Use of Model Payload for Europa Mission Development
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Abstract— **During the long early development of the Europa Mission concept, the team used a hypothetical, straw-man payload, called the *Model Payload,* to assist in the development of a complete mission design. The Model Payload comprised a suite of science instruments, and was structured to meet the science objectives of the mission. The science objectives were defined in terms of a set of specific physical measurements that would need to be made, including quality attributes such as resolution, accuracy, coverage, etc. The Model Payload was designed to acquire these data with the required attributes. A set of notional instruments was chosen to be able to meet the full set of science objectives. Each notional instrument was based on current capabilities and technologies of actual, similar instruments, and modeled with enough detail to be able to estimate aspects of the instrument such as power usage, pointing stability needs, thermal accommodation needs, etc. This paper discusses the basis for the Model Payload and how it was used to develop the mission design, observation and data acquisition strategy, needed spacecraft capabilities, spacecraft-payload interface needs, mission system requirements, and operational scenarios. Then we present a comparison of the Model Payload to the actual payload, recently selected by NASA for the proposed Europa Mission. The focus is on how well this process enveloped and constrained the design space and guided the development and analysis of not only instrument requirements, but also those of the flight system and the mission operations system. Specifically, we discuss those areas in which the Selected Payload drove the mission design and which areas remained unchanged. Lastly, we present lessons learned from the use of a Model Payload.**

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1. INTRODUCTION

There has been a NASA mission to further explore Jupiter's ice moon Europa at some stage of planning since the late 1990s. The latest incarnation of the mission concept, conceived in 2012 as a partnership between the Caltech Jet Propulsion Laboratory (JPL) and the Johns Hopkins Applied Physics Laboratory (APL), utilizes a multiple-flyby trajectory with closest approaches as close as 25 km to the surface of Europa. This strategy allows coverage of 70% of the surface while reducing the radiation dosage compared to a conventional orbiter. In response to the National Research Council planetary science decadal survey in 2011, the Europa Mission science definition team (SDT) came up with a set of minimum science objectives, shown in Table 1.

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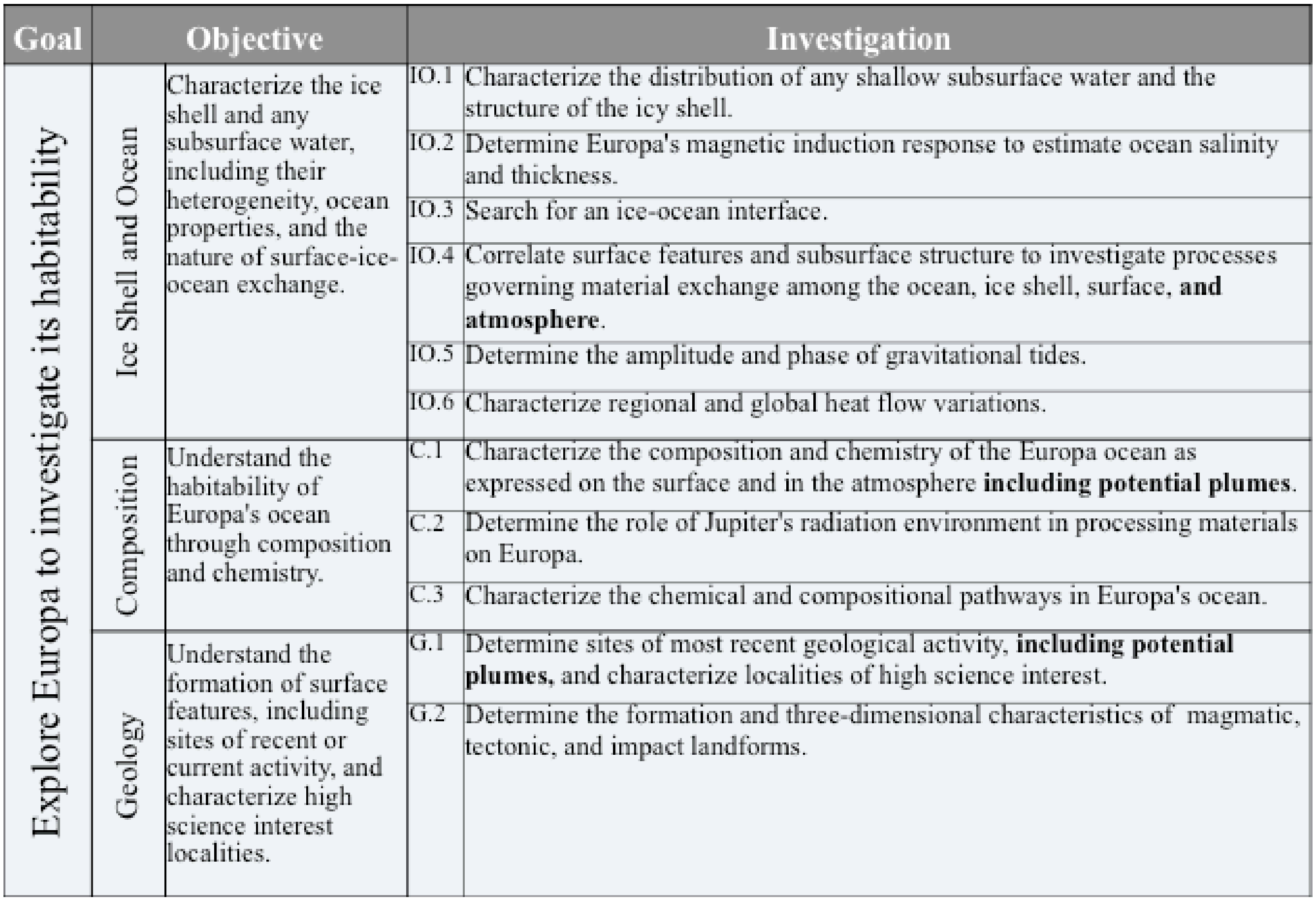
Table 1. Proposed Europa Mission Science Traceability Matrix



Goal	Objective		Investigation	
Explore Europa to investigate its habitability	Ice Shell and Ocean	Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange.	IO.1	Characterize the distribution of any shallow subsurface water and the structure of the icy shell.
			IO.2	Determine Europa's magnetic induction response to estimate ocean salinity and thickness.
			IO.3	Search for an ice-ocean interface.
			IO.4	Correlate surface features and subsurface structure to investigate processes governing material exchange among the ocean, ice shell, surface, **and atmosphere**.
			IO.5	Determine the amplitude and phase of gravitational tides.
			IO.6	Characterize regional and global heat flow variations.
	Composition	Understand the habitability of Europa's ocean through composition and chemistry.	C.1	Characterize the composition and chemistry of the Europa ocean as expressed on the surface and in the atmosphere **including potential plumes**.
			C.2	Determine the role of Jupiter's radiation environment in processing materials on Europa.
			C.3	Characterize the chemical and compositional pathways in Europa's ocean.
	Geology	Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.	G.1	Determine sites of most recent geological activity, **including potential plumes,** and characterize localities of high science interest.
			G.2	Determine the formation and three-dimensional characteristics of magmatic, tectonic, and impact landforms.

