						Mission Architecture							Ocean Worlds											
Science Question	**Science Goal**	**Science Investigation**	**Measurements and Studies**	**Instrument or technique**	**Instrument Tech Gap**	Multiple Flyby	Orbit	Lander	Rover	Subsurface	Sample Return	**Mission Tech Gap**	Europa	Enceladus	Titan	Triton	Ceres	Pluto	Uranian Satellites	Mid-sized Saturnian Sats	Ganymede	Callisto	Other KBOs
1 What are the conditions that lead to the formation of ocean worlds?	1.1 Investigate the composition of the primordial material that formed Ocean Worlds.	1.1.1 Identify the reservoirs of material from which Ocean Worlds formed	Measure isotopic ratios, including D/H, of small bodies	Mass Spectrometer		x	x	x	x	x	x						x						
			Measure elemental abundance, including both volatile and refractory specieis of small bodies	Neutron Spectrometer (H)		x	x	x	x		x						x						
				Gamm-ray Spectrometer (H, O, Cl, S, K/Th/U)		x	x	x	x		x						x						
				X-ray Spectrometer (S, P, Mg/Al/Si/Fe)	CNO have been demonstrated in the lab but not existing flight instruments			x	x		x						x						
				LIBS				x	x		x						x						
			Improve understanding of mixing within the forming solar system	Numerical Modeling									x	x	x	x	x	x	x	x	x	x	x
		1.1.2 Constrain the phase, chemical, and isotopic composition of the building blocks of Ocean Worlds (organic matter, inorganic rocky materials, ices)	Measure elemental abundance, including both volatile and refractory specieis of small bodies	Neutron Spectrometer (H)		x	x	x	x		x						x						
				Gamm-ray Spectrometer (H, O, Cl, S, K/Th/U)		x	x	x	x		x						x						
				X-ray Spectrometer (S, P, Mg/Al/Si/Fe)	CNO have been demonstrated in the lab but not existing flight instruments			x	x		x						x						
				LIBS				x	x		x						x						
			Measure Isotopic ratios, including D/H, of small bodies	Mass Spectrometer		x	x	x	x	x	x						x						
	1.2 Understand how ocean worlds form within, and external-to, circumplanetary systems	1.2.1 Determine the processes by which ocean worlds form within a circumplanetary system, identify which processes have occurred in each circumplanetary system, and constrain formation timescales.		Numerical Modeling									x	x	x	x		x	x	x	x	x	
		1.2.2 Determine how dwarf planets form and constrain their formation timescales.	Measure elemental abundance, including both volatile and refractory species, of dwarf planets	Neutron Spectrometer (H)		x	x	x	x		x						x	x					x
				Gamm-ray Spectrometer (H, O, Cl, S, K/Th/U)		x	x	x	x		x						x	x					x
				X-ray Spectrometer (S, P, Mg/Al/Si/Fe)	CNO have been demonstrated in the lab but not existing flight instruments			x	x		x						x	x					x
				LIBS				x	x		x						x	x					x
			Measure Isotopic ratios, including D/H, of dwarf planets	Mass Spectrometer		x	x	x	x	x	x						x	x					x
				Numerical Modeling													x	x					x
		1.2.3 Assess the conditions that drive ocean worlds to differentiate, the mechanisms by which differentiation occurs, the consequences of differentiation for interior structure and composition, and the corresponding timescales.		Numerical Modeling									x	x	x	x	x	x	x	x	x	x	x
	1.3 Constrain the orbital evolution of Ocean Worlds	1.3.1 Determine the current dynamical state of planet-satellite systems, including current dynamical interactions between objects within each system.	Measure the current orbits of bodies in orbit around the giant planets (astrometry)	UV occultation																			
				Visible imaging and event timing		x	x						x	x	x	x		x	x	x	x	x	
		1.3.2 Identify possible past resonant and non-resonant interactions between bodies within each system and constrain the probability that such interactions occurred.		Numerical Modeling									x	x	x	?		x	?	?		x	
		1.3.3 Identify and quantify processes capable of transporting dwarf planets from their region of origin to other parts of the solar system, including capture by larger bodies.	Measure the current size-frequency distribution of small bodies (inclusive of moons) throughout the solar system	Ground based imaging				x	x								x						x
			Improve understanding of material mixing within the forming solar system	Numerical modeling														x					x
		1.3.4Assess whether possible past resonances or capture events had the potential to dissipate energy within Ocean Worlds.		Numerical Modeling									x	x	x	x		x	x	x	x	x	
	1.4 Identify the sources and magnitude of heating within Ocean Worlds, and how energy is transported through them	1.4.1 Measure the current surface heat flow of Ocean Worlds.	Measure the temperature structure of the ice shell	Heat flow probe				x	x				x	x	x	x	x	x	x	x	x	x	?
