National Aeronautics and Space Administration

Business Case for Networked Constellations

Principal Investigator: Julie Castillo-Rogez (322)
Ryan Park (392), Anton Ermakov (392), Francis Nimmo (UCSC), Gregg Hallinan (Caltech)

Program: Strategic Initiative

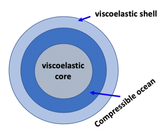
Project Objective:

This Initiative is designed to advance science and technologies related to networked constellations of spacecraft and surface assets, to ensure that the qualitative changes in science and exploration that become possible with distributed sensors are available for JPL mission development.

This task investigates the application of networking between multiple assets to deep space mission concepts of high interest to the scientific community but that are currently limited by telecommunication architectures. In FY19 we focused on a geophysical and geodetic experiment applied to Saturn's moon Enceladus. The objective of this work was to quantify measurement requirements and identify suitable mission architectures.

Parameter	Assumed truth (mostly from Hemingway et al, 2019)	Range*
Shell thickness	21.22 km	2 – 40 km
Shell density	900 kg/m³	600 – 1100 kg/m³
Shell shear modulus	3.3 GPa	1 – 10 GPa
Shell Poisson's ratio	0.33	0.25 – 0.45
Shell viscosity	10^{15} Pa s	10^{14} – 10^{20} Pa s
Ocean thickness	42.5 km	2 – 80 km
Ocean density	1050 kg/m³	920 – 1300 kg/m³
Ocean compressibility	2.15 GPa	2 – 3 GPa
Core radius	188.5 km	100 - 248 km
Core density	2480 kg/m³	2000 – 3000 kg/m³
Core shear modulus	40 GPa	10 – 100 GPa
Core Poisson's ratio	0.33	0.25 – 0.45
Core viscosity	10^{21} Pa s	10^{19} – 10^{22} Pa s

*These extreme ranges do not represent the current the state of uncertainty of Enceladus' interior.



Measured quantity	Value
GM	7.2 km³ s⁻²
Radius	252.2 km
Gravity harmonics	J_2, C_{22}, J_3 In less et al., 2014
Shape harmonics	up to *n* = 16 in Tajeddine et al., 2017
Libration amplitude	0.120 deg +/- 0.014
Tidal Love numbers	Not measured

5

Figure 1. Parametrization of internal structure for the Monte Carlo Markov Chain and available observational constraints.

Table 1. Traceability of Enceladus Enceladus science objectives to measurement requirements resulting from this work.

	Science requirement	Measurement requirement
1	Determine global dE/dt to ~10% and variations on regional scales. *Current uncertainty on global production ~5 to 55 GW*	An uncertainty of 0.5 GW in dE/dt requires measuring Im(k_2) with an uncertainty of $3 \cdot 10^{-4}$.
2.a	Determine the average shell thickness to ±2 km	Multiple combinations of measurements uncertainties are possible. For example: libration to 1 meter; k_2, h_2, l_2 to 10^{-4}; admittance to 0.5 mGal/km for 4<=n<=10. *[Ryan has done this case it yields +/- 1 km on shell thickness]*
2.b	Determine lateral shell thickness variations at n=30 (λ~50 km)	Gravity and shape up to n = 30 (λ~50 km)
3.a	Determine the rigid/elastic shell thickness to ±2 km	Gravity-topography admittance up to n = 30 (λ~50 km)
3.b	Determine lateral rigid/elastic shell thickness variations at n=30 (λ~50 km)	Lateral variations of elastic thicknesses (to n=30) can be derived from analyzing localized gravity-topography admittance; needs to have admittance up to several times 30. *Search for regional variations instead*

FY18/19 Results:

This work was developed under the premise that a future mission to Enceladus, as currently expressed in the outer planet exploration community, would focus on life search and not necessarily promote gravity science. Hence, this study explored ways to add a payload to an Enceladus mission focused on chemistry measurements that would acquire critical information on Enceladus' static and dynamic gravity properties with limited impact and requirements levied on the mothership.

