KISS Symposium: Capturing an Opportunity at Apophis

Final Report 2025

Keck
INSTITUTE FOR SPACE STUDIES

Courtesy NASA/JPL-Caltech

KISS Symposium: Capturing an Opportunity at Apophis

July 31 – August 1, 2024

Study Leads

Jose Andrade
Mechanical & Civil Engineering Department, California Institute of Technology
jandrade@caltech.edu

Carol Raymond
Jet Propulsion Laboratory, California Institute of Technology
carol.a.raymond@jpl.nasa.gov

Adriana Daca
Mechanical & Civil Engineering Department, California Institute of Technology
adaca@caltech.edu

Artur Chmielewski
Jet Propulsion Laboratory, California Institute of Technology
artur.b.chmielewski@jpl.nasa.gov

Study Report prepared for the W. M. Keck Institute for Space Studies (KISS)

We conducted the research in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Pre-Decisional Information For Planning and Discussion Purposes Only

DOI: 10.26206/m8mtp-68715

Recommended citation (long form):

Abell, P., Adell, P., Asphaug, E., Bell, J., Benner, L., Binzel, R., Bouman, K., Chodas, P., Davidsson, B., Dekany, R., DeMartini, J., Dotson, J., Elachi, C., Fesq, L., Golish, D., Haynes, M., Hirabayashi, M., Keane, J., Kim, Y., Laabs, M., Park, R., Plettemeier, D. 2025. “KISS Symposium: Capturing an Opportunity at Apophis.” A. E. Daca, J. E. Andrade, C. A. Raymond, and A. B. Chmielewski (Eds.) Report prepared for the W. M. Keck Institute for Space Studies (KISS), California Institute of Technology.

Recommended citation (short form):

Daca, A. E., Andrade, J. E., Raymond, C. A., and Chmielewski, A. B. (Eds.). 2025. “KISS Symposium: Capturing an Opportunity at Apophis.” Report prepared for the W. M. Keck Institute for Space Studies (KISS), California Institute of Technology.

Acknowledgements

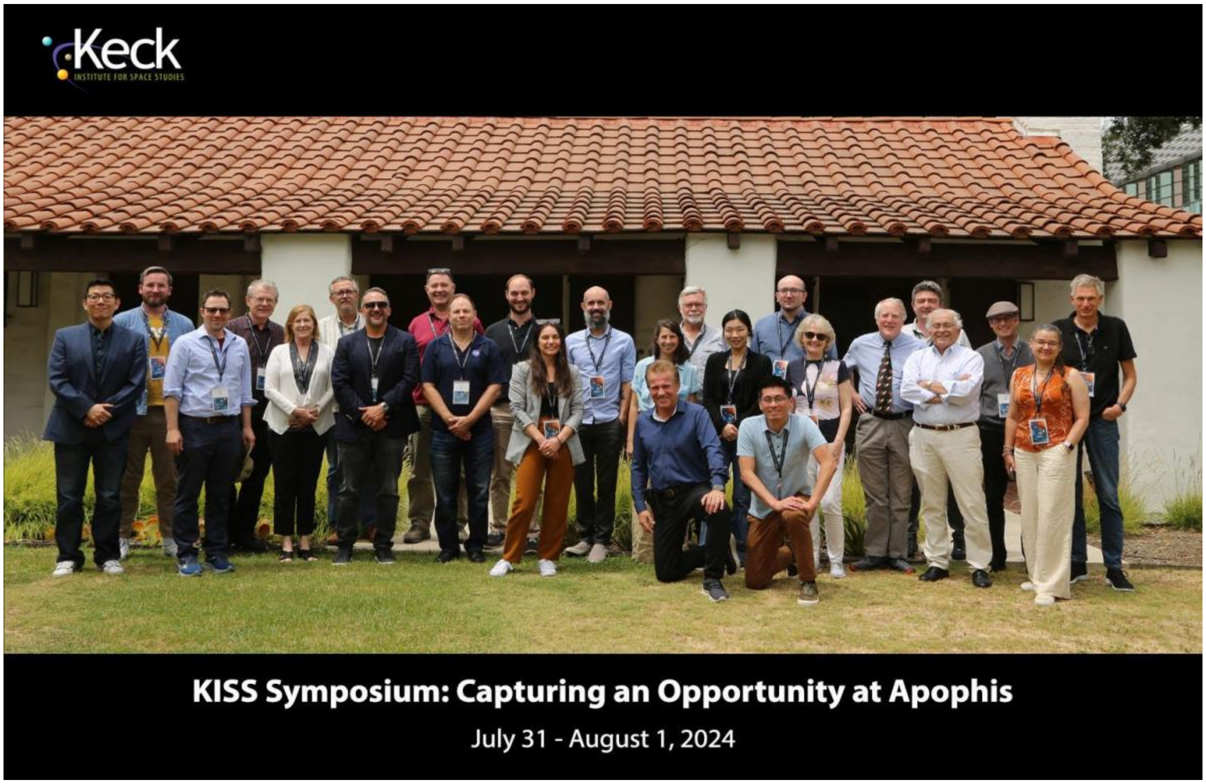
Prof. Bethany Ehlmann
Director

Harriet Brettle
Executive Director

Janel Wilsey
Editing and Formatting

Cover Image: NASA/JPL-Caltech

Workshop Participants



Jose Andrade
Caltech, Study Lead

Adriana Daca
Caltech, Study Lead

Paul Abell
NASA Johnson

Philippe Adell
JPL

Erik Asphaug
University of Arizona

Jim Bell
Arizona State University

Lance Benner
JPL

Richard Binzel
MIT

Katie Bouman
Caltech

Artur Chmielewski
JPL, Study Lead

Paul Chodas
JPL

Bjorn Davidsson
JPL

Rich Dekany
Caltech

Joseph DeMartini
University of Maryland

Jessie Dotson
NASA Ames

Charles Elachi
Caltech

Lorraine Fesq
JPL

Dathon Golish
University of Arizona

Mark Haynes
JPL

Toshi Hirabayashi
Georgia Tech

James Keane
JPL

Yaeji Kim
University of Maryland

Martin Laabs
TU Dresden

Ryan Park
JPL

Dirk Plettemeier
TU Dresden

Carol Raymond
JPL, Study Lead

Table of Contents

Table of Figures

1 Executive Summary

We held our two-day symposium “Capturing an Opportunity at Apophis” on July 31 and August 1, 2024. We organized the Symposium at Caltech and JPL to solicit feedback on a mission under development by Caltech, in collaboration with JPL, to rendezvous with Apophis before and escort it through its close Earth flyby in 2029.

