IAA-L-0401P

LUGH/MERCURY EXPRESS: A PROPOSED MULTI–PLATFORM FLYBY MISSION TO MERCURY

P. E. Clark, S.A. Curtis, G. Marr, D. Reuter
Laboratory for Extraterrestrial Physics, NASA/GSFC, Greenbelt, MD 20771 USA
S. McKenna–Lawlor
Space Technology Ireland Limited, Maynooth/NUI, Co. Kildare, Ireland
Pamela.Clark@gsfc.nasa.gov

ABSTRACT: LUGH is a fast (1 year), low cost, high heritage, high data return (100 Gbits), 3-platform, dual-flyby Pathfinder Mission to Mercury. It is designed to investigate the planet's interior structure and magnetic field to 3rd order; provide imaging/mapping and bulk composition of the entire surface, determine the composition of the exosphere, and model the 3D structure, composition, key boundaries, wave/particle interactions, dynamics and particle sources/sinks of the magnetosphere. These objectives are met through the hitherto unprecedented means of flying a well-instrumented spacecraft with equatorial periapses supported by two polar nanoprobes, thereby substantially expanding the measurement capability of a single spacecraft. Measurements at Mercury which can be uniquely provided by LUGH include a comprehensive field, particle, and plasma dataset, including high speed, energetic neutral atom spectrometry to monitor the magnetospheric/solar wind interaction. LUGH would also allow more complete interpretation of planned orbiter data.

1. LUGH (LOW–COST, UNIFIED, GEOPHYSICS AT HERMES)/MERCURY EXPRESS

1.1 Historical Background

Less is known about Mercury than about any other inner planet. Before 1974, studies of Mercury involved astronomical observations from which its orbit, rotation period, radius and mass were determined. Three encounters by Mariner 10 (M10) in 1974 and 1975, provided the first in-situ observations of one hemisphere. An especially important discovery was that Mercury has an intrinsic magnetic field, implying that the planet has a partially molten, iron-rich core and, thus, a history of extensive geochemical differentiation. However, lack of global coverage (only 45% of the surface was imaged), and the limited nature of many onboard measurements, lead to largely unconstrained theories of Mercury's origin and history.

1.2 Overview of the LUGH Mission/its Scientific Objectives

LUGH is a cost–effective, low–risk/high yield, 3-platform, dual-flyby, pathfinder mission to Mercury which, for less than 2/3 the cost of an orbiter and in less than one year, will complete the primary exploration of the planet, collecting 100 Gbits of data while critically focusing the objectives of later missions. LUGH's unique, multidisciplinary, 3-platform payload allows it to provide (1) a comprehensive survey of Mercury's interior, surface, atmosphere, and magnetosphere; (2) bulk elemental abundance measurements in both hemispheres, from which essential parameters for models of Solar System/ terrestrial planetary core formation and interior differentiation processes can be derived; (3) a global survey of Mercury's major terranes (tectonic, volcanic, and impact structures); (4) the first determination of the 3-D magnetic structure of Mercury's magnetosphere and its interaction with the solar wind; (5) unique, high

