

Appendix Table S1 Science Traceability Matrix (STM) describing how an orbiter + lander space mission to Callisto addresses seven key Science Goals (“Callisto mysteries”) about this singular Galilean moon *

Science Goal (“Callisto Mystery”)	Science Question	Measurement Objective	Orbital Observations			Surface Observations		
			Measurement Requirement	Type of Instrument	Constraint on Mission or Platform	Measurement Requirement	Type of Instrument	Constraint on Mission or Platform
G1- Origin and Formation	What was the environment in which Callisto formed?	D/H ratio of surface ice	n/a	n/a	n/a	D/H ratio with a precision of better than 10^{-4}	Mass spectrometer μLIBS (to be qualified) TLS	μLIBS uses laser ablation to produce the gas phase to be measured MS and TLS require sampling mechanism + vapourisation system
	What is the moment of inertia and internal structure of Callisto?	Seismic body waves arrival time of primary (P, S) and reflected/ converted secondary phases of Callisto quakes and impacts				3 axis ground acceleration with sensitivity better than $10^{-11} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ in the 0.1-10 Hz bandwidth	3 axis very Broad Band seismometer with sampling at more than 20 samples per second	To be deployed near or below the platform and maintained in lander of sun shield shadow Operation shall be more than 17 days for monitoring the tidally triggered seismicity Operation shall be more than three 17-day tidal cycles for confirming the presence of deep moonquakes nests
	What is the radius of the major internal discontinuities?	P and S direct wave spectra, duration and apparent quality factor of the shear wave coda of Callisto quakes and impacts						
	What are the compositions and states of the major interior layers How large are heterogeneities? What are the elastic thicknesses of the icy and silicate layers?	Gravitational coefficients (J_2 , C_{22})	Independent determination of J_2 and C_{22} to an accuracy better than 0.01 mGal	Radio tracking (X-band or Ka-band)	Near-polar, low-altitude circular orbit preferred			

		Long-wavelength topography	Degree-2 topography to an accuracy better than 3 m*	Laser altimeter (preferred) or stereo topography from imaging	Near-polar orbit			
		Moon obliquity	Pole orientation to better than 0.02 °(1 km)	Laser altimeter and repeat imaging	Image resolution better than 1 km Near-polar orbit	Pole orientation to better than 0.02 °(1 km)	Laser or radio tracking of surface element	Tracking measurements should last more than 17 days
		High-order gravity moments	Gravity coefficients to better than l=60	Radio tracking (X-band or Ka-band)	Mission duration >1 year at 100 km altitude (X-band) or >2 years at 200 km (Ka-band)			
G2- Cratering History	What is the subsurface structure and degree of relaxation of impact basins?		Gravity coefficients to better than l=150*	Radio tracking (triple link X/Ka/Ka)	Mission duration >1 year and altitude 50 km			
		Short wavelength topography	Topography with resolution better than 0.5 km (ideally 100 m) horizontally and 10 m vertically	Laser altimetry or stereo imaging	90%-95% coverage of surface			
	What is the spatial and size-frequency distribution of impact craters on Callisto?	Color and/or multispectral imaging	Pixel resolution better than 500 m	Imager (color/multispectral)	Global coverage			
		Global monochrome imaging	Pixel resolution better than 100 m	Imager (monochrome)	Global coverage			
G3 - Ice Shell and Ocean	What are the characteristics of the ice shell?	Short-wavelength gravity to determine ice shell density	Gravity coefficients to better than l=150*	Radio tracking (triple link X/Ka/Ka)	Mission duration >1 year and altitude 50 km			
		Activity of tidally triggered quakes				3 axis ground acceleration with sensitivity better than $5 \times 10^{-11} \text{ m s}^{-2} \text{ Hz}^{-1/2}$	3 axis very Broad Band seismometer with sampling at more than 20 samples per second	To be deployed near or below the platform and maintained in lander or sun shield shadow
	What are the characteristics of Callisto’s ocean?	Dispersion of Rayleigh and						

