Table STM-A. Science Traceability Matrix A (STM-A) for the GANGOTRI Mission Concept. For legibility and conceptual flow, STM is bifurcated, one relating mission goals and aims to NASA goals (Table STM-A); and the other associating mission aims with physical parameters, observables, and performance requirements (Table STM-B). For brevity, we only **excerpt** relevant text with ellipsis (…) of the NASA Visions and Voyages 2013 – 2022 decadal survey (V&V) [NRC, 2011], mid-term review (MTR) [NAS, 2018] and NASA's science plan (SP) [2014]. The Committee on Astrobiology and Planetary Sciences (CAPS) report [*NAS*, 2017] identifies Mars as a key target for each V&V goal excerpted.

Examples of NASA Goals	GANGOTRI Science & Human Exploration Goals	GANGOTRI Objectives (Aims)
V&V: How do the climate, and especially the water cycle, vary with orbital and obliquity variations? ...more detailed examination of ... layered sedimentary rocks for the record of ... climate ... to improve the understanding of volatile budgets and cycles. **SP:** ...characterize and understand Mars as a system, including its current ... climate... **MTR:** ...(<3 Ga Age) Climate Change Amazonian...What processes formed shallow, excess ice? … How do those ... relate to obliquity variations...?	**SG.** Understanding climate-driven processes of mid-latitudinal glaciers as a key H2O reservoir within Mars's critical zone.	**SG1.** Test the latest H2O reservoir exchange model for Mars using D/H isotopic signatures. **SG2.** Resolve a paradoxical divergence between theoretical and observed atmospheric D/H variance for Mars. **SG3**. Determine the extent to which englacial siliciclastics and sulfate-rich aerosols undergoing low-pH alteration may yield martian sulfate sedimentary strata.
V&V: ...understanding of the astrobiological potential of the observable water-ice deposits... **SP:** ...characterize and understand Mars as a system, including its...biological potential...	**SB.** Determining the habitability and biomarker preservation potential of young martian glaciations.	**SB1.** Determine the extent to which ancient organics and microorganisms can be deposited, immured, and preserved in young glaciers. **SB2.** Determine whether any presence of organics and microorganisms was driven by aeolian-deposited englacial dust.
V&V: To reduce the cost and risk for future human exploration, robotic ... missions ... to acquire information concerning potential resources… **MTR:** ...investigating the distribution of shallow excess ice will quantify an important resource to provide astronauts with water and oxygen...	**HE.** Understanding the utility of glacial ice as an in situ resource (ISR) for humans.	**HE1.** Establish a ground-truth reference volume for H2O ice as a possible ISR. **HE2.** Identify which glacial H2O extraction and purification methods would be optimal for ISR use. **HE3.** Determine forward and backward biological contamination thresholds before using readily accessible martian ice as an ISR.

Table STM-B.

Aims	Required physical parameters	Required observables	Platform and mission performance requirements
SG1	SR1. Englacial hydrogen isotopic abundance	SO1. Mass spectroscopy of D/H molar ratios	SP1. SAM specifications with δD resolution (2SD) of ±100‰
SG2	SR2.1 Englacial hydrogen isotopic variations	SO2.1 Same as SO1	SP2.1 Same as SP1

	SR2.2 Climate & weather governing glacial instability SR2.3 Overnight energy exchange at glacial sites	SO2.2 Local temperature, pressure, wind velocity, and humidity over 1 Mars year SO2.3 Thermal characterization with infrared spectroscopy	SP2.2 MEDA specifications, corrected for the spacecraft's thermal effects. SP2.3 MiniTES specifications
SG3	SR3.1 Extensiveness, composition, and layering of englacial siliciclastics, salts, and trapped gases, including dust-ash layers. SR3.2 Contextual surface geochemistry and mineralogy across overlying regolith and ground ice boundary	SO3.1.1 Relative englacial abundances of phyllosilicates, perchlorates, sulfates, and other mineralogic and amorphous components. SO3.1.2 Complementary isotopic measurements of H, C, O, S, and Cl SO3.1.3 Optical scattering by englacial dust. SO3.2.1 Bulk regolith concentration of major silicate forming elements (Fe, Si, Al, Ca, Mg), mobile elements significant for brine activity (Cl, S, H), and large ion lithophiles significant for distinguishing aqueous versus igneous processes (K, Th). SO3.2.2 Infrared spectroscopy of surficial minerals. SO3.2.3 Compositional and physical stratification across the regolith-ice boundary layer.	SP3.1.1 SAM evolved gas chromatography and mass spectroscopy operating up to 800 °C with 70 µg/kg sensitivity to evolved volatiles. SP3.1.2 Same as SP3.1.1 SP3.1.3 Dust logger with 405 nm laser to illuminate surrounding glacial ice in a horizontal fan (90° wide) at 1 - 2 mm vertical resolution in backscatter mode. SP3.2.1 NGRS with better than 15% precision for targeted elements. SP3.2.2 MiniTES infrared spectral resolution specification SP3.2.3 Piezo-ceramic acoustic seismometer with 1 kHz bandwidth of finer than 10 cm vertical resolution, and SP3.2.1
SB1	Type abundance of aromatic organic molecules and microbial cell components.	SBO1.1 Evolved gas chromatograph mass spectrum SBO1.2 UV fluorometric detection of organics and microbial cells SBO1.3 UV microscopic imaging of organics, microbial cell components, and granular material	SBP1.1 SAM system using retention times on the gas chromatograph and full separation of isobaric interferences. SBP1.2 UV fluorometer with up to 4 excitation wavelengths, 16 emission channels, and mm-resolution sensitive to 50-100 cells/ml. SBP1.3.1 Sample staining sub-micron resolution UV microscope with 10, 1, and 0.1 µM sieves for melt slurry. SBP1.3.2 Darkfield imaging in four wavelengths and excitation fluorescence at four wavelengths, including D-UV.
SB2	Physical association between organic molecules, microbial cell components, and siliciclastics	Same as SBO1.2, SBO1.3	Same as SBP1.2, SBP1.3.1, SBP1.3.2
HE1	Depth, lateral extent, and concentration of H2O ice	HO1.1 Geologic mapping with optical imagery HO1.2 Same as SO3.1.3, SO3.2.1, & SO3.2.3	HP1.1 MHS imaging at 10 - 30 cm / pixel resolution for km scale aerial surveying HP1.2 Same as SP3.1.3, SP3.2.1, SP3.2.3

