Enhanced electromagnetic sounding of Europa's ocean using CubeSats

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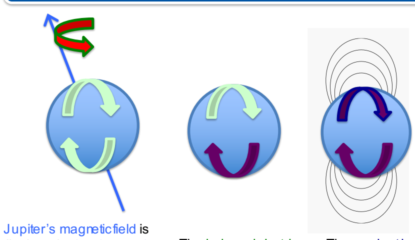
Introduction

If the Europa Multiple Flyby Mission (EMFM) carried a CubeSat deployer, what CubeSats would you put in it?

- Hypothetical concept study funded by JPL In 2014
  - Examples of small, secondary satellites on major planetary missions
- Europa Multiple Flyby Mission is in development for 2022 launch
  - Will orbit Jupiter and make 45 close flybys of Europa
- A primary goal of Europa Multiple Flyby Mission (EMFM) is investigating the ocean below Europa's icy surface
  - Ice shell above the ocean is estimated to be 10 to 100 km thick
  - Properties of this ocean can only be inferred indirectly
  - Electromagnetic sounding is a major sources of data on this ocean
- "CubeSAt for ice Layer Thickness" (CSALT) concept
  - Use multiple 1U or 1.5U CubeSats each on separate encounters
  - Make simultaneous magnetic field measurements with EMFM
  - Fly along a trajectory parallel to but separated EMFM
  - Electromagnetic sounding of Europa will be significantly enhanced

I: Electromagnetic sounding



Jupiter's magnetic field is tilted, so the background field at Europa rotates with a 11.1 hour period. This produces an induced electric field

The induced electric field drives electric currents in the ocean inside Europa's ice shell

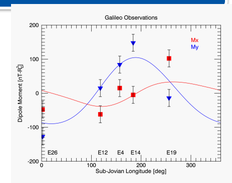
These electric currents generate an ***induced magnetic field*** which spacecraft can observe during a flyby

The *Galileo* magnetometer observed Europa's ocean through electromagnetic sounding

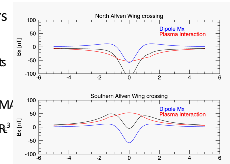
The large uncertainty (>15%) limited the result to a detection, not a determination of ocean properties

Measurements at 1% or lower uncertainty can reveal the ocean's **depth, thickness and conductivity (salinity.)**

II: Induction and Plasma Interaction

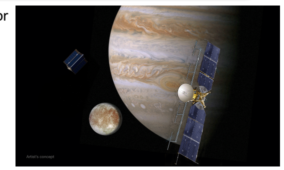


- The ocean is not the only source of magnetic field perturbations
- Strong perturbations from the plasma interaction between Jupiter's magnetosphere and Europa's atmosphere/ionosphere
- This is the largest source of uncertainty in determining the phase and amplitude of the ocean-induced dipole
  - The uncertaianty is 10-100 nT-R_E^3 (>10%) [Crary et al., EGU 2014]
  - There are several ways to reduce this uncertainty to <1%
- Measurements to constrain models of the plasma interaction
  - Allow estimats of the plasma perturbation to be subtracted from data
  - Plasma Instrument for Magnetic Sounding (PIMS)
    - Set of ion and electron Faraday Cups
    - Part of EMFM payload for exactly this reason
    - Resource-limited and may not allow removal of perturbations to <1%



- Multiple encounters can reduce errors
  - Illustrated by approximate model
    - Neubauer, 1980 Alfven wing currents
    - Closure current through body
    - M_A=0.27, 25% slowing of flow, 0.26 M/
    - Also shown is field from 100 nT-R_E^3 induced dipole.
    - The field is calculated along a trajectory for two polar encounters, north and south, similar to those some planned for EMFM
  - North pole encounter: Induced and interaction signatures correlated
    - W/out accounting for interaction, induced dipole overestimated by 47 nT-R_E^3
  - South pole encounter: Induced and interaction signatures anti-correlated
    - W/out accounting for interaction, induced dipole **under**estimated by 46 nT-R_E^3
  - Analyzed together the errors from the interaction would nearly cancel
- The real world will not be this kind
  - Real encounters will have less ideal geometries, cancelation will be partial
    - Errors from the interaction will be reduced but not eleminated
  - Induced dipole amplitude at multiple phases required
  - Multiple encounters with different geometries would be required a multiple number of phases
  - Jupiter's plasma conditions are highly variable
  - Plasma conditions on each encounter will be different
  - Multiple encounters required to average out plasma variability, at multiple phases, at multiple encounter geometries
- **Multiple x Multiple x Multiple >> 45**
- **This would require far more than the planned 45 EMFM encounters**

