Jet Propulsion Laboratory
California Institute of Technology

EUROPA CLIPPER

Science Implications of ICEMAG Descope

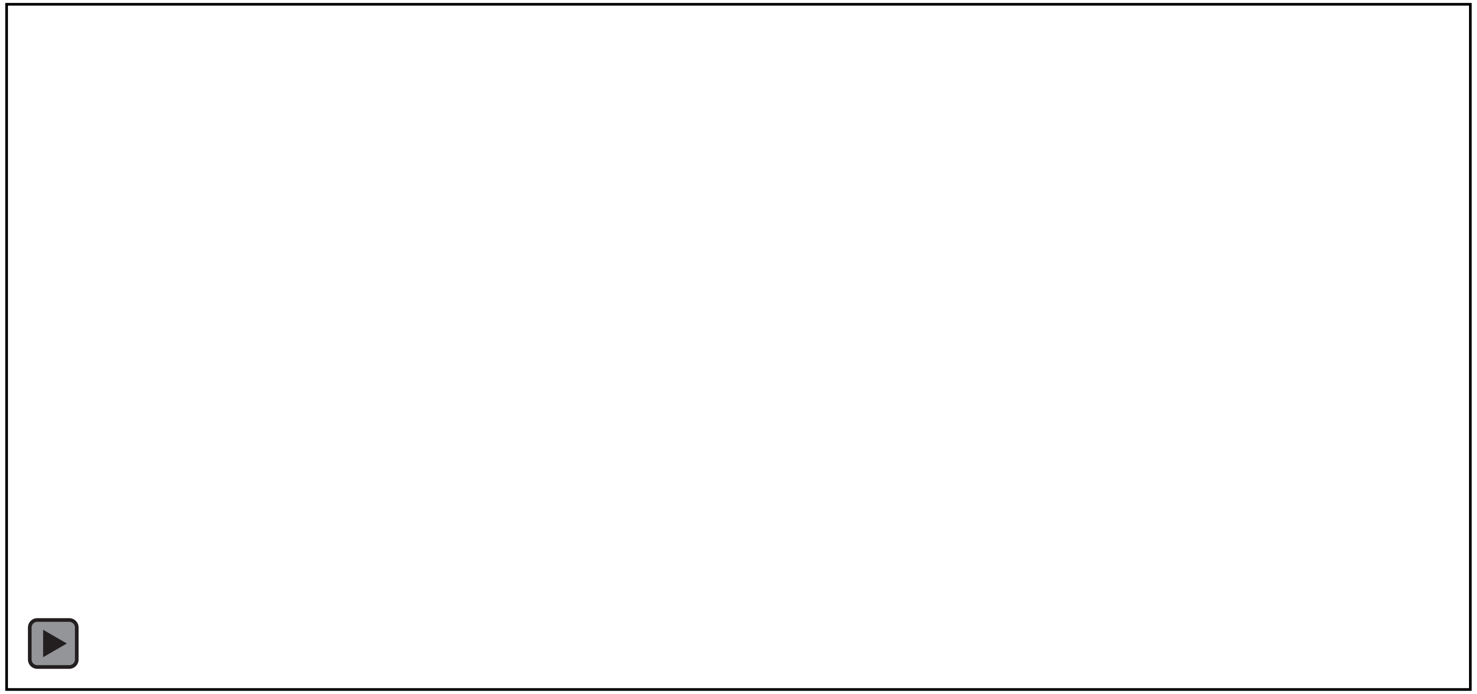
Robert Pappalardo, Europa Clipper Project Scientist[1]
Haje Korth, Europa Clipper APL Deputy Project Scientist[2]
Carol Raymond, ICEMAG Principal Investigator[1]
[1]Jet Propulsion Laboratory, California Institute of Technology; [2]Johns Hopkins University Applied Physics Laboratory

March 27, 2019

Summary: Science Impact of Descoping the SVH Sensors

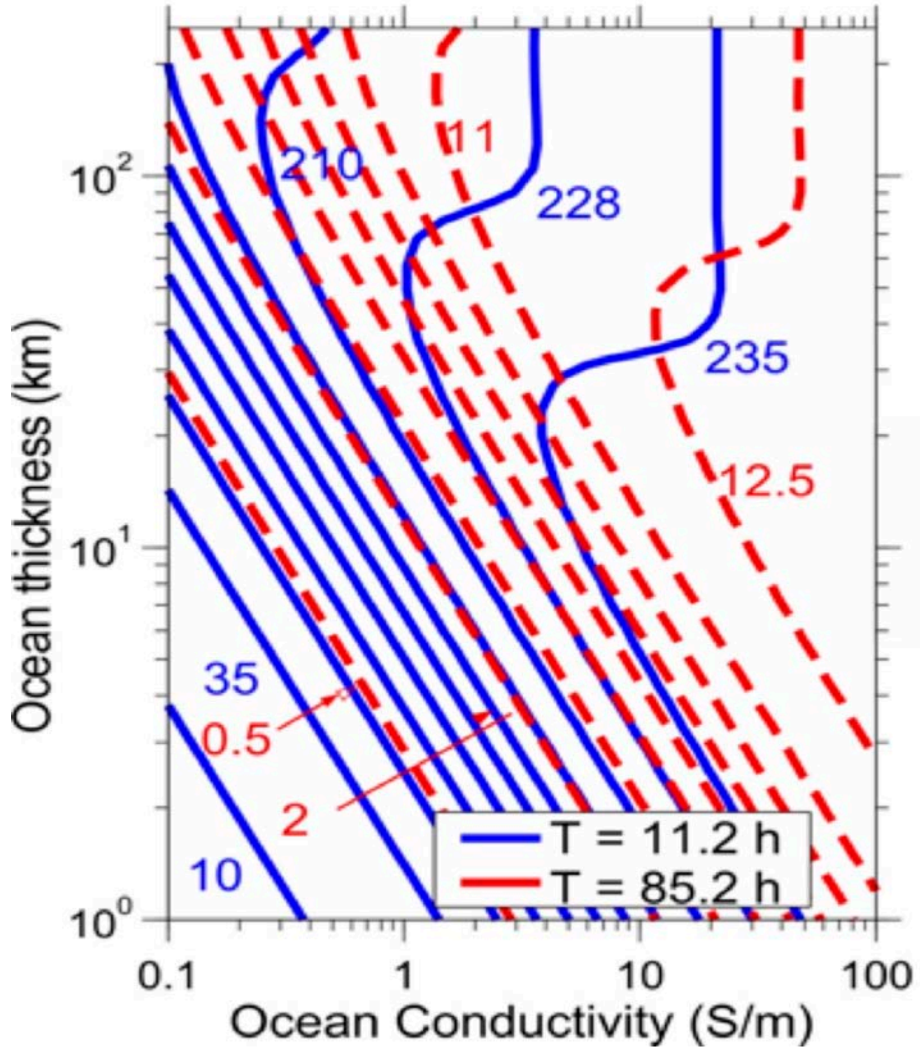
- Descope of the ICEMAG scalar-vector helium (SVH) sensors means there will be no absolute measurement of the magnetic field, limiting reliable retrieval of the induction signal at Europa's orbital period (85 hr), which is central to characterizing Europa's ocean properties
- Puts at significant risk the current Level 1 requirement:
  - **Constrain the <u>average thickness of the ice shell</u>, and the <u>average thickness and salinity of the ocean</u>, <u>each to ±50%</u>**
- Other Baseline Level 1 requirements are not affected; Threshold Level 1 requirements are not affected; and Mission Success Criteria can still be achieved
- Lack of ocean thickness and salinity information will limit our understanding of Europa's ocean habitability, interior structure, compositional fractionation, and plume provenance
  - Ocean salinity is especially relevant to ocean habitability (specifically: water activity, available energy for metabolism, and long-term history of water-rock reactions), quite important to the mission goal of understanding Europa's habitability
- Other instruments cannot reliably recover the lost science:
  - Data from other Europa Clipper compositional instruments provide limited information on ocean salinity, given possible fractionation within Europa, plus we cannot be assured of flying through a putative plume sourced from the ocean
  - Combined radar (ice shell) and Gravity Science (total H_2O layer) are not expected to be definitive for ocean thickness
  - Ice shell thickness could potentially be constrained from radar ranging (h_2) plus gravity science (k_2), but how precisely is in progress, and these are not currently required measurements of the mission