		Love surface wave compared to P and S arrival Receiver function at the landing site				in the 0.1-10 Hz bandwidth		Operation shall be more than 17 days for monitoring the tidally triggered seismicity
		Moon librations	Location of surface features in inertial space to better than 1 m*	High-resolution imaging (+ altimetry)	Advantageous to include terminator in images	Location of surface features in inertial space to better than 1 m	Radio or laser tracking of surface element	Tracking measurements should last more than 17 days
		Moon obliquity	Pole orientation to better than 0.02 °(1 km)	Laser altimeter and repeat imaging	Image resolution better than 1 km Near-polar orbit	Pole orientation to better than 0.02 °(1 km)	Laser or radio tracking of surface element	Tracking measurements should last more than 17 days
		Magnetic induction	Magnetic field to better than 1 nT	Magnetometer (+ radio sounding of ionosphere)	Passes at different magnetic longitudes	Surface magnetic field to better than 1 nT	Magnetometer	Duration should exceed one tidal period (17 days)
		G4 - Callisto-Jupiter Tidal Interactions	How much tidal energy is Callisto dissipating? Do we have deep Callisto quakes triggered by the tide?	Callisto diurnal tidal deformation	Degree-2 time-variable gravity to better than 0.1 mGal (measuring k_2/Q requires 0.02 mGal)	Radio tracking	Near-polar, circular low-altitude orbit preferred	Long-period seismic response to better than 0.1 mGal*
	Degree-2 time-variable topography to better than 2 m			Laser altimetry	Near-polar, circular low-altitude orbit preferred	3 axis ground acceleration with sensitivity better than $10^{-11} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ in the 0.1-10 Hz bandwidth		
	How rapidly is Callisto migrating?		Callisto ephemeris	Along-track position to 10 m precision over 3-year baseline	Radio tracking (+ VLBI)			

G5 - Surface Chemistry	What are the chemical and physical characteristics of Callisto's surface?	Global/ regional surface composition	Global hyperspectral mapping 0.8-5.0 μm at $\sim 2\text{-}5$ km/px and spectral sampling ≤ 10 nm + targeted hyperspectral mapping on ROI at <100 m/px Co-registered global multispectral imaging at $\sim 0.2\text{-}0.5$ km/px (≥ 4 bands: pan + RGB).	VNIR–SWIR hyperspectral imaging spectrometer (0.8–5 μm) + multispectral optical camera (pan + RGB, ideally + NIR).	Requires sustained orbital mapping (not flybys) to achieve homogeneous global products and controlled geometry; downlink-limited two-tier strategy (global survey + ROI bursts)	Ground truth of spectral endmembers and mixing at grain scale: identify phases responsible for bands (CO_2 , sulfur-bearing, organics proxies) and validate orbital unmixing	Raman IR spectrometer + microscopic imager and/or LIBS	Static lander; site representativeness is the main limitation LIBS can perform at standoff distance (e.g. 20 cm to 50 cm) from a fixed location on the lander
		Global/ regional elementary composition of non-ice material	Map abundances/ ratios of major rock-forming elements (Mg, Al, Si, Ca, Fe) at global/ regional scales ($\sim 10\text{-}100$ km) Co-registration with geology and irradiation context	X-ray imaging/ spectroscopy	Needs long integration and repeated coverage; benefits strongly from simultaneous energetic-particle context (for particle-induced X-rays) and stable orbital geometry	Local elemental composition for calibration/ validation of orbital XRS and to link elemental ratios to lithology	XRF or LIBS	XRF requires contact or stand-off head at the surface; dust/roughness affects measurements LIBS performs at standoff distance (e.g. 20 cm to 50 cm) from a fixed location on lander
		Surface thermophysical properties	Temperature/emissivity mapping over a broad range of local solar times to retrieve thermal inertia proxies: regional products at $\sim 10\text{-}50$ km, ROI at $\leq 1\text{-}5$ km, including night-side coverage ($T \sim 80\text{-}170$ K)	Thermal IR radiometer/ thermal imager mid-IR (sensitivity spanning roughly $\sim 7\text{-}50$ μm , ideally extending longer to improve night-side SNR)	Requires orbital phase that samples many local times (months-years) Flybys cannot provide diurnal curves; low-altitude phases improve ROI resolution	Diurnal temperature curve + regolith thermal conductivity/ heat capacity proxy at the landing site	Temperature sensors (surface/subsurface), simple thermal probe	Must survive at least one local day/night cycle; good thermal coupling to regolith required
		Physical state of volatiles and mixing modes	Constrain “dirty ice” vs clean ice vs adsorbed/clathrate-like storage via: hyperspectral mapping 0.8–5 μm at <100 m/px on ROI plus repeat	VNIR–SWIR hyperspectral imaging spectrometer + high-resolution multispectral imager + optional	Needs repeatable viewing geometry and co-registration stability; benefits from low-altitude mapping arcs	Direct determination of volatile phase and grain-scale mixing (ice grain size,	Raman IR spectrometer + microscope; optional sampler/scoop	Surface access to regolith; shallow sampling (cm-dm) greatly improves diagnostics