We engaged a focused group of 26 individuals from academia and NASA in the discussions (see participant list). Our participants brought a broad range of expertise, including representation from both planetary science and engineering disciplines. Most participants were based in the US, except for two international participants.

We structured the Symposium as a mix of activities, including keynote talks, breakout sessions with fewer than ten individuals where we discussed predefined topics in detail, lightning talks, and group discussions.

Overall, the Caltech mission concept received very positive feedback from our group, and we recommend the following next steps:

- Develop a public communications strategy concerning the Apophis close approach
- Facilitate and participate in an Apophis session at LPSC
- Prepare a publication summarizing Apophis modeling and data
- Refine the Caltech mission science case
- Conduct trade studies to evaluate minor changes to the mission concept (radar geometry and frequency, adding more instruments)
- Coordinate timelines and objectives with other Apophis missions
- Ensure modelers, mission teams, and observational astronomers have open lines of communication, promptly sharing new data and predictions to inform mission planning and maximize science return.

Many of these follow-on activities are underway.

2 Motivation and Objectives

We primarily focused our “Capturing an Opportunity at Apophis” Symposium on evaluating the expected scientific return from a mission under development jointly by Caltech and JPL, along with industry partners, to rendezvous with Apophis before and escort it through its close Earth flyby. Before Caltech assumed mission leadership, it was known as DROID (Distributed Radar Observations of Interior Distributions) (Raymond et al., 2023).

Asteroid 99942, also known as Apophis, will make a close approach to Earth on April 13, 2029, coming within 31,860 kilometers of Earth, which falls within the geostationary belt. This presents a unique opportunity to study its characteristics and trajectory, enhancing our understanding of near-Earth objects and planetary defense.

We focused the scientific motivation for the mission on what we can learn regarding Apophis’s strength and interior structure from observations before, during, and after its closest approach, as well as an active bistatic radar experiment. We organized the Symposium to assess the adequacy of the planned instruments and operational strategy and to feed forward in designing and modeling the deflection of a hazardous asteroid. We also sought suggestions for additional measurements that would enhance the science return.

We established the following objectives for this KISS symposium:

- Review what we can learn from specific measurements at Apophis and how they will advance the science of planetary defense, using the Small Bodies Assessment Group's Apophis Specific Action Team Report (Dotson et al., 2022) as a backdrop
- Guide the Apophis mission planning team at Caltech and JPL to ensure the highest science return within cost and other constraints
- Define how we will utilize the open data to apply knowledge gained regarding the nature of rubble pile asteroids in general, and Apophis in particular, to reduce modeling uncertainties in designing a future deflection attempt

We sought the following outcomes from the Symposium:

A set of recommendations to the mission team regarding the highest priority instrument capabilities and data products to exploit the Apophis close flyby opportunity and improve readiness for mitigating a hazardous asteroid

A plan for follow-on activities to prepare for using the mission data to understand Apophis' interior and provide inputs to asteroid deflection modeling codes

3 Symposium Summary

We focused our "Capturing an Opportunity at Apophis" Symposium on evaluating the expected science return from a mission under development jointly by Caltech and JPL, along with industry partners, to rendezvous with Apophis during its close Earth flyby in 2029. Below are details regarding symposium attendance and demographics, proceedings, and outcomes.

3.1 Attendance and Demographics

We held the Symposium fully in-person except for one virtual keynote presentation. Our twenty-six attendees came from academia (mostly US-based, with two international attendees) and several NASA centers. The group included radar experts, planetary scientists, asteroid modeling experts, tomography specialists, the first author of the Apophis Specific Action Team Report (Dotson et al., 2022), members of the Hera, RAMSES, and OSIRIS-REx/APEX teams, and members of the Caltech/JPL Apophis mission team. You can see the complete list of participants in Section 3.1.

3.2 Symposium Proceedings

We held the Symposium on July 31 and August 1, 2024, at the Keck Center on Caltech's campus. You can find the full agenda in Appendix C. We began Day 1 of the Symposium with keynote talks about the Caltech Apophis mission plan, the importance of Apophis' interior, the SBAG Specific Action Team report and science outcomes, and predictions of Apophis' internal structure in response to its 2029 flyby. Following the keynote talks, we held breakout discussions. We pre-defined breakout topics for day 1, and the organizing team ensured each breakout group included at least one of our members. We allowed symposium attendees to join the breakout group of their choice. We summarize the topics, discussions, and conclusions of the breakout sessions held on the first day in Section 3.3.1. After the breakout sessions, groups reported on their discussions, and we held a group discussion. We wrapped up Day 1 of the Symposium by soliciting breakout topic suggestions for Day 2 and lightning talk sign-ups, followed by dinner at the Caltech Athenaeum.

We began Day 2 of the Symposium with a keynote talk on what we can learn from low-frequency radar observations of Apophis, followed by lightning talks on resurfacing modeling and estimates, COSYMO (the Complex Systems Modeling Group at Caltech[1]) modeling of Apophis, surface transponder for real-time rotational state measurements, and radar opportunities. Following the lightning talks, we held breakout discussions. We summarize breakout discussions for day 2 in Section 3.3.2. After the breakout sessions, groups reported back, and we held final group discussions, including a session to draft symposium outputs, recommendations for the mission team, and a plan for follow-up activities.

3.3 Symposium Outcomes

Below, we summarize our breakout session discussions

3.3.1 Day 1 Breakout Sessions

3.3.1.1 Feedback on the Caltech mission concept and how it fits with other missions to Apophis

Group Members

Philippe Adell, Jim Bell, Art Chmielewski, Richard Dekany, Lorraine Fesq (scribe), Dathon Golish, Yaeji Kim, Martin Laabs, and Dirk Plettemeier

General Feedback

Our group strongly supported the Caltech mission concept, with particular enthusiasm for its potential to leverage bistatic radar. We discussed the Caltech mission's capacity to differentiate itself, especially if RAMSES is fully funded, as it may carry a monostatic radar instrument. We recommended that the Caltech mission team focus on bistatic radar as a differentiating factor, offering unique insights into Apophis' interior structure. We further suggested adding a radar instrument to the mothership for enhanced penetration at lower frequencies, given available payload margins, and incorporating a lightweight thermal IR imager to provide additional data.