2. MODEL PAYLOAD DESCRIPTION

The Model Payload consists of a set of *notional instruments* designed to meet the full set of science objectives. Each notional instrument is based on the current capabilities and technologies of actual, similar instruments.

Ice Penetrating Radar (IPR)

The IPR characterizes the distribution of shallow subsurface water and structure of the ice shell; searches for an ice-ocean interface; and correlates surface features, subsurface structures, and geological processes. In order to fully meet these objectives, the derived measurement requirements are 10 m vertical resolution radar depth sounding from the surface to 100 m (3 km depth desired) and 100-m vertical resolution from the surface to 1 km (30 km depth desired). To support these measurements, it was also required to obtain nadir altimetry with 10 m vertical resolution and cross-track surface topography (stereo imaging) to 100 m vertical resolution.

The Model Payload's notional IPR configuration is a dual-frequency sounder with a 60-MHz channel with 10-MHz bandwidth for shallow sounding and a 9-MHz channel with 1-MHz bandwidth for deep sounding. Similar instruments are Mars Express' MARSIS and MRO's SHARAD.

Topographical Imager (TI)

The primary science objectives met by the TI are stereo imaging of landforms for geology and de-cluttering of radar returns from surface topography. The derived measurement requirements specify that the observations are in the visible spectral range with a single monochromatic spectral band. The field of view (FOV) is 58° for stereo separation. The image width at closest approach is 100 km, with a signal-to-noise greater than 100.

The notional TI instrument uses pushbroom imaging with stereo obtained through along-track overlap, with 20-m vertical resolution. Similar instruments are MESSENGER's MDIS, MRO's MARCI, and New Horizons' Ralph/MVIC..

ShortWave Infrared Spectrometer (SWIRS)

SWIRS was included in the Model Payload to characterize the surface composition for representative landforms and to characterize exogenic materials. Its derived measurement requirements are to observe in a spectral range of 850 nm to 5.0 µm, with a spectral resolution of 10 nm, to include 420 spectral channels, and maintain a spatial resolution of 300 m at 2000 km altitude.

The notional SWIRS implementation utilizes ~4 scans per flyby: two at ≤10 km per pixel and two at ≤300 m per pixel. A similar instrument is Chandrayaan's M^3.

Reconnaissance Camera (RC)

The RC instrument meets the primary science objectives of characterizing potential future landing sites (including hazard assessments), characterizing geologic history, and taking digital elevation maps. The derived measurement requirements specified a pixel resolution of ≤0.5 m, the inclusion of stereo imaging, and 5×10 km of areal coverage per site.

The notional RC instrument configuration consists of a pushbroom panchromatic imager with a two-position flip mirror providing stereo views on a single pass. Similar instruments are LRO's LROC and New Horizon's LORRI.

Thermal Imager (ThI)

ThI has the ability to meet three primary science objectives: characterize potential future landing sites, measure surface temperatures and thermal inertia (rock abundance, particle cohesion), and hot spot detection. The imager's derived measurement requirements necessitated <0.5K noise equivalent differential temperature (NEDT) between 90K and 130K, and ≤250 m per pixel resolution from 100-km range; lower resolution global/regional coverage; and bolometric albedo measurements.

The notional ThI instrument is a pushbroom imager with a 40-pixel wide thermopile array operating at room temperature, with a scan mirror that switches from nadir to space to internal blackbody target viewing. The imager has two spectral bands, 8-35 µm and 35-100 µm. Similar instruments are LRO's Diviner and THEMIS.

Neutral Mass Spectrometer (NMS)

The NMS was included in the Model Payload to address the science objective of determining the elemental, isotopic and molecular composition of Europa's atmosphere and ionosphere. The derived measurement requirements to meet this objective stipulate a mass range of 1 – 150 Daltons, a mass resolution of 200 and a sensitivity of 10 particles/cm^3.

The notional NMS instrument is a two-frequency RF instrument with a secondary electron multiplier detector. Similar instruments are Pioneer Venus Orbiter's NMS and Nozomi's NMS.

Magnetometer (MAG)

The primary science objectives of MAG are to determine Europa's magnetic induction response to constrain salinity and ocean thickness. The derived measurement requirements are a three-axis instrument with a sensitivity of 0.1 nT at 8 vectors/s.

The notional MAG instrument is a dual 3-axis fluxgate sensor with an intensity range of ±1024 nT. Similar instruments are Galileo's MAG and MESSENGER's MAG.

Langmuir Probes (LP)

The primary science objectives met by the LP are to characterize the local plasma density, temperature, and flow in order to constrain (in conjunction with modeling) the magnetic contribution from currents not related to the surface and ocean. The derived measurement requirements are the determination of local plasma density, temperature, and flow; electric field vectors from near-DC to 3 MHz; electron temperature; and ion currents.

The notional LP instrument consists of dual 5-cm diameter spheres mounted on 1-m long booms. Similar instruments are Rosetta's LAP and Cassini's RPWS.

Model Payload Summary

The resources estimated for the Model Payload are shown in Table 2.

Table 2. Model Payload Resource Summary

Instrument	CBE Mass (kg)	CBE Power (W)	Data Volume (Gb/flyby)
IPR	36.7	57	23.6
TI	5.3	7.9	4.86
SWIRS	20.3	21.1	0.5
RC	15.5	24	6.0
ThI	8.5	11	0.2
NMS	8.1	25	0.012
MAG	2.7	4.5	0.1
LP	4.3	2.8	1.2
Totals:	**101.4**	**153.3**	**36.472**

3. USE OF MODEL PAYLOAD IN SYSTEM DEVELOPMENT

The Model Payload influenced the development of requirements on mission design, mission operations, spacecraft design, and the overall mission system. Each of these influences is discussed in turn.

