Gravity Science Requirements for Future Icy/Ocean Worlds SmallSats Missions

AE 8900 MS Special Problems Report
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December 20, 2020

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Over the past decade, there has been growing interest in developing mission concepts designed to explore the icy satellites of the gas giants Jupiter and Saturn, some of which harbor a subsurface ocean and are geologically active, such as Europa, Enceladus and Titan. While the Galileo and Cassini missions provided data that helped improve our understanding of these bodies, these missions were not dedicated for icy moons exploration and hence many questions were left unanswered. These bodies are complex and less understood than terrestrial planets and have unique features of their own. In addition, the presence of an ocean makes these bodies key destinations in the search for life elsewhere in the Solar System. Measurement of a celestial body's gravity field provides fundamental information on the body's internal structure including mass distribution, tectonic process and thermal evolution. Prior gravity science experiments have enabled the development of gravity field models of various bodies such as Mars, Mercury, Jupiter, Europa, Saturn, Titan and Enceladus. While gravity science alone cannot constrain the interior models due to its non-uniqueness, gravity data combined with additional measurement data such as altimetry and topography mapping can provide a better understanding of these complex worlds and their interactions with their parent planet. This paper discusses the current knowledge and unknowns of icy moons with a focus on Europa and Enceladus and proposes science objectives needed for a SmallSat icy moons exploration missions and potential measurement techniques for improved gravity science return.

I. Introduction

Over the past two decades, research into planetary bodies in the outer Solar System especially the satellites of the large planets such as Europa, Enceladus, Ganymede and Titan, has suggested that these bodies may harbor a subsurface ocean underneath their icy shells[1–5]. As a result icy moons such as Europa, Enceladus and Titan have been considered top targets in the search for life elsewhere in the solar system by the National Aeronautics and Space Administration(NASA). These bodies are complex and less understood than terrestrial planets and have unique features of their own with Europa's widely distributed and visible cracks and streaks; geological activity in the form of active

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plumes at Enceladus and thick atmosphere and smooth surface at Titan. A number of mission studies [6–12]have been conducted for the exploration of these bodies in the past, some of which are being developed to be launch this decade(*Europa Clipper, Dragonfly, Europa Lander*). Current exploratory missions to outer planetary systems have been in the NASA Flagship/New Frontiers mission class consisting of large monolithic satellites with multiple scientific instruments that have a long development period as well associated high costs. In the interest of conducting high-value planetary science in a cost effective manner, it is crucial to explore low-cost small spacecraft designs with shorter development times that are high-risk, high-reward missions complementing larger Flagship/New Frontier missions and further the understanding of the outer planetary systems. SmallSats are spacecrafts that are less than 200 kg in mass while CubeSats are a subset that use a standardized size and form factor. With advances in spacecraft technology as well as the rise of SmallSat missions especially CubeSats, it's important to begin considering these types of missions for deep space applications[13]. NASA is preparing to launch thirteen CubeSats on the Artemis-I mission in late 2021 that will demonstrate scientific and technological capabilities of the operation of CubeSats beyond Low Earth Orbit(LEO) with the goal of opening access to deep space.

The goal of this paper is to formalize a set of requirements needed for a SmallSat icy moons mission with specific emphasis on conducting gravity science. In this paper, the current knowledge of icy moons is discussed focusing on Europa and Enceladus obtained from the past missions. A set of science objectives for an icy moons exploration mission is developed from past mission concepts and guides such as the decadal survey and NASA roadmaps. Key measurements that can achieve those objectives are discussed and various measurement techniques are introduced including current and potential technologies.

II. Background

A. Why ocean worlds?

For a long time the concept of habitability was constrained to having a rocky planetary body of the right size be at the right distance called the Habitable Zone from a star with geophysical conditions that allow complex life forms to evolve. In our Solar System, the Earth is the only planet that meets these conditions. Due to the limited scope of this concept, a new classification of potential habitats has been put forth by [14] :

- Class I : potential Earth-analog environments
- Class II : planetary environments where life may originate but a planet evolves differently from Earth
- Class III : planetary bodies with subsurface oceans which interact with silicates
- Class IV : planetary bodies on which there are liquid water layers between two layers of ice or above ice

These new classifications have led to an increase in interest in the outer regions of the Solar System, mainly the satellites in the Jovian and Saturnian system. Images and data from the *Voyager* missions led to the classification of a separate set of bodies, ocean worlds defined as a planetary body with a liquid ocean on or under the ice layer [15]. The results from subsequent missions, *Galileo* and *Cassini* have allowed researchers to confirm the existence of these oceans on icy moons such as Europa and Enceladus, and Titan with strong evidence of subsurface oceans on Ganymede and Callisto. Dedicated exploration to these icy moons/ocean worlds remains a high priority for the scientific community.

Europa and Enceladus stand out from other ocean worlds due to evidence of interaction between the surface and the ocean, for Europa has few craters compared to other moons in the Solar System as well as a surface that has a chaotic terrain[16, 17], and for Enceladus the observation of plumes in the South Pole[18]. These conclusions have led investigators to propose dedicated missions to explore Europa and Enceladus. Currently only a Europa mission is in development (*Clipper*) while an Enceladus space mission is still in early conceptual studies phase. Additional missions to explore the satellites of the gas giants include the Jupiter ICy moons Explorer(*JUICE*) developed by the European Space Agency (ESA) to be launched in 2022 to explore Ganymede and will also conduct two flybys of Europa, and Applied Physics Laboratory's(APL) *Dragonfly*, a drone to explore Titan to be launched in the late 2020s. National Research Council's(NRC) most recent decadal survey identifies two crucial areas of investigations for ocean worlds are to: 1) better constrain the internal mass distribution by measuring the static gravitational fields and topography and 2) to probe the existence and nature of internal oceans by measuring tidal variations in gravity and topography[19]. The thickness of the satellite's ice shell is critical to understanding the possible exchange of material between ocean and surface.

B. Missions to ocean worlds

The gas giants and their satellites have been a target for exploration since the beginning of space exploration. Existing data on Europa and Enceladus comes from missions for which they weren't the sole target of study but instead part of a mission to explore a number of bodies. *Pioneer 10* in December 1973 took the first spacecraft image of Europa showing a heterogenous surface[20]. In the late 1970s, a rare alignment of the outer planets offered an opportunity to send spacecrafts to explore them by means of multiple gravity assists. Two spacecrafts-*Voyager 1* and *Voyager 2* returned valuable information enhancing the understanding of these outer planets and their satellites. Observational data from the *Voyager* missions resulted in constraining Europa's size to the modern values and both spacecrafts took extensive images of the surface of the satellites that showed Europa's surface to be smooth with cracks that were indicated by long linear markings and Enceladus' extraordinarily high albedo with both satellites to having complex and youthful surface geology. A majority of the information that exists today about Europa was obtained by the *Galileo* mission and about Enceladus from *Cassini* .

