
Introduction: Gravity science is among the most efficient means of investigating planetary interiors from orbit. However, it is not used as extensively as it might be, particularly in the outer solar system because of conflicts between the radio science and other vital investigations, which have incompatible pointing needs. Gravity science is traditionally done using Doppler tracking of the flight system from the DSN. This requires that a spacecraft antenna be directed towards Earth; and in the Saturn system and beyond, only a high-gain antenna (HGA) would be able to close the link. Thus, in order to track the trajectory of the flight system as it passes by a target, either the HGA must be gimbaled to keep Earth in the field of view, or the entire flight system must be oriented in order to maintain the link. The former is costly and complex, while the latter trades against other investigations that require certain instruments to be pointed to nadir or ram. Moreover, the low altitudes that are helpful for gravity science may interfere with other science goals or impose risk or complexity in operations.

Here, we obviate these challenges by physically decoupling the gravity science investigation from the rest of the flight system. The Subsurface Water Assessment and Reconnaissance of Moons (SWARM) mission concept consists of a carrier spacecraft (or “queen”) with an HGA for communicating with Earth, two low-gain antennas (LGA) providing omnidirectional coverage. Accompanying the queen is a fleet of cubesats or smallsats (“workers”) carrying no instrumentation other than a radio science beacon and potentially a laser or microwave ranging system. The “hive” (queen + workers) are launched together, cruise to a target planetary system and enter orbit about the planet. The hive orbits the planet, and performs close flybys of the icy moons (similar to the Cassini tour of the Saturn system).

On approach to each encounter, the queen spacecraft releases a pair of smallsat workers on a close flyby in a leader-follower configuration. During the pass, the pair transmit and receive carrier and ranging from each other, which they retransmit to the queen (as shown in Figure 1). The queen later relays the data to Earth using the HGA after the encounter during a standard downlink. Each pair of smallsats is intended to be used only on a single encounter, powered by a battery for several hours of data collection.

This approach has a number of advantages:

• By using the queen as a relay, the workers need not communicate directly with Earth. This eliminates the need for HGAs on the workers and commensurate power for RF transmission, and reduces the overall size of the workers.
• The HGA need not be pointed at Earth during the pass. The data can be returned during nominal downlink periods.
• Short-range, two-way communication between the workers and queen eliminates the need for an ultra-stable oscillator as a frequency reference.
• Omnidirectional coverage with LGAs enable the queen to receive transmissions from the workers while in any orientation, allowing any payload.
• Single-use workers operate on batteries without need for onboard power generation.
• Reducing the size and complexity of the workers allows us to carry many of them. A fresh pair can be deployed at every encounter with a planetary body without expending substantial resources.
• The workers can safely pass much closer to a planetary body than the main spacecraft would normally fly without endangering the rest of the mission [1, 2]
• SWARM could either be a stand-alone mission, or be included as an investigation on part of a larger mission with the primary spacecraft taking the role of the queen.

Mission Concept: Exploration of the outer solar system over the past few decades has revealed a number of ocean worlds, including Europa, Ganymede, Enceladus, and Titan [1]. Most of these are large icy moons, however Enceladus has shown that even the smaller “mid-size” moons may harbor subsurface oceans [2]. A number of additional candidate ocean worlds, such as of Triton and Pluto demonstrate that icy bodies may be able...
to maintain liquid water in their interiors long after tidal heating has diminished [3]. Thus, there may be more ocean worlds in the solar system than have currently been identified.

In particular, the Saturn and Uranus systems each host several mid-sized (~400–1500 km diameter) moons that may be ocean world candidates. Confirmation of these oceans would require probing their interiors. From space, there are three primary methods by which this could be accomplished [4]. First, a magnetometer could detect an induced magnetic field in a saline subsurface ocean. Second, ice-penetrating radar could detect an ice-water interface. Third, measurements of the gravity field can identify tidal deformations of the ice shell and internal mass anomalies that reveal the ice shell thickness and mass density distribution.

Magnetic induction is how Europa’s ocean was discovered [5], but Saturn or Uranus have far weaker magnetic fields than Jupiter and may not induce as strong a signal in their moons’ oceans. Radar sounding has the potential to detect an ice water interface, but ice-penetrating radars require large antennas and substantial power. Gravity science requires no hardware above the spacecraft’s telecom capabilities, but can present operations challenges with pointing requirements that may preclude other measurements in the nadir or ram directions. A few dedicated gravity science passes were performed on Cassini, and these confirmed the presence of oceans on Enceladus and Titan [6,7].

The goals of SWARM include:
- Investigate the interiors of mid-sized moons
- Identify potential new ocean worlds
- Measure tidal variations in the shapes and gravity of these moons
- Detect seafloor topography
- Constrain knowledge of the strength and thickness of the ice shells.

SWARM will conduct this geophysical investigation of mid-sized icy moons using a combination of Doppler tracking and ranging in order to characterize the gravity anomalies that cause variations in the orbits of the spacecraft. Visible imaging will provide context, allowing us to tie gravity measurements to surface features. Examples of interior structures that could be identified using line-of-sight gravity measurements are illustrated in Figure 2.

**Figure 2:** Examples of subsurface structures that may produce detectable gravity anomalies: seamounts at the bottom of the liquid ocean; diapirs, brine pockets, and melt pockets in the solid ice.

Although Cassini recently explored the Saturn system, it had a very broad set of objectives. Despite numerous flybys of the icy moons, Cassini had limited opportunities to investigate the interiors of those bodies. The gravity measurements that were made confirmed one subsurface ocean and suggested others, demonstrating the effectiveness of this technique. The Uranus system has not been visited since Voyager 2’s flyby, but the images of the five largest moons reveal landforms that may be evidence of subsurface oceans, and is in need of further investigation. Either the Saturn or Uranus system would present an ideal target for a gravity science mission to search for ocean worlds. SWARM would address all three science goals for studies of planetary satellites in the Visions and Voyages Decadal Report [8], and would contribute to two of the three “big” questions highlighted in OPAG’s 2019 Report [9].