Mission Design

Given the Model Payload, a reference science tour was designed and optimized to demonstrate the feasibility of a multiple Europa flyby mission that could meet the science objectives outlined in the 2011 Planetary Decadal Survey. Table 3 summarizes the geometric constraints levied on the mission design for this reference mission stemming from the conceived Model Payload

Table 3. Model Payload Observation Constraints

Instrument		Velocity (km/s)	Altitude (km)	Viewing Geometry	Coverage
IPR	Deep	< 6	≤ 1000	Groundtrack lengths ≥ 1600 km	Distributed in 11 of 14 panels with ≥ 3 groundtracks in each anit-Jupiter panel and ≥ 2 groundtracks in each sub-Jupiter panel. Each groundtrack must intersect another below 1000 km (intersection may lie outside panel of interest)
	Shallow		≤ 400	Groundtrack lengths ≥ 800 km	
SWIRS		< 6	≤ 66,000	Local solar time between 9:00 and 15:00	≥ 70% of Europa at better than 10 km/pixel ~100 representative landforms at better than 300 m/pixel distributed across 11 of 14 panels All reconnaissance sites at better than 300 m/pixel
Topographical Imager			≤ 4000	Required incidence angles in the range of 20° to 80° and solar phase angle ≤135°	Stereo imaging spanning radar ground tracks ≥70% of Europa at better than 1 km/pixel ≥ 25% of Europa at better than 250 m/pixel
				Desired Incidence angles in the range of 45° to 70° and solar phase angle ≤135°	
NMS		< 7	≤ 200	Within 10° of spacecraft ram direction when below 200 km	Global distribution
Magnetometer			continuous	N/A	Flybys distributed across a range of orbital phases and System III longitudes (better than each 45° of longitude)
Langmuir Probe			continuous	N/A	Same as MAG
Reconnaissance Camera			≤ 50	Required incidence angles in the range of 20° to 80° Desired incidence angles in the range of 45° to 70°	Required at least 15 2x10 km images at better than 0.5 m/pixel Desired at least 15 5x10 km images at better than 0.5 m/pixel
Thermal Imager			≤ 1000	10:00 to 15:00 local solar time	All reconnaissance sites at better than 250 km/pixel Selected reconnaissance sites at better than 15 km/pixel
			≤ 60,000	3:00 to 6:00 and 10:00 to 15:00 local solar time	

The tour design objective of the multiple Europa flyby mission concept is to balance the Model Payload coverage of Europa with Total Ionizing Dose (TID), ΔV, and mission duration, which affects operations costs. The cornerstone feature of the mission design is to dip briefly into the harsh radiation environment near Europa to collect a high volume of quality science data and then retreat from the most intense portions of the radiation environment to downlink the Europa data.

Whereas a conventional orbiter would be constantly exposed to radiation (thus increasing the TID requirements on the payload), the multiple flyby approach minimizes the total radiation exposure with corresponding benefits to hardware design (e.g. savings in total shielding mass) and operations (e.g. through reduced pressure to respond quickly to safing events while in the radiation-heavy environment nearest Europa). The reference science tour consists of 45 Europa, 5 Ganymede, and 9 Callisto flybys over the course of 3.5 years and a TID of 2.7 Mrad(Si).

The operations concept strives for simple, repetitive operations. Intending to keep operations cost down, the spacecraft follows the same attitude profile for each flyby. Below 66,000 km altitude, the instrument deck is pointed nadir while the HGA is fixed in the velocity (wrt Europa) direction. The data return strategy is to return data during 8 hour sessions with the DSN during the non-flyby portions of each Jupitor orbit. These alternate with 8 hours of low-power operations to allow the battery to recharge prior to the next flyby. The number of Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs), or the size of the solar arrays, is chosen to handle the notional flyby science profile.

Spacecraft Design

The proposed spacecraft design with the Model Payload is shown in Figure 1.

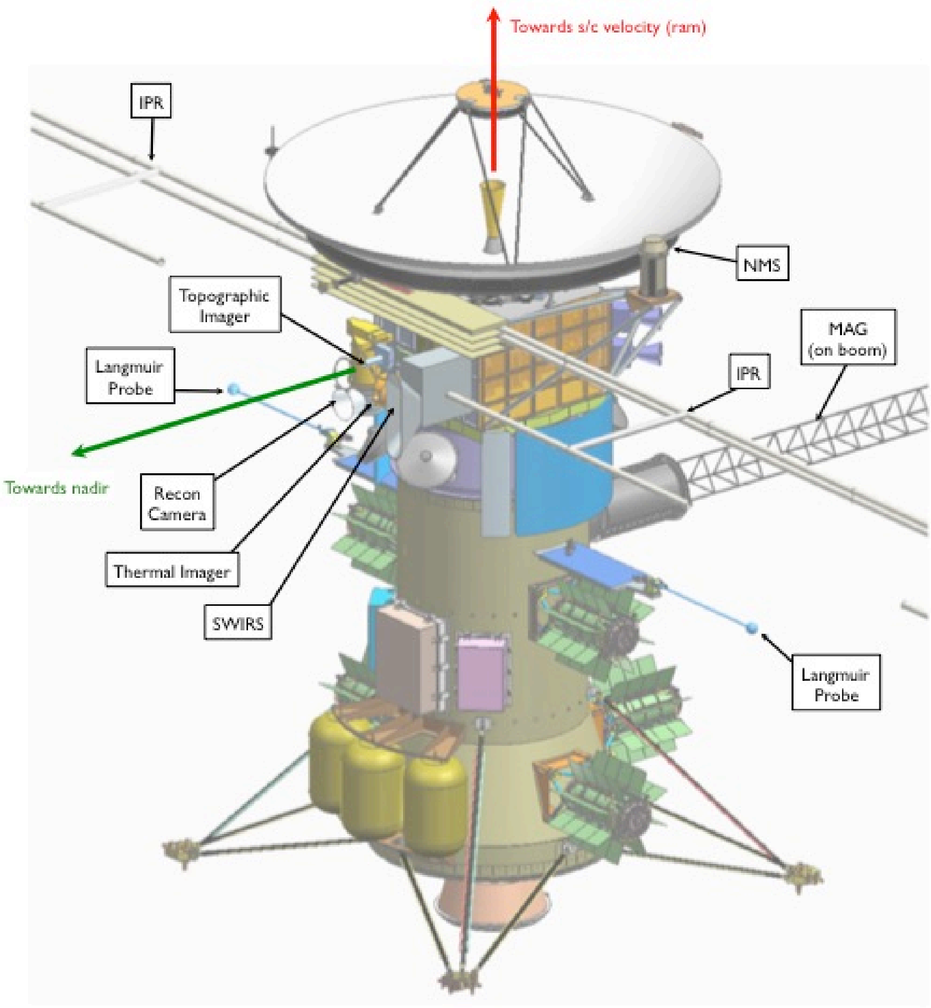


Figure 1. Spacecraft Configuration Concept With Model Payload

The configuration provides a shielded vault to house the instrument-provided electronics chassis, and structure to support the instrument sensor hardware (detectors, antennae, and supporting hardware). This structure is located external to the spacecraft vault to provide necessary viewing geometry and other accommodation needs. Instruments needing nadir pointing for flybys are accommodated on the Nadir Platform Assembly. Instruments not requiring nadir pointing are accommodated using secondary structure.