Galileo was developed in 1980s to orbit Jupiter for two years collecting valuable data about its magnetic field, internal structure and atmosphere. The orbits were designed to include flybys of its largest moons for both altering its orbit around Jupiter as well as observing them. In the nominal mission timeline *Galileo* conducted three flybys of

Europa. At the end of the two years after reaching Jupiter with the spacecraft in good health, in 1997 NASA extended the mission twice to conduct additional science of the largest moons with the first being called the *Galileo Europa Mission* (GEM). This two-year extension allowed the spacecraft to conduct eight additional flybys with the closest approach being at an altitude of 200 km from Europa's surface taking medium-resolution and high resolution images that provided key evidence of active geological deformation on the surface[20]. Gravity and magnetometer data and images obtained contributed to the evidence of a sub-surface ocean[21, 22].

Cassini -*Huygens* was a mission developed in the 1990s to explore the Saturnian System. The mission consisted of a Saturn orbiter, *Cassini* developed by NASA, and Titan lander-*Huygens* developed by European Space Agency(ESA). Initially designed to operate for four years, *Cassini's* mission was extended twice, first four two years and then for a further seven years. This allowed the spacecraft to conduct targeted flybys of the Saturn's moons. Throughout its mission lifetime, it encountered Enceladus a total of 23 times shedding new light about the tiny moon. While already a main target of flyby exploration during the nominal mission, the detection of plumes erupting from the Enceladus' Southern pole that offered proof that the icy moon is geologically active[23, 24] solidified the need for more observations of Enceladus during Cassini's extended mission.

In the late 2000s, NASA along with the ESA began working on a joint mission to investigate the Jovian system called the Europa Jupiter System Mission(EJSM). This mission consisted of two spacecrafts: a NASA-led Jupiter Europa Orbiter(JEO) and an ESA-led Jupiter Ganymede Orbiter(JGO). These spacecraft while each conducting stand-alone measurements would carry out an in-depth study of the Jupiter system under the overarching EJSM theme of "The emergence of habitable worlds around gas giants"[6, 25]. JEO's science objectives included characterizing Europa's ocean and ice shell, determining its chemistry and understanding the geological features on the surface. To achieve this, the spacecraft would carry 11 instruments and dual band telecom systems for accurate tracking. Some of these instruments included the ice penetrating radar(IPR) and wide-, medium- and narrow-angle camera packages[25]. Due to the harsh radiation environment around Jupiter that would limit the data return from JEO and high costs associated with development, it was cancelled and instead a flyby mission *Europa Clipper* previously known as Europa Multiple Flyby Mission was selected for further development[26]. *Clipper* will orbit Jupiter but will conduct a number of flybys around Europa collecting data using its nine instruments some of which are an ice penetrating radar and an imaging system. Additionally, gravity radio science will be conducted using *Clipper's* X- and Ka-band antennas[27]. While *Clipper's* science objectives remain the same from JEO, it will also characterize hazards for a potential future lander mission[26]. By conducting a flyby mission, *Clipper* will minimize the time spent in harsh radiation environment while still enabling high value science return. This mission is expected to launch in the mid 2020's and reach Jupiter in the early 2030's. A secondary payload opportunity with *Clipper* , called the Europa Tomography Probe(ETP) is a proposed mission concept to accurately characterize the interior of Europa with a <500 kg orbiter by measuring Jupiter's magnetic fields and Europa's gravitational field through Inter-Satellite Link (ISL) with *Clipper* [28, 29].

C. Europa

Europa, one of the four Galilean moons has been a prime candidate for exploration ever since images from *Voyager* missions showed linear features that as well as a smooth surface that suggested an active surface harboring a subsurface ocean[30]. This led to Europa being an exploration target for *Galileo* , which conducted observations of the satellites during its main and extended mission and solidified the assumption of an icy surface overlying a global ocean[22, 31]. Lack of any major craters imaged by *Voyager* and *Galileo* show that Europa's surface is young with an active ice shell suggesting a dynamic ocean[32, 33].

1. Icy Shell and Ocean

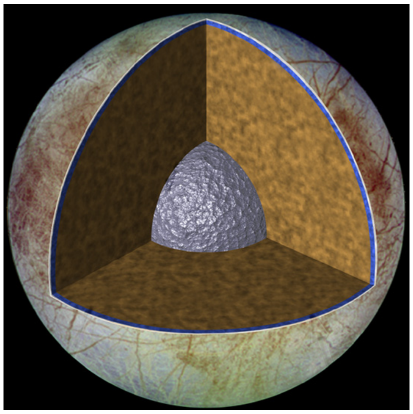
The depth of this icy surface is still unknown. Estimates of ice shell thickness of Europa range from <1km to >30km[31, 34–37] but these are based on underlying assumptions of the internal structure such as assuming Europa is in hydrostatic equilibrium [22, 31] but this has yet to be verified through independent measurements. The presence of an ocean on Europa would lead to an increase in tidal amplitudes on the satellite. Compared to tides on Earth which are caused by the Moon, Europan tides are enormous due to Jupiter. Although the relative distance between Jupiter and Europa is greater than the distance between Earth and Moon, Jupiter is about 25,000 times more massive than the Moon. These tides have a number of major effects such as [16]:

- Tides distort the global shape of Europa
- Tidal friction leads to the internal heating which could explain the presence of a liquid ocean
- Tides have a profound influence over the orbital evolution of Jupiter's larger satellites. Jupiter's largest moons-Io, Europa and Ganymede are locked in a 4:2:1 orbital Laplace resonance around Jupiter which keeps the slightly eccentric orbits of these moons from becoming circular

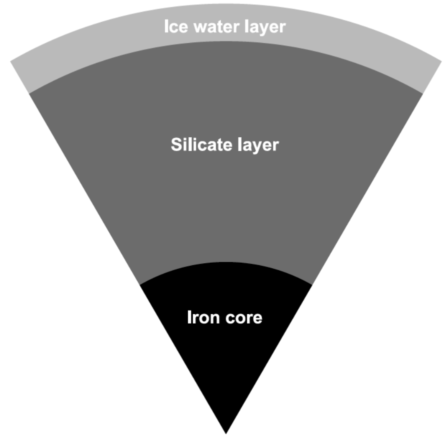
Tidal distortion, internal heating, and orbital evolution are all interdependent through the workings of Europa's tides. The gravitational interactions between Jupiter and the other moons on Europa lead to frequent stress resulting in intense tidal flexing while also producing heat through friction warming the water near the mantle[2, 38, 39].