				RADAR		x	x	x	x				x	x	x	x	x	x	x	x	x	x	?
				Seismometer				x	x				x	x	x	x	x	x	x	x	x	x	?
			Remote sensing heat flow measurements	Microwave Radiometer		x	x						x	x	x	x	x	x	x	x	x	x	x
		1.4.2 Constrain the heat flow from the rocky interior of Ocean Worlds.	Measure the temperature of fluids eminating from the rock interior	Thermometry (requires ocean access)						x		requires ocean access	x	x				?	?	?			?
			Measure the temperature structure of the seafloor	Heat flow probe (requires ocean access)						x		requires ocean access	x	x				?	?	?			?
			Assess whether volcanism is occurring at the seafloor	Seismometer				x	x				x	x	x	x		?	?	?			
				Gravity		x	x						x	x	x	x		?	?	?			
			Asess whether tectonism is occurring at the seafloor	Seismometer				x	x				x	x	x			x			x	x	
				Gravity		x	x						x	x	x			x			x	x	
		1.4.3 Determine how and where tidal dissipation occurs on Ocean Worlds.	Measure the tidal love numbers k2 and h2	Antenna array		x	x						x	x	x	x	x	x	x	x	x	x	x
				Laser altimeter		x	x						x	x	x	x	x	x	x	x	x	x	x
				Visible imaging		x	x						x	x	x	x	x	x	x	x	x	x	x
			Measure the rotation state (libration)	Visible Imaging		x	x						x	x	x	x	x	x	x	x	x	x	x
				SAR		x	x						x	x	x	x	x	x	x	x	x	x	x
			Improve understanding of material properties (energy dissipation)	Laboratory Studies																			
				Numerical modeling																			
		1.4.4 Determine when, where, and how energy is transferred through Ocean Worlds	Determine whether convection is occurring in the ice shell, ocean and rocky core	RADAR Sounder		x	x						x	x	x	x	x	x	?	?	x	x	?
				Seismometer				x	x				x	x	x	x	x	x	?	?	x	x	?
				Numerical modeling									x	x	x	x	x	x	?	?	x	x	?
			Determine whether energy is advected from the rocky interior or ice shell by (cryo)volcanism	Gravity Antenna array		x	x						x	x	x	x	x	x	?	?			
				Thermal Imager		x	x						x	x	x	x	x	x	?	?			
				In situ search for hydrothermal activity (requires ocean access)						x			x	x		x		x					
	1.5 Investigate the surfaces of Ocean Worlds and constrain their geologic history.	1.5.1 Identify and assess the internal and external processes that generate stress within ice shells, drive tectonic deformation, and produce surface topography on Ocean Worlds.	Characterize the three-dimensional morphology of surface features	Visible imager		x	x	x	x				x	x	x			x			x	x	
				RADAR Sounder		x	x						x	x	x			x			x	x	
				Laser altimeter		x	x						x	x	x			x					
				Seismometer				x	x				x	x	x			x			x	x	
			Examine subsurface structures	RADAR sounder		x	x						x	x	x	x	x	x	x	x	x	x	x
				Seismometer				x	x				x	x	x	x	x	x	x	x	x	x	x
			Constrain sources of stress	Numerical modeling									x	x	x	x		x		x	x	x	
		1.5.2 Investigate exogenic processes, including impact cratering and space weathering, that have modified the surfaces of ocean worlds.	Characterize the three-dimensional morphology of impact craters	Visible imaging		x	x	x	x				x	x	x	x	x	x			x	x	
				RADAR Sounding		x	x						x	x	x	x	x	x			x	x	
				Laser altimeter		x	x						x	x	x	x	x	x	x	x	x	x	x
				Seismometer				x	x				x	x	x	x	x	x			x	x	
			Determine the spatially variable size-frequency distribution of impact craters	Visible Imaging		x	x						x	x	?	x	x	x	x	x	x	x	x
			Measure the composition of the regolith to determine alteration	IR Spectrometer		x	x	x	x		x												
				UV Spectrometer		x	x	x	x		x												
			Measure the particle flux to the surface	Plasma Instrument		x	x	x	x														
		1.5.3 Evaluate whether aqueous or cryovolcanic processes have modified the surfaces of ocean worlds.	Characterize the three-dimensional morphology of surface features	Visible imager		x	x	x	x				x	x	x	x	x	x	x	x	x		x
				RADAR Sounder		x	x						x	x	x	x	x	x	x	x	x		x
				Laser altimeter		x	x						x	x	x	x	x	x	x	x	x		x
				Seismometer				x	x				x	x	x	x	x	x	x	x	x		x
			Measure the composition of the surface	IR Spectroscopy		x	x	x	x		x												
		1.5.4 Constrain the physical (e.g., mechanical, electromagnetic, optical) properties of the near surface and regolith, including mass wasting processes	Characterize the morphology and distribution of mass-wasting features	Visible Imager		x	x	x	x				x	x	x	x	x	x	x	x	x	x	x