The flight system thermal control is primarily provided by a pumped fluid loop and multi-layer insulation (MLI) covering most of the external surfaces. The fluid loop collects thermal energy from the vault and distributes it throughout the spacecraft. Where close thermal coupling is necessary for a specific component, an appropriate thermal interface is implemented. Anytime the spacecraft is less than 1.0 AU from the Sun, the High Gain Antenna serves as a thermal shield, protecting the Nadir Platform Assembly from direct solar illumination.

To minimize costs, the instrument avionics interfaces (power and data) are assumed to be standard, with the final design decided during the accommodation of the selected (not notional) instruments.

System Requirements

Prior to instrument selection, the Model Payload drove requirements development. The science team developed the preliminary Science and Reconnaissance Requirements Document (SRRD) based on the science traceability matrix from the SDT. In response to the SRRD, an initial Payload Requirements Document (PLRD) focused on the instrument performance requirements. Along with the PLRD, a Spacecraft-to-Payload Interface Requirements Document (IRD) captured the spacecraft-to-instrument accommodation requirements.

4. SELECTED PAYLOAD DESCRIPTION

The Selected Payload is composed of set of science instruments chosen by NASA to achieve the science objectives of the Europa Mission. This highly capable suite of instruments not only meets the original set of science objectives, but exceeds them. The Selected Payload contains two instruments and responds to the updated science objectives that now include the search for plumes ejected from the surface of Europa and an analysis of dust particles in the area of Europa. The selected instruments are described in the following paragraphs.

Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON)

REASON's science objectives are very similar to those of the notional IPR instrument: to characterize the distribution of shallow subsurface water and structure of the ice shell; search for an ice-ocean interface; and correlate surface features, subsurface structures, and geological processes. REASON's enhancement over the IPR is to use interferometry in the VHF band to remove clutter along the off-nadir portions of the swath. This technique reduces or removes the need for supporting cross-track topography imaging. Projected REASON performance capabilities include 10 m vertical resolution depth sounding from 300 m to 4.5 km, and 100 m vertical resolution from 1 to 30 km.

Like the notional IPR, REASON is a dual-frequency sounder with a 60-MHz band with 10-MHz bandwidth for shallow sounding, and a 9 MHz band with 1-MHz bandwidth for deep sounding. The 60MHz band is divided into two receiving channels for interferometry.

Europa Imaging System (EIS)

The two notional instruments Topographic Imager and Reconnaissance Camera were realized with an even more capable dual-camera system, the EIS. The instrument contains a wide-angle camera (WAC) and a narrow-angle camera (NAC).

The science investigations being met by EIS include investigation of geologic structures and processes, correlation of surface features with subsurface structure and possible water, studying the ice shell thickness and ocean interface, and identifying scientifically-compelling landing sites, as well as producing digital terrain models for use in decluttering REASON data. The measurement requirements consist of imaging the moon in the visible spectral range, including near-global coverage at 50 m-resolution or better for 95% of the surface.

The WAC field of view (FOV) is 48° crosstrack by 24° alongtrack, for a resolution of up to 11 m/pixel at 50 km altitude. It can operate in both mono or pushbroom stereo mode. The WAC has 6 filters for color imaging.

The higher-resolution NAC, with its 2.3° by 1.2° field of view, is a 2-axis gimbaled instrument, with a 60° range of motion in each axis, enables more coverage of the moon without changing the orientation of the spacecraft. The NAC can also produce stereo imagery with a resolution of 0.5 m/pixel at 50 km of altitude.

Europa Ultraviolet Spectrograph (Europa-UVS)

Europa-UVS has no corresponding instrument in the Model Payload, but offers new capabilities to hunt for and uniquely characterize plumes erupting from Europa's surface. UVS would also investigate the composition and chemistry of Europa's atmosphere and surface and study how energy and mass flow around moon and its environment.

The instrument is a sensitive imaging spectrograph that can observe in a spectral range of 55 nm to 210 nm and can achieve a spectral resolution of <0.6 nm full width at half maximum (FWHM) for a point source and a spatial resolution of 0.16° through its airglow port and 0.06° through its high spatial resolution port. This high-heritage instrument is an integrated unit with co-located electronics and sensor optics. The instrument does not contain a scan mirror, so the spacecraft must provide the maneuvering capability necessary to obtain complete spatial images of the moon.

SUrface Dust Mass Analyzer (SUDA)

SUDA is also a new instrument that was not part of the Model Payload. This instrument would detect and characterize small particles in the atmosphere around Europa, allowing an analysis of the composition of the particles ejected from the surface of the moon. SUDA can capture up to 40 particles per second at closest approach. The instrument measures not only the density and composition of particles, but also the velocity, allowing backtracking to the originating surface position of materials, and thus to a mapping of the surface composition.

Mapping Imaging Spectrometer for Europa (MISE)

MISE, analogous to the Model Payload SWIRS, would acquire data enabling spectral analysis of the composition of the surface of Europa, including the presence of organic compounds, acid hydrates, salts, and other materials germane to assessing the habitability of the ocean on Europa. MISE data will also enable the investigation of the geologic history of Europa and characterization of currently-active geologic processes. The instrument would produce images at better than 25 m/pixel resolution in close flybys, at 300m/pixel resolution at higher altitudes, and at 10 km/pixel resolution for global-scale analysis.

MISE has a spectral range of from 800 to 5000 nanometers with a spectral resolution of 10 nm. It has FOV of 4.3° in cross-track, and from 0.75° to 4° (one pixel) in along-track. It also has a +/-30° along-track scan mirror.

To maintain detectors at the necessary cryogenic temperatures, the instrument is using a cryogenic 2-stage radiator which requires views of cold sinks.

Europa Thermal Emission Imaging System (E-THEMIS)

The Europa Thermal Imaging System (E-THEMIS), analogous to the Model Payload ThI, is a 3-band Infrared imager with variable line integration times to optimize the sensitivity during the approach to Europa. The detector is an uncooled microbolometer array with 3 filters integrated in front of the detector to define the three observational bands: 7-14µm, 14-28 µm, and 28-70 µm. The E-THEMIS imaged field of view is 5.7° cross-track and 4.3° along-track.

E-THEMIS would detect and characterize thermal anomalies on the surface that may indicate recent active venting or resurfacing on Europa. It would also determine the regolith particle size, block abundance, and sub-surface layering for landing site assessment and surface process studies, and it will identify active plumes.

E-THEMIS would image the Europan surface at a resolution of 5 x 22 m (including spacecraft motion) from 25 km altitude, with a precision of 0.2 K for 90 K surfaces and 0.1 K at 220 K, with an accuracy of 1-2.2 K from 220-90 K. The instrument will obtain images with up to 360 cross-track pixels with a 10.1 km wide image swath from 100 km.

MAss Spectrometer for Planetary EXploration/Europa (MASPEX)

The MASPEX instrument is a neutral mass-spectrometer that would determine the chemical composition, especially the distribution and density variations of major volatiles and key organic compounds, of the Europa atmosphere and exosphere through multiple flybys at altitudes < 1000 km. It is a more capable replacement for the Model Payload NMS.

