Detectability of Earth’s Temporary Natural Satellites with LSST

Mikael Granvik
Department of Physics, U Helsinki, Finland
in collaboration with
B. Bolin (U Hawaii), R. Jedicke (U Hawaii), G. Fedorets (U Helsinki)
WHAT?
MINIMOONS IN COMPARISON TO THE MOON

- small
- highly inclined
- highly eccentric
- large semi-major axis
- temporarily captured, but...
- make at least one revolution around Earth
NEAR-EARTH OBJECTS & MINIMOON CAPTURE

not to scale

Granvik - Earth's minimoons – Cambridge, UK

2013 Sep 9-12
NEAR-EARTH OBJECTS & MINIMOOON CAPTURE

Granvik - Earth's minimoons – Cambridge, UK

2013 Sep 9-12
NEAR-EARTH OBJECTS & MINIMOON CAPTURE

not to scale

Hill Sphere ($R_H$)

L2

L1

to Sun

Granvik - Earth's minimoons – Cambridge, UK

2013 Sep 9-12
MINIMOON TRAJECTORIES

2013 Sep 9-12
Granvik - Earth's minimoons – Cambridge, UK
MINIMOOON TRAJECTORIES

astronomical units

Granvik - Earth’s minimoons – Cambridge, UK
MINIMOON TRAJECTORIES

Granvik - Earth's minimoons – Cambridge, UK

2013 Sep 9-12
MINIMOON R-\theta

Geocentric Ecliptic Longitude (degrees)

2013 Sep 9-12
Granvik - Earth's minimoons – Cambridge, UK
Minimoon R-θ

cleared by Moon

Earth & Moon not to scale
MINIMOONS ON THE SKY

Fig. 1.— TCO normalized sky-plane residence distribution with no restrictions on apparent magnitude or rate of motion in an opposition-centric ecliptic reference system. Negative opposition-centric longitudes are west of opposition. The values are the fraction of the population in $3^\circ \times 3^\circ$ bins.
Mean life = 9.5 months

Mean # of orbits = 2.9

Mean lifetime = 9.5 months
MINIMOON EVIDENCE

Spacewatch circa 1994
1994 DoD SPACE SURVEILLANCE NETWORK

• discovered 3 ‘mystery objects’ during a ‘small object test’
• orbits with ‘no known human activity’
• 10-20 cm if metallic
  – larger if stone
• match minimoon orbits
• ‘This class of debris object may warrant further evaluation.’
2006 RH$_{120}$

Catalina Sky Survey

Earth’s first known minimoon

3 meters

* not a real image
MINIMOON METEOR?

1% of minimoons impact Earth’s atmosphere

Brown et al. 2012
HOW MANY MINIMOONS ARE THERE?

2

0.5 meter dozen

one every 50 years

2013 Sep 9-12
Granvik - Earth's minimoons – Cambridge, UK
How Many Minimoons Are There?

These estimates are based on extrapolations – we don’t know the actual orbital distribution of objects in this size range!
Why?
Telescopic Observations Provide Context, Laboratory Analyses Provide Details
Cosmochemists prefer samples of all asteroid types to, e.g., understand the asteroid-meteorite connection.

Not a cosmochemist!
CHALLENGES WITH ASTEROID SAMPLE RETURN MISSIONS

- limited target choice
- small returned mass
- long & expensive missions

NASA OSIRIS-REx

JAXA Hayabusa-2

http://www.j-spec.jaxa.jp/e/activity/hayabusa2.html
MINIMOONS PROVIDE:

• multiple targets and missions
• massive samples
• ultra-low delta-v
• cheaper missions
  —much less cost/mass
How?
THE GRAND PLAN

Earth Captures a Minimoon

Supplied orbit image of asteroid 1999 AN11 - Bowell et al.