	How are exogenic processes modifying the surface?		observations at different local times/phase angles to separate compositional vs photometric/thermal effects Constrain regolith thickness, dielectric properties, and vertical distribution of ice-rich vs ice-poor materials to support interpretation of surface mixing modes	thermal IR + optional radar sounder (active/passive)	Radar sounding (optional) provides complementary near-surface constraints	porosity, cementation; CO ₂ physical state)		
		Surface/ atmosphere interactions Key isotopic ratios in surface and atmosphere	Repeat mapping of the same terrains to detect process signatures: changes in band depths/slopes and compositional gradients at <100 m/px (ROI) with matched photometric conditions; link to irradiation environment (leading/ trailing, latitude)	Multispectral imager +0.8-5 μm hyperspectral spectrometer	Needs long-lived orbiter to provide revisit cadence and local-time diversity; robust photometric normalization pipeline	Local measurement of radiation products in regolith and their depth dependence (upper mm-cm)	Mini mass spectrometer and/or Raman; radiation monitor	Needs exposure to ambient environment; contamination control important
G6 - Atmosphere & Ionosphere	How is Callisto's atmosphere sustained?		Isotope abundances in atmosphere	Neutral mass spectrometer, dM/M>1000, mass range: 1-150 u	Altitudes below 1000 km			
		Atmosphere composition, distribution and variability	Gas emission and absorption features (Local) composition (and abundances) of molecules and atoms	UV spectrograph, 80-200 nm, spectr. resolution <0.1 nm Neutral mass spectrometer, dM/M>1000, mass range: 1-150 u	Frequent observing cadence covering the parameter space: Callisto's orbital positions, longitude and latitude, magnetospheric conditions (longitude)	(Local) composition (and abundances) of molecules and atoms	Neutral mass spectrometer, dM/M>1000, mass range: 1-150 u	

	What are the sources (production mechanisms) and sinks (loss processes) of the ionosphere?	Ionosphere composition, distribution and variability	Total electron content along line-of-sights through atmosphere Composition and abundances	Radio occultations or active radar measurements Ion mass spectrometer Electron spectrometer Langmuir probe	Like above: covering parameter space and repeated coverage			
G7 - Magneto-spheric Dynamics, Auroral Processes and Plasma Sources	What are the processes governing plasma and electromagnetic interactions between Callisto and the Jovian magnetosphere?	Magnetospheric plasma and energetic particles distribution and variability Investigation of drivers and processes of main aurora emissions	Plasma composition, distribution functions, and moments Electron spectrometer: 10 eV-20 keV Ion mass spectrometer: M/dM>4, 10 eV-50 keV Energetic charged particle: 30 keV-1 MeV UV: 50-200 nm X-ray: 0.5-5 keV Magnetic field: <5 pT resolution	Ion mass spectrometer Electron spectrometer Charged particle detector UV spectrometer X-ray spectrometer Magnetometer Electric field waves instrument	Frequent observing cadence covering the parameter space: Callisto's orbital positions, longitude and latitude, magnetospheric conditions (longitude) Elliptical, polar orbits Nadir pointing Boom, EMC control	Particle fluxes: 500 keV-50 MeV (electrons) and 500 keV-100 MeV (ions)	Radiation monitor	Pointing towards the sky
		Plasma and field signatures of Callisto/ magnetosphere interactions and Callisto-related aurora	Magnetic field: <5 pT resolution UV: 50-200 nm	Magnetometer UV spectrometer	Frequent observing cadence covering the parameter space: Callisto's orbital positions, longitude and latitude, magnetospheric conditions	Surface magnetic field to better than 1 nT	Magnetometer	Two-point measurements between lander and orbiter

					(longitude) Nadir pointing Boom, EMC control			
		Variability sources: Io torus, solar wind, outer magnetosphere	Ion: M/dM>4, 10 eV- 50 keV ENA: 0.5-300 keV	Ion mass spectrometer ENA imager	Frequent observing cadence covering the parameter space: Callisto's orbital positions, longitude and latitude, magnetospheric conditions (longitude) Remote-sensing of the Io torus Elliptical, polar orbits			

*denotes a measurement that may be hard to attain