			Measure the physical properties (porosity) of the regolith	Thermal Imager		x	x	x	x				x	x	x	x	x	x	x	x	x	x	x
				In situ measurement				x	x				x	x	x	x	x	x	x	x	x	x	x
				Seismometer				x	x				x	x	x	x	x	x	x	x	x		
	1.6 Determine the composition of the non-ice materials on and within Ocean Worlds to study their origin and chemical evolution	1.6.1 Measure the composition and distribution of non-water ice materials (e.g., salts, organics, non-water ice) on the surface of ocean worlds.	Measure the composition of the icy surface	IR Spectrometer		x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x
				UV Spectrometer		x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x
				Visible Imager		x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x
			Measure the composition of the atmosphere	Mass Spectrometer																			
				Dust Detector																			
		1.6.2 Constrain the composition of the seafloor, including species indicative of water-rock interactions	Determine the composition of the seafloor	Spectrometer						x		Access to subsurface ocean and seafloor	x	x		x	?	?	?	?			?
			Measure the composition of fluids immenating from the seafloor	Mass Spectrometer						x			x	x		x	?	?	?	?			?
			Measure the composition of plume material sourced from the seafloor	Mass Spectrometer		x	x	x	x				x	x		x							
				Dust Detector		x	x	x	x				x	x		x							
				Laboratory Analysis							x		x	x		x							

						Mission Architecture							Ocean Worlds										
Science Question	**Science Goal**	**Science Investigation**	**Measurements and Studies**	**Instrument/Investigation**	**Instrument Tech Gap**	Multiple Flyby	Orbit	Lander	Rover	Subsurface	Sample Return	**Mission Tech Gap**	Europa	Enceladus	Titan	Triton	Ceres	Pluto	Uranian Satellites	Mid-sized Saturnian Sats	Ganymede	Callisto	Other KBOs
2 Where do water oceans exist in the interiors of outer solar system bodies?	2.1 Reveal interior structures of icy worlds	2.1.1 Determine the thickness and composition of the outer ice layer	Directly measure the thickness of the ice shell	RADAR Sounder		X	X						X	X		X	X	X	X				
				Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
				Passive EM				X	X				?	?	?	?	X	?	?	?			
				Magnetometer		X	X						X				?		?		X	X	
				In-Situ Traverse						X		Development of landing and mobility systems for operation in cryogenic and/or vacuum environments	X	X	X	X	X	X	X	X	X	X	X
			Measure the gravity field to constrain the thickness of the ice shell	Antenna array		X	X						X	X	X	X	X	X	X	X	X	X	X
				USO		X	X						X	X	X	X	X	X	X	X	X	X	X
			Measure the low-degree shape	Visbile Imager		X	X						X	X		X	X	X	X	X	X	X	X
				RADAR Altimeter		X	X						X	X	X	X	X	X	X	X	X	X	X
				Lasar Altimeter		X	X						X	X	X	X	X	X	X	X	X	X	X
				Vis/UV occultation		X	X						X	X		X	X	X	X	X	X	X	X
			Measure the rotation	Visible Imager		X	X						X	X		X	X	X	X	X	X	X	X
			Measure the composition of the ice shell	IR Spectrometer		X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
				Color Imager		X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
				UV Spectrometer		X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
				In situ compositional measurements (see Q4 for detail)	see Q4	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
		2.1.2 Determine the existence and spatial extent of any liquid water reservoirs	Directly measure the thickness of global liquid layers	Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
				Magnetometer		X	X						X				?		?		X	X	
				In-Situ Traverse						X			X	X	X	X	X	X	X	X	X	X	X
			Measure the gravity field to constrain the thickness of the combined ice/ocean layer	Antenna array		X	X						X	X	X	X	X	X	X	X	X	X	X
				USO		X	X						X	X	X	X	X	X	X	X	X	X	X
			Search for liquid reserviors within the ice shell	RADAR Sounder		X	X						X	X	X	X	X	X	X	X	X	X	X
				Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
				Passive EM				X	X				?	?	?	?	?	?	?	?	?	?	?