The instrument contains a multi-bounce time-of-flight (MBTOF) mass spectrometer with a closed ion source, pulsers, a detector and associated electronics. MASPEX can classify particles with masses in the range 2 – 1000 Daltons with mass resolution (which varies with integration time) from about 7000 to 24000.

Interior Characterization of Europa using Magnetometry (ICEMAG)

ICEMAG is a four-sensor magnetometer composed of 2 flux gate (FG) sensors and 2 scalar-vector helium (SVH) sensors. The sensors are spaced along a 5 m long boom extending from the spacecraft. This instrument would, like the Model Payload MAG, measure the magnetic field near Europa, which is induced by Europa's movement through Jupiter's strong field. Measuring the induced field in Europa over multiple frequencies constrains the ocean and ice shell thickness to +/- 2km, and ocean conductivity to less than +/- 0.5 S/m. ICEMAG measures the magnetic field with an accuracy better than 1.5 nT in all three axes.

ICEMAG's data would be used in conjunction with the Plasma Instrument for Magnetic Sounding plasma measurements to better isolate the induced magnetic field from other field components caused by plasma in the Europa ionosphere.

Plasma Instrument for Magnetic Sounding (PIMS)

PIMS would measure the density, flow and energy of ions and electrons in the orbit of the spacecraft around Jupiter and especially near Europa. This instrument works in conjunction with ICEMAG and is key to determining Europa's ice shell thickness, ocean depth, and salinity by correcting the magnetic induction signal for plasma currents around Europa, thereby enabling precise magnetic sounding of Europa's subsurface ocean. It replaces the Model Payload LP.

PIMS has a magnetospheric and an ionospheric mode. In the first, it can detect electrons with energies in the range 10 eV – 2 keV, and ion energies in the range 20 eV – 7 keV. In ionospheric mode, it can detect electrons and ions in the energy range 1 – 50 eV. It has an energy resolution of 10% deltaE/E, and a sensitivity of 0.5pA/cm^2 – 10^5 pA/cm^2.

PIMS is composed of two sensor heads, each hosting two Faraday cups (FCs), each with a 90-degree FOV, measuring the 1.5-dimensional velocity distribution function (VDF; a 1-D reduced distribution function plus vector flow angles as a function of energy/charge) of ions and electrons. The FCs measure the current produced on metal collector plates by charged particles with sufficient energy per charge (E/q) to pass through a modulated retarding grid placed at variable (AC) high voltage (HV).

Selected Payload Resources Summary

The resources estimated for the Model Payload are shown in Table 4.

Table 4. Selected Payload Resource Summary

Instrument	Mass CBE (kg)	Power CBE (W)	Data Volume (Gb/flyby)
Total	**156.9**	**176.25**	**39.6**

*Individual instrument resources are not available for publication at this time.

5. COMPARISON OF MODEL PAYLOAD TO SELECTED PAYLOAD

Between the time the Europa Mission science investigation announcement of opportunity (AO) was released in 2014 and when the instruments were selected in 2015, solar arrays were selected as the baseline power system over MMRTGs. The HGA antenna was also moved to improve the overall flexibility for instrument accommodations.

Universally, NASA selected a payload whose capability far exceeds the capability of the Model Payload, as well as adding a new science objective: the search for plumes. The payload went from 8 to 10 instruments (although the RC and TI cameras were selected as a single delivery package). The additional instruments include a dust analyzer (SUDA) and an ultraviolet spectrograph (Europa-UVS). The mapping of the Model Payload to the Selected Payload is shown in Table 5.

The increased capabilities of the Selected Payload naturally implied an increase in spacecraft resource estimates, which have had a ripple effect on the mission concept and spacecraft designs. A comparison of resources before and after selection is shown in Table 6.

Table 5. Mapping of Model Payload to Selected Payload

Model Payload	Selected Payload
IPR	REASON
TI	EIS
SWIRS	MISE
RC	EIS
ThI	E-THEMIS
NMS	MASPEX
MAG	ICEMAG
LP	PIMS
	SUDA
	Europa-UVS

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Table 6. Comparison of Selected to Model Payload Resources

Selected Mass (kg)	Model Mass (kg)	Mass Increase (kg)	Selected Power (W)	Model Power (W)	Power Increase (W)	Selected Data Volume per Orbit (Gb)	Model Data Volume per Orbit (Gb)	Data Volume Increase (Gb)
156.85	101.4	55.45	176.25	153.3	22.95	39.63	36.47	3.16

Mission Design

The basic premise of the baseline mission design remains unchanged: it is still a multi-flyby trajectory that will focus on repeatable, simple science flyby operations. However, as the selected payload is folded into the concept of operations, the specifics of the implementation will be tuned to better meet the needs and constraints of the actual instruments. Based on the selected instruments' proposals, the amount of coverage required has not significantly changed, but the inclusion of additional instruments and new science objectives will likely require additional observations not accounted for in the Model Payload.