CubeSAt for ice Layer Thickness (CSALT) Concept



- CSALT spacecraft will be 3, 1U or 2, 1.5U CubeSats
  - 10x10x10 cm, 1.33 kg or 15x10x10 cm, 2.00 kg
  - 3x1U is baseline, 2x1.5U is performance floor while adding 50% margins
- Each carries a magnetometer, star tracker as its payload
  - CubeSat orientation will not be controlled but it must be know
- Designed to satisfy a ±0.1 nT requirement without a boom
  - Magnetically clean star trackers have been flown (e.g. Ørsted and Juno)
  - Other electronics and telecommunication systems need development
  - Small number of components and exclusive use of batteries will greatly help
- Battery powered for 3 day mission (possible 12 hour extended mission)
- CSALT will relay all data through the Clipper
  - 1200 bps using a 0.25-2 W radio and an omnidirectional antenna
  - This link will also be used for tracking (range only) of the CubeSat.
- Spacecraft will be released from EMFM individually, one per encounter
  - Approximately 2 ¾ days prior to closest approach and drift in low power mode (<1 W)
  - At closest approach – 3 hours, transition to 3 W science mode (2 hour warm-up time)
  - Key measurements from -1 hour to +1 hour (inside 10 R_E)
- Measurements along **two well-separated trajectories** (CSALT & EMFM)
  - Errors from plasma interaction will be **greatly reduced** in a **single** encounter
  - Measurements are at the **same** phase and plasma conditions
- A dual encounter is worth **multiple x multiple** encounters by EMFM alone
- CSALT will provide 2—3 dual encounters

V: Deployment and Trajectory

- CSALT trajectory must be well-separated from EMFM
- CSALT and EMFM must remain above horizon at closest approach
- Closest approach above ionosphere (less ambiguous measurements)
- Close for strong induced field signature, >50% surface amplitude
- Target 300 ±100 km closest approach altitude
- 1200 km (42°) separation from EMFM at closest approach
- After encounter, trajectories diverge: 7500 km separation at +2.2 hrs
  - Radio communications limit at 2 W transmitted power
- Requires deployment at 5 m/s, 67.5 hours prior to closest approach
  - 2.5 times faster than from a standard deployer
  - The speed and direction controlled to 10% and 4°
  - Deployer will modifications for this and to allow sequential deployments.

VI: Radiation

- Radiation is a major design driver for EMFM
- Most of the dose is accumulated during Europa encounters
  - Prior to first encounter, total integrated dose (TID) will be relatively low
- All three CSALT will be deployed during the first five encounters
- Radiation estimate assumes:
  - 50 mil Al thickness shell for CubeSats, 100 mils from walls of deployer
  - 1.33 g-cm^{-3} Al (equivalent) from CubeSat components
- TID of 64 krad for parts in faces of CubeSat prior to fifth encounter
  - Only 6.6 krad for parts in center
- 18 and 0.6 krad, respectively, during science encounter itself
- Existing commerical (COTS) parts can not be used
  - 15-165 krad (RDF of 2) can be achieved by replacing sensitive parts
  - Mass and power budget assume properties similar to existing COTS parts

VII: Planetary Protection

- Planetary protection is a serious concern for CSALT
  - CSALT will end mission in an orbit similar to Europa
  - CSALT has no propulsive capabilities for disposal
  - Spacecraft will eventually impact Europa, 5 year mean time to impact
- Unlike EMFM, CSALT components are not heavily shielded
  - No "Vault" for sensitive electronics
- Even the most shielded parts accumulate 27 krad/year
- 5 years exposure is 145 krad in center of CubeSat, 5 Mrad on faces
- Planetary protection requirements similar to EMFM can be satisfied

VI: Conclusions and Open Issues

- CSALT will enhance the magnetic sounding of Europa's ocean
- CSALT/EMFM encounters worth many stand-alone encounters
- Impact on EMFM mission is minimal
  - ~10 kg of payload mass
  - Reorient EMFM spacecraft for deployment at c/a-65 hours
  - Receive and relay telemetry and support ranging
- Adding CubeSats to EMFM adds no risk to primary mission
  - Success of CSALT is not necessary for success of EMFM
  - CubeSat interface designed to remove risk and impact to primary mission
- Development of CubeSats for planetary missions needs discussion
  - Are CubeSats a "spacecraft" or a free-flying instrument?
  - CubeSats are inherently not Class A hardware
    - Requiring Class-A development would add significantly to cost
    - Are COTS parts allowed? What margins are required?
- Are these Europa CubeSat concepts "CubeSats" or class A nanosats?