Europa's Ocean Thickness and Conductivity Can be Derived from Induced Magnetic Field Measurement at Multiple Frequencies



- Europa's induction response at multiple frequencies probes of the depth and salinity of the conductive ocean
  - Jupiter–Europa synodic period = 11.2 h; Europa orbital period = 85.2 h
- Induction efficiency at the synodic period (11.2 h) provides ice shell thickness, if conductivity is known
- Measurement of Europa's induced magnetic field at Europa's 85.2 h orbital period requires high precision (~0.1 nT) over flyby time scales, and high absolute accuracy sustained over the course of the mission (~1 nT over 2+ yr)

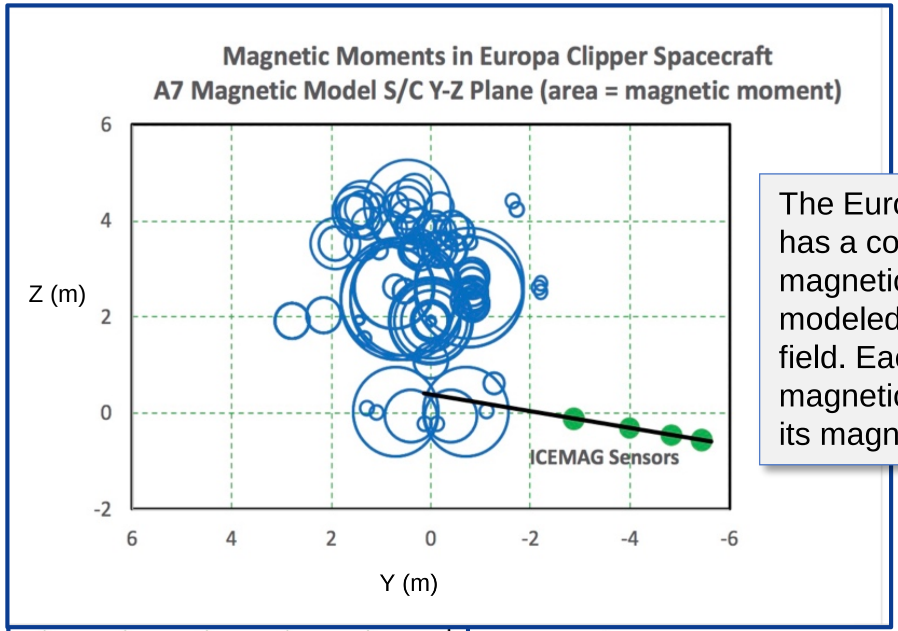
Induced Magnetic Field at Europa (nT)



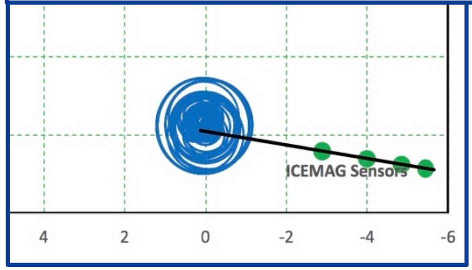
[Khurana, 2002]

Spacecraft Magnetic Field Removal

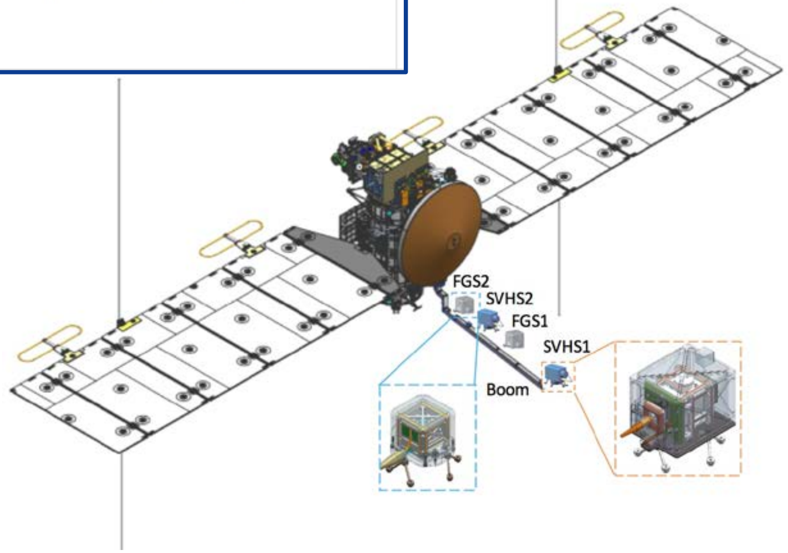
- ICEMAG had a unique approach to magnetic mapping by a flyby mission in a dynamic ambient field, with variable magnetic noise and offsets
- Intended to enable the long-term stability needed to connect flybys into a single measurement set
- ICEMAG configuration employed 2 fluxgate (FG) and 2 scalar-vector helium (SVH) magnetometers to measure the complex spacecraft field, to allow the spacecraft field to be removed from the data
- Multiple sensors permit correction at a cadence fast enough to separate transient spacecraft noise from the induction field, and permit identification and removal of higher-order spacecraft fields
- ICEMAG enabled a relaxed magnetic cleanliness requirement of 10 nT field at end of 5 m boom
- A 2-fluxgate system would need a >15-m boom and a more stringent magnetic cleanliness program to allow spacecraft field removal at sub-nT levels



The Europa Clipper spacecraft has a complex and strong magnetic field that cannot be modeled as a simple dipolar field. Each circle here is a magnetic moment, scaled to its magnitude.



For comparison, this diagram represents a dipolar space-craft field.



Magnetometer Comparison

- Fluxgate magnetometers:
  - Sense the imbalance of the voltage induced in a coil surrounding a ferromagnetic material oscillating between saturated states of opposite magnetization direction, as created in presence of an ambient magnetic field
  - **Fluxgate offsets change due to temperature variations and thermal gradients and can drift over time, so require periodic calibration in flight**
  - Fluxgate magnetometers have high precision (<0.1 nT), but offset uncertainty and inability to remove the spacecraft field results in errors ~3 nT on long-term retrieved induction accuracy