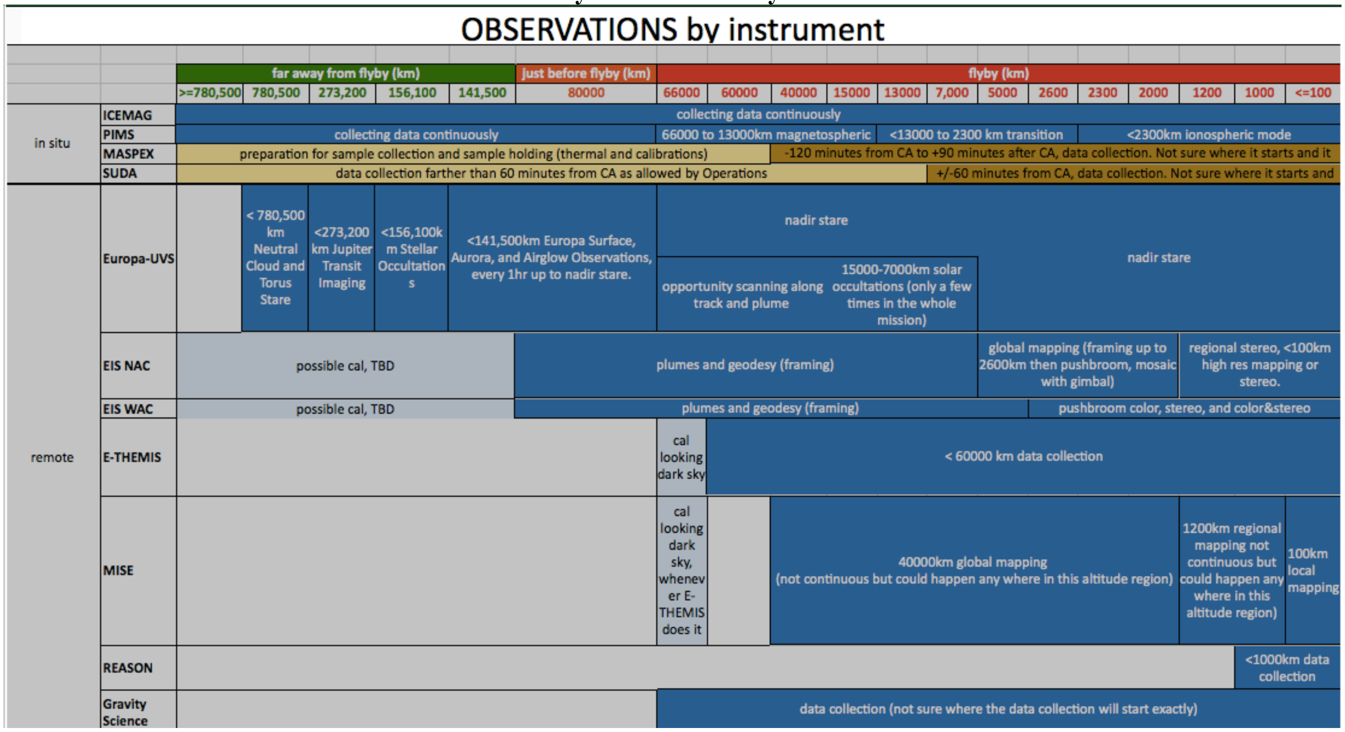
Observing Scenarios

There are significant changes to the observing scenarios, mostly due to the added objective for plume searches. For example, EIS and Europa-UVS would hunt for plumes by taking images of the limb while far away from closest approach. Both Europa-UVS and E-THEMIS investigations benefit from regular scans across Europa's disk on the approach and departure phase of a flyby. Similarly, the performance improvements of MASPEX over the notional NMS would require keeping the instrument powered beyond the flyby portion of the trajectory for additional sample analysis. Table 7 captures the preliminary observation plans.

Data Return Strategy

The data return strategy is unchanged. The overall data return volume did not significantly increase over that of the Model Payload.

Table 7. Selected Payload Preliminary Observation Plans



<table>
<tr><th colspan="21">OBSERVATIONS by instrument</th></tr>
<tr><th></th><th></th><th colspan="5">far away from flyby (km)</th><th>just before flyby (km)</th><th colspan="13">flyby (km)</th></tr>
<tr><th></th><th></th><th>>=780,500</th><th>780,500</th><th>273,200</th><th>156,100</th><th>141,500</th><th>80000</th><th>66000</th><th>60000</th><th>40000</th><th>15000</th><th>13000</th><th>7,000</th><th>5000</th><th>2600</th><th>2300</th><th>2000</th><th>1200</th><th>1000</th><th><=100</th></tr>
<tr><td rowspan="4">in situ</td><td>ICEMAG</td><td colspan="19">collecting data continuously</td></tr>
<tr><td>PIMS</td><td colspan="6">collecting data continuously</td><td colspan="4">66000 to 13000km magnetospheric</td><td colspan="4"><13000 to 2300 km transition</td><td colspan="5"><2300km ionospheric mode</td></tr>
<tr><td>MASPEX</td><td colspan="8">preparation for sample collection and sample holding (thermal and calibrations)</td><td colspan="11">-120 minutes from CA to +90 minutes after CA, data collection. Not sure where it starts and it</td></tr>
<tr><td>SUDA</td><td colspan="11">data collection farther than 60 minutes from CA as allowed by Operations</td><td colspan="8">+/-60 minutes from CA, data collection. Not sure where it starts and</td></tr>
<tr><td rowspan="8">remote</td><td rowspan="2">Europa-UVS</td><td rowspan="2"></td><td rowspan="2">< 780,500 km Neutral Cloud and Torus Stare</td><td rowspan="2"><273,200 km Jupiter Transit Imaging</td><td rowspan="2"><156,100km Stellar Occultations</td><td colspan="2" rowspan="2"><141,500km Europa Surface, Aurora, and Airglow Observations, every 1hr up to nadir stare.</td><td colspan="6">nadir stare</td><td colspan="7" rowspan="2">nadir stare</td></tr>
<tr><td colspan="3">opportunity scanning along track and plume</td><td colspan="3">15000-7000km solar occultations (only a few times in the whole mission)</td></tr>
<tr><td>EIS NAC</td><td colspan="5">possible cal, TBD</td><td colspan="7">plumes and geodesy (framing)</td><td colspan="4">global mapping (framing up to 2600km then pushbroom, mosaic with gimbal)</td><td colspan="3">regional stereo, <100km high res mapping or stereo.</td></tr>
<tr><td>EIS WAC</td><td colspan="5">possible cal, TBD</td><td colspan="8">plumes and geodesy (framing)</td><td colspan="6">pushbroom color, stereo, and color&stereo</td></tr>
<tr><td>E-THEMIS</td><td colspan="6"></td><td>cal looking dark sky</td><td colspan="12">< 60000 km data collection</td></tr>
<tr><td>MISE</td><td colspan="6"></td><td>cal looking dark sky, whenever E-THEMIS does it</td><td></td><td colspan="8">40000km global mapping
(not continuous but could happen any where in this altitude region)</td><td colspan="2">1200km regional mapping not continuous but could happen any where in this altitude region)</td><td>100km local mapping</td></tr>
<tr><td>REASON</td><td colspan="17"></td><td colspan="2"><1000km data collection</td></tr>
<tr><td>Gravity Science</td><td colspan="6"></td><td colspan="13">data collection (not sure where the data collection will start exactly)</td></tr>
</table>

Spacecraft Configuration

The most challenging accommodation effort for the Selected Payload has been developing a spacecraft configuration that simultaneously meets the needs of all the instruments. The nadir deck assembly expanded to support both the Europa-UVS (not present in the notional payload), and the increased field-of-regard for the EIS camera. Both the MASPEX and SUDA instruments desire 2π steradian keep-out zones to prevent sample contamination. The PIMS instrument not only has a large field of view (270°), but also has electrical keep-out zones to prevent sample contamination. Finding an appropriate location for the MISE radiator FOV has been very challenging with the switch to solar arrays, and may result in the addition of a cryocooler. ICEMAG has stringent requirements on reconstructed attitude and position knowledge, which settled the design on a dedicated 5 m boom. The electromagnetic coupling between the REASON antenna pulses and the solar arrays has resulted in considerable constraints on the positioning of the radar.

The new baseline configuration, which is still being worked to better accommodate MISE and REASON, is shown in Figure 2.

Guidance, Navigation, and Control (GNC)

The GNC architecture did not change, but the capability of the subsystem may need to be improved to handle the pointing knowledge requirements for ICEMAG.