Coordination with Other Missions

We also recommended that the Caltech mission carefully align its objectives and timelines with those of other Apophis missions, including OSIRIS-APEX (DellaGiustina et al., 2023), RAMSES (Küppers et al., 2024), DESTINY+ (Sarli et al., 2018), and Janus (Scheeres et al., 2024). Below, we summarize our discussions and recommendations for coordinating with OSIRIS-APEX, RAMSES, and DESTINY+.

---

[1] https://cosymo.caltech.edu/

OSIRIS-APEX

OSIRIS-APEX will not be able to resolve Apophis until mid-May 2029, approximately one month after the Earth's Close Approach (ECA), and will arrive at Apophis in mid-June, approximately two months after the ECA. Operations will begin with shape and gravity mapping to inform orbit insertion. We consider it important that the Caltech mission arrive before ECA to observe Apophis' reaction to Earth's tidal forces, and to collect pre- and during-encounter data products that APEX will produce post-encounter, including (i) shape, gravity, and mass measurements, (ii) 50-cm pixel resolution global color map (multispectral VBW and X wavelengths), and (iii) 10-cm pixel resolution panchromatic map.

We recommend coordinating mapping resolution and ensuring that researchers can resolve expected changes. We also recommend cross-calibration, coordinated stereo imaging, and orbit coordination (staying out of each other's way). We see opportunities for differentiation, including bistatic radar for direct measurement of the interior, thermal imaging, and observations at geometries that APEX is less suited for, such as 0° phase angles (which RAMSES can observe effectively).

RAMSES

RAMSES may deploy a surface package before ECA, which may or may not include the following instruments: a seismometer, a transponder to monitor spin, and/or a monostatic radar instrument. If the RAMSES seismometer CubeSat lands at the end, we could achieve a much higher SNR. JuRa (Juventas radar) could interact with the two Caltech CubeSats to do multi-static radar. Finally, JAXA will provide a thermal imager.

DESTINY+

DESTINY+ would conduct a flyby ~1 year before ECA. This mission's dust analyzer and imaging capabilities (hi-res monochromatic camera, medium resolution 4-color camera) could offer early reconnaissance of Apophis, particularly in initial assessment of geologic diversity, spin-state refinements, surface color variations, and dust activity.

3.3.1.2 How could a pre-encounter Apophis mission be used to further planetary science and planetary defense objectives?

Group Members

Paul Abell, Richard Binzel, Paul Chodas, Jessie Dotson (scribe), Toshi Hirabayashi, Carol Raymond (session lead)

We concluded that a pre-encounter mission to Apophis offers a unique opportunity to significantly advance planetary science (PS) and planetary defense (PD) objectives. It would improve our understanding of potentially hazardous asteroid (PHA) formation and response to external perturbations like planetary tidal forces. Apophis' close Earth approach offers a very rare opportunity to use tidal forcing to probe an asteroid.

A pre-encounter Apophis mission would provide data to:

- Test models of impact-driven interior evolution (internal structure) (PS)
- Test resurfacing models to interpret how asteroids evolve in general (PS)

- Constrain internal strength properties (PS, PD)
- Inform models of response to deflection (kinetic impactor) (PD)
- Determine the cohesive strength of surface materials (PS, PD)

Such a mission would additionally provide ground truth for Earth-based observations. In situ observations can teach us about the strengths and limitations of ground-based data. It would allow us to evaluate our level of ignorance ("known unknowns") and discover the unexpected. We believe it is important to "know thy enemy". Furthermore, a pre-encounter mission would demonstrate international collaboration and spacecraft coordination in planetary defense, and has the potential to inspire public awareness and interest in space exploration, planetary defense, and the broader importance of asteroid research.

3.3.1.3 Data to modelling—what are the mutual benefits and potential gaps?

Group Members

Jose Andrade, Lance Benner, Adriana Daca, Mark Haynes, James Keane (scribe), Joe DeMartini, Ryan Park (session lead)

Our group first identified data available from ground-based observations and in-situ missions, then discussed how the data feeds into models and vice versa. We summarize these conversations below.

Ground-based Data

We will have light curves available starting in 2028, providing more information about Apophis' spin state and orientation. Our ground-based data also includes resolved imaging with 8-10 m telescopes with some modest number of pixels (i.e., as good as several meters at the closest approach). The European Extremely Large Telescope, being built in Chile, may be able to observe Apophis. This is a 39 m diameter telescope with first light planned for ~2028–2029. However, we mentioned this telescope's slew rate as a possible issue.

In situ Data

The DESTINY+ flyby in 2028 may provide a great "snapshot" of Apophis. We will also have gravity data from rendezvous missions (OSIRIS-APEX, RAMSES, and the Caltech mission). The gravity data will likely only be degree-2 unless there are ejected particles to observe.

Both ground-based and in situ Data

During in-situ measurements, we can make infrared observations from ground-based observatories and the OSIRIS-APEX IR spectrometer. We can also make radar observations both from the ground and in situ. We summarize our estimates for penetration depth and resolution from ground-based and in situ radar observations in Table 1. Note that penetration depth depends on the level of scattering, which depends on the asteroid properties, so we cannot accurately predict penetration depth before performing the radar measurements.

Table 1. Our estimates of penetration depth and resolution for ground-based and in-situ radar observations of Apophis.

Radar Observation Mode	Estimated Penetration Depth	Estimated Resolution
Ground-based	~10's of cm	~ 1 m
In-situ	• RAMSES: ~10's to ~100's of m • Caltech: ~100's of m (bistatic gives direct imaging of subsurface structure)	~ 10 m (both RAMSES and the Caltech mission)

Radar data within several weeks of the flyby will build on light curves and can inform shape and spin-state. We believe light curves and radar should be sufficient for shape and spin-state changes, regardless of spacecraft capabilities.

Models

Our models include physical or structural models (Brozovic et al., 2018) such as shape, orientation, spin, spin-state, and interior structure models (including density, shape, size, and distribution of boulders). We also include simulations (DeMartini et al., 2019; Kim et al., 2023; Hirabayashi et al., 2021) predicting spin changes, structural changes, and resurfacing due to the close approach.

Synergy Between Models and Data:

Spin-state and orientation are major inputs to simulations of the close approach. Orientation has huge implications for Apophis' rotation period change and surface effects. We need a timeline of orientation uncertainty before/through 2029, ideally within a few degrees. We noted that it is difficult to model non-principal axis rotation.