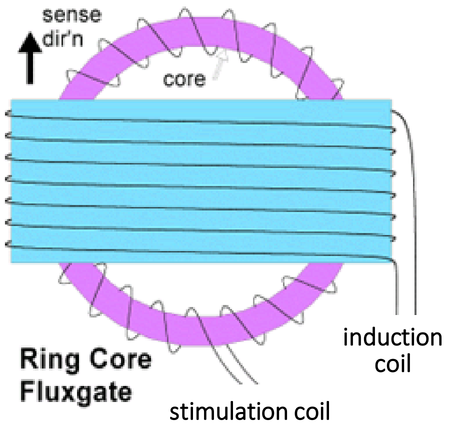
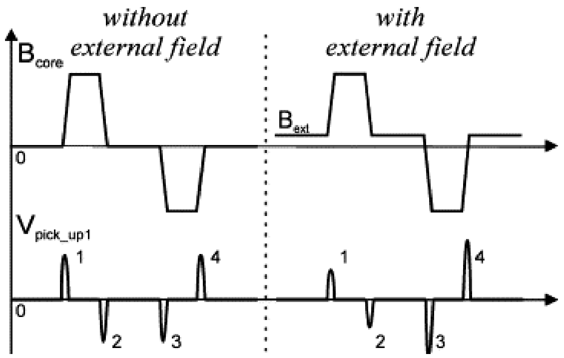
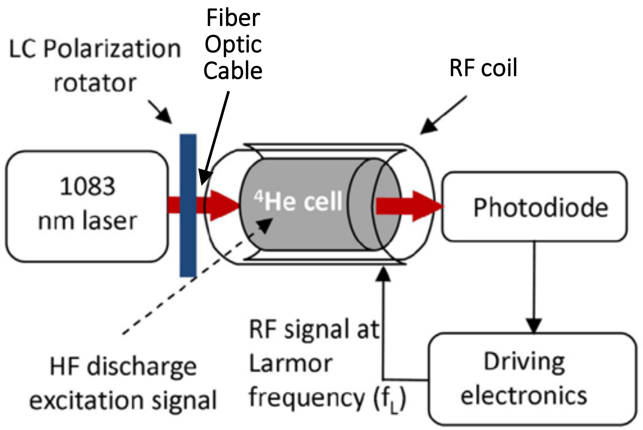


Image credit: sensorland.com

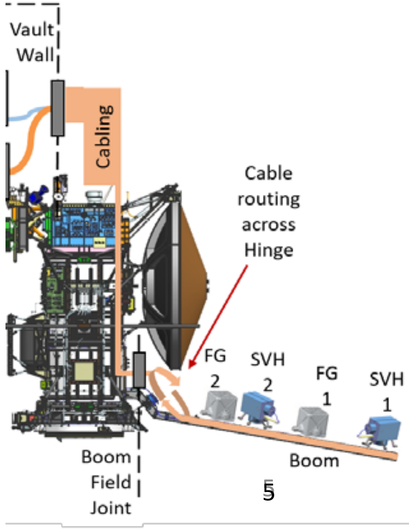


[Drljača et al., 2004]

- Helium magnetometers:
  - Senses a magnetic resonance with the resonance frequency proportional to the magnetic field
  - **He magnetometer measurements are absolute because the constant of proportionality is an atomic constant**
  - Fiber optic cable guiding circularly polarized laser light from the electronics to the sensors is sensitive to radiation and temperature, so has been challenging to accommodate
  - Absolute measurement such as provided by a He magnetometer would have ensured an order of magnitude improvement of flyby-to-flyby accuracy over the Europa Clipper mission duration



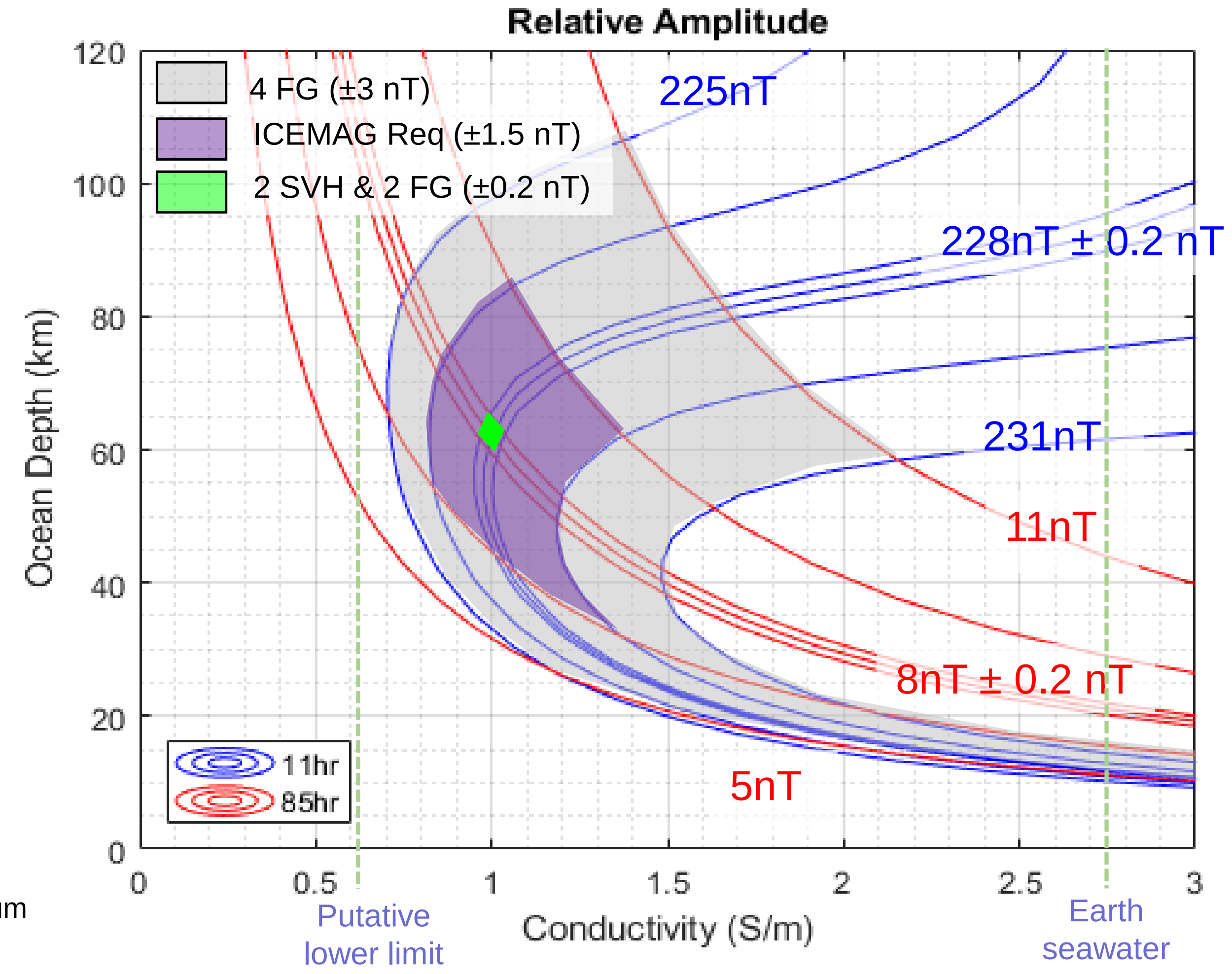
[Rutkowski et al., 2014]



Impact of Descoping SVH Sensors: Ocean Properties

- Without correction, drifting zero-level offsets of the fluxgate sensors can result in errors that significantly degrade the accuracy of the induction retrieval
  - Errors for the 4-FG system include contributions from residual low-frequency dynamic spacecraft fields and uncalibrated offsets and gains
- An example of the impact of this error on the determination of ocean parameters is illustrated by plotting the expected uncertainty in the thickness-conductivity solution* for an example case of a 60-km thick ocean with conductivity of 1.0 S/m
  - **Case with absolute reference data** yields tight bounds on ocean thickness and conductivity
  - **4-FG case** yields a huge error on ocean thickness, and conductivity range from freshwater to seawater

* Errors are determined by an induction simulation that utilizes a realistic error spectrum