Thermal

Thermal control would still be provided by a thermal loop and MLI. However, the temperature inside the vault would be higher than most traditional spacecraft employ, so additional analysis is required to assess the impact to the instrument electronics design.

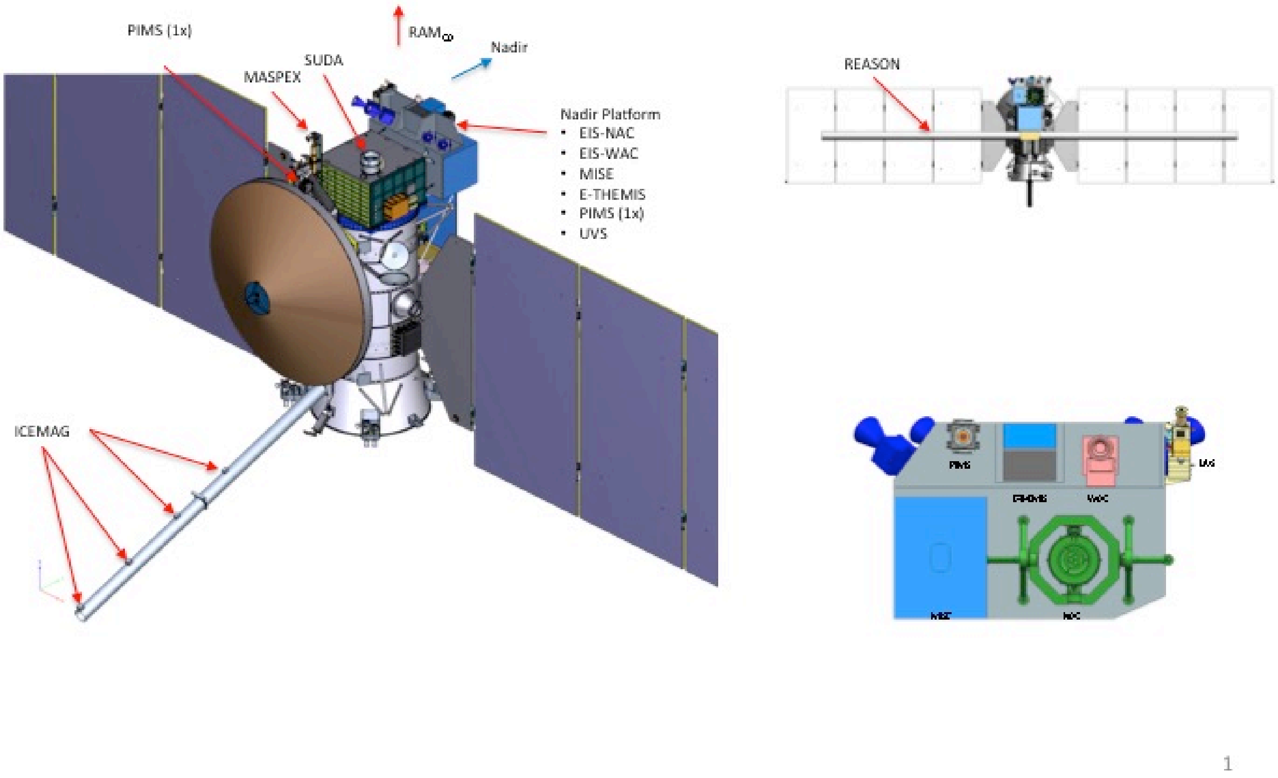


Figure 2. Europa Mission Baseline Spacecraft Configuration with Selected Payload

Power Sizing

The strategy for accommodating the power needs of the instruments did not change, though total power requirements have grown relative to the notional design. The size of the solar arrays must be adjusted to maintain appropriate margins above observation scenario needs for the Selected Payload.

Mass

The spacecraft mass has grown significantly due to the Selected Payload. Not only are there more instruments, but most of them exceed the mass estimates for their Model Payload counterparts. The spacecraft mass also grew due to support structure for the instruments and the increase in solar array size for more power during flyby observations.

6. LESSONS LEARNED

Overall, the use of the Model Payload greatly aided the Europa pre-project in scoping out the design, but the approach did have its limitations. There were some lessons learned from the experience that the team would advise others to address in future early mission design work.

Stressing the Design

For mission costing and scope, the pre-project team scaled the instruments for minimum performance to meet the science objectives. The team also looked at how increasing the capability of the instruments would impact mass, power, and data requirements of the spacecraft, as well as considering the effect of adding an additional instrument. These impacts were captured as potential liens and the impact to margins were assessed. However, this analysis did not include the subsequent changes to spacecraft configuration that would be necessary to accommodate the growth. The lack of “room to grow in” caused a significant strain on the spacecraft design post-selection.

Switch to Solar Arrays

During the trade between a power system based on solar arrays versus one using MMRTGs, the team compared the impacts using the notional payload. These impacts were determined to be negligible or workable within the notional instrument design and solar arrays were selected. However, without more detailed knowledge of the actual radar characteristics, the impact of the solar array on the radar performance was beyond the understanding of the pre-project team. It turns out that the impact of the switch on the selected radar (REASON) is substantial.

Early Requirements Development

Using the Model Payload to develop the initial requirements document has had a significant pay-off for the project. Within six months of payload selection, the team was able to have a strong set of preliminary level 2, level 3, and key level 4 requirements for the selected instruments. Because the structure and scope of each document was defined, it was relatively straight forward for the team to swap out the Model-Payload-based requirements with the new payload requirements. Additional work was required for the two instruments that were not represented by the Model Payload, but having an existing document with pre-established formats and scope expedited this process.

Each of the instrument teams is able to review the S/C-to-Payload IRD to identify challenging requirements and negotiate with the spacecraft very early on in the design process. The team is aware that the requirements will continue to evolve as the instrument and spacecraft designs mature, but early concurrence on critical interfaces has been established.

The model-payload-based requirements development process did have its challenges. In particular, the Model Payload requirements developed significant institutional inertia – linkages, documents, policies – despite not being linked to existing instruments. Thus, selected instruments started out on the project being directly compared against specifications that may or may not apply to their instrument design. This comparison made some accommodation efforts more challenging, especially when the selected instruments had significant design divergences from the Model Payload. A related drawback of this approach to requirements development is that the spacecraft design matured quickly without the benefit of working with equally mature instrument designs. In some cases, the selected instrument is being redesigned, driven by the spacecraft decisions made based on the Model Payload. Despite these issues, the Europa Mission team was able to leverage the Model Payload concept to provide the framework for a relatively quick accommodation of the selected instruments, and work is ongoing to update and correct lingering assumptions from the Model Payload.

