mimic small thermal inertias.

2) SOMEWHAT AMBIGUOUS: Medium thermal inertia values (a few hundred to ~1500). This range could be caused by several different types of surfaces, including mixtures of fine and coarse grains or indurated sediments. In all likely scenarios, the effective mean grain size would still be smaller than the thermal skin depth, which is a few cm on RQ36. One possible exception that will be important for us to investigate or put to rest is if the surface material for some reason has a low native thermal conductivity. A single sample of a single CM meteorite has had its thermal conductivity measured (Opiel et al.), and it was not very low. It may be useful for the team to follow up on this and measure thermal conductivities of more analog meteorites, particularly at low atmospheric pressure.

3) AMBIGUOUS, BUT USEFUL for deciding where not to go: High thermal inertia values (> about 1500) imply bedrock, a heavy degree of induration, or at least grain sizes larger than the thermal skin depth. It is more than likely that we would not want to sample such a region.

SPICE data will be required for all observations for both deriving thermal inertia and for making global and site-specific maps.

Expected Data Return by Mission Phase

Orbit Phase-B

Reconnaissance

(Site-Specific Thermal Inertia Maps): OTES will observe the candidate sampling ellipse(s). The data collected will consist of calibrated radiance spectra for each OTES integration over the sampling ellipse. This measurement will be at a single time of day. Temperatures will be derived from these radiance measurements. Thermal inertia will be derived for each OTES spot in the ellipse by varying thermal inertia in the thermal model to reproduce the temperature measured by OTES at the known time of day. The expected data product is a map of thermal inertias compiled from each OTES spot within the sampling ellipse.

Availability of Input Data Products

The basic input for all thermal inertia products is OTES data during the appropriate phase. In some cases, calibrated thermal radiance spectra will be used directly. In others, temperatures derived from the calibrated thermal radiance spectra will be used.

Temperature is retrieved from OTES calibrated radiance spectra using what is generically referred to as an emissivity-temperature (ET) separation algorithm. Numerous such algorithms exist in the literature for thermal IR data, and the ET algorithm for OTES already exists – we will use the code that was written for the Mini-TES predecessor instruments. This code exists at Arizona State University and is run using the open source Davinci software program available at: http://davinci.asu.edu/ . The data are in units of Kelvin.

Bond albedo at the spatial resolution of the OTES data (or better) is required as an input for thermal inertia retrieval. These may come from either OVIRS or OCAMS measurements of spectral reflected radiance from the asteroid. Surface slopes at the spatial resolution of the OTES data (or better) are also required. These may come from OLA measurements of the asteroid shape and topography. Time of day (and incidence, emission, and phase) for each OTES measurement is also required.

Data Processing Tasks

A mission-specific, validated thermal model will be finalized before arrival at RQ36. When the data are in hand, the model will be run for each OTES spot. Thermal inertia will be varied to find the best fit to the input data (with appropriate uncertainties carried through).

The primary input data products (the OTES calibrated radiances and temperatures) should be available within one to two hours of their downlink. Upon receipt of calibrated radiances and temperatures, it will be possible to calculate preliminary thermal inertia values. These preliminary thermal inertia values will be used to inform sample-site selection.

Final thermal inertia estimates, to be used for detailed science including Yarkovsky, will require the Bond albedo and surface slope inputs. Once those values are available, thermal models should take several minutes per OTES spot to run. Verification and validation times will likely take on the order of days. At this point in time, it is premature to estimate exactly when in the DRM the SAWG will be able to close out each science requirement completely (probably on the order of several weeks); a good portion of the scientific analysis will be tactical in nature, but that work likely will not result, for example, in publication-quality map products, which may take several months to complete.

Time-frame for Data Processing

It is difficult to estimate the time required at this point because the thermal model has not been finalized. However, based on experience with existing thermal models, it is expected that the thermal model will require at most several minutes per OTES spot. Including validation, it is anticipated that thermal inertia results should be available to the mission within several days, up to possibly two weeks.

There will likely be some delay due to time to derive Bond albedos and surface slopes from the OVIRS and OLA data, which may in turn delay derivation of final thermal inertia values.

Analysis and verification methods

The thermal model will be validated by its accuracy in reproducing measured temperatures during approach, preliminary survey, and detailed survey phases. Additional validation can come from checking consistency of high spatial resolution spot measurements with lower spatial resolution observations from previous phases that cover the same region of the surface. The approach phase results will be directly compared with thermal inertia estimates from the Spitzer Space Telescope, which will provide another degree of validation. Thermal inertia cannot be verified without knowledge of the absolute thermal inertia of the surface area observed by OTES at RQ36, which we will never have.

Validation of the algorithm against previously developed algorithms and expected results will come from application to existing data sets. These data sets may include telescopic observations of asteroids, spacecraft observations of asteroids (e.g., Dawn at Vesta) and comet nuclei (e.g., Deep Impact at Tempel 1) and possibly the Moon (LRO/Diviner) and Mercury (MESSENGER).

The algorithm flow will also be tested by blind tests, applying the algorithm to modeled data using our best understanding (shape, etc) of 1999 RQ36.

Software

A thermal model will be developed before arrival at the asteroid. The general form of the algorithm used will be 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 measurements.

For the Reconnaissance Phase data, thermal inertia will be varied to reproduce the temperature measured by OTES for each spot measurement.

There are several existing models that may be used; the science team has not yet decided on a specific model.