SVH sensor descope increases uncertainties in estimates of ocean thickness and conductivity, limiting our understanding of Europa's ocean habitability, interior structure, compositional fractionation, and plume provenance

Impact of Descoping SVH Sensors: Ocean Salinity

Low Conductivity Case:

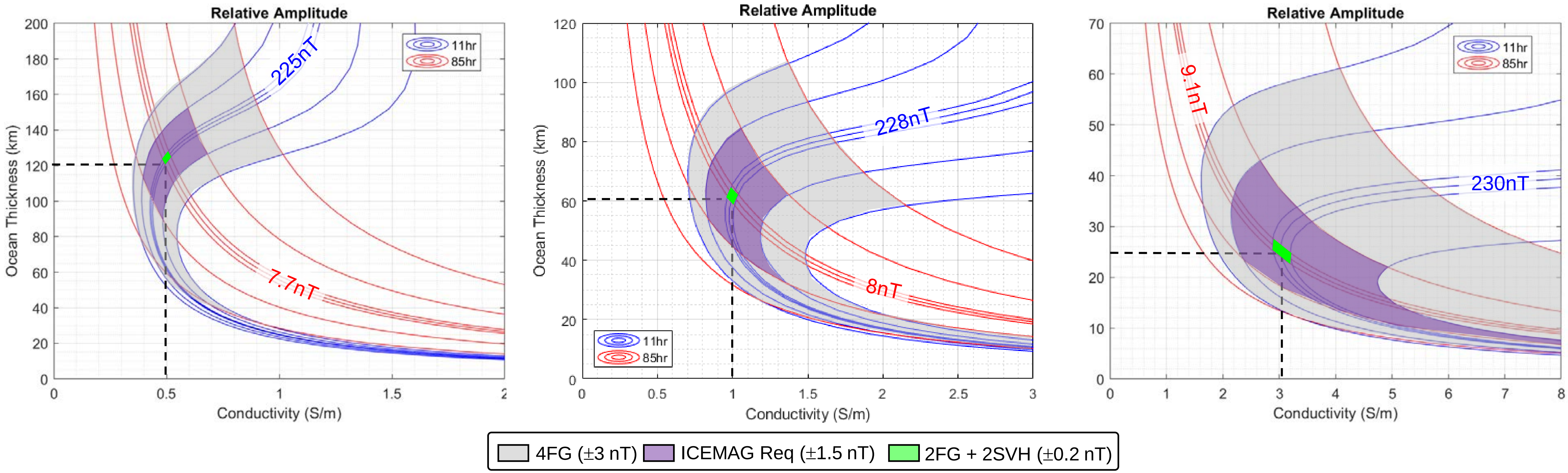
Conductivity: **0.5 S/m**
Ocean Thickness: **120 km**
Fixed Ice Thickness: 10 km

Medium Conductivity Case:

Conductivity: **1.0 S/m**
Ocean Thickness: **60 km**
Fixed Ice Thickness: 20 km

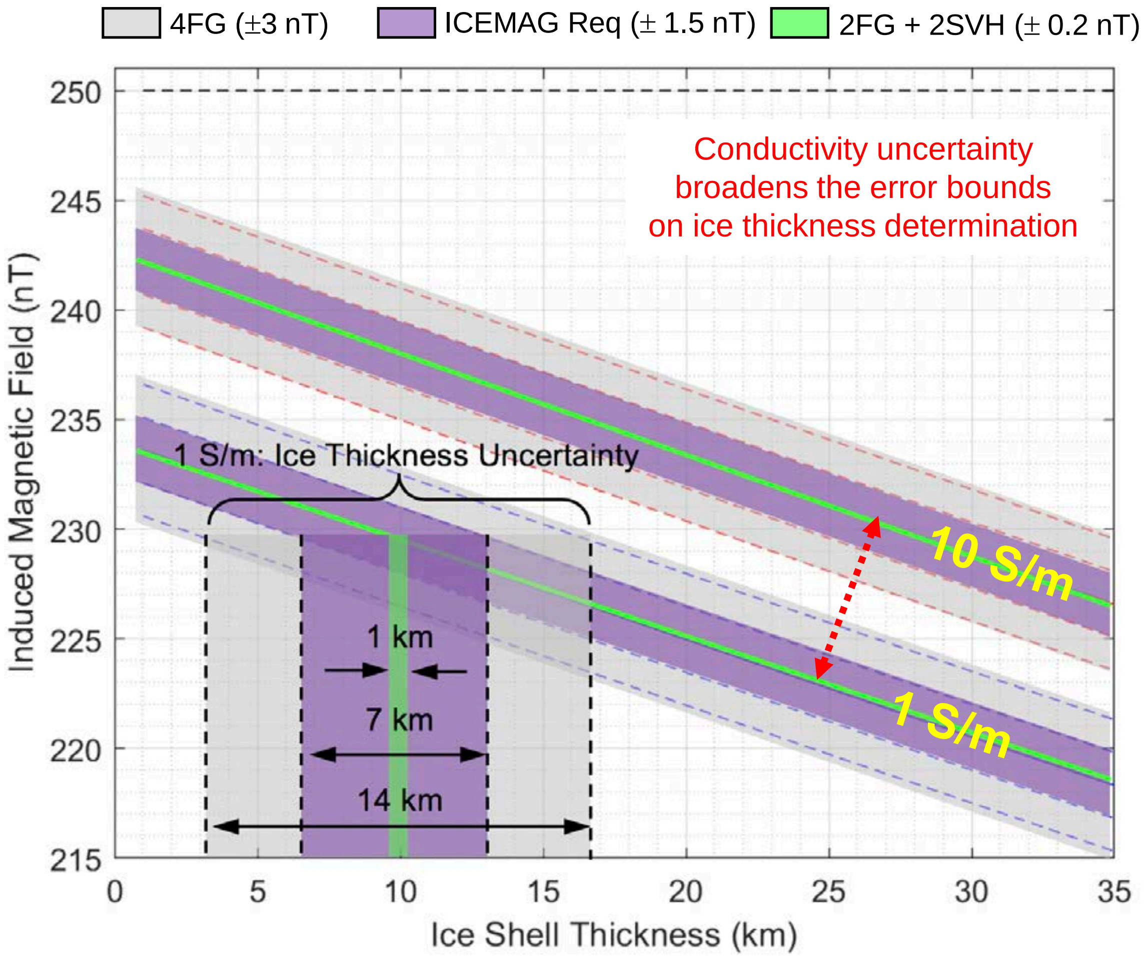
High Conductivity Case:

Conductivity: **3.0 S/m**
Ocean Thickness: **25 km**
Fixed Ice Thickness: 30 km



Conductivity is only weakly constrained for oceans with conductivity > ~2 S/m
Errors in conductivity (salinity) rise non-linearly as conductivity increases