2. Interior Models

Due to the limited type of data available i.e. no radar or altimetry data, the internal structure has to be inferred indirectly [22, 31, 40]. By analyzing gravity data from four Europa flybys, [31] found that the satellite is in hydrostatic equilibrium and the interior is highly differentiated into a water-ice shell, rocky mantle(mainly silicate), and a metallic core which is generally known as the three-layer model as shown in Fig 1. Gravity measurements are unable to distinguish between water and ice due to similar densities. This model is consistent with Moment of Inertia(MoI) and density measurements[22, 31, 40, 41]. However a two-layer model is also put forth where Europa consists of a rocky-metallic core and water-ice layer which is consistent with gravitational data but from the inferred density of the core in this model, the three-layer model is more plausible.



(a) Interior cross-section[NASA/JPL]



(b) Three-layer model[42]

Fig. 1 Possible interior structure of Europa

3. Unknowns and Future Exploration

The Decadal Survey identifies a mission to Europa as the second highest priority mission due to "its potential for an extraterrestial habitable life"[19]. While *Voyager* and *Galileo* gave us valuable information about Europa, there were many questions that were left unanswered and the belief is *Clipper* will help answer some of them if not all. In order to better understand the potential for life in the outer Solar System, NRC believes that a Europa mission is necessary with the goal of confirming the presence of an interior ocean, characterizing its ice shell and understanding its geological history. Any orbiter mission to Europa must have the capability to measure these tidal deformations through gravity measurements as well as topographic mapping.

D. Enceladus

Enceladus, like Europa has been one of the most interesting icy satellites. It is the most reflective surface in the Solar System due to its surface composition consisting mainly of water ice as well as one of the most geologically active bodies due to the detection of its active plumes erupting in the Southern Pole. Enceladus is locked in a 2:1 orbital resonance with Dione, one of Saturn's larger moons leading to a slightly eccentric orbit(e = 0.0047) around Saturn which is assumed to drive internal tidal heating. But Enceladus, apart from Titan, is interesting in the sense that much of the geological activity and subsurface ocean cannot solely by explained by orbital resonance and eccentric orbits since Mimas, another Saturn moon has a higher eccentricity (e = 0.0202) but doesn't exhibit any thermal or geological activity. Little had been known about Enceladus since its discovery in the 1700's until the *Voyager* missions conducted a flyby of Saturn in the 1981. Images from *Voyager* II showed Enceladus to be the most active satellite surface in the Saturn system due to its complex and youthful surface geology and consisting of craters that are less than a few hundred millions years old suggesting the surface is constantly undergoing change by endogenic processes[23, 24, 43]. Most of what the scientific community knows about Enceladus has been a result of observations conducted by the *Cassini* spacecraft.

1. Icy Shell and Ocean

Gravity and topography data from *Cassini* show the ice shell thickness to be in the range of 30-40 km at the South Pole and up to 60 km at the equator [3, 44]. However [45] suggests that when incorporating gravity data with shape and libration data, the ice shell is significantly thinner, between 2 and 5 km. *Cassini* also provided evidence for a subsurface ocean at Enceladus through its major discovery of the south polar particle and water vapor plumes [18, 23, 24, 44]. Combined with measurements from *Cassini* 's onboard instruments such as the Ion Neutral Mass Spectrometer(INMS), and Ultraviolet Imaging Spectrograph (UVIS) that analyzed the composition of the plume,researchers concluded that the source of Enceladus' plumes to be a pressurized subsurface liquid water reservoir[46]. Initially thought to be locally concentrated at the South Pole[23, 44], observations and investigations by *Cassini* during subsequent flybys and analysis of Doppler data revealed that this water ocean to be global, deepest at the South Pole and becoming thinner moving away from the high southern latitudes[3, 45, 47, 48]. In order for a global ocean to exist a high level of heat must be produced. The source of this heat in the case of Enceladus is still unknown but multiple hypothetical models have been put forth that can possibly answer this question however there is no consensus among researchers. Tidal heating is often suggested as a probable heating source [49, 50] but whether tidal heat dissipation is recent, ongoing or episodical, is still an open question[2, 51–54]. Radiogenic heating due to the radioactive decay of the rocky has also been studied but it is highly likely that a combination of tidal and radiogenic heating has sustained the internal ocean[18, 53].

2. Interior Models

Gravity and topography data for spherical harmonic degree and order-2 recovery of Enceladus' gravity field do not support a relaxed hydrostatic body[44, 55]. There is high uncertainty among researchers about the level of differentiation of Enceladus' interior but most models agree that it consists of a low density rocky core and water-ice shell. Estimates of Enceladus' degree-3 from Cassini data imply a negative gravity anomaly at the south pole[44] but due to its small magnitude there must exist a subsurface positive gravity anomaly[56].

3. Unknowns and Future Exploration

A dedicated flyby or orbiter mission would better help understand the geological/plume activity, its relation to Enceladus' orbit around Saturn as well as better constrain the interior models. Though there were around 23 flybys of Enceladus, *Cassini* was only tracked for three of them allowing recoveries of satellites recovery field up to degree-3 zonal harmonic coefficient although higher order gravity terms were determined from global long wavelength topographic maps[55]. A sustained Enceladus focused mission would allow homogenous global mapping that can result in determination of static gravity field to higher degrees from radio tracking. Additionally instruments such as ice penetrating radars and altimeters would greatly expand on the knowledge of Enceladus by measuring the globally varying ice shell thickness and its dependence on tidal distortion.

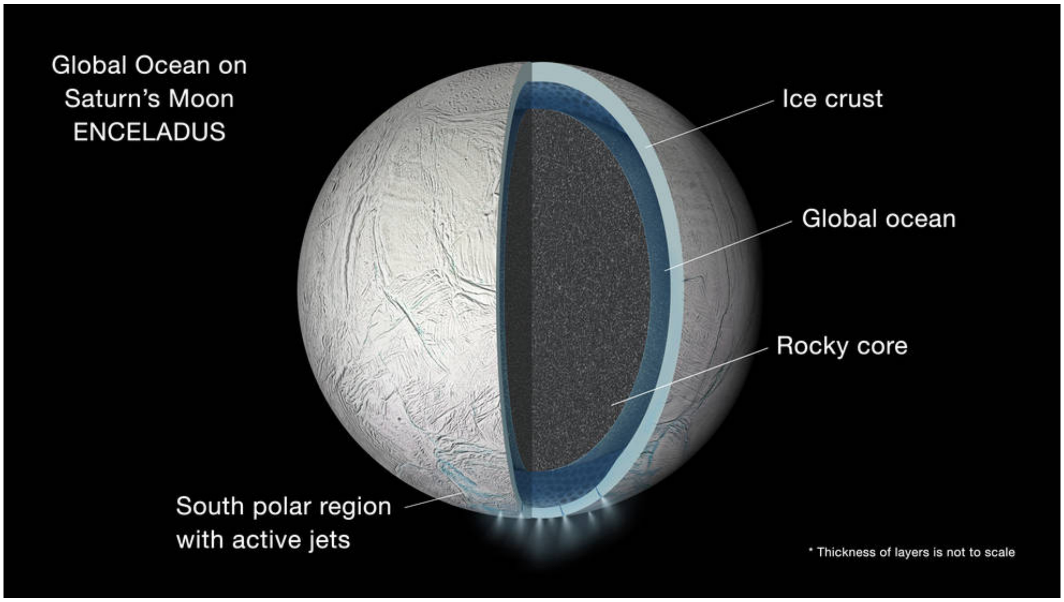


Fig. 2 Interior Model of Enceladus [NASA/JPL]

III. Science Objectives

To better understand these worlds, a set of high-level goals and objectives have been put forth by the 2011 Planetary Science Decadal Survey to guide the advancement of the study of planetary satellites including the earlier mentioned ocean worlds. They are as follows[19]:

- How did the satellites of the outer solar system form and evolve?