System	Science Objectives	Measurement Goals
Interior	1) To provide essential parameters to model the formation of the Solar System, Mercury at its core. 2) To determine the source, strength and orientation of Mercury's internal magnetic and gravitational fields. 3) To determine the core/mantle/crust interaction	1) To obtain bulk elemental abundance measurements for Mercury's surface, its crust, mantle and core. 2) To obtain the first multiprobe, direct measurements of the low altitude, external magnetic field near the equator and both poles. 3) To determine internal moments of the magnetic field to 3rd order. 4) To determine moments of inertia, C_{20} and C_{22} to better than 10% accuracy.
Surface	1) To complete a geological survey of both hemispheres 2) To determine geochemical signatures and origin of major terranes and large tectonic features. 3) To determine the nature of crustal rocks and minerals and the history of tectonic, volcanic, and impact activity.	1) To obtain 1 km/pixel visible imaging of Mercury's entire surface. 2) To obtain higher resolution (hundreds of meters) spectral, imaging, and elemental abundance data for representative tectonic, volcanic, and impact features along the groundtrack. 3) To obtain UV measurements of sulfur, aluminum, and calcium.
Atmosphere	1) To provide a complete survey of Mercury's atmospheric constituents. 2) To determine variability and provide distribution maps of atmospheric constituents. 3) To understand the interaction between the Exosphere, Magnetosphere, Solar Wind, Surface, and Interior.	1) To obtain bulk abundances of atmospheric constituents. 2) To determine the distribution of atmospheric constituents. 3) To measure the soft X-ray background flux. 4) To measure distributions of atmospheric ion species in solar wind plasma, the magnetosheath, and the magnetosphere. 5) To obtain multipoint magnetic and electric field measurements.
Magnetosphere	1) To map and model Mercury's magnetosphere in 3D. 2) To determine the interaction of the Solar Wind, Exosphere, and Surface with the Magnetosphere. 3) To determine sources/sinks and bulk composition of magnetospheric plasma.	1) To obtain 3D magnetic (to 3rd order) and gravitation (to 2nd order) field measurements. 2) To obtain high resolution particle, wave, and magnetic field measurements of the magnetosphere 3) To monitor magnetospheric dynamics at high time resolution

FIGURE 1: SUMMARY CHART FOR LUGH SCIENCE GOALS AND MEASUREMENT OBJECTIVES

time resolution, monitoring of magnetospheric dynamics; (6) tests of gravitation theory. LUGH's mission goals are summarised in **Figure 1**. The science return from LUGH is compared with that from Mariner 10 and NASA's planned Messenger Mission (Section 1.5) in **Figure 2**.

LUGH exploits the ability of an inexpensive launch vehicle to directly transfer a payload from the Earth to Mercury in just over 100 days and return to Mercury for a second encounter 264 days later when the planet's opposite side is illuminated. The resonance between Mercury's orbital and rotational periods is utilized to minimize the time between opposite face encounters (<9 months) associatively minimize mission duration (thus limiting the thermal radiation and onboard propulsion requirements associated with long flight times). These trajectories are comfortably achievable with either the Delta II 7925H or the Soyuz equivalent launch vehicle,

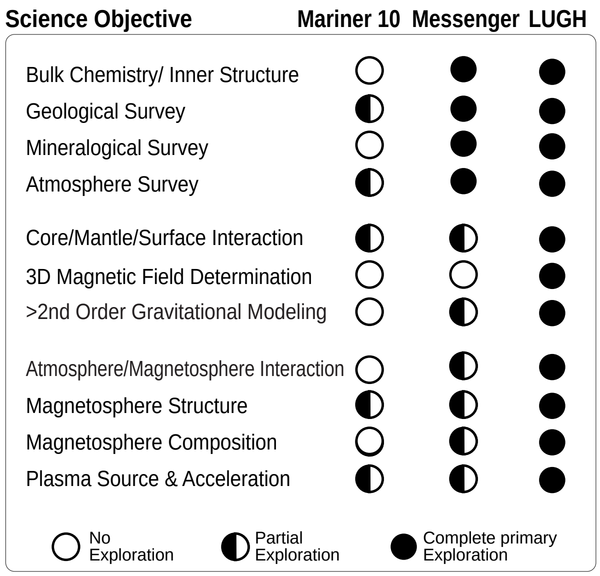

Figure 2: Comparison of Mercury Missions

Launch	Encounter 1	C3	delta V
12/20/05	04/01/06	44.7	902
12/01/06	03/16/07	42.0	777
11/12/07	03/01/08	40.7	808
10/25/08	02/16/09	41.5	1179
10/10/09	02/02/10	44.7	1533

Figure 3: LUGH Operational Dates

which have two-week windows every 340 days. The minimum C^3 (twice the combined kinetic and potential energies per unit mass in km^2/sec^2 required for the launch vehicle) and delta V (the velocity change required from the LUGH propulsion system in m/s to achieve the heliocentric period change to ~264 days) are shown in **Figure 3.**