The shape model of Apophis also has significant implications for surface effects. As we refine the shape model, we can refine simulations. We require improved estimates of Apophis' orientation and shape to estimate where resurfacing might occur, allowing prioritization of imaging in these areas before/during/after the close approach. We may need models "ready to go" to "fire them up" when the flyby happens. We also require before and after images to infer surface material properties.

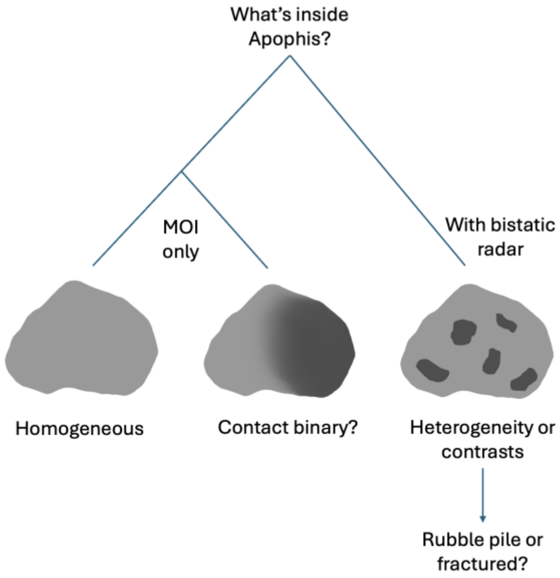


Figure 1. Adaptation of a whiteboard drawing by James Keane during our "Data to Modelling" breakout session illustrating how bistatic radar improves upon knowledge of the interior structure gained from MOI. MOI can differentiate between largely homogeneous (e.g., monoliths or rubble piles with similar composition throughout) and largely heterogeneous bodies (e.g., contact binaries). In contrast, bistatic radar can detect more detailed heterogeneity and identify the structure as a rubble pile or fractured body.

Image credits – Apophis shape outline: Brozovic et al., 2018.

Measuring spin-state changes through the flyby can also constrain the moments of inertia (MOI). This, coupled with gravity measurements, can give us the full MOI. Essentially, spin-state changes provide another source of information about the interior mass distribution to corroborate radar data interpretation. See Figure 1 for an illustration of what we can learn about the interior structure from MOI alone vs. MOI combined with bistatic radar. We also noted that things will probably happen that we haven't predicted.

Follow-up Questions

- J2 (oblateness) + MOI + shape will give information about the global structure.
- How do we compute β (momentum enhancement factor due to debris ejected from impact during a deflection attempt, e.g., as seen with the DART mission (Cheng et al., 2023))?
- What is stress?
- How well do we need to know physical parameters?

3.3.2 Day 2 Breakout Sessions

3.3.2.1 Communications—what are the key factoids/talking points for Apophis?

Group Members

Paul Abell, Jose Andrade, Jim Bell (scribe), Lance Benner, Richard Binzel (session lead), Paul Chodas, Dathon Golish, James Keane (in absentia)

Our breakout group discussed public communications around Apophis, consolidating messaging from different institutions, and "getting the facts straight." We summarize the discussions below with some additional notes from the editors.

Factoids

- Rarity of the Apophis flyby

  ("An object this large, coming this close...", "Once per ~millennium event...")
  The latest calculations estimate the Apophis close approach as a once-in-seven-thousand-year event (Farnocchia & Chodas, 2021)

- Apophis' orbit will change dramatically—not a threat for ~100 years, but we must keep tracking to understand its future hazard potential.
- Apophis' spin state will change—understanding this will help us model the internal structure and mitigation potential.
- The DART impact was an incredibly popular "public event" and provides a great model for public/media communications.
- Apophis won't be visible from North America during closest approach—manage expectations for US visibility.
- NASA (and maybe ESA, and maybe Caltech) are sending spacecraft to study Apophis, in addition to ground-based radar and optical telescopes
- NASA and the United Nations work to coordinate efforts to track PHAs like Apophis (TBD: PDC simulations; must be worded appropriately)

Potential Talking Points and Actions

- "We have a front row seat to observe a very rare natural phenomenon—a close approach"
- 'The US public wants to know that NASA is protecting the Earth"
- NASA/the community need to develop a simple Fact Sheet for common messaging/communications

Messaging Issues and Concerns

- Is the public/media only going to focus on the threat? Will there be a media frenzy? Can NASA/the community ensure that messaging is factual?
- Extraordinary opportunity to learn/teach about PHAs, and an extraordinary opportunity for misinformation

What are the questions the public is likely to ask?

- Why is this important to me/us? (Why should we care?)
- What is it? Where does it come from? (Size analogies: Empire State Building, Eiffel Tower, Rose Bowl)
- When did we see it coming? What is the government/NASA going to do about it? (surveys, radar)
- Is it really going to miss us? How do we know? (It has been tracked for decades; tracking uses the same math as Mars rover landings)
- Will it affect Earth-orbiting satellites?
- Will my cell service get cut off?
- How can we see it? (From where, how/when to view it, how long, etc.)

- How many Apophises are out there, and what is the government/NASA doing about them? (Vera Rubin/LSST, NEOSurveyor)