  Understanding the composition and internal structure of the satellite can provide greater insight into their formation as well as their dependence on their parent planet.

- What processes control the present-day behavior of these bodies?

  Icy/ocean worlds are highly dynamic and alive with geological and/or atmospheric activity. Studying these processes can provide more insight into the interactions between the environments.

- What are the processes that result in habitable environments?

  The main motivation for understanding these worlds is to determine if they are habitable and to what extent. Characterizing the available energy sources as well looking for bio signatures can help guide the scientific community towards establishing the potential for life elsewhere

The NASA Roadmap to Ocean Worlds document describes the content and priorities for investigations that are needed for the exploration of ocean worlds developed by the Ocean Worlds Program team[57]. The overarching goal is to: " Identify ocean worlds, characterize their oceans, evaluate their habitability, search for life and ultimately understand any life we find". Using these goals as a guide and science objectives developed in prior missions studies- *Jupiter Europa Orbiter, Europa Multiple Flyby Mission, Enceladus Orbiter, Ganymede Orbiter, Titan Saturn System Mission* [6–10], a formalized set of objectives for a icy/ocean world science mission were developed.

A. Objectives and Investigations Required:

1. Ice Shell

The first step in understanding icy/ocean moons is to fully characterize the ice shell. Constraining the thickness as well its uniformity across the body is critical to identifying any possibility of ice-ocean exchange as this allows any chemicals found in water to be exposed to radiation at the surface(i.e Europa). The ice shell at Europa is theorized to be of two layers: a brittle/elastic conductive layer and ductile convective ice layer. However it is believed that the lower estimates of the ice shell thickness correspond only to the ductile layer while the higher estimates incorporate both layers[37]. Measuring the thickness is also useful for understanding tidal heat generation and if there are localized regions of high heat production or global corresponding to the relative thickness of the ice shell. Moreover data also shows that due to the smaller size of Enceladus compared to Europa, tidal deformation amplitudes are very sensitive to ice shell thickness wherein for Europa it's only slightly dependent[38].

1.1 Characterize thickness and regional variations of the ice shell to within $\pm 5km$

1.2 What is the distribution of conductive vs convective layers?

1.3 Any presence of interfaces for ice-ocean exchange?

1.4 Characterize surface motion over tidal cycle

2. Ocean

Any effort to assess the potential habitability of an icy/ocean world must involve the studying the ocean to understand how it functions. The constant interaction of the ocean with the icy shell and the rocky mantle as well the exchange of surface materials could enable the ocean to have the necessary compounds needed for life[48, 57, 58]. Presence of oceans on Europa and Enceladus have been confirmed by prior missions, *Galileo's* magnetometer and gravity data for Europa and *Cassini's* plume detection and gravity for Enceladus, the satellites were not designed to study any kind of subsurface ocean(primary mission objective being the study of the parent planet) and so there are plenty of questions still unanswered that include the properties of the ocean such as thickness, localized vs global, spatial and temporal variations, tidal heat generation and dissipation, etc. While gravitational data alone is unable to provide constraints on the ocean thickness, as it cannot distinguish between liquid water and ice[40] it can provide information on regional variations in thickness. Ocean thickness constrains can be obtained by coupling gravitational data with additional measurements from radar or magnetometers.

2.1 Characterize the thickness and regional variations of the ocean to an accuracy of $\pm 5km$

2.2 Identify sources of ice-ocean surface interfaces

2.3 Determine amplitudes of the induced gravitational tides

3. Interior

Limited information is available about the internal structure of icy moons/oceans and but most models include an icy shell, subsurface ocean, and a rocky-metallic core inferred from gravity and shape data[1, 22, 31, 40, 44, 56]. Moment of Inertia and average density can be obtained from gravitational data that allow the interior models to be well constrained to two or three layer structures. While most Europa interior models assume hydrostatic equilibrium and to first order spacecraft data matches with this assumption, *Cassini* data for Enceladus suggests that the body exhibits large deviations from it. The non-hydrostatic behavior of Enceladus can be explained by the assumption of isostasy in which the ice shell is floating above the subsurface ocean[47, 59]. Shape measurement of Europa from imaging data has also supported its hydrostatic behavior [60] however independent and dedicated measurements must be collected for verification. *Galileo* and *Cassini* have provided valuable data in constraining the thicknesses of the interior layers, it varies from model to model as multiple model combinations correspond to the data obtained from spacecrafts. Furthermore the differentiation of these layers is still uncertain as well as the amount of interaction between the layers. Geophysical models developed from gravity and topographic data can provide constrains on the composition of the interior[41] as well as density distribution between the internal layers. For Europa, [61] discussed the possibility of signals from the deep interior(long wavelength) dominating the gravity field compared to surface features(short wavelength). While majority of the surface ice shell is made of water-ice, non-ice material appear on the surface suggesting these were deposited through interior processes[62]. Additionally the effect of tidal evolution in the interior and its processes is still not well characterized.

3.1 What are the thicknesses of the different layers of these satellites?

3.2 How well differentiated is the interior?

3.3 Does tidal heating only affect the ice shell and ocean or is it active in the mantle/core?

3.4 Is there any activity at the ocean-mantle/ocean-core interface?

4. Geology

Icy/ocean worlds despite being covered with mostly ice have a number of interesting and complex features that can convey a great deal of information about its geological activity. Geological features on the surface provide important information about internal processes[40]. Enceladus, with the observation of its plumes and Europa, with its relatively young and sparsely cratered surface, are believed to be geologically active through resurfacing by cryovolcanic and/or tectonic processes[16, 24, 34, 62, 63]. Imaging data from *Galileo* provided evidence for global resurfacing from formation of ridges and faulting[21]. Active processes on these bodies may be in response to either endogenic or exogenic processes or a combination of both. [64] summarizes Europa's geological terrain to consist of tectonic-representing tidal effects of stress and chaotic-representing thermal processing, where the former is identified by visible lineaments correlating with tidal tension patterns and latter by dark splotches on a global scale. As tidal stresses vary on a diurnal timescale, these determine how the various fractures are propagated and indeed Europa's surface has cracks consistent with periodic tidal stresses. Topographic mapping using stereo imaging or altimetry of these bodies can be important in identifying areas with thin ice indicating near-surface liquid water.