		2.1.3 Determine the structure, density, and composition of the deep interior and how those properties change with depth	Measure the static gravity field to determine the bulk density and moment of inertia	Antenna array		X	X						X	X	X	X	X	X	X	X	X	X	X
				USO		X	X						X	X	X	X	X	X	X	X	X	X	X
			Measure magnetic fields to search for the signature of a metallic core	Magnetometer		X	X						X	X	X	X	X	?	?	?	X	X	?
			Measure seismic waves that travel through the deep interior	Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
	2.2 Examine the surfaces of ocean worlds to identify features indicative of an extant subsurface ocean	2.2.1 Search for the existence of warm features that are indicative of current geologic activity or near-surface liquids	Measure spatial variations in surface temperature	Thermal Imaging		X	X						X	X		X	X	X	X	X	X	X	X
				IR Imaging	Low temperature	X	X						X	X	X	X	X	X	X	X	X	X	X
		2.2.2 Assess whether the composition and spatial distribution of non-ice material reveals the existence of a present-day ocean	Measure the spatially variable composition of the surface	IR Mapping Spectrometer		X	X						X	X	X	X	X	X	X	X	X	X	X
				UV Mapping Spectrometer		X	X						X	X		X	X	X	X	X	X	X	X
				Visible Imager		X	X						X	X		X	X	X	X	X	X	X	X
				In Situ				X	X		X		X	X	X	X	X	X	X	X	X	X	X
		2.2.3 Search for surface changes indicative of current geologic activity	Measure changes in surface feature morphology and morphometry	Visible Imager		X	X						X	X	X	X	X	X	X	X	X	X	X
				IR Imaging		X	X						X	X	X	X	X	X	X	X	X	X	X
			Investigate ground motions associated with tectonics, mass wasting, and other geologic activity	Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
			Measure changes in topography	Visible Imaging		X	X						X	X		X	X	X	X	X	X	X	X
				RADAR/LiDAR Altimeter		X	X						X	X	X	X	X	X	X	X	X	X	X
				Synthetic Apperature Radar		X	X						X	X	X	X	X	X	X	X	X	X	X
		2.2.4 Evaluate whether surface geology is indicative of extant subsurface liquid water reservoirs	Characterize the morphology of surface features	Visible Imager		X	X						X	X	X	X	X	X	X	X	X	X	X
			Characterize subsurface structures	Seismometer				X	X				X	X	X	X	X	X	X	X	X	X	X
				RADAR Sounder		X	X						X	X	X	X	X	X	X	X	X	X	X
	2.3 Explore atmospheres, exospheres, tori of Ocean Worlds	2.3.1 Detect and explore plumes to determine whether they connect to subsurface liquid reservoirs	Search for plumes	Magnetometer		X	X						X	X		X							
				UV Spectrometer		X	X						X	X		X							
				Visible Imager		X	X						X	X		X							
				Plasma Detector		X	X						X	X		X							
				Dust Detector		X	X						X	X		X							
			Measure the composition and density of plume material	Mass Spectrometer		X	X						X	X		X							
				Dust Detector		X	X						X	X		X							
				IR Spectrometer	Transmission spectroscopy has not been demonstrated for a planetary plume	X	X						X	X		X							
				UV Spectrometer		X	X						X	X		X							
		2.3.2 Investigate the atmosphere to understand the composition of the surface and links to an ocean.	Measure the spatially variable density and composition of the atmosphere (exosphere)	Dust detector		X	X						X	X	X	X	X	X	X	X	X	X	X
				Mass Spectrometer		X	X						X	X	X	X	X	X	X	X	X	X	X
				UV Spectrometer		X	X						X	X		X	X	X	X	X	X	X	X
			Measure the ionosphere	Radio occultation		X	X						X	X	X	X	X	X	X	X	X	X	X
		2.3.3 Measure the space environment to understand the sources and sinks of the atmosphere and how material and energy are transported.	Measure the plasma environment	High energy particle detector		X	X						X	X	X	X			X	X	X	X	
				Low energy particle detector		X	X						X	X	X	X			X	X	X	X	
				Neutral particle detector		X	X						X	X	X	X			X	X	X	X	