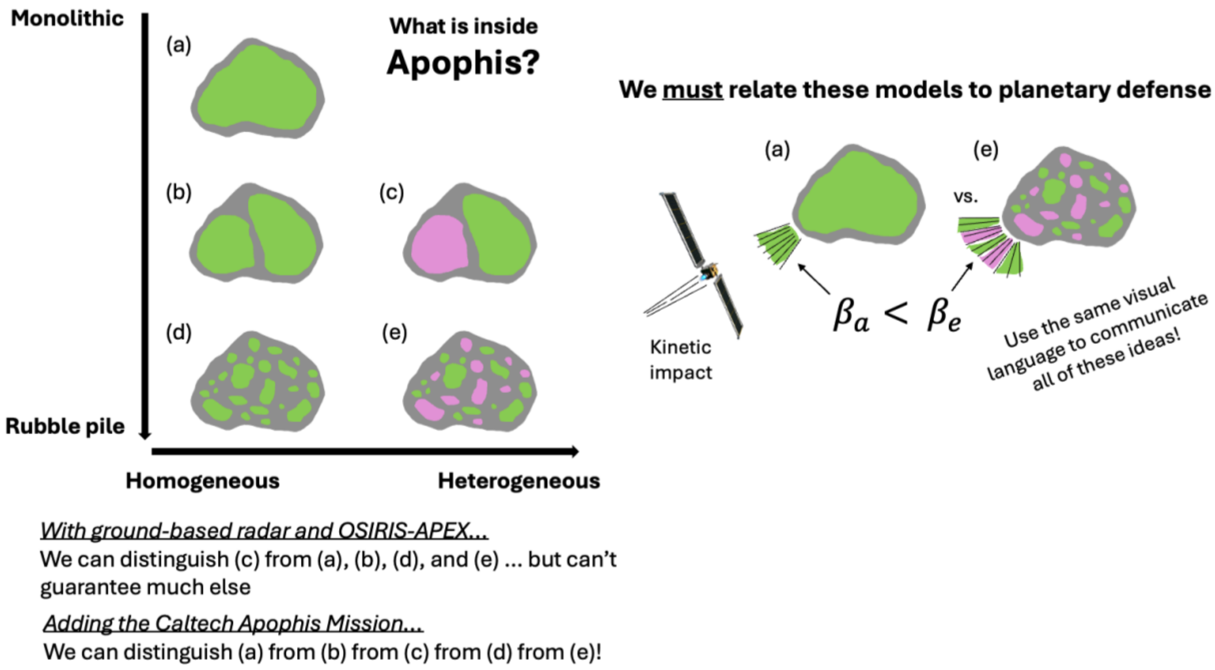


Figure 2. Adaptation of a sketch by James Keane illustrating a notional set of graphics that we could use to communicate both planetary science and planetary defense aspects of Apophis missions to the public. β is a factor describing momentum enhancement due to ejected debris imparting additional thrust to the asteroid during a deflection attempt. The diagram on the right shows that β would be larger for rubble pile asteroids, illustrating the importance of knowing what's inside an asteroid before attempting to deflect it.

Image credits -- Apophis shape outline: Brozovic et al., 2018; DART graphic (kinetic impactor): JHU/APL.

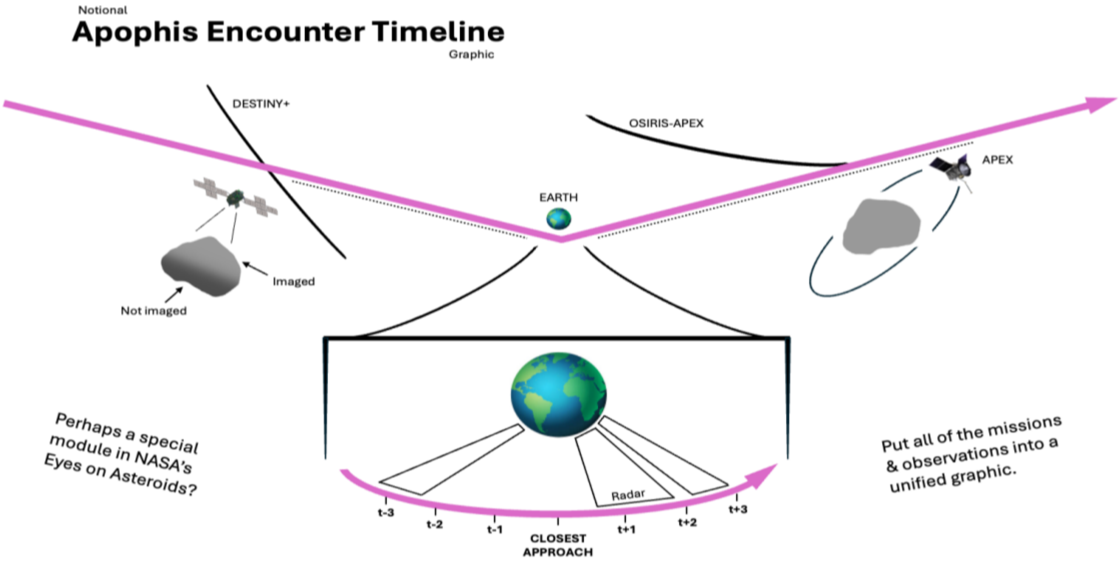
Recommendations from James Keane (in absentia):

Advocating for Apophis requires a set of key graphics, visuals, and other media that bridge all of the activities (OSIRIS-APEX, RAMSES, DESTINY+, Caltech Apophis mission, ground-based radar, and ground and space-based optical). Figure 2 shows an example of graphics illustrating planetary science and planetary defense concepts for public communication. Figure 3 provides an example of an Apophis encounter timeline, allowing the public to view information about all missions and observations in a unified graphic.

We recommend creating an app that would allow the public to easily figure out what's going on with Apophis, how to observe it, and the current status of Earth/space-based observations. We could base it on the 2024 Eclipse website[2], and perhaps NASA/OSIRIS-APEX could lead this effort. See Figure 4 for an illustration of a possible webpage and mobile application.