4.1 Locating young ridges and characterize their formation

4.2 Identifying sites of recent geological activity through imaging at resolutions of 100 m/pixel or better

4.3 Identifying the 3-D characteristics of surface features to a vertical resolution of ±10 m and horizontal resolution of ±100m or better

4.4 Characterizing geological activity including ice shell tectonics, plume activity etc over tidal cycle

IV. Prcoess Modelling

After formulating the key science objectives, a major process to be measured is the gravitational field. Measurement of a celestial body's gravity field supplemented provides fundamental information on the body's internal structure including mass distribution, tectonic process and thermal evolution. Additional measurements such as topography mapping, surface imaging and limb profiling can constrain the thickness of the outer shell as well as allow for correction of non-hydrostatic effects. Let's look in detail some of the required measurements:

A. Gravity Modeling

Gravity science experiments have enabled researchers to map gravity fields and probe internal structure of various bodies such as Mercury [65, 66], Mars[67, 68], Europa[22, 31, 69], Titan [70] and Enceladus[44]. For terrestrial worlds like Earth, perturbations in the gravity field arise from gravity anomalies, the largest of which come from the surface topography[61]. For planetary bodies with sub-surface oceans, gravity anomalies rise from deformation caused by tidal forcing[69].

The external gravitational field of a celestial body using a spherical harmonics model is represented as [71]

$$V(r,\lambda,\phi) = \frac{GM}{r}\left[1 + \sum_{n=2}^{\infty}\sum_{m=0}^{n} \frac{R_e^n}{r^n}\bar{P}_{nm}(\sin\phi)(\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda))\right] \tag{1}$$

where G is the gravitational constant, M is mass of icy satellite, R_e is the equatorial radius, n is the degree, m is the order, $\bar{P}_{nm}$ are the normalized associated Legendre polynomial, $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are the normalized Stokes coefficients, λ is the longitude and ϕ is the latitude. For a perfectly spherical body, the body's gravitational body is that of a point mass

Table 1 Summary of science objectives and associated required measurement

Goal	Objective	Measurement
Ice Shell	Characterize thickness and regional variations of the ice shell	Static gravity field recovery(direct), tidal Love number determination (indirect)
		Topographic differences from global topographic profiles
		Sounding profiles of subsurface dielectric horizons
	What is the distribution of conductive vs convective layers?	Sounding profiles of subsurface dielectric horizons for mapping of subsurface thermal horizons
	Any presence of interfaces for ice-ocean exchange?	Topography mapping of surface using altimeter and stereoimaging
	Characterize surface motion over tidal cycle	Time variable gravity(direct), tidal Love number(indirect)
		Crossover topography using global surface profiles
Ocean	Characterize thickness and regional variations of the ocean	Static gravity field recovery and tidal Love number determination
		Topographic mapping
		Sounding profiles of subsurface dielectric horizons
	Identify sources of ice-ocean surface interfaces	Topography mapping
		Infrared and thermal imaging
	Determine amplitude and phase of gravitational tides	Time variable gravity(direct), tidal Love number(indirect)
		Surface altimetry
Interior	Characterize the interior layers of the body	Static gravity field recovery
		Sounding profiles of subsurface dielectric horizons
	Characterize the differentiation of the interior	Static gravity field recovery
Geology	Locate young ridges and characterize their formation	High resolution and spectral imaging
		Topography mapping
	Identify sites of recent geological activity	High resolution surface and thermal imaging of targeted features
		Crossover topography using global surface profiles
	Identify the 3D characteristics of surface features	Topography Mapping
	Characterize geological activity over tidal cycle	Time variable gravity(direct), tidal Love number(indirect)
		Topography Mapping

and not much can be inferred about its interior. However most bodies exhibit some form of spherical asymmetry that can be a result of external and/or internal processes. The most interesting of spherical harmonic coefficients are of degree and order 2 that account for the majority of the perturbations and can be related to the moments of inertia(MoI) of the body by the following expressions[72]:

$$I_{xx} - I_{yy} = -4MR_e^2 C_{22} \tag{2}$$

$$I_{yy} - I_{zz} = MR_e^2 (C_{20} + C_{22}) \tag{3}$$

$$I_{zz} - I_{xx} = -MR_e^2 (C_{20} - 2C_{22}) \tag{4}$$

$$I_{xy} = -2MR_e^2 S_{22} \tag{5}$$

$$I_{yz} = -MR_e^2 S_{21} \tag{6}$$

$$I_{zx} = -MR_e^2 C_{21} \tag{7}$$

While these relations hold independent of internal density heterogeneity, there is a limitation to determining MoI of the icy satellite as it is impossible to uniquely specify them through gravity data alone but can only solve for the differences between them. Additional information about the satellite's rotational dynamics is required. Another key observation is that for any mass distribution a set of coordinates can be defined for the satellite such that products of MoI in Eqs. (5)–(7) are zero and so are C_{21}, S_{21}, S_{22} resulting in only the coefficients $C_{20}(-J_2)$ and C_{22} to be measured. The harmonic coefficients C_{20}(the dynamical polar flattening) and C_{22} (the dynamical equatorial flattening) terms provide constrains on the internal structure by directly relating to the radial distribution of density[65, 72]. These parameters are also important in determining whether the satellite is in hydrostatic equilibrium through the ratio J_2/C_{22} which has to be $10/3$ for a hydrostatic body. Determination of these parameters for Europa by earlier studies have imposed the hydrostatic constraint on the a-priori information[31] and therefore only rely on uncertainty in one of the two parameters. However individual determination of these parameters is required for confirmation of hydrostatic equilibrium as this assumption doesn't hold for degree-2 coefficients for Enceladus[44]. Additional determination of the Stokes coefficients of the gravity fields beyond degree and order 2 imposes constraints on the possible existence of any significant mass anomalies. The determination of the $J_3(-C_{30})$ value for Enceladus indicates a negative mass anomaly at the South Pole where water vapor plumes were observed[44]. The measurement techniques that are generally used to determine gravity parameters will be be covered in the next section.