Impact of Descoping SVH Sensors: Ice Shell Thickness



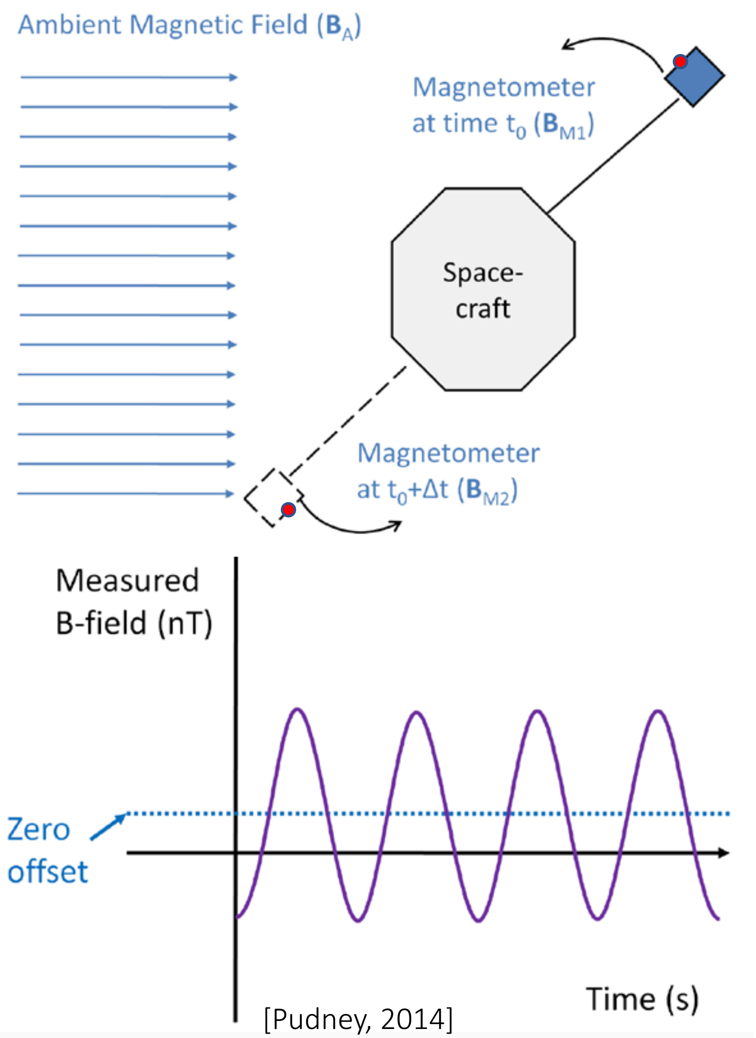
Plotted is the induced magnetic field at the 11.2 hr period (nT) vs ice shell thickness (km), for ocean conductivity of 1 and 10 S/m

- Intrinsic error doubles between the conservative ICEMAG requirement (±1.5 nT) and the 4-FG estimate (±0.3 nT)
- For the 1 S/m example shown, the ±50% Level-1 requirement is met for ice shell thickness >15 km
- However, ice shell thickness determination is conductivity dependent, such that error in conductivity increases error in ice shell thickness, especially for high conductivity oceans

Ice shell thickness measurement accuracy depends on conductivity, which in turn depends on accurate determination of induction at the 85-h period

Partial Recovery of Measurement Accuracy

- Facility magnetometer with 4 fluxgates is less capable than original payload with SVH sensors, but lost measurement accuracy may be partially recovered
- Regular ***spacecraft rolls*** and other maneuvers may permit determination of zero levels
  - Although the large spacecraft maneuvers slowly, and extended maneuver time would impact spacecraft resources, additional work is underway to understand how currently planned spacecraft maneuvers can aid calibration of offsets, what additional maneuvers would be most beneficial to this calibration, and whether zero levels determined near apoapse represent the spacecraft environment during flybys
- ***Longer boom*** would allow sensor mounting farther from spacecraft source fields, more closely approximating the spacecraft field as dipolar
  - NASA has directed to implement the facility magnetometers on the existing 5-m boom, and boom changes could impact the propulsion module design, but the impacts will be examined and assessed
- More stringent ***magnetic cleanliness*** would reduce spacecraft contributions to the measured magnetic field
  - We wish to avoid spacecraft and payload design changes or material choices that would increase cost and complexity, but will look to identify any simple improvements
- The new Team Leader and reconstituted Mag science team will be charged with fully characterizing the measurement accuracy and potential science return of the facility magnetometer



[Pudney, 2014]