During Encounter 1 (E1), two Nanoprobes (NPs) will be launched and directed over the poles by the main spacecraft. The NPs will carry instrumentation, which is cross-calibrated with corresponding instruments of the main payload. A 50 Gbit on-board memory allows data gathering unimpeded by telemetry constraints. Such a 3-platform mission is presently unprecedented in planetary exploration, and allows simultaneous 3D measurement of Mercury’s magnetic and gravitational fields, which cannot be made by single orbiters. Further, the extremely fast flight times to first and second Encounters, judicious use of high heritage hardware, selective spacecraft redundancy and a multiprobe approach, mean that LUGH can realize a science return substantially beyond the capability of single orbiter ESA Flexi, or NASA Discovery Class missions. The highly experienced science team will accomplish the science objectives of LUGH in 1 year from launch, and associated analysis techniques will set the standard for future planetary missions.

<u>1.3 Relationship to the Mercury Messenger Mission</u>

NASA’s Mercury Messenger Mission, a Discovery Mission budgeted at M$290, the budget cap, is in an early phase of development. Launch is scheduled for 2004 or 2005. It is a six year mission, with a five year cruise, including one or two flybys, and a one year orbital phase. The scientific payload includes a camera; UV, X-ray, Gamma-ray, and neutron spectrometers; an energetic particle/plasma spectrometer; a magnetometer. The spacecraft design if very simple, and includes fixed solar panels and a fixed antenna. These conditions allow for only one pointing mode during Cruise, thereby limiting the flight calibration opportunities for some instruments. High-rate downlink communications during the data-gathering on-orbit phase is not allowed. Also, low rate data playback with instruments pointed away from Mercury is implemented during a significant portion of every orbit. This feature, as well as the relatively small capacity of the solid state data recorders and necessity to fly at, or near, the terminator, to meet thermal requirements, limits the quality of the data considerably. After 1 year in orbit, Mercury Messenger will have obtained only 1/5 the 100 Gbits of data the

LUGH will obtain during its two Encounters. Although Messenger will swing by Mercury twice before going into orbit, obtaining 5 Gbits of data, these encounters are not optimal since the 200 km periapsis is, in each case, in the unilluminated hemisphere, thereby limiting coverage for many key instruments. Overall, the magnetospheric, atmospheric, and surface coverage Messenger will obtain during its swingbys is limited relative to what can be obtained with LUGH. On the other hand , Messenger, during its orbital phase, will be able to provide higher resolution coverage of the surface and atmosphere in the northern hemisphere due to its high northern latitude periapses. LUGH equatorial flybys can compensate for the limited equatorial and southern hemisphere coverage provided by Messenger. By combining the best quality surface and atmospheric data obtained by LUGH with the best obtained by Messenger, global imaging of Mercury with high spatial and temporal quality can be optimized.

2. LUGH PAYLOAD CONCEPT

LUGH instruments are optimised in terms of speed and resolution to meet the mission's scientific objectives. Sharing of spacecraft resources (e.g. DPUs, Mechanical boxes) will be implemented whenever possible. All instruments can survive Mercury's thermal radiation environment as well as solar energetic particle radiation (using combinations of built in fault detection and recovery mechanisms, suitable shielding, and radiation hard components).

2.1 Description of the Instrument Complement

Key parameters of LUGH's instruments are presented in **Figure 4**. All fly on the main spacecraft. Identical Magnetometers, Star Cameras and Transponders fly on each of the nanoprobes.

3. HARDWARE REQUIREMENTS

3.1 Thermal Design

Exposure to high thermal radiation during both encounters is short and minimal. Thus, using a passive design approach, LUGH, can survive (a) its relatively short duration, low altitude, flybys when spacecraft surfaces facing the Sun are exposed to high thermal radiation; (b) the widely varying thermal environment between 0.45-1.00 AU. Temperature fluctuations are minimized, and the spacecraft and its onboard components maintained within their operating ranges by utilizing a high temperature, composite-based, heat shield and thermal radiators During Cruise, thermostatically controlled heaters will maintain spacecraft temperatures above their minimum allowable level. All external components will be thermally pre-tested.