B. Tidal Modeling

Measuring the tidal deformation of the satellite's surface during its revolution around its planet can verify the presence of a subsurface ocean. Key parameters can be obtained from gravity data and/or altimeter of a spacecraft while tidal deformations can be directly measured on the surface. A key measure of ocean depth and ice shell thickness is to relate it to the solid-body tide Love numbers k and h. Changes in a body's gravity field due to internal mass redistribution is tied to k_n and the time-varying surface radial deformation is related to the h_n number. While k_n can be measured by gravity science experiments and is enough to confirm the presence of an ocean, h_n requires altimetric measurements and is needed to constrain the ice shell thickness. Previous studies have shown the expected accuracy of ice shell thickness from a dedicated orbiter mission to be in the order of a few kilometers[69, 73]. The sensitivity to tidal parameters via orbital perturbations may be supplemented by a more direct measurement of the tidal distortion of the surface of the satellite if a spacecraft is provided with a laser altimeter or obtaining altimetric data through radar sounding and topographic maps [74–79]. For full detection and characterization of the satellite's ocean, the dynamical response to the parent planet's tidal forces must be determined at different points in the satellite's orbit during its tidal cycle(∼3.5 days for Europa, ∼1.3 for Enceladus).

Depending on favorable tracking data and/or surface displacement measurements, k_n and h_n can individually be determined. However a common method employed to constrain the ice-shell thickness for a hydrostatic body, such that h_n and k_n depend only on the density structure of the satellite is to set for the degree-2/ Love numbers, $h_2 = 1 + k_2$[75, 80–82] and using the parameter $\Delta = 1 + k_2 - h_2$. For a global ocean to be present at Europa values of k_2 range from $0.14 - 0.26$ calculated in [80] depending on thickness and strength, while [73] shows that estimating Δ to an accuracy of 0.02 should give an accuracy better than 10 km. Generally for a $15 - 30$ km Europan ice shell, the k_2 and h_2 values are $0.26 - 0.24$ and $1.24 - 1.22$. According to the science requirements for the *Europa Clipper* mission, for confirmation of an ocean k_2 and h_2 must be accurate to < 0.06 and < 0.3 respectively and for measuring the ice shell thickness to ±10 km requires the Love numbers to be both accurate to < 0.015[79].

1. k_2 from Gravity Data

Changes to the Stokes coefficients due to tidal variations are given by [71] :

$$\Delta\bar{C}_{nm} - i\bar{S}_{nm} = \frac{k_{nm}}{2n+1}\frac{GM_p}{GM_s}\left(\frac{R_s}{r_p}\right)^{n+1}\bar{P}_{nm}(\sin\phi_p)e^{-Im\{\lambda_p\}} \tag{8}$$

where k_{nm} represents degree n and order m Love numbers, M_p is the mass of the parent body causing the tidal potential-Jupiter(for Europa) and Saturn(for Enceladus), r_p represents the distance of the parent planet from the satellite, ϕ_p and λ_p are the satellite fixed latitude and longitude of the parent planet. In Eq. (8), the time variable nature of tides comes from the time dependent variables r_p, ϕ_p, and λ_p based on the different phases of the tidal cycle. Most of the prior studies done have only considered the real part of the second-degree tides k_2 [69, 73, 74, 83, 84]. By setting $m = 0$ in Eq. (8), we get

$$\Delta\bar{C}_{20} = \frac{k_2}{5}\frac{GM_p}{GM_s}\left(\frac{R_s}{r_p}\right)^3\bar{P}_{20}(\sin\phi_p) \tag{9}$$

Separating tidal contributions to the satellites gravitational field from static contributions can be done by measuring a spacecraft's acceleration at the same location relative to the satellite at different instances of time corresponding to different locations in the tidal cycle.

2. h_2 from Surface Displacement

The surface displacement measurement can be taken by altimeters or range measurements from radars using a crossover based technique to cancel large scale topography effects [78, 82]. Crossover points are the geographic locations on the satellite's surface where two ground tracks interact. The altimeter observation H can be expressed as:

$$H = |\vec{r}| - (R_s + \delta H) \tag{10}$$

where $\vec{r}$ is the satellite-spacecraft radius vector and δH is the radial deformation. The amplitude of this radial deformation is directly related to the Love number h given by

$$\Delta H = \frac{hV_p(\psi)}{g} \tag{11}$$

where V_p is the tide inducing potential of the parent planet, ψ is the and g is the acceleration due to gravity at the satellite's surface. Using the same assumption of only considering the second degree tides, Eq. (11) becomes

$$\Delta H = \frac{h_2 V_2(\psi)}{g} = \frac{h_2}{g}\left(\frac{GM_p}{r_p}\right)\left(\frac{R_s}{r_p}\right)^2 P_{20}(\cos\psi) \tag{12}$$

V. Measurement Techniques

Most of the above discussed measurements especially gravity field recovery require parameter estimation usually done from navigation data which is also used to inform measurements taken from onboard sensors(altimeters, cameras, etc). All of this boils down to obtaining accurate orbit determination data. This section highlights current orbit determination techniques, suggests new potential technologies while also highlighting specific sensor types for collecting addtional measurements. Gravity measurements traditionally require spacecraft tracking data while topographic mapping is done by the use of an altimeter and/or an imager.

A. Radio Science

Gravity Radio Science(GRS) involves using radio tracking data of spacecrafts to obtain gravity coefficients of planets through parameter estimation. The most commonly used method for vehicles in deep space is Doppler tracking. Doppler tracking is based on frequency shift of the radio waves due to the relative motion between transmitter and receiver generating range-rate measurements. There are generally three types of Doppler tracking: "one-way" where the spacecraft transmits a downlink signal using an on-board oscillator and the ground station compares the received frequency against a local oscillator; "two-way" where a radio signal is emitted from the ground station to the spacecraft and using a transponder, a downlink signal is transmitted by the spacecraft; and "three-way" which is a combination of one-way and two-way and involves two ground stations.

Spacecraft Doppler tracking is referred to as an integrated time/time-average Doppler measurement as frequency shift cannot be measured instantaneously. Doppler tracking has long been used for orbit determination(OD) of interplanetary spacecrafts. Current navigation techniques rely mainly upon X-band radio links(8.2-8.4 GHz) while Ka-band links(32-34GHz) have also been tested[85, 86]. For Jovian and Saturnian systems, gravity measurements have been obtained through tracking of *Pioneer 10 and 11*, *Voyager 1 and 2*, *Galileo* and *Cassini* spacecrafts. *Juno* currently orbiting Jupiter, has a dedicated radio science mission intended to improve performance from prior missions to the planet through favorable orbital geometry and dual-band instruments utilizing both X-band(primarily for communications) and Ka-band(for gravity science) frequencies[87]. Accuracy of DSN based navigation systems are at level of 0.1 mm/s at 60 s integration time for Doppler and 1-5 m for ranging. As widely as this technique has been used, there are some limitations. Only one of the DSN stations has capabilities for Ka-band uplink which requires the spacecraft pass to be conducted in view of that station imposing additional mission constraints, while there are some concerns with the 40 year old equipments used by DSN. Nevertheless, to meet more demanding accuracy requirements of future space mission and science investigations and enable large number of spacecrafts to venture into deep space, additional orbit determination methods must be studied for complementing the data provided by DSN.