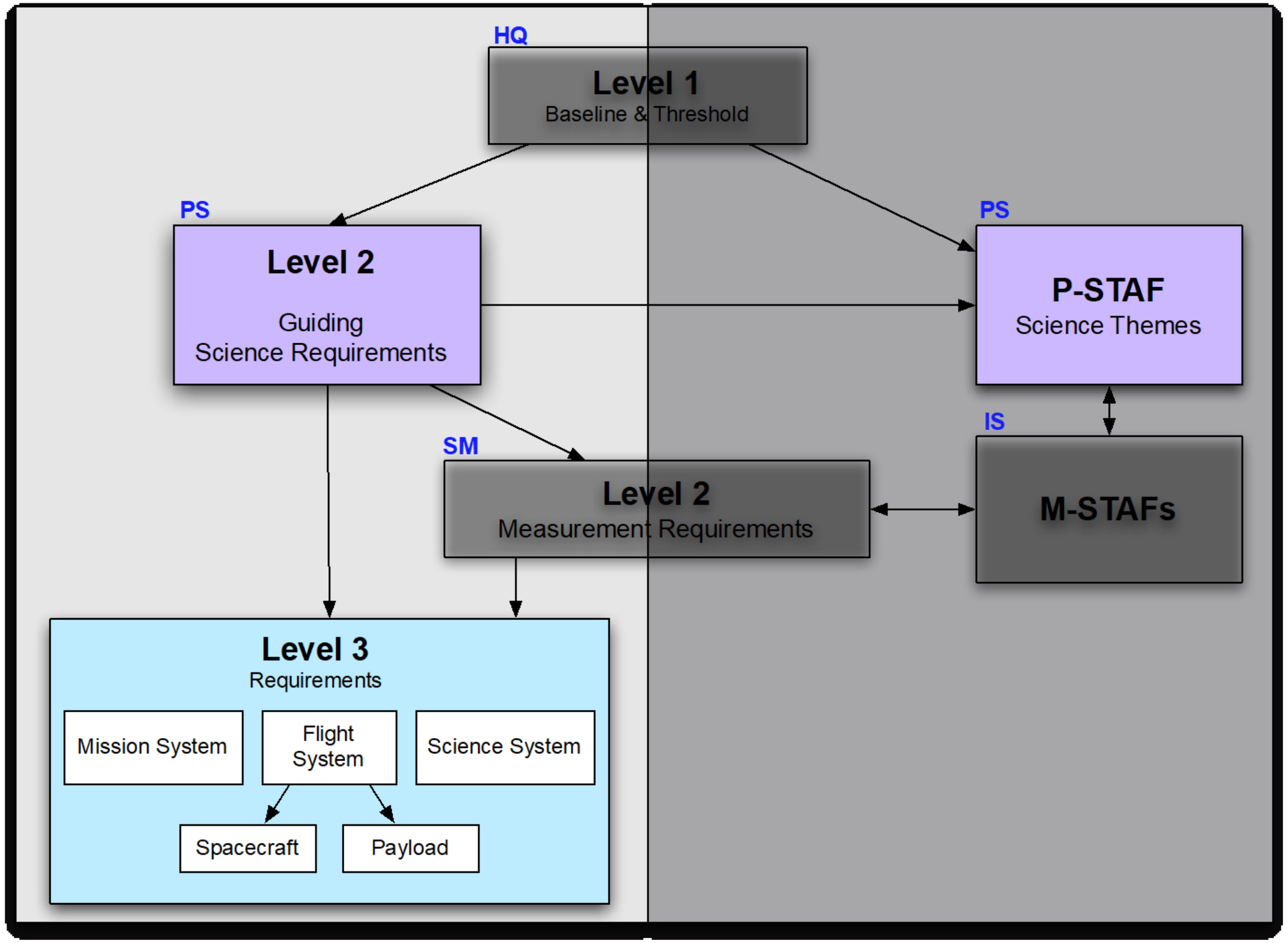
Recommended Science Teaming Structure

- Project Scientist received detailed input from across the full Europa Clipper Science Team
  - Telecon and WebEx meetings, written communications, private phone conversations, and in-person discussions
- Team Leader
  - Given immediate need, Team Leader for development (Phases C/D) should be chosen from among the existing Europa Clipper Science Team members, with established magnetometry expertise
  - Open competition to the planetary science community for the post-launch operations (Phase E) Team Leader
  - Should have budget and managerial authority over the Magnetometer Science Team members
  - Should be able to nominate their own Deputy Team Leader, whether from inside or outside the Europa Clipper team
  - Diversity should be considered in selection of the Team Leader and Deputy Team Leader
  - During development: Provide oversight of science instrument operations and science data processing definition
  - During operations: Oversee instrument operations and data processing, calibration, analysis, and archiving
- Science Team Members as Co-Investigators
  - Should be designated as Co-Investigators, mirroring the science management organization of a PI-led team
  - Designating as Co-Investigators assures future ability to promote early career members onto the science team
  - Team Leader should assess whether any additional team expertise is currently needed, given new mag configuration
- Science Interface Lead
  - A member of the Europa Clipper Project Science Team knowledgeable of the magnetometer hardware will serve as the information interface between engineering team and the Magnetometer Science Team during development
  - Attends relevant project engineering meetings and facilitates conversations to ensure science requirements are met
  - Ensure an Instrument Scientist and a role parallel to the function of the Instrument Engineer (IE) are also included

Backup

Post-PDR NASA Charges regarding Europa Clipper Requirements from NASA to the Project Manager and Project Scientist

- The project is directed to recommend changes to Level 1 requirements as appropriate to reduce complexity and cost risk.
- The project is directed to scrub the Level 2 requirements that exceed Level 1 requirements, and to reduce environmental requirements as appropriate to reduce complexity and cost risk.



Proposed Edits to Baseline Level 1 Science Requirements: Ice Shell & Ocean

	Baseline Level 1	Recommended Level 1 (tracked)	Recommended Level 1 (accepted)	Rationale for Change
Ice Shell & Ocean	Map the vertical subsurface structure beneath ≥50 globally distributed landforms to ≥3 km depth*[, to understand the distribution of subsurface water and processes of surface-ice-ocean exchange]*.	Map the vertical subsurface structure ~~beneath ≥50 globally distributed landforms~~ in regions of potential surface-ice-ocean exchange to ~~≥3~~ >3 km depth along globally distributed ground tracks achieving a total cumulative length ≥30,000 km~~*[, to understand the distribution of subsurface water and processes of surface-ice-ocean exchange]*~~.	Map the vertical subsurface structure in regions of potential surface-ice-ocean exchange to >3 km depth along globally distributed ground tracks achieving a total cumulative length ≥30,000 km.	Clarifies the intent of the L1, provides significant relief on mission design and provides margin on downlink and data storage. Baseline is achievable in ≈20 flybys, so reduces cost risk by permitting instruments to collect data non-simultaneously if EMI becomes a significant technical problem.
Ice Shell & Ocean	Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to ±50%.	Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to ±50%.	Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to ±50%.	No recommended changes: N/A.

Proposed Edits to Baseline Level 1 Science Requirements: Composition

	Baseline Level 1	Recommended Level 1 (tracked)	Recommended Level 1 (accepted)	Rationale for Change
Composition	Create a compositional map at ≤10 km spatial scale, covering ≥70% of the surface*[, to identify the composition and distribution of surface materials]*.	Create a compositional map at ≤10 km spatial scale, covering ≥70% of the surface, sufficient to identify non-ice materials especially organic compounds ~~[, to identify the composition and distribution of surface materials]~~.	Create a compositional map at ≤10 km spatial scale, covering ≥70% of the surface, sufficient to identify non-ice materials especially organic compounds.	Clarifies intent of the requirement, specifying the relevance of organic compounds.
	Characterize the composition of ≥50 globally distributed landforms, at ≤300 m spatial scale*[, to identify non-ice surface constituents including any carbon-containing compounds]*.	Characterize the composition of ≥~~50~~ 0.3% of the surface, globally distributed ~~landforms,~~ at ≤300 m spatial scale, sufficient ~~[,~~to identify non-ice ~~surface constituents including any carbon-containing~~ materials, especially organic compounds~~]~~.	Characterize the composition of ≥0.3% of the surface, globally distributed at ≤300 m spatial scale, sufficient to identify non-ice materials, especially organic compounds.	Significant reduction in the required total areal coverage, accomplishable in ≈30 flybys. Wording change to clarify the requirement, aiding mission design and requirements validation. Elimination of explanatory brackets.
	Characterize the composition and sources of volatiles, particulates, and plasma, with sensitivity sufficient to identify the signatures of non-ice materials including any carbon-containing compounds, in globally distributed regions of the atmosphere and local space environment.	Characterize the composition and sources of volatiles, particulates, and plasma, ~~with sensitivity~~ sufficient to identify the signatures of non-ice materials ~~including any carbon-containing compounds~~, especially organic compounds, in globally distributed regions of the atmosphere and local space environment.	Characterize the composition and sources of volatiles, particulates, and plasma, sufficient to identify the signatures of non-ice materials, especially organic compounds, in globally distributed regions of the atmosphere and local space environment.	Clarifies intent of the requirement, specifying the relevance of organic compounds.

Proposed Edits to Baseline Level 1 Science Requirements: Geology, Current Activity

	Baseline Level 1	Recommended Level 1 (tracked)	Recommended Level 1 (accepted)	Rationale for Change
Geology	Produce a controlled photomosaic map of ≥80% of the surface at ≤100-m spatial scale*[, to map the global distribution and relationships of geologic landforms]*.	Produce a controlled photomosaic map of ≥80% of the surface at ≤100-m spatial scale~~*[, to map the global distribution and relationships of geologic landforms]*~~.	Produce a controlled photomosaic map of ≥80% of the surface at ≤100-m spatial scale.	Simplification of requirement language to eliminate explanatory brackets.
	Characterize the surface at ≤25-m spatial scale, and measure topography at ≤15-m vertical precision, across ≥50 globally distributed landforms*[, to identify their morphology and diversity]*.	Characterize the surface at ≤25-m spatial scale across ≥5% of the surface with global distribution, ~~and measure~~ including measurements of topography at ≤15-m vertical precision~~, across~~ within at least one third of that surface area~~ 50 globally distributed landforms*[, to identify their morphology and diversity]*~~.	Characterize the surface at ≤25-m spatial scale across ≥5% of the surface with global distribution, including measurements of topography at ≤15-m vertical precision within at least one third of that surface area.	Simplification of requirement language, aiding mission design and requirements validation, and elimination of explanatory brackets.
	Characterize the surface at ~1-m scale to determine surface properties, for ≥40 sites each ≥2 km x 4 km.	Characterize the surface at ~1-m spatial scale to determine surface properties, for ≥~~40~~ 18 globally distributed sites ~~each ≥2 km x 4 km~~.	Characterize the surface at ~1-m-spatial scale to determine surface properties, for ≥18 globally distributed sites.	Relaxes and simplifies requirement. Permits increasing flyby velocity, enabling Clipper:Europa 6:1 resonance.
Current Activity	Search for and characterize any current activity, notably plumes and thermal anomalies, in regions that are globally distributed.	Search for and characterize any current activity, notably plumes and thermal anomalies, in regions that are globally distributed.	Search for and characterize any current activity, notably plumes and thermal anomalies, in regions that are globally distributed.	No changes: N/A.