HE2	Chemical (e.g., sulfates) and physical (e.g., siliciclastics) constituent abundance in ice	Same as SO3.1.1, SO3.1.2, SO3.1.3	Same as SP3.1.1, SP3.1.3
HE3	Microbial or biogenic material in ice	Same as SBO1.1, SBO1.2, SBO1.3	Same as SBP1.1, SBP1.2, SBP1.3.1, SBP1.3.2
All	All except SR2.2, SR2.3, SR3.2	All except SO2.2, SO2.3, SO3.2.1, SO3.2.2, SO3.2.3 and HO1.1	Thermal ablation drill penetrating 10 - 100 m depths. Sample preparation-delivery system from borehole to rover deck.

Table SA. Spacecraft architecture (SA) for the GANGOTRI mission concept

Component	Heritage or TRL	Details	Expected Mass (kg)
EDL Platform	M2020	EDL Platform and landing system based on the skycrane system adapted for the weight and momentum of the GANGOTRI rover.	2400 [NASA]
Rover	M2020	Rover chassis as the base design. Key enhancements include wheel design for enhanced excavating ability, Radioisotope Power System (RPS) optimization for the drill and rover, and acoustic seismometer integration into wheels.	900 [NASA]
Thermal Ablation Drill	THOR*	Thermal source options, sample preparation, and sample delivery to the deck are key areas for development. Likewise, science payload consisting of dust logger, fluorometer, and microscope are to be incorporated. * Thermal High-voltage Ocean-penetrator Research (THOR)	75
MHS	M2020	MHS imaging systems will be modified for mapping.	1.81 [Agle, 2019]

Table SMA. Sample analysis at Mars Minimal Adaptation (SMA) for the GANGOTRI mission concept by Franz and Mahaffy, showing configuration options for volatile and isotope measurements.

Measurement or resources	Full SAM	SAM without GC[1]	QMS/TLS minimal[1,2]
Delta-D and Delta-18O in water to fully meet mission requirements	XXX	XXX	XXX
C, O, S, N, Cl isotopes in CO_2, SO_2, NO, and HCl	XXX	XXX	XXX

Clays, sulfates, sulfites, perchlorate, nitrate identification	XXX	XXX	XXX
Organic identification	XXX	X	X
Instrument mass	36.9 kg	30 kg[3]	20 kg[3]
Instrument volume	2.5 CU FT	1.8 CU FT	1.2 CU FT
Energy per experiment	1200 watt-hours	800 watt-hours	800 watt-hours
Data volume	20 Mega bytes	15 Mega bytes	15 Mega bytes

Note 1: Estimate to be worked as part of the engineering study. QMS: Quadrupole Mass Spectrometer; TLS: Tunable Laser Spectrometer

Note 2: QMS/TLS minimal configuration includes single oven, 10 sample cups, and single wide range pump

Note 3: Mass of the sample manipulation system internal to the instrument would depend on the mission requirements for number of samples to be analyzed.

Table CA. Cost Assessment (CA) for the GANGOTRI mission concept. Mission baseline minimum Rough Order of Magnitude (ROM) cost estimate in FY19 $ value, using V&V Appendix G mission cost estimates as a point of reference.

Cost category	Minimum cost estimate $M	Justification
Project management/system engineering/mission assurance	97	Cost efficiencies from MSL-Mars2020 heritage compared to a Mars polar mission
EDL and rover platform, including thermal drill and sample preparation-delivery system	400	Cost efficiencies from MSL-Mars2020 heritage compared to a Mars polar mission
Payload	19 (NGRS)+75 (SAM)+50 (fluorometer, microscope, dust logger)+23 (MHS)+50 (cameras and MiniTES)	Estimates from ongoing instrument development, prior work, and public information
Mission operations system/ground data system	40	Cost efficiencies from MSL-Mars2020 heritage compared to a Mars polar mission
25% Reserve	189	
Minimum Mission total	943	

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