B. Altimetry

Altimetry is a method of obtaining range measurements by transmitting electromagnetic pulses towards a surface and measuring the time it takes to get the pulse back from different locations in an orbit. From these range measurements relative to an ellipsoidal surface of the planetary body, accurate surface topographic maps can be constructed. Two basic types of satellite altimetry have been used for flight applications-radar and laser. Both radar and laser work on the same measurement principle but operate differently. Radar altimeters use radio waves and have a wider footprint on the target area while laser altimeters use lasers with a narrower beam on the surface. Laser altimeters have been successfully used in spaceflight applications for obtaining topography and shape of planets such as the Moon(*Lunar Reconnaissance Orbiter*),Mars(*Mars Global Surveyor*) and Mercury(*MESSENGER*)[76][88][89].

Both altimeters have the potential to measure surface deformations using the crossover technique demonstrated for Mars [90]. Simulation studies conducted in [73] for use of laser altimeters for a mission to Europa show that it is possible to obtain h_2 and so constrain the ice shelf thickness combined with tidal gravity measurements. The *JUICE* mission will carry on-board the Ganymede Laser Altimeter to measure the radial deformation of Ganymede's outer ice shell. Performance studies conducted show that for a mean instrument range error of 7 m, the error in measuring h_2 is 2% for a four month, 500 km altitude orbiter mission[77]. [78] studied the capability of using the ice penetrating radar aboard *Clipper* combining altimetry and stereographic measurements to evaluate the potential for measuring tidal Love numbers and Europa's ice shell thickness. The study found that the ice shell thickness can be constrained to ±15 km which would be useful if the ice-layer is found to be > 20 km. For < 20 km, the direct use of radar sounding would be sufficient in detecting the ice-ocean boundary. TARGIT, a CubeSat that is currently being developed at Georgia Tech by the SSDL to test the accuracy of a miniaturized altimetry system with the goal of launching compact altimeters on CubeSats for future planetary missions for ranging and topographic mapping. Another compact altimetry system is being developed by Fibetek, Inc [91] for CubeSat platforms with resolution ranges up to to 1000 km ranging for planetary topography.

C. Limb Profile Measurements

Limb profiling has been used to obtain shapes of planetary bodies for a long time as well as to identify any variations in lateral shell thickness. Particularly data from images taken by *Voyager* , *Galileo* and *Cassini* have helped obtain shape profiles of the icy satellites[60, 92–95]. A satellite's shape can be used to infer about its internal structure whether it's in hydrostatic equilibrium or not. While these bodies may be in an equilibrium ellipsoidal shape, departure from it can reveal information about any internal dynamic processes present. The global shape data obtained for Europa in [60] do not show any variations in lateral shell thickness which lead to conclusions that either the ice shell is thin (<35 km) or that there are no major lateral shell variations.

In this technique, spacecraft imaging data is used to measure limb positions by matching a model of the brightness around a sharp edge to observed brightness on scans across the limb[60, 92, 93]. While the perfect images for limb profiling would involve 360° limb arcs for lowering the uncertainty on the center of the satellite, images that have more than 180° offer high accuracy in stabilizing the fit center. The imaging co-ordinates are highly dependent on accurate OD and knowledge of camera properties(focal length and distortion).

D. Optical Navigation

Optical navigation utilizes images of planets, moons and stars for OD. Traditionally the processing and estimation are done at the ground station combined with radiometric tracking data to obtain accurate measurements. However with the advancements in spacecraft computing technology there has been significant interest in on-board processing of these images for autonomous navigation. Optical navigation involves the use of an on-board camera to take line-of-sight images of planets, moons, asteroids, stars[96, 97], landmarks on a body's surface and lit horizon[98]. Depending on the location of the target body and the mission objectives one or a combination of the above images are used for navigation. The first instance of autonomous navigation was used by the Deep Space 1 mission using a system called AutoNav developed by JPL as a technology demonstration. Similar systems have been developed for subsequent missions such as Natural Feature Tracking for OSIRIS-REx and Small-body maneuvering Autonomous Real-time Navigation for the Double Asteroid Redirection Test[99, 100].

For icy moons exploration a combination of images of planets, nearby moons and asteroids as well as surface features can greatly aid in OD. Simulations done by researchers at JPL utilized the large number of moons available in the Jupiter and Saturn system for navigation[101]. For *Clipper* trajectory, uncertainties in position only using AutoNav was obtained to 10-100s of km requiring the use of radio tracking for improvement. The same system used for a *Cassini* trajectory performed better, one of the major factors being the Saturnian system has multiple visible moons while moons of the Jupiter system are dominated by the four largest. Major limitations in optical navigation include resolution of the camera used for taking the required images as this directly relates to the positional accuracy while also depending on the number of visible targets and high data requirements.

E. Gravity Gradiometers

Gravity gradiometry is the measure of variation in acceleration due to gravity or more specifically the second derivative of the gravity potential. Measurements are conducted by an ensemble of accelerometers arranged in three orthogonal axes[102]. According to [103], satellite gradiometer senses the: the orientation of the satellite; the orbit of the satellite; and the gravity field of the primary body. The most well-known example of satellite gradiometry was also the first of its kind, the Gravity and steady-state Ocean Circulation Explorer (GOCE) launched by ESA in 2009. The mission's purpose was to determine the spatial variations of Earth's static gravity field with maximum resolution and accuracy[102]. However the instrument on GOCE weighed several hundred kilograms making it unfeasible for small sat deep space missions and so there is a need for small-sized, low cast gradiometers. [104] is currently developing a MEMS-based gradiometers for use in deep space applications and JPL is working on a Quantum Gravity Gradiometer that uses cold-atom inferometery[105–107]. While these instruments may not directly obtain navigation data, they can directly measure gravity data and further constrain gravity field of planetary bodies when coupled with navigation data.

F. Inter-Satellite Links

ISLs are a method of orbit determination technique utilizing accurate range and range-rate measurements between two spacecrafts. For applications in gravity science these measurements involve two spacecraft in identical orbits separated by a distance of 50-200 km along track. This setup basically forms a long single-axis gradiometer allowing both spacecrafts to feel the same change in acceleration seconds apart as they pass over a surface and measuring the relative change in their distances through onboard ranging instruments. This was demonstrated for Earth with the Gravity Recovery and Climate Experiment(GRACE) and it's follow on mission (GRACE-FO) and for the Moon, the Gravity Recovery and Interior Laboratory(GRAIL). GRACE and GRACE-FO both used a K-band(18-27 GHz) system for inter-satellite ranging and Global Positioning System (GPS) receivers for accurate tracking while also carrying on-board accelerometers to account for non-gravitional forces while GRAIL used Ka-band for intersatellite ranging and X-band DSN Doppler tracking from Earth [108–110]. GRACE-FO also carried a laser ranging interferometer as a technology demonstration for an alternate ranging system for future gravity mapping missions.