---

[2] https://eclipse-explorer.smce.nasa.gov/

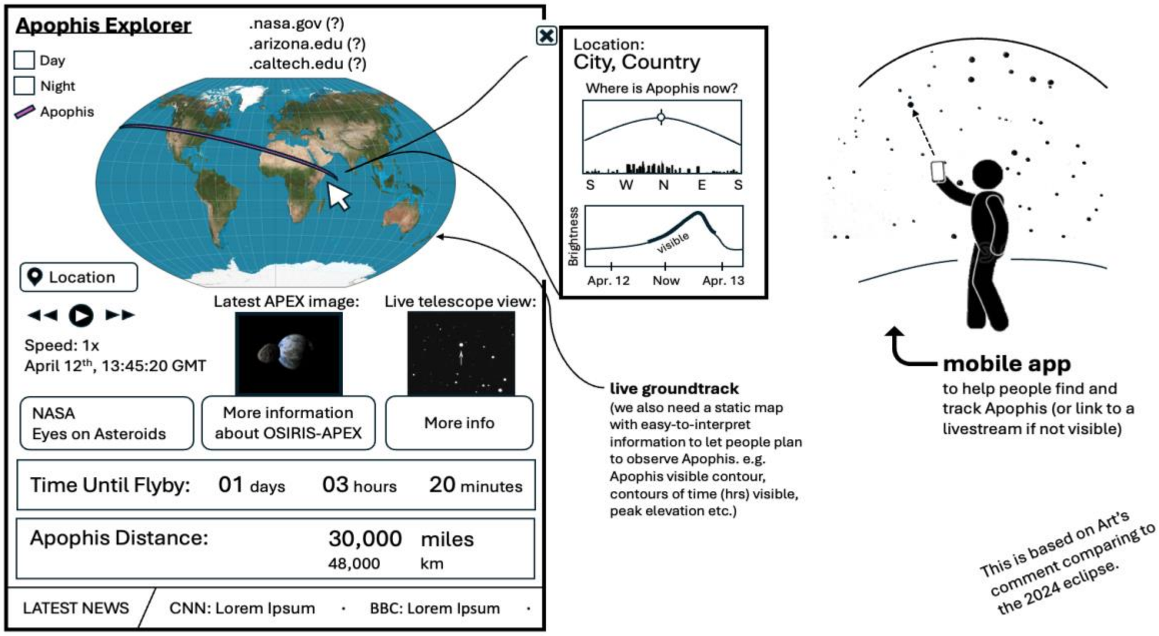


Perhaps a special module in NASA's Eyes on Asteroids?

Put all of the missions & observations into a unified graphic.

Figure 3. Adaptation of an illustration by James Keane showing a notional Apophis encounter timeline with all missions and observations in a unified graphic.

Image credits – Apophis shape outline: Brozovic et al., 2018; DESTINY+ graphic: Sarli et al., 2018; Earth: clipartpng.com/?2165,earth-png-clip-art; APEX graphic: NASA/University of Arizona/Lockheed Martin.



live groundtrack (we also need a static map with easy-to-interpret information to let people plan to observe Apophis. e.g. Apophis visible contour, contours of time (hrs) visible, peak elevation etc.)

mobile app to help people find and track Apophis (or link to a livestream if not visible)

This is based on Art's comment comparing to the 2024 eclipse.

Figure 4. Illustration adaptation by James Keane presenting a possible Apophis Explorer webpage and mobile application to help the public track and view Apophis.

Image credits – "Latest APEX image": NASA, Eyes on Asteroids; "Live telescope view": Rick Fienberg; Earth map: Daniel R. Strebe, 2011; Star map: Garrett Putman Serviss; LA skyline: https://ameico.com/products/the-line-city-skyline-silhouette-netsuite-copy?variant=39370217390138; man walking with phone: 1samoylow, dreamstime.com.

3.3.2.2 Mechanical properties of Apophis—how do we measure strength?

Group Members

Katie Bouman, Adriana Daca, Bjorn Davidsson, Joe DeMartini, Jessie Dotson, Toshi Hirabayashi (session lead), Yaeji Kim (scribe), Ryan Park, Carol Raymond

Our group discussed physical properties of asteroids related to their strength, the definition of asteroid strength in different contexts, and methods to measure asteroid physical properties/strength. We summarize the discussion below.

What physical properties are important to measure?

- Strength
- Gravity
- Mass
- MOI
- Rubble pile vs. monolithic
- Inferring strength, but can be independent

Density, porosity, surface composition, regolith, structural integrity, seismic properties

What is the definition of strength?

- Local (surface) vs. global strength (interior strength)

  Surface strength vs. interior strength: There is an order-of-magnitude difference between them

- Strength from the impact perspective vs. strength from the geologic perspective

Geological perspective: Cohesive strength, Young's modulus, compression, tension, shear
Impact physics perspective: Aerodynamic strength

- How to determine [β] (momentum enhancement factor, also discussed in Section 3.3.1.3)

How do we measure properties?

- Observe existing surface morphology.
- Observe tidal resurfacing (unique to Apophis)
- Observe/infer subsurface stratigraphy—crater wall or unique surface morphology exposing subsurface interior.
- Determine MOI (accuracy may be an issue)

Measure dielectric properties—for example, fragmentation after crater changes dielectric properties.

Example: APEX—firing jets to test and measure surface properties

We believe an asteroid's interior structure (rubble pile vs. monolithic) significantly determines its strength and response to a deflection attempt. Bistatic radar will allow us to determine the interior structure of Apophis and infer its strength. We can use observations of surface changes due to Earth's tidal forces to estimate the cohesive strength of the surface material, which is important for determining β (Stickle et al., 2022).

3.3.2.3 All the flavors of radar

Group Members

Philippe Adell, Art Chmielewski, Charles Elachi, Lorraine Fesq (scribe), Mark Haynes (session lead), Martin Laabs, Dirk Plettemeier

Our group considered two scenarios: 1) RAMSES does not carry a radar instrument, and 2) RAMSES carries JuRa (monostatic radar). In both scenarios, the Caltech mission carries a bistatic radar. We summarize ensuing discussions below, with some additional notes from the editors.

Scenario 1: RAMSES does not carry a radar instrument

In this scenario, the Caltech mission carries bistatic radar at 60 MHz or a different frequency, and RAMSES and Caltech carry out independent science. Our current baseline is for the Caltech mission to carry a modified version of JuRa (60 MHz) with the fewest modifications possible. We recommend holding the same frequency as the baseline for cost and heritage reasons, but still considering other frequencies.

Scenario 2: RAMSES carries JuRa (monostatic radar)

In this scenario, the Caltech mission carries bistatic radar (our current baseline is a 60 MHz modified version of JuRa). RAMSES and Caltech operations would need to be coordinated if using the same band.

Recommendations

We will need to modify the JuRa instruments to make the radars bistatic. We recommend considering different frequencies, holding 60 MHz as the baseline, and considering 30 MHz over the next 6 months to evaluate the technical/science trade. We also recommend considering equipping the mothership with a third radar. We could add a 60 MHz radar to the mothership as a baseline, and consider lower frequencies with larger antennas. The mothership can accommodate the weight and power (25–30 W peak power consumption). This would provide more coverage, better penetration, lower sampling requirements, higher likelihood of transmitting through the body, less scattering losses, and redundancy.

We also recommend landing one (or both, if radar on mothership) CubeSat(s) at the end of the mission, similar to CONSERT (a bistatic radar instrument onboard ESA's Rosetta spacecraft and its Philae lander (Kofman et al., 2020)). Our breakout group also recommended having just one CubeSat with radar and a mothership with radar to lower mission cost, although the measurement geometry is better with two CubeSats.

Why carry bistatic radar on the Caltech mission if RAMSES flies monostatic radar?