3.2 Nanoprobes

Two identical nanoprobes (NPs) with heritage based on Goddard's Nanospacecraft Development Program and the FT-5 Nanospacecraft Technology Missions, extend the reach of LUGH to Mercury's polar regions. The NPs each weigh 11 kg and have 20W power requirements. The NP concept is driven by simplicity in design/integration/operation. The NPs will be integrated and tested in parallel. They require no active attitude control system, solar array or battery charging. The design involves a stacked storage configuration during Cruise and a soft release prior to Encounter. Each NP carries a spinning momentum wheel to provide stability during release and to ensure release attitude knowledge. At release, the spin axis of each NP will be perpendicular to both the spacecraft-sun line and the velocity vector. After release, the momentum wheels transfer momentum via friction to the Probes, which will then spin up to the rate required to implement experiment sensor sweeps. The deployed mechanical properties show a spin axis moment of inertia ~1.4 times the maximum moment of inertia in the spin plane

Instrument PI/Heritage	**Measurement** Type, Resolution, Coverage	**Technical Parameters** Weight, Volume, Power, Data Rate	**Data Products**	**Heritage**
(VNIS/UVS) **Visible/near IR Imaging**	Images: global at1km selected features at 100m .4–1.1μ, 50-nm bandwidth spectra accompanying images	10kg; 23,000 cm^3 45 W; 64mb/s active pointing along groundtrack	1km global and 100m selected feature maps Pyroxene, Olivine, Ilmenite abundance maps; Ca and Al abundance at limb	Leisa EO-1
Ultraviolet Spectrometer Reuter GSFC/USA	700-3300A spectra at 5-10A resolution .015x.6 deg^2 FOV for atmospheric constituents	6kg; 8,000 cm^3 4W; 1.4 kb/s; 2 week active period near periapsis	temporal and spatial maps of Figure 6 species; models of atmospheric origin	Rosetta
(XRS) **X-ray Spectrometer** Grande/ RAL/UK	1-10 keV spectra 200 eV res., 30° FOV Mg, Al, Si, Ca, Ti, S, Fe lines and solar output	3.5kg; 2,500 cm^3 7W; 4 kb/s 3 solar monitors at 120° intervals around spacecraft body	Mg, Al, Si, Ca, Fe bulk abundances for quadrants and selected features; Models for geochemical differentiation	Smart-1
(MAG) **Magnetometer** Primdahl IAU/DK **(ASC)** **Star Camera** Jorgensen IAU/DK	DC magnetic field +/- 655 nT 3 vectors/sec 0-1 Hz noise inertial attitude, 1"pointing,7"twists	0.5 kg; 400 cm^3 1 W; 1 kb/s (combined system)	3D magnetic field components and maps, core formation models spacecraft position, pointing determination	Astrid-2
Energetic Particle Spectrometer (EPS) Grande/RAL/UK	Protons: .045-3MeV; Electrons: .014-1MeV 15° pitch angle bins 360° coverage @10msec resolution	2 kg; 1,500 cm^3 4 W; 140 kb/s	plasma moments, flux gradients, E/angle spectrograms, radiation belts, magnetosphere boundaries	Polar Cluster
Low Energy Plasma Detector (LEP) Lundine IRF/Sweden	3-30,000 ev, 1-135 amu/Q, 3 sec/3D scan ions, electrons	6 kg, 7,500 cm^3 10 W; 10 kb/s	3D distribution plots, plasma moments, bulk ion flow models	Cassini DS-1
Energetic Particle Analyzer (EPA) McKenna-Lawlor STIL/Ireland	Protons: .025-50 MeV Electrons: 20-350 KeV 2 10-channel spectra/sec	1 kg; 1,309 cm^3 1.5 W; 0.2 kb/s	Intensity fluxes and the energy spectra of ions and electrons, at different locations and times	Giotto
Energetic Neutral Atom Imager (ENA) Barabash/ IRF/Sweden	images,10-1,000keV, 30%E res, 12°x12°FOV 8x8 SSD matrix <20-sec resolution	2 kg; 87,000 cm^3 2.5 W	Determine frequency and duration of plasma injections and decay times of magnetospheric storms	Mars Express
Tri-Axial Search Coil Antenna (SCA) LeFeuvre ParisObs/France	AC magnetic field spectrograms .01-10 kHz, 2-3 spect./sec $0.9x10^{-11}$ nT^2/Hz at 1kHz, $2.5x10^{-11}$ nT^2/Hz at 10 kHz	0.6 kg; 200 cm^3 0.5 W; 20 kb/s	Waveforms, frequency-time spectrograms magnetospheric boundaries	GEOS Interball
Electric Field Instrument (EFI) Bougeret ParisObs/France	AC electric field spectrograms, 1-500 kHz, 64 channels 2-3 spectra/sec $1nV/m/Hz^{-.5}$	4.6 kg, 4,600 cm^3 2.8 W; 2.5 kb/s	temporal electric field plots electron density plots radio intensity spectrograms and source direction	Wind Cassini
Transponder, Radio Science (STM) Winterhalter JPL/USA	coherent X-band doppler/range spectra model gravity field anomalies	0.5 kg; 600 cm^3 11.7 W 12 kb/s (down)	derive J_2,C_{20},C_{22}, 2^{nd} order gravity maps extent core/mantle coupling and crustal equilibrium	