VI. Requirements Formulation

Considering one of the icy moons- Europa, we indicate the dynamic processes occurring with their estimated magnitudes and timescales in Fig. 3 [39, 111]. Key processes to note are the diurnal tides that are a result of Europa's eccentric orbit around Jupiter occurring at a period of (3.55 days). The wavelength of these processes have been derived for a ice shell of about ~ 15 km thickness which is decoupled from the interior by a global ocean. For different thickness models, the wavelengths differ. Measuring the above processes requires a near continuous mapping of Europa both at high and low altitudes. High altitudes are desirable for detecting long-wavelength gravity signatures that are a result of the mantle while low altitude mapping is useful for resolving the gravity field for higher degrees as well as altimetry and imaging. In mission scenarios where spacecraft lifetime is several months if not years, multiple sets of measurements can be taken that allow improved gravity knowledge whereas with SmallSats, due to high radiation from Jupiter, their lifetimes are limited to a few weeks so the required measurements need to be carefully targeted for achieving maximum return. Based on the measurements required and the planned measurement techniques Table 2 puts

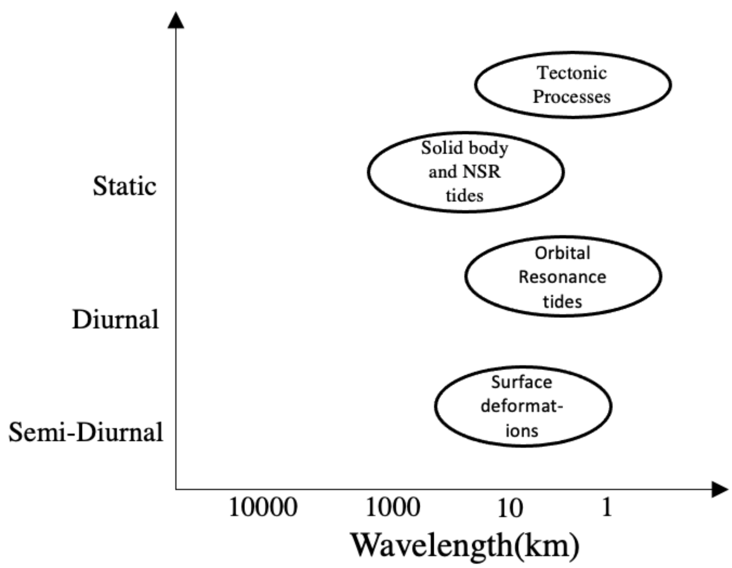


Fig. 3 Estimated processes on Europa

forward a pseudo-measurement suite and requirements for it to address the science objectives:

Table 2 Minimum Measurement Requirements for Europa

Measurement Type	Requirement
Static gravity field	Recovery of Stokes coefficients up to degree and order 10
Tidal Love numbers	k_2 and h_2 to < 0.015
Crossover topography using global surface profiles	Topographic differences at crossover points, 1m vertical accuracy

For Europa, Fig. 4 shows a comparison between requirements on tidal Love number and static gravity field recovery for *Clipper* [26], expected improvements from a SmallSat orbiter[69, 73] and current knowledge of the gravity field[31].

These requirements were developed to determine the thickness to 50% uncertainty for Europa Clipper and ± 5 km ice shell thickness.

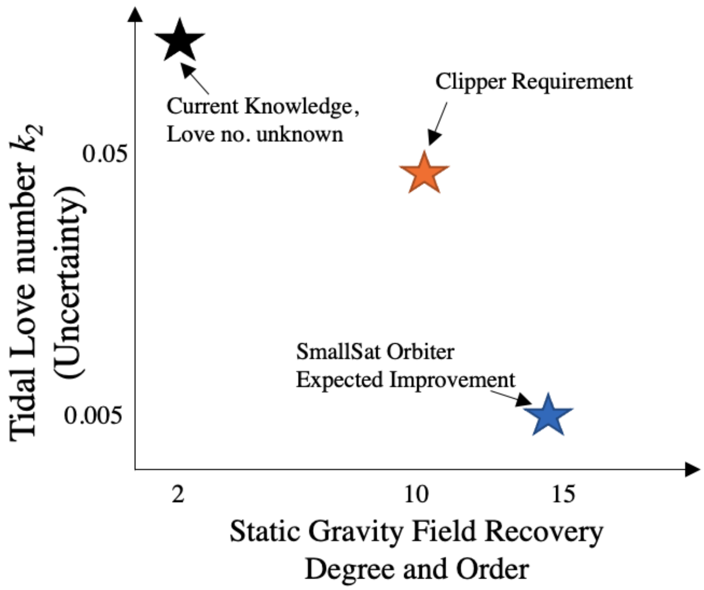


Fig. 4 Expected k_2 performance

Considering the measurement requirements of *Clipper* as a threshold for any improvements to be made by new mission concepts, and breakthrough requirements being those for a hypothetical best case scenario mission that has minimal constraints, the table below compare the temporal and spatial resolution requirements of key measurements compared with those that can be expected from a SmallSat mission. The values below were inferred from literature as well as publicly available information regarding the upcoming *Clipper* mission whose requirements have been frequently updated based on new trajectories as well as instrument constraints.

Table 3 Comparison of spatial and temporal resolutions of key measurements

	Resolution	**Threshold(*Clipper*)**[26]	**Breakthrough**[6, 61]	**SmallSat Orbiter (Expected)**[28, 69, 73]
Gravity	Spatial	500 km	100 km	250 km
	Temporal(tidal cycles)	4	<0.25	<1
Altimetry	Spatial	800 km	50 km	400 km
	Temporal	4	<0.25	<1

VII. Conclusions and Next Steps

This paper highlights key scientific objectives that are required for any in-orbit SmallSat mission to explore the icy moons of the outer planets with a focus on conducting gravity science investigations using SmallSats. The next steps involve the development of a custom simulation environment similar to those provided by astrodynamics tools such as General Mission Analysis Tool(GMAT), Evolutionary Mission Trajectory Generator (EMTG) and Mission Analysis, Operations, and Navigation Toolkit Environment(MONTE) but for a more focused and amenable mission scenario. The simulation study will involve the use of the geophysical model developed to describe how it affects the orbit of the spacecraft and the measurements done by the spacecraft. Preliminary models developed will be used to validate by independently simulating gravity and spacecraft instrument measurements to verify the results obtained in earlier studies to confirm that the geophysical model of the icy moons as well the gravitational model of the parent planet system is consistent with the literature and moving on to investigate the orbit design around the icy moons as well as the number of SmallSats required for achieving the mission requirements.

Acknowledgments

This work was partially supported by Georgia Tech's Daniel Guggenheim School of Aerospace Engineering Graduate Research Fellowship and would like to acknowledge my advisor Dr. Brian Gunter's mentorship during this project.

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