ICEMAG Contribution to Europa Clipper Level-1 Requirements on Ice Shell and Ocean

						ICEMAG		ICEMAG, Fluxgates only	
B/T	**L1 RQ Number**	**L1 Requirements**	**Science Themes**	**Science Theme Definitions**	**Approach**	**Magnetic**	**Waves**	**Magnetic**	**Waves**
Baseline	RQ106.317	Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to +/-50%.	Ice Shell Properties	Thickness and thermophysical properties of the ice shell.	Induction	P			
			Ocean Properties	Existence, thickness, and salinity of the ocean.	Induction	P		E?	
Threshold	RQ106.325	Confirm the presence of a subsurface ocean, and constrain whether the ice shell is in a “thin” (several km) or “thick” (10s km) regime.	Ice Shell Properties	Thickness and thermophysical properties of the ice shell.	Induction	P		P	
			Ocean Properties	Existence of the ocean.	Induction	P		P	

P Primary — Can provide, most robustly and with greatest probability, science data necessary to fully achieve a given approach.

I Independent — Can enable a given approach to be achieved, though potentially less robustly than from Primary instrument’s data.

E Enhancing — Expected to further enhance overall science return beyond that of Primary or Independent instrument.

Without the absolute calibration provided by the SVH sensors, ice shell thickness measurements would be degraded, while ocean properties (thickness and salinity) could not be reliably attained.

The Prospects and Limitations of Other Techniques (PSTAF)

Pre-ICEMAG Descope

				Investigation:	REASON		EIS			MISE	E-THEMIS	Europa-UVS	ICEMAG	PIMS	SUDA	MASPEX	GRAVITY
				Meas. Class:	RADAR		Visible			Infrared	Thermal	Ultraviolet	Magnetic	Plasma	IMS	NMS	Gravity
				Designator:	HF + VHF		WAC + NAC			MISE	E-THEMIS	Europa-UVS	ICEMAG	PIMS	SUDA	MASPEX	Gravity
L1 Requirement	**Science Themes**	**Theme Definitions**	**Approach**	**Approach Coding**	**Sounding (HF + VHF)**	**VHF Ranging**	**Limb (Global Shape)**	**Geodesy (Libration)**	**RADAR Suport Imaging**	**Day Scans**	**Scans & Stares**	**Scans, Stares, Occultations, Transits**	**Magnetic**	**Cations, Anions, & Electrons**	**Endogenic Particle**	**Ambient & Cryotrap**	**Fanbeam & LGA tracking**
Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to +/-50%.	Ice Shell Properties	Thickness and thermophysical properties of the ice shell.	Induction	1	B		B	B	B	B	B	B	P1	S1	B	B	B
			RF Probing	2	I1		B	B	S1	B	E	B	B	B	B	B	B
			Tidal Amplitude (h_2) & Gravity (k_2)	0		E					B						E
			Libration & Shape	0	E		E	E	B	B	B	B	B	B	B	B	E
	Ocean Properties	Existence, thickness, and salinity of the ocean.	Induction	1	B		B	B	B	B	B	B	P1	S1	B	B	B
			Shape and Gravity	0	B		E	E	B	B	B	B	B	B	B	B	E
			Composition	0	B		B	B	B	E	B	B	B	B	P1	E	B

P	**Primary:** The instrument that can provide, most robustly and with greatest probability, the science data necessary to fully achieve a given approach as pertinent to a Theme, in the nominal mission plan.
I	**Independent:** An instrument (other than a Primary instrument) whose science data can enable a given approach as pertinent to a Theme to be achieved, though potentially less robustly than from a Primary instrument's data. Moreover, a change to the mission plan may be required for the data from an Independent instrument to achieve the approach in question.

S	**Supportive:** Said of an instrument whose science data is required to enable data from the Primary instrument to fully achieve a given approach as pertinent to a Theme.
E	**Enhancing:** Said of an instrument whose data is expected to further enhance the overall science return beyond that of data from a Primary or Independent instrument in achieving a given approach as pertinent to a Theme. There is no dependency implied between a Primary or Independent instrument and an Enhancing instrument.

Approach Coding: 0 is not required of the mission

The Prospects and Limitations of Other Techniques (PSTAF)

Post-ICEMAG Descope

				Investigation:	REASON		EIS			MISE	E-THEMIS	Europa-UVS	ICEMAG	PIMS	SUDA	MASPEX	GRAVITY
				Meas. Class:	RADAR		Visible			Infrared	Thermal	Ultraviolet	Magnetic	Plasma	IMS	NMS	Gravity
				Designator:	HF + VHF		WAC + NAC			MISE	E-THEMIS	Europa-UVS	ICEMAG	PIMS	SUDA	MASPEX	Gravity
L1 Requirement	Science Themes	Theme Definitions	Approach	Approach Coding	Sounding (HF + VHF)	VHF Ranging	Limb (Global Shape)	Geodesy (Libration)	RADAR Suport Imaging	Day Scans	Scans & Stares	Scans, Stares, Occulations, Transits	Magnetic	Cations, Anions, & Electrons	Endogenic Particle	Ambient & Cryotrap	Fanbeam & LGA tracking
Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to +/-50%.	Ice Shell Properties	Thickness and thermophysical properties of the ice shell.	Induction	X	B		B	B	B	B	B	B	P1 X	S1	B	B	B
			RF Probing	2	I1		B	B	S1	B	E	B	B	B	B	B	B
			Tidal Amplitude (h_2) & Gravity (k_2)	0		E ?					B						E ?
			Libration & Shape	0	E		E	E	B	B	B	B	B	B	B	B	E
	Ocean Properties	Existence, thickness, and salinity of the ocean.	Induction	X	B		B	B	B	B	B	B	P1 X	S1	B	B	B
			Shape and Gravity	0	B		E	E	B	B	B	B	B	B	B	B	E
			Composition	0	B		B	B	B	E	B	B	B	B	P1	E	B

P	**Primary:** The instrument that can provide, most robustly and with greatest probability, the science data necessary to fully achieve a given approach as pertinent to a Theme, in the nominal mission plan.
I	**Independent:** An instrument (other than a Primary instrument) whose science data can enable a given approach as pertinent to a Theme to be achieved, though potentially less robustly than from a Primary instrument's data. Moreover, a change to the mission plan may be required for the data from an Independent instrument to achieve the approach in question.

S	**Supportive:** Said of an instrument whose science data is required to enable data from the Primary instrument to fully achieve a given approach as pertinent to a Theme.
E	**Enhancing:** Said of an instrument whose data is expected to further enhance the overall science return beyond that of data from a Primary or Independent instrument in achieving a given approach as pertinent to a Theme. There is no dependency implied between a Primary or Independent instrument and an Enhancing instrument.

Approach Coding: 0 is not required of the mission

The Prospects and Limitations of Other Techniques

Ice Shell Properties

- **Radio Frequency Probing (Radar Sounding):**
  - *Prospects:* Possibility to penetrate the ice shell to sub-ice ocean.
  - *Limitations:* Prospects for radar penetration to an ocean are best for a thin (~kilometers) and clean ice shell, as the radar signal is attenuated in the (more plausible) occurrence of warm convecting ice and/or chloride or brine impurities.
- **Tidal Amplitude & Gravity:**
  - *Prospects:* Gravitational (k_2) and tidal (h_2) Love numbers, in combination, will constrain ice shell elastic thickness.
  - *Limitations:* Requires high-precision radar ranging at cross-over points measured from <1000 km, topographic characterization of cross-over regions, improved true anomaly coverage by the trajectory, and small radial orbit error necessitating 70-m-antenna equivalent tracking, and may not enable the current L1 precision; elastic thickness may be less than total ice thickness.
- **Libration & Shape:**
  - *Prospects:* Libration can constrain ice shell thickness, and limb-derived topography and shape can constrain ice shell thickness.
  - *Limitations:* Libration is large only for a thin-shell case, may be below detection limits, and may not be diagnostic depending on internal structure; ice shell thickness can be derived from limb topography only in the unlikely case of a conductive ice shell.