				Plasma Wave detector		X	X						X	X	X	X			X	X	X	X	
				UV Spectrometer		X	X						X	X		X			X	X	X	X	
			Measure the magnetic environment	Magnetometer		X	X						X	X	X	X			X	X	X	X	

						Mission Architecture							Ocean Worlds											
Science Question	**Science Goal**	**Science Investigation**	**Measurements and Studies**	**Instrument or technique / Investigation**	**Instrument Tech Gap**	Multiple Flyby	Orbit	Lander	Rover	Subsurface	Sample Return	**Mission Tech Gap - also remember to look at the OPAG technology priorities presentation from Tibor; overarching gaps**	Europa	Enceladus	Titan	Triton	Cores	Pluto	Uranian Satellites	Mid-sized Saturnian Sats	Ganymede	Callisto	Other KBOs
	3.1 Constrain the chemical composition and corresponding properties of the ocean	3.1.3 Constrain the salinity of the ocean	Measure ocean salinity	Electrochemical sensor array						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
				Microwave Interferometric Radiometer		x	x	x					x	x	?	?		?	?	?	x	x	?
			Measure the electrical conductivity	Magnetometer		x	x	x	x	x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
		3.1.2 Measure the pH of the ocean	Measure ocean pH	Electrochemical sensor array						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
				HRMS (High-Resolution Mass Spectrometry)						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
				Chemical indicators						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
		3.1.3 Determine the chemical composition of the ocean (inorganic species, organic compounds, dissolved gases)	Measure the composition of the ocean water	Electrochemical sensor array						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
				Mass Spectrometer						x	x	Requires ocean access	x	x	?	?		?	?	?	x	x	?
			Measure the composition of the ocean directly or through plume sources	Mass Spectrometer		x	x	x	x				?	x		x			?				
		3.1.4 Estimate the redox state of the ocean and quantify redox disequilibria																					
	3.2 Determine the physical properties of the ocean	3.2.1 Determine the temperature and density of the ocean as a function of depth and identify any lateral variations.	Measure the gravity field to recover density of ocean	Gravimeter		x	x						x	x	?	?		?	?	?	x	x	?
		3.2.2 Characterize the ice-ocean and ocean-rock interfaces.	Measure topography and boundary conditions of interfaces	seismometer				x	x				x	x	?	?		?	?	?	x	x	?
		3.2.3 Constrain the ocean circulation.		Numerical Model						x		Requires ocean access	x	x	?	?		?	?	?	x	x	?
		3.2.4 Evaluate the long-term stability of the ocean.	Determine current state of ocean	Numerical Model																			
3 Do ocean worlds have past or present environments conducive to life?	3.3 Identify the sources and sinks in the ocean that can maintain chemical disequilibria	3.3.1 Characterize how exogenic processes (e.g., radiation) create oxidants, reductants, or other biologically useful material (e.g., tholins, certain metals) on the surfaces of ocean worlds.	Meaure the composition of the surface and near surface material	IR Spectrometer		x	x	x	x				x	x	x	x	x	x	x	x	x	x	x
				UV Spectrometer		x	x	x	x				x	x	x	x	x	x	x	x	x	x	x
				Mass spectrometer						x	x		x	x	x	x	x	x	x	x	x	x	x
		3.3.2 Identify where and how material is exchanged between the surface, ocean, and interior of ocean worlds.	Measure and constrain composition throughout surface, ocean, and interior	Spectrometers, ESA		x	x	x	x	x	x		x	x	?	?		?	?	?	x	x	?
		3.3.3 Assess whether hydrothermal activity, volcanism, or tectonism occurs at the ocean seafloor	Observe ground motions for signs of activity	Seismometer				x	x				x	x	?	?		?	?	?	x	x	?