Bistatic radar provides greater science return compared to monostatic systems. Monostatic radar systems receive signals that are reflected or scattered back from the surface and interior of the asteroid. Thus, they are suited to detecting geological structure (Haynes et al., 2020). Bistatic radar systems, on the other hand, receive signals that have been transmitted through the asteroid. Dielectric permittivity can be estimated from the propagation delay, providing insight into the asteroid's composition.

Tomography combining measurements from multiple positions provides insight into heterogeneities in the asteroid's composition in addition to its internal structure (Haynes et al., 2020; Hérique et al., 2018). Bistatic radar allows discrimination between aggregate and monolith structures, estimation of the size distribution and internal structure of constituent blocks or heterogeneities, and offers valuable constraints for modeling composition and micro- and macro-porosity. Spatial variability in these properties reveals heterogeneities of parent bodies and highlights segregation mechanisms during cratering, disruption, and re-accretion processes (Hérique et al., 2018).

The Caltech mission plans to perform both monostatic and bistatic radar. Scientists can combine monostatic and bistatic radar measurement data to characterize Apophis comprehensively. Monostatic radar is the primary measurement source for characterization of the interior block and void size distributions at >= 25 m. Bistatic radar is the primary measurement source for determining differences in lobes (if the body is bilobed), global average permittivity to constrain bulk porosity, and the degree of material heterogeneity at hectometer scales.

Understanding the structure of both the deep interior and the subsurface is crucial for understanding and modeling planetary accretion and collisional history as well as constraining internal composition and porosity (Hérique et al., 2018). We have no direct knowledge of porosity distribution inside a small asteroid or how the interior structure relates to surface strength. These uncertainties pose risks to landing, sample acquisition, resource utilization, and planetary defense applications like predicting deflection outcomes or atmospheric disruption (Haynes et al., 2020; Hérique et al., 2018).

Bistatic radar is relatively new and untested. This is an important technology for planetary defense (PHA reconnaissance) and planetary science. Bistatic radar measurements were conducted at Comet 67P between ESA's Rosetta spacecraft and its Philae lander, but the mission did not obtain enough data to perform full tomography of the body (Kofman et al., 2020). Bistatic radar has never been performed on an asteroid before. The Hera mission, which launched on October 7, 2024, will reach the Didymos/Dimorphos binary asteroid system in December 2026 and will perform monostatic radar (Michel et al., 2022), mainly focusing on the orbiting body, Dimorphos, which the DART mission impacted in 2022 (Cheng et al., 2023).

Furthermore, bistatic radar has never been performed using two CubeSats. Using two CubeSats (rather than a lander and a spacecraft, as Rosetta did) allows for spatial coverage of the entire asteroid. Bistatic radar also provides redundancy with the RAMSES mission and its JuRa instrument.

Improvement Options

- Adding radar to the mothership to achieve a multistatic configuration and gain redundancy
- Changing the frequency to be more aligned with the size of Apophis

In this case, the antenna size would potentially need to be doubled

We recommend conducting a trade study comparing the benefits of changing the frequency vs. antenna size requirements

4 Conclusions and Recommendations

The 'Capturing an Opportunity at Apophis' Symposium sparked many fruitful discussions and helped solidify directions for future work. Overall, the Caltech mission concept received strong support from symposium participants, and the group developed a plan for follow-on activities. Below is a summary of the recommendations, next steps, and outputs that will be generated from the Symposium.

4.1 Talking point development for the Apophis close approach

- As discussed in Section 3.3.2.1, the community must consolidate public messaging around Apophis.
- We suggested that an effort should be made to develop talking points around the Apophis close approach, focusing on outreach and engaging underrepresented communities.
- The Planetary Society's Apophis FAQ[3] site has been suggested as the primary resource for public messaging.

4.2 Facilitate and participate in Apophis Session at LPSC

- We suggested that a session on Apophis and/or planetary defense be organized at LPSC 2025
- Symposium participants were encouraged to submit abstracts on Apophis and planetary defense to LPSC 2025

4.3 Modeling and data summary leading to a publication

- We recommend that a summary of Apophis modeling and data be compiled, leading to a publication
- Several symposium participants have begun work on a review paper focusing on knowns, unknowns, current science knowledge gaps, and how the Caltech mission fills those gaps

4.4 Caltech mission science case refinement

- We recommend that the study lead refine the Caltech Apophis mission science case, considering how the Caltech mission fits within the landscape of others (RAMSES and OSIRIS-APEX), focusing on bistatic radar as a differentiating factor offering unique insights into Apophis' interior structure.
- The science case has been refined and was presented to the community at the 56th Annual Meeting of the AAS Division for Planetary Sciences in October 2024 (Daca et al., 2024) and at the SBAG meeting in January 2025 (Raymond et al., 2025)

4.5 Other Recommendations

- Add radar to the mothership
- Land one (or both, if radar on mothership) CubeSat(s) at end of mission
- Consider having just one CubeSat with radar and a mothership with radar to lower cost

---

[3] https://www.planetary.org/articles/will-apophis-hit-earth

- Conduct a trade study regarding radar frequency
- Incorporate a lightweight thermal IR imager
- Carefully align objectives and timelines with other missions, including OSIRIS-APEX, RAMSES, DESTINY+, and JANUS.
- Have models ready to update predicted resurfacing locations as orientation and shape estimates are refined leading up to ECA, so that imaging efforts before/during/after the close approach can focus on areas where surface activity is predicted to occur.

5 Acronyms

AAS	American Astronomical Society
ECA	Earth Closest Approach
CONSERT	Comet Nucleus Sounding Experiment by Radiowave Transmission
DART	Double Asteroid Redirection Test
DESTINY+	Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science
ESA	European Space Agency
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
JuRa	Juventas Radar
LPSC	Lunar and Planetary Science Conference
MOI	Moment of inertia
NASA	National Aeronautics and Space Administration
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer
OSIRIS-APEX	Origins, Spectral Interpretation, Resource Identification, and Security – Apophis Explorer
PD	Planetary defense
PDC	Planetary Defense Conference
PHA	Potentially hazardous asteroid
PS	Planetary Science
RAMSES	Rapid Apophis Mission for Space Safety
SBAG	Small Bodies Assessment Group
SNR	Appendix A Signal-to-noise Ratio
TBD	To be determined

6 References

Brozović, Marina, et al. "Goldstone and Arecibo radar observations of (99942) Apophis in 2012–2013." Icarus 300 (2018): 115-128.