Ocean Properties

- **Shape & Gravity:**
  - *Prospects:* Shape and static gravity can constrain H_2O-layer thickness.
  - *Limitations:* Little measurement improvement is expected over existing Galileo results, and composition uncertainty dominates the uncertainty in layer thicknesses.
- **Composition:**
  - *Prospects:* Surface composition and ejected particulates can indicate major salt species; composition of plume particulates and gases can directly indicate ocean salinity and other geochemical properties.
  - *Limitations:* Fractionation between ocean and surface may limit conclusions regarding ocean salinity and other properties; plumes (if real) may tap subsurface lakes rather than the ocean.

Europa Clipper Thematic Working Group Summary Findings

- **Habitability Working Group:** *Co-Chairs Jonathan Lunine (Cornell), Britney Schmidt (Georgia Tech)*
  - Descope of the ICEMAG SVH sensors would jeopardize primary constraints on ocean thickness and salinity that are essential to understanding the chemical conditions in Europa's ocean, including water activity, available energy for metabolism, pressure at the water-rock interface, and long-term history of water-rock reactions that might support a global biosphere.
- **Interior Working Group:** *Co-Chairs Carol Paty (Univ. Oregon), James Roberts (JHU/APL)*
  - The proposed descope of the ICEMAG SVH sensors will preclude direct measurement of the ocean thickness and salinity, and will degrade measurement of the ice shell thickness; other Europa Clipper measurements will not be sufficient to replace the science loss.
- **Composition Working Group:** *Co-Chairs Jason Soderblom (MIT), Murthy Gudipati (JPL/Caltech)*
  - Descoping the ICEMAG SVH sensors would result in very significant science loss: the ability to characterize the composition of Europa's ocean and the exchange of material between its interior and surface, and observations by other instruments via plumes and/or surface observations are not an effective replacement.
- **Geology Working Group:** *Co-Chairs Geoff Collins (Wheaton College), Julie Rathbun (PSI)*
  - Increased uncertainty in average global ice shell thickness and loss of ocean salinity information risks ambiguous interpretations of several key aspects of Europa geology, which could degrade our scientific confidence in linking observed surface features to the ocean.

Habitability Working Group Findings

- The Habitability Thematic Working Group for the Europa Clipper affirms the critical importance of ICEMAG measurements of the induced magnetic field at Europa at multiple frequencies, and strongly suggests that the instrument not be descoped.
- The determination of Europa's ice thickness is a key factor for determining the nature and rates of chemical exchange between Europa's active surface and its underlying ocean to which ICEMAG contributes unique information.
- Most important, ICEMAG is the primary instrument to provide constraints on ocean thickness and salinity that are essential to understanding the chemical conditions in Europa's ocean, including the activity of water, available energy for metabolism, and pressure at the water-rock interface, as well as the long-term history of water-rock reactions that could support a putative biosphere.
- Additionally, knowledge of the ocean depth and salinity would improve inferences of Europa's deeper interior structure.
- All of this information will be needed to properly interpret Europa Clipper data on habitability and to prepare for future missions, such as a Europa lander and a deep drilling mission to probe the ocean directly.

Interior Working Group Findings

- Detection of a potential subsurface ocean on Europa by the magnetometer on Galileo was a key motivation for proposed future exploration of Europa by a flight system which includes a magnetometer with sufficient absolute accuracy to allow more detailed characterization of Europa's subsurface ocean, namely independent determination of ocean layer thickness and conductivity.
- ICEMAG is the only instrument on the payload capable of making observations which would enable determination of the ocean thickness and salinity. Ocean thickness could be inferred from a combination of radar and gravity measurements of the ice shell thickness and moment of inertia, respectively. While the precision of these estimates may be an improvement over Galileo, in absence of constraints on the oceanic composition/salinity, they would not be definitive.
- The approach of measuring the ice shell properties using multiple instruments is powerful, as each technique is sensitive to different ice shell characteristics (e.g., rheology, total thickness, thickness of the cold elastic layer). In combination these measurements can provide insight into the ice shell that would elude a single instrument measurement, and provide robustness to ice shell characterization.
- Planned measurements of the tidal Love numbers with Gravity Science and REASON will enable confirmation of the presence of an ocean, but will not constrain the ocean thickness and would provide only constraints on the depth of the ice-ocean interface, with ambiguity due to uncertainties on ice shell rheology and oceanic composition (density). The proposed descope of the SVH sensors would remove our ability to resolve these ambiguities.
- The proposed descope of the SVH sensors would reduce the accuracy of ICEMAG's measurements because of the loss of absolute calibration, would jeopardize independent determination of the ocean thickness and salinity, and would degrade the accuracy of the determination of the ice shell thickness.

Composition Working Group Findings

- Descoping the ICEMAG SVH sensors would result in very significant science loss: the ability to characterize the composition of Europa's ocean and of the exchange of material between its interior and surface, both of which are fundamental to the Europa Clipper level 1 science requirements.
- Understanding Europa's ice-shell thickness, ocean depth, and ocean conductivity (and thus salinity), are critically important to fully understanding Europa's geochemistry and interior structure, and to modeling its physical and chemical evolution, as captured by the relevant level 1 science requirement.
- While constraints can be placed on the composition and salinity of Europa's plumes and exosphere from SUDA dust observations, the composition of gases in its plumes and exosphere from MASPEX gas observations, and the composition of surface materials believed to be sourced from the interior from MISE spectroscopy observations, relating these constraints to ocean salinity requires major assumptions and significant modeling that will be poorly constrained and therefore cannot satisfy the level 1 requirement.
- This information is also fundamental to modeling the dynamical transport of material from the ocean to the surface, which is a key component of understanding Europa's geochemistry. REASON radar observations can only constrain ice-shell thickness under very specific conditions and are not a replacement for ICEMAG SVH-based observations.

Geology Working Group Findings

- Under some combinations of ice shell thickness, salinity, and radar results, there may be a large uncertainty in the average global ice shell thickness, which translates into several other geological uncertainties outlined below.
- Geophysical models for the formation of several common types of terrain features (e.g. chaos, ridges) depend on the distance between the surface and water derived from the ocean, and without a reliable ice shell thickness it will be more difficult to distinguish among plausible models.
- Lack of independent knowledge of ice shell thickness may affect the interpretability of shallow radar reflectors associated with geological features, making it uncertain what role the ocean plays in forming such features, and the degree of connectivity between geological features and the ocean.
- Constraints on ocean salinity are necessary for understanding ice shell rheology, fluid fractionation processes within the ice shell, and how much radar attenuation is due to temperature or salinity effects. All of these factors are important for interpreting the formation of surface features, distinguishing among formation models, and understanding the extent to which material can be exchanged between the surface and ocean.
- Because future landing site reconnaissance is within the purview of our working group, we also point out that lower confidence in landform formation models directly affects our confidence in selecting a landing site where material sourced from the ocean could be sampled. The uncertainty in ocean connectivity may also increase the level of caution necessary for planetary protection in lander operations.