7. CONCLUSION

The use of the Model Payload was essential in the development of the Europa Mission pre-project in order to fully scope out the mission concept and spacecraft designs prior to NASA selecting the official payload. The project team was able to develop a baseline design that accommodated, with some additional effort, the Selected Payload. Beyond that, the use of the Model Payload allowed for an easier development of mission requirements. This technique can be leveraged to accelerate the accommodation phase of a mission and allow for reasonable assessments of resources and scope. Future users of this technique should design to resources estimates with large margins (including some for additional instruments) and should make an effort to avoid closing out major design trades prior to the selection of the actual instruments.

ACKNOWLEDGEMENTS

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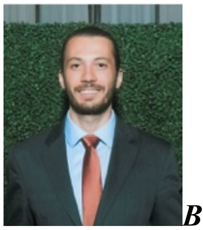
BIOGRAPHIES

Kari Lewis *has been a flight system engineer at JPL since 1996. She joined JPL after graduating with her BS in Aerospace Engineering from the University of Texas at Austin. She also received her MBA from the Anderson School of Business at the University of California, Los Angeles in 2004. Ms. Lewis has worked several missions in her career, including Deep Space 2, Mars Reconnaissance Orbiter, Mars Science Laboratory, Jason-3, and recently Europa. Her current position is lead payload system engineer for the Europa mission. Kari has received the NASA excellence in system engineering award for her work with model based system engineering on Europa.*

Kenneth P. Klaasen *is a retired Principal Engineer formerly on staff at the Jet Propulsion*

Laboratory. He received his BS degree in physics from Calvin College and his MS in aerospace engineering from the University of Michigan in 1969. He has over 40 years of experience in solar system exploration using remote sensing instrumentation and has been involved in many solar system exploration missions including Mariner 10, Viking Orbiter, Galileo, Cassini, Deep Impact, and Stardust-NExT. Ken has served as the Experiment Representative for the imaging experiments on several of these missions and as a member of the Galileo Imaging, Deep Impact, EPOXI, and Stardust-NExT Science Teams. His primary responsibilities have included imaging system calibration, experiment planning, and mission operations. He has done science payload system engineering for advanced studies of Europa orbiter, Pluto flyby, Solar Probe, Jupiter Icy Moons Orbiter, and Europa Multi-flyby missions and has served as the instrument lead on the JPL Advanced Projects Development Team. He has published over 70 papers on the global properties of various planets, satellites, asteroids, and comets and on spacecraft imaging instruments and experiments. Ken has been awarded the Exceptional Service Medal and 3 Exceptional Achievement Medals by NASA. Asteroid 16958 has been named Klaasen for his contributions to cometary science

Dr. Sara Susca *has been with JPL since 2011. She has been part of the Europa Mision Payload team since 2014; she is currently the EIS and PIMS Instrument Engineer. Before that, she managed various projects and contributed in developing new technologies for vision based navigation. Prior to JPL, she spent three years at Honeywell developing new technology for GPS denied navigation. She received her PhD in Electrical Engineering from UCSB in 2007.*



Bogdan Oaida *joined JPL's systems engineering organization after receiving a B.S.E. in Aerospace Engineering in 2007 and a M.Eng in Space Engineering in 2008, both from The University of Michigan. Prior to his current assignment as a payload systems engineering on the Europa Mission, he was the project systems engineer for the OPALS project and also participated in a number of proposal efforts for Earth observing missions.*

Dr. Melora Larson *has been a member of the Technical Staff at at the Jet Propulsion Laboratory (JPL) for more than 20 years. She has worked on space related projects since she was an undergraduate at Stanford University where she worked on the Gravity Probe-B experiment while earning her BS in Physics. She joined JPL after receiving her Ph.D. from the University of California, Santa Barbara. Dr. Larson has supported several space missions and investigations including the Space Shuttle experiment CHeX, the Spitzer Space Telescope, and the James Webb Space Telescope. She is currently a Technical Group Supervisor at JPL and the Instrument Engineer for the E-THEMIS instrument on the Europa mission.*

Tony Vanelli *joined JPL in 1997 after obtaining his BSEE at the University of Texas at Austin and his MSME and Mech.Eng. degrees at the California Institute of Technology. At JPL, he helped develop the attitude control system (ACS) for Deep Space One, and later led development of the rover attitude and pointing system used for the Mars rovers Spirit and Opportunity, and subsequently Curiosity. Between rover missions, he joined the Dawn ACS team during its launch campaign and led the team up to Dawn's encounter with Vesta. He is currently working as part of the payload engineering team for the upcoming Europa mission.*

Alex Murray *is a senior systems engineer with the Jet Propulsion Laboratory, California Institute of technology. He is currently serving as Payload Systems Engineering staff and radar Instrument Engineer for the Europa project, and recently served as a payload systems engineer on the InSight mission to Mars. Previously he led software engineering tasks involving flight, ground, and simulation software for various missions and for technology development projects at JPL, including Grace Follow On, Mars Science Laboratory, Aquarius and*

ASTER. Previously he led and developed software for a variety of projects at TRW (now Northrop-Grumman), and he served as a system engineer for the European weather satellite agency, Eumetsat, as well as software engineer for the Dresdner Bank in Frankfurt, Germany. He holds BS and MS degrees in mathematics from The Ohio State University.

Larry Frank *is a member of the APL Principal Professional Staff in the Space Exploration Sector's Space System Analysis (SAS) Group and is current working as the Payload Accommodation System Engineer for the Europa Mission. Previously he led the System Performance Testing activities for the New Horizons Mission. His experience includes participation in the Science Definition Teams for both the Van Allen Probes Mission and Solar Probe Mission and was the Project System Engineer for the Far-Ultra Violet Spectroscopic Explore Mission. Larry holds a BSEE degree from Catholic University of America.*

Dr. Laura Jones *earned her B.S. in Aerospace Engineering at Virginia Tech and went on to study at Cornell University, where she obtained her M.S. and Ph.D. in Aerospace Engineering specializing in Dynamics and Controls. She then joined JPL in 2012 as a guidance and control systems engineer, where she has served as the project systems engineer balloon-borne sub-arcsecond pointing demonstration, the attitude control lead for an interplanetary CubeSat mission, and the PI a Mars Sample Capture technology development effort. She is also the co-founder and co-manager of the SmallSat Dynamics Testbed, which enables small satellite projects to quickly perform hardware-in-the-loop attitude control testing and characterization. She is currently a member of the Europa payload team, where she serves as the instrument engineer for Europa-UVS.*

Valerie Thomas *has more than thirty years technical and management experience at JPL, including roles as the Deputy Manager, Mission Assurance Office and the Dawn Project Flight System Manager. She has also led avionics developments for the X2000 Project, the TES Instrument, and the Cassini Project. Valerie received a BS degree from Cornell University and an MS degree from Texas A&M University, both in mechanical engineering. She is currently the Europa Project Payload Manager.*