Figure 4: Instrument Descriptions

- thereby ensuring stability. The NPs are entirely passive. Their trajectories are established aboard the parent spacecraft prior to release using autonomy software. They are dormant except for the receivers, which will "listen" at regular intervals controlled by a timer.

3.3 Communications

LUGH's mission strategy combines high data volume with low demand on ground based communications. High capacity (50 Gbit) solid state recorders allow data to be burst into memory during each Encounter, and played back gradually to the Earth station in the following month. During Cruise, communication with Earth will be relatively infrequent, except during the period of NP Release (from 30 days prior to E1), when radiometric tracking will be performed almost continuously. The NPs will transmit their data to Earth in real, or near-real, time since their distances from the main spacecraft diverge shortly after the data taking period ends and will exceed the prevailing link margin after E1 plus one hour.

3.4 Autonomy

LUGH's major manoeuvres, probe release and Encounters, are highly autonomous. Data taking is also handled autonomously aboard the NPs. The data transmission rate has been sized at 150% of the collection rate to ensure that all data will be captured. Because LUGH encounters Mercury near aphelion, solar noise is minimised during the downlink of data to Earth.

4. MISSION IMPLEMENTATION

4.1 The Spacecraft and Launch Vehicle

The design for the spacecraft and its systems (based on a concept study by *Curtis et al.* 1998) is not particularly challenging technologically since, as periapsis occurs at aphelion, the flyby is fast, and time spent at <0.5 AU is <40 days (See solar system trajectory in **Figure 5**). The payload instruments and NPs weigh ~60 kgs. The payload instruments and NPs weigh ~60 kgs. The total spacecraft weight will be ~500 kg. This makes the multi-platform package flyable on a Delta II 7925H, or on a Soyuz derivative with comparable performance.

4.2 Launch Trajectories

The nominal launch date for LUGH is December 2006 (Fiscal 2007). However, launch windows of ~2 weeks occur every 340 days (**Figure 3**). LUGH requires injection into a heliocentric transfer orbit to Mercury (travel time to E1 ~100 days). A few days after E1, an orbit correction manoeuvre is implemented to place the spacecraft in a Mercury-harmonic orbit (period 264 days). **Figure 5** shows the trajectory tracks for all 3 platforms during key mission phases. A post-separation checkout will be conducted prior to E1.