Cheng, Andrew F., et al. "Momentum transfer from the DART mission kinetic impact on asteroid Dimorphos." Nature 616.7957 (2023): 457-460.

Daca, Adriana, et al. "Capturing an Opportunity at Apophis." AAS/Division for Planetary Sciences Meeting Abstracts. Vol. 56. No. 8. 2024.

DellaGiustina, Daniella N., et al. "OSIRIS-APEX: an OSIRIS-REx extended mission to asteroid apophis." The Planetary Science Journal 4.10 (2023): 198.

DeMartini, Joseph V., et al. "Using a discrete element method to investigate seismic response and spin change of 99942 Apophis during its 2029 tidal encounter with Earth." Icarus 328 (2019): 93-103.

Dotson, Jessie L., et al. Apophis specific action team report. Lunar Planetary Institute, 2022.

Farnocchia, Davide, and Paul W. Chodas. "A Recipe for Estimating the Frequency of Asteroid Close Approaches to Earth." Research Notes of the AAS 5.11 (2021): 257.

Haynes, Mark, et al. "Asteroids Inside Out: Radar Tomography." (2020). Community White Paper for the Planetary Decadal Survey, 2023-2032.

Hérique, Alain, et al. "Direct observations of asteroid interior and regolith structure: Science measurement requirements." Advances in Space Research 62.8 (2018): 2141-2162.

Hirabayashi, M., Y. Kim, and M. Brozović. "Finite element modeling to characterize the stress evolution in asteroid (99942) Apophis during the 2029 Earth encounter." Icarus 365 (2021): 114493.

Kim, Yaeji, et al. "Tidal resurfacing model for (99942) Apophis during the 2029 close approach with Earth." Monthly Notices of the Royal Astronomical Society 520.3 (2023): 3405-3415.

Kofman, Wlodek, et al. "The interior of Comet 67P/C–G; revisiting CONSERT results with the exact position of the Philae lander." Monthly Notices of the Royal Astronomical Society 497.3 (2020): 2616-2622.

Küppers, Michael, et al. Status of ESA's Rapid Apophis Mission for Space Safety (RAMSES) Concept. No. EPSC2024-199. Copernicus Meetings, 2024.

Michel, Patrick, et al. "The ESA Hera mission: detailed characterization of the DART impact outcome and of the binary asteroid (65803) Didymos." The planetary science journal 3.7 (2022): 160.

Raymond, Carol A., et al. "The DROID Mission Concept to Characterize Apophis Through Its 2029 Earth Closest Approach." LPI Contributions 2851 (2023): 2533. Raymond, Carol A., et al. "The Caltech Mission to Apophis." 32nd Meeting of the NASA Small Bodies Assessment Group (SBAG) (2025), JPL Open Repository. DOI: 10.48577/jpl.EZBRJJ

Sarli, Bruno Victorino, et al. "DESTINY+ trajectory design to (3200) phaethon." The Journal of the Astronautical Sciences 65 (2018): 82-110. Scheeres, D. J., et al. "Janus: Future opportunities relevant to Apophis." LPI Contributions 3006 (2024): 2071.

Stickle, Angela M., et al. "Effects of impact and target parameters on the results of a kinetic impactor: predictions for the Double Asteroid Redirection Test et(DART) mission." The planetary science journal 3.11 (2022): 248.

7 Workshop Agenda

Wednesday July 31, 2024 Keck Center Think Tank, Room 155 - Caltech

Time	Event	Speaker
8:30 - 9:00	Coffee and Refreshments	
9:00 - 9:15	Workshop Logistics and Introduction to KISS	Harriet Brettle
9:15 - 9:45	Participant Introductions	Harriet Brettle
9:45 - 10:15	Vision and goals for this Symposium	• Carol Raymond • Jose Andrade
10:15 - 10:45	Break	
10:45 - 11:20	Keynote #1 – Introduction to the Caltech Apophis mission plan	• Carol Raymond • Jose Andrade
11:20 - 12:00	Keynote #2 – The Importance of Apophis' Interior	Erik Asphaug
12:00 - 1:00	Lunch	
1:00 - 1:45	Keynote #3 – SBAG Specific Action Team report and science outcomes	Jessie Dotson
1:45 - 2:30	Keynote #4 – Predictions of Apophis's internal structure in response to its 2029 flyby	Toshi Hirabayashi
2:30 - 3:30	• Breakout discussion sessions: • Feedback on the Caltech mission concept and how it fits with other missions to Apophis • How an Apophis mission will be used to further planetary science and planetary defense objectives • Data to modelling – mutual benefits and identification of potential gaps	Groups
3:30 - 4:00	Break	
4:00 - 5:00	Report outs from breakout groups and Plenary discussion	Team Leads
5:00 - 5:30	Solicitation of Lightning Talks and Breakout Group topics for day 2	Team Leads
5:30 - 6:00	Pack up and walk to the Athenaeum	All
6:00	Dinner at the Athenaeum	

Thursday, August 1, 2024 - Keck Center - Think Tank, Room 155

Time	Event	Speaker
8:00 - 8:30	Institute Opens – FREE THINK TIME	
8:30 - 9:00	Coffee and Refreshments at Keck Center	
9:00 - 9:15	Logistics and Team Lead Goals for the Day	Harriet Brettle and Team Leads
9:15 - 09:45	Keynote Talk # 5 – What can be learned from low-frequency radar observations of Apophis?	Mark Haynes
9:45 - 10:30	Lightning Talks • Resurfacing Modeling and Estimates • COSYMO Modeling of Apophis • Transponder on Surface for RT Rotational State Measurements • Radar Opportunities	• Joe DeMartini • Adriana Daca • Martin Laabs • Lance Benner
10:30 - 11:00	Break	
11:00 - 12:00	• Breakout discussion sessions – topics • Communications – what are the key factoids/talking points for Apophis? • Mechanical Properties of Apophis – how do we measure strength? • All the flavors of radar	Groups
12:00 - 12:30	Report outs from breakout groups and Plenary discussion	Groups
12:30 - 2:00	Group Picture and Lunch	
2:00 - 3:00	• Group Pulse • Open Discussion of Breakout Group Recommendations and Path Forward	All
3:00 - 3:30	Informal Small Group Collaboration Time	All
3:30 - 4:00	Break	
4:00 - 5:00	• Final Session drafting Symposium outputs: • Set of recommendations to the mission team • A plan for follow-on activities	Groups
5:00	Institute Closes	