	3.4 Determine the occurrence and properties of near-surface, localized liquids within the ice shell	3.4.1 Characterize the depth and geological context of near-surface liquids	Characterize subsurface structures and locations of near-surface liquids	Seismometer				x	x	x			x	x	x	x	x	x	x	x	x	x	x
				RADAR		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x
			Identify geologic features associated with subsurface liquids	visual imaging		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x
				SAR									x	x	x	x	x	x	x	x	x	x	x
				lidar		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x
		3.4.2 Assess the temperature of the near-surface liquids	Measure/Infer the temperature of near-surface liquids	Thermal Imager		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x
				Heat Probe				x	x	x			x	x	x	x	x	x	x	x	x	x	x
		3.4.3 Constrain the composition of the near-surface liquids	Measure the salts present and concentrations	Mass spectrometry				x	x	x			x	x	x	x	x	x	x	x	x	x	x
			Determine the elemental distribution (CHNOPS and trace elements)	electrochemical sensor array				x	x	x			x	x	x	x	x	x	x	x	x	x	x
			Characterize density changes	radar, seismic		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x
			Measure conductivity, temperature, pH, pressure	conductivity probe, thermistor, pH meter, pressure sensor				x	x	x			x	x	x	x	x	x	x	x	x	x	x

						Mission Architecture							Ocean Worlds											
Science Question	**Science Goal**	**Science Investigation**	**Measurements and Studies**	**Instrument or technique**	**Instrument Tech Gap**	Multiple Flyby	Orbit	Lander	Rover	Subsurface	Sample Return	**Mission Tech Gap**	Europa	Enceladus	Titan	Triton	Cores	Pluto	Uranian Satellites	Mid-sized Saturnian Sats	Ganymede	Callisto	Other KBOs
4 Is there evidence for present or past life in plume material, on the surface, or in the interior of ocean worlds?	4.1 Search for organic signatures of present or past life	4.1.1 Measure the relative abundances of relatively simple organic species, including amino acids, carboxylic acids, sugars, and nucleobases/nucleotides.	Inventory organic species	HRMS	See cell M9	x	x	x	x		x	Key mission tech gap unique to multiple flyby missions is that the sample size will be extremely small (on the order of a microliter). This makes all forms of organic analysis challenging, and a performance model relating sample size and instrument LOD is essential. Also contamination becomes a critical issue. Enceladus is a special case where plume fly-throughs potentially enable collection of larger sample volume with a multi-flyby or orbital mission than on other worlds.	x	x	x	x	x	x	x	x	x	x	x
				S-MS (e.g., GC-MS)	See cell F9	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x
				LIF (various)	See cell F 13	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x
		4.1.2 Determine the level of complexity in organic molecules.	Comprehensive inventory of organic molecules that include both volatile & condensed phases, as well as soluble and insoluble fractions (e.g. kergogen) and abundant & trace species	Vibrational spectroscopy (i.e. IR, Raman, SERS Raman)	Ability of non-sampling instruments (VS or FS) to address this science objective at the necessary sensitivity for ocean worlds missions has not been demonstrated by any team. The results from the SHERLOC instrument on the Mars Perseverance mission are particularly illustrative in understanding this key measurement aspect. SHERLOC is the state of the art non-sampling spaceflight instrument in organic detection, utilizing Fluorescence spectroscopy and Raman spectroscopy for organic detection. SHERLOC fluorescence measurements observed in Martian samples early in that mission can be readily explained as Cerium doping of sulfate minerals. However later measurements on samples analyzed at higher elevations acquired Raman vibrational transitions associated with organic compounds. Nonetheless, even these measurements are not capable of creating an inventory of compounds, or indentifying and quantitating the different organic molecules present. So although these sorts of mapping and spectroscopy instruments are ideally suited for creating mineralogical maps, and identifying the presence of organics in those maps, they cannot currently produce inventories of organics. If it was possible to close this technology gap somehow, so that non-sampling instruments could in fact deliver this sort of measurement science, that would be a game-changer for ocean world mission payloads.			x	x		x		x	x	x		x					
				Fluoresence spectroscopy				x	x		x		x	x	x		x						