4.3 Operations during Launch, Cruise, Nanoprobe, Data Taking and Data Playback Modes

After launch injection, the spacecraft is initialised, the solar arrays deployed, and a sun-pointing orientation established. Detailed checkout of the spacecraft and instrument systems will then be performed, followed by a short Cruise to E1. During **Cruise**, the spacecraft remains pointed at the Sun and additional instrument calibration and background data collection performed. During **Nanoprobe Mode**, from E1-30 days to E1, the spacecraft is targeted toward Mercury's north pole, and the first NP released. The spacecraft is then re-targeted toward the south pole. The second NP is released at E1-20 days. The spacecraft then performs a final TCM to alter its course to traverse the planet's equator. The NPs communicate with the Earth stations directly. Since the Closest Approach (CA) of each probe to the planet's surface occurs after polar flyby, a 100-km minimum probe altitude at periapsis is planned. This will result in altitudes over the poles of ~300 km (n-pole) and 450 km (s-pole), well within acceptable limits. Seven days prior to E1, an Encounter Command Schedule is uploaded to the spacecraft and the science instruments checked-out. At E1-1 week, low-rate data collection (**Observatory Mode**) commences. During this phase, LUGH assumes a Mercury-pointing attitude and, thereafter, remains 'locked' onto the planet throughout E1. High rate data collection (**Global Coverage Mode**, and, for closest approach, **High Resolution Mode**) begins for the instruments 2 hours prior to CA. The 2 NPs each take data from 1 hour before until 1 hour after CA. Several days after E1, the spacecraft performs a major TCM to achieve the 264-day Mercury-harmonic orbit. Tracking is performed to verify the new trajectory. Science data can be stored in the onboard memory without restriction for the measurements. A rate of 50 kbps **(Data Playback Mode)** allows all 50 Gbits of E1 data to be downlinked in 30 days (8 hours/day), assuming a factor of 2 data volume increase with encoding, and a 2:1 lossless data compression. E2 occurs 364 days after launch (for the 2006 opportunity). Again the spacecraft is targeted over the equator. However, for several days prior to this encounter it passes behind the Sun. A further 50 Gbits of E2 data is downlinked within 30 days. The end of this transmission marks mission end.

5. PAYLOAD CLOSURE WITH MISSION OBJECTIVES

By providing bulk abundances of major elements, **XRS** will determine which model of solar system formation is most valid. **VNIS** will determine the abundances of Fe– and Ti bearing minerals. When data from **VNIS** and **XRS** are combined, a sophisticated interpretation of the petrology of major surface features can be made [*Clark and McFadden*, 2000]. Core formation, interior structure, and geochemical differentiation can be inferred from these measurements. **VNIS** will provide a global geological inventory, as well as insights into timing of major events. The simultaneous multi–point **MAG** data will allow non–unique, global, magnetic field determination with spherical harmonic coefficients through octupole, as well as determination of the radius of the dynamo. From **Gravity** measurements, a 10 to 100 time improvement in C20 and C22 (to 0.5 to 5% accuracy) will be possible [*Anderson et al*, 1988, 1996]. When these measurements are combined with available estimates of Mercury's physical libration and obliquity, direct measurement of Core–Mantle coupling [*Peale*, 1976, 1988] and estimates of crustal thickness should be possible. **UVS** will provide a comprehensive atmospheric survey and atmospheric species maps, from which, when combined with data from other instruments, atmospheric/surface/magnetosphere/solar wind interaction can be derived. **LEP** will provide a direct determination of solar wind particle composition. **EFI** will determine electron density and temperature. Ions created by charge exchange with magnetospheric and solar wind ions will excite low frequency hydromagnetic waves detectable by **MAG** as long–period fluctuations. High frequency ion acoustic and whistler mode waves will be observed by **SCA** and **EFI** [*Wu et al*, 1987], providing high time resolution measurements of particle distribution and magnetospheric dynamics. **ENA** will characterize the nature of substorm activity in a highly variable environment and, along with **LEP** and **EPS**, will determine the density and composition of ionized and neutral components. **EFI** and **SCA**, which measure EM waves will signal the high frequency waves of the bowshock. **EPA** will monitor the response of the magnetosphere to IP activity and the penetration of ions and electrons into the magnetosphere. Measurements of the IMF direction by **MAG** and of wave activity and of fluxes of backstreaming electrons by **LEP** and **EPS** will define the leading edge of the foreshock.