The mission architecture for the Enceladus gravity science investigation was developed in multiple steps: science definition, measurement requirements, and mission design.

a. Science Definition: Key science objectives and requirements are presented in Table 1. For an orbital investigation, realistic science objectives are limited to better constraining heat dissipation and the properties of the icy crust. Gravity patterns of tidal dissipation and convection in the rocky mantle are too faint to be detectable from gravity measurements.

b. Measurement Requirements: An example of Monte Carlo Markov Chain triangle plot is presented in Figure 2. Measurement requirements are gathered in Table 1. The science requirements of interest can be met by a combination of libration, admittance, and tidal Love number determinations using the orbit parameters described below.

c. Mission Design: Because of Enceladus' strong degree 3, a stable orbit is of relatively high altitude with a periapsis of ~150 km and apoapsis of ~200 km. If the state is propagated beyond 9 days (i.e., without maintenance) then the orbital eccentricity increases and the periapsis altitude dips to 100 km. However orbit is still stable and well behaved after 1 month. The results of the covariance analysis are presented in Figure 3. For a single orbiter, the gravity field can be recovered to degree 9-10. For dual spacecraft (GRAIL-like) case, the gravity field can be recovered to degree 23. It is expected that the required harmonic n=30 could be achieved if the mean altitude were decreased to ~130 km.

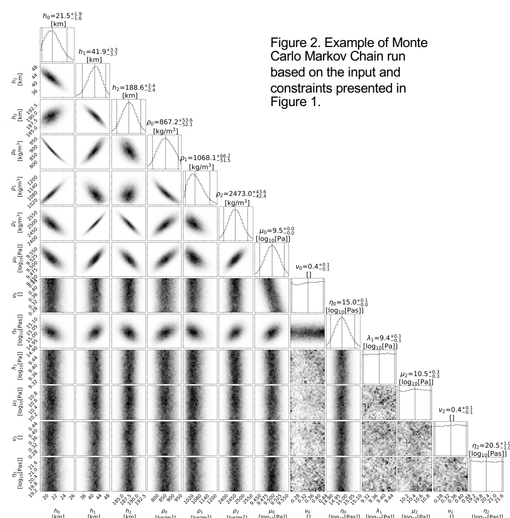


Figure 2. Example of Monte Carlo Markov Chain run based on the input and constraints presented in Figure 1.

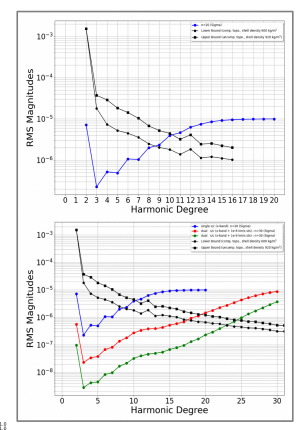


Figure 3. Covariance analysis results (1-sigma) for a single orbiter (left) and two orbiter (right) mission architectures at a mean altitude of 170 km (see text for details on trajectory parameters).

Benefits to NASA and JPL (or significance of results):

This work explored the role of networked constellations for enabling unique scientific investigations that are not achievable with classical, monolithic architectures. For example, stable orbits around Enceladus require an altitude of at least 100 km, are eccentric, and with an incllination lower than 70 degrees. In these conditions, the sensitivity of a classical radio science investigation is not sufficient to meet scientific objectives of interest to the Ocean Worlds community. Instead, this work demonstrates that a two-spacecraft architecture, for example based after the GRAIL mission at the Moon, results in an increase in sensitivity by two orders of magnitude, meeting the measurement requirements.

Building on the success of GRAIL mission, many missions have considered the application of a two spacecraft architecture for gravity science to other planetary bodies. To the best of our knowledge, this study is the first to quantify the benefits of that type of architecture at an icy moon. The advantage of the mission scenario considered in this study is that it allows a significant increase in science return for a potentially small impact on resources. Specifically, it demonstrates that a short-lived constellation is sufficient to meet significant science objectives and thus can be implemented within the resources of a small satellite. This result forms a basis for future missions to consider. Future work should consider science return as a function of the number of deployable assets.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Copyright 2019. All rights reserved.

PI/Task Mgr. Contact Information: Julie.C.Castillo@jpl.nasa.gov

Poster No. RPC-079