				GC-MS	This science objective requires the analysis of organics that are not volatile, such as the critically important amino acids, which are water soluble, and they simply decompose if heated to the temperatures used by the GC-MS technique. There have been approaches developed in which a chemical solution (known as a derivatization agent) is added to a sample, with the goal of giving rise to chemical reactions between the non-volatile polar compounds (like amino acids) and the derivatization agent, to produce a new molecule that is in fact volatile, and which can be analyzed using the technique of GC-MS. Unfortunately, when this approach is attempted on a real sample containing water, salts, or minerals, the derivatization agent reacts with these other substances (which are present at much higher concentrations) instead of the desired targets. So there is a fundamental technology gaps associated with the use of existing TRL-9 sampling instruments to address critical aspects of this science objective. This technology gap can be addressed by either developing new "front end" sample processing to separate organics from water/mineral/salt prior to performing derivatization, or by utilizing liquid-based techniques to perform these analyses.			x	x		x	The key technology gap for HRMS is sample preparation - all the S-MS techniques mentioned here would benefit from a higher resolution mass spectrometer. However just because an MS has intrinsically high mass resolution does not signify that it is necessarily sensitive to organics, or is capable of creating inventories of organics present. The sensitivity of a mass spectrometer system is dictated by the amount of material from the environment that can then be separated from its natural sample matrix, ionized, and then transferred into the mass analyzer region of the mass spectrometer. If this sample front end processing does not include the physical separation of different organics from one another prior to mass analysis (like the way it is done in S-MS analyzers), then the data product acquired is a superposition of a wide range of signals that can be difficult to relate to the original composition of the natural sample. The main technology gap for the HRMS concept is therefore efficient sample pre-processing prior to analysis, and development of a means of data analysis that enables a determination of the original composition of the sample. The true test of this functionality would come from the analysis of ocean world analog samples.	x	x	x		x					
				Liquid Separation - MS	There are various technology gaps associated with the use of liquid-based S-MS instrumentation which is currently at TRL-5. The challenges with HPLC and LC variants stem from the need to develop a system that can stored dry and then somehow primed with liquid using an extremely high pressure pump during a mission, or which can be primed with liquid and left in that state for an entire mission prior to use. A "path-to-flight" for advancing these instrument concepts beyond TRL-5 is not clear, and this technology gap must be bridged for either of these approaches to be useful on ocean worlds.			x	x		x		x	x	x		x					
					The need for operating electrospray ionization during spaceflight. This technique is used to transfer liquids from the separation column or capillary into the mass spectrometer, and in doing so, ionizing organics present. This process of ionization requires the instrument to create a temperature/pressure/humidity controlled environment between the liquid separation portion of the instrument and the gas-phase mass spectrometer portion. This link in the analysis chain is currently the fundamental technology gap that must be addressed.			x	x		x		x	x	x		x					
		4.1.3 Measure the type, chirality and abundance of amino acids and sugars. Measure the type, saturation, and carbon chain length of carboxylic acids.	Separation science measurements of sugars, amino acids and carboxylic acids in liquid and gas phases	S-MS (GC-MS, HPLC-MS, LC-MS, CE-MS)	These science measurements have the same technology gaps mentioned above, except for the critically important case of amino acid analysis, mass spectrometry detection is not required, so there are fewer technology gaps to be bridged (in particular the development of an electrospray ionization interface to mass spectrometry.) The analysis of amino acids can be performed using HPLC, LC, or CE. A derivatization process is still required for these analyses, in this case to transform amino acids into labeled molecules that can be interrogated by the technique of laser-induced fluorescence. But unlike the gas phase derivatization mentioned earlier for GC separations, this technique has been demonstrated to function at the levels of detection required for ocean worlds missions.			x	x		x		x	x	x		x					
				CE-LIF, uCE-LIF, ME-LIF	These instrument systems are TRL-5. Next stage of development to acheive TRL-6 is to build a pressurized, temperature controlled enclosure to house the instrument, and an interface between this instrument system and a sample collection system. For liquid-based analysis, the environment must be pressurized and elevated in temperature above 0C.	x		x	x		x		x	x	x		x					
		4.1.4 Measure carbon chain lengths and geometry of lipids	Measure the relative abundance and composition of long-chain aliphatic hydrocarbons	S-MS	See above	x		x	x		x		x	x	x		x					
				uCE-LIF	See above			x	x		x		x	x	x		x					