K. Tsuchiya, UH HA

Simulated minimoon trajectory

q_D (LD)

q_T (LD)

The Grand Plan includes:

- Earth Captures a Minimoon
- Diagrams and images of space equipment and configurations
- A man holding a model of a planetary object
DISCOVERING MINIMOONS

not captured, too faint
captured, too faint
captured, less faint, fast

Optical system needs to provide
• wide coverage
• high sensitivity
• short exposures
**Observable Minimoon SFD**

![Graph showing the distribution of minimoons in terms of diameter and absolute magnitude. The graph compares the number of objects detected by different surveys (LSST, HSC, PS1, ATLAS) across various absolute magnitude values.]
Cut-offs employed:
Apparent mag: 24.7 V  Rate of motion: 10 deg/day
LSST HARDWARE + IPP CAN DETECT MINIMOONS, BUT CAN LSST SURVEY CADENCE + MOPS DISCOVER THEM?
Test Capabilities of Existing Algorithms with PS1 MOPS

Pipeline Design

The MOPS pipeline operates by using a linear nightly processing model in which data are ingested and processed in the order they are observed. Nightly data are ingested from a live transient detection stream and discrete processing stages are executed until all processing is completed for the entire night. Many of the MOPS processing stages build upon data structures created from prior nights. Out-of-order processing can be handled in a limited number of modes of operation as necessitated by the current Pan-STARRS1 system. Enhancements to the MOPS pipeline to perform full processing on out-of-order data while preserving essential MOPS efficiency computations is still under development. The fundamental difficulty in out-of-order processing lies with the amount of data that needs to be recomputed when new observations are inserted in the middle of the temporal data stream. The existing MOPS design prefers nights to be added incrementally; insertion into the middle of the existing dataset essentially forces all subsequent nights to be reprocessed.

Pipeline resource scheduling and management are handled by the Condor high-throughput-computing software (Thain et al. 2005). Condor provides effective, flexible management of hardware resources that need to run the MOPS production pipeline simultaneously with test simulations or experimental processing of MOPS data.

The MOPS pipeline is designed to be reliable in the event of cluster resource limitations and hardware failure (e.g., power outages, node failures). Working in tandem with Condor’s process management infrastructure, the MOPS pipeline can be restarted easily at the proper point in the pipeline with all data structures intact. As an example, in 2011 the MOPS production MySQL database suffered a complete failure yet the MOPS pipeline was back online within hours after restoring the database from a backup.

The discussion of each element of the MOPS pipeline is deferred to § 5 where we follow the processing of detections from beginning to end of the pipeline and quantify the performance of each step using Pan-STARRS1 data.

Hardware

The Pan-STARRS1 MOPS runs on a modest cluster of standard Linux rack-mounted computers. MOPS makes no special demands on hardware so long as the cluster can keep up with incoming data. During early stages of MOPS design, we based hardware requirements on estimates for transient detections stored and orbits computed per night of observing for a Pan-STARRS4-like mission, and scaled down the storage for Pan-STARRS1 volumes. The current Pan-STARRS1 processing hardware is capable of keeping up with a Pan-STARRS4-like data stream, except for the storage of detections in the database. Table 2 lists the major hardware components employed by the Pan-STARRS1 MOPS production processing cluster, and Figure 2 shows the functional relationships between the MOPS hardware components.

To ensure against most of the types of disk failures we are likely to encounter, we use a multiple-parity redundant array of...
ALTERNATIVE APPROACH:
STATISTICAL INTER-NIGHT LINKING ALGORITHM
ALTERNATIVE APPROACH: STATISTICAL INTER-NIGHT LINKING ALGORITHM

rigorous & nlogn
APPLICATIONS TO EXTREME CASES

Spitzer-centric view

Geocentric view

Ecliptic y-axis [AU]

Ecliptic z-axis [AU]
THE NEXT STEPS (CONCERNING MINIMOONS)

• Produce large set of synthetic minimoons that can be processed by PS1 and LSST MOPS.
• Verify that LSST survey cadence is suitable for discovery.
• Test capability of (mainly k-dim tree linking) algorithms in PS1 and LSST MOPS to discover them.
• If MOPSs fail, then verify that the existing statistical code can do it.
• Optimize statistical codes by utilizing parallel processing architectures (GPU, Xeon Phi, etc) and developing faster numerical methods.
• We have a grad student working on all this.
GRAVITY ONLY VS. GRAVITY & RADIATION PRESSURE

Orbit for: 2006RH120

Lunar distances (x)
Lunar distances (y)
Lunar distances (z)

Gravity only

Gravity + radiation pressure

OORB
JPLHOR
REFERENCES


• Chyba et al. (2013), ‘Time-minimal orbital transfers to temporarily-captured natural Earth satellites’, Journal or Industrial and Management Optimization.