		4.1.5 Search for biopolymers (proteins, carbohydrates, RNA, DNA, or information-containing polymers not present in terrestrial biology).	Polymer sequencing	Nanopore analyzer	Although not highlighted by the Europa Lander mission study, the Enceladus Orbilander report highlights the use of a nanopore analyzer for an lander. At the time of the publications on that mission, a nanopore analyzer was described as TRL-2. The reasons for this are associated with the fact that this technology does not yet have a clear path for development on an ocean world mission. The primary technical hurdle is that field portable versions of this sort of instrument still require the use of complex, relatively fragile terrestrial biological molecules to perform key instrument functions. So although it is definitely possible for astronauts to perform these sorts of measurements on the International Space Station, using relatively fresh reagents stored as specified by instrument manufacturers, it is not clear how such an instrument would be packaged in a sterile manner, integrated on a spacecraft, and then stored for up to 15 years (example for an Enceladus mission), while still making sure that biological molecules remain viable (keep in mind that spacecraft and instrument sterilization, planetary protection, and contamination control protocols are specifically designed to degrade and destroy biological molecules.) The biggest tech gap for this instrument concept is either developing a plan to incorporate these instrument components while simultaneously preserving their function and meeting mission requirements of biological cleanliness, or to completely replace all these molecules with more robust inorganic equivalents. And after the development and demonstration of such a system, it would need to be fully automated, and shown to work on an appropriate ocean world planetary analog material, which could include solid salt, or mixtures of salt and ice.			x	x		x		x	x	x		x					
			DNA/RNA Sequencing	DNA Sequencer				x	x		x		x	x	x								
		4.1.6 Search for organic molecules with metabolic function (i.e., ATP).						x	x		x		x	x	x								
		4.1.7 Search for pigments or fluorescence	High-spatial resolution spectroscopy	UV/Vis/Fluoresence spectroscop	Performing correlated mapping on samples accessible to the mission: unlike on Perseverance, samples won't be flat abrasion patches on the surface. How will spatial mapping be performed on acquired samples?			x	x		x		x	x	x			x					
	4.2 Search for inorganic signatures of present or past life	4.2.1 Measure isotopic fractionation	Measure C, and N isotopic ratios and D/H	HRMS				x	x		x		x	x									
		4.2.2 Search for biominerals											x	x									
		4.2.3 Determine the elemental distribution (CHNOPS and trace elements)	Measure elemental abundance	HRMS				x	x		x		x	x									
				Electrochemical sensor array (ESA)				x	x		x		x	x									
		4.2.4 Measure chemical disequilibria (redox pairs)		ESA				x	x		x		x	x									
				HRMS				x	x		x		x	x									
	4.3 Search for morphologic signatures of present or past life	I4.3.1 dentify cell-like structures, biomineral structures, and biofabrics	High-spatial resolution imaging	Imagers	Similar to microscopes, high-resolution imagery will require high data volume. May need intermediate-resolution imagery similar to MAHLI, in between context imagers and microscopic images. Consider multiple filters and perhaps polarization filters?			x	x	x	x	Tech gap for subsurface missions to oceans of Europa or Enceladus - what sort of payload / onboard sample handling and data analysis / data return will be possible?	x	x									
			High-spatial resolution spectroscopy	mapping spectrometers including IR spectroscopy, UV/Vis/Fluoresence spectroscopy, Raman spectroscopy	Performing correlated mapping on samples accessible to the mission: unlike on Perseverance, samples won't be flat abrasion patches on the surface. How will spatial mapping be performed on acquired samples?			x	x		x		x	x									
	4.4 Search for active microbial life	4.4.1 Assess cell motility	Microscopic imaging and video capture	Microscope	Data volume for microscopy is very high, especially given that the field of view for measurements is relatively small. To determine if there are cells that are moving, video imagery is required which is extremely data intensive. And from a larger perspective, microscopes also require significant non-trivial sample preparation: would cells present be dissolved in a fluid and then imaged? If not, then how would they be imaged in a real matrix? If they are present in vesicles inside salt crystals, how can the microscope be verified to function, and how deeply can it image into a sample? In general, how is the sample prepared? Might require AI / ML assistance for analysis of large data volume of microscope images; return small volume of images flagged as potentially interesting			x	x	x	x		x	x									
		4.4.2 Measure metabolic response to stimuli		Labeled-release or heating experiment, similar to Viking lander?	How much has direct life detection instrumentation developed since the Viking-era labeled release / metabolic "chicken soup" experiments? Must be agnostic to type of metabolism, and not rely on earth-centric chemical makeup			x	x	x	x		x	x									
	4.4 Explore and understand the abiotic background	4.4.1 Study and categorize the inorganic / abiotic chemical abundances	Measure elemental abundance	Vibrational spectroscopy (i.e. IR, Raman, SERS Raman); Fluoresence spectroscopy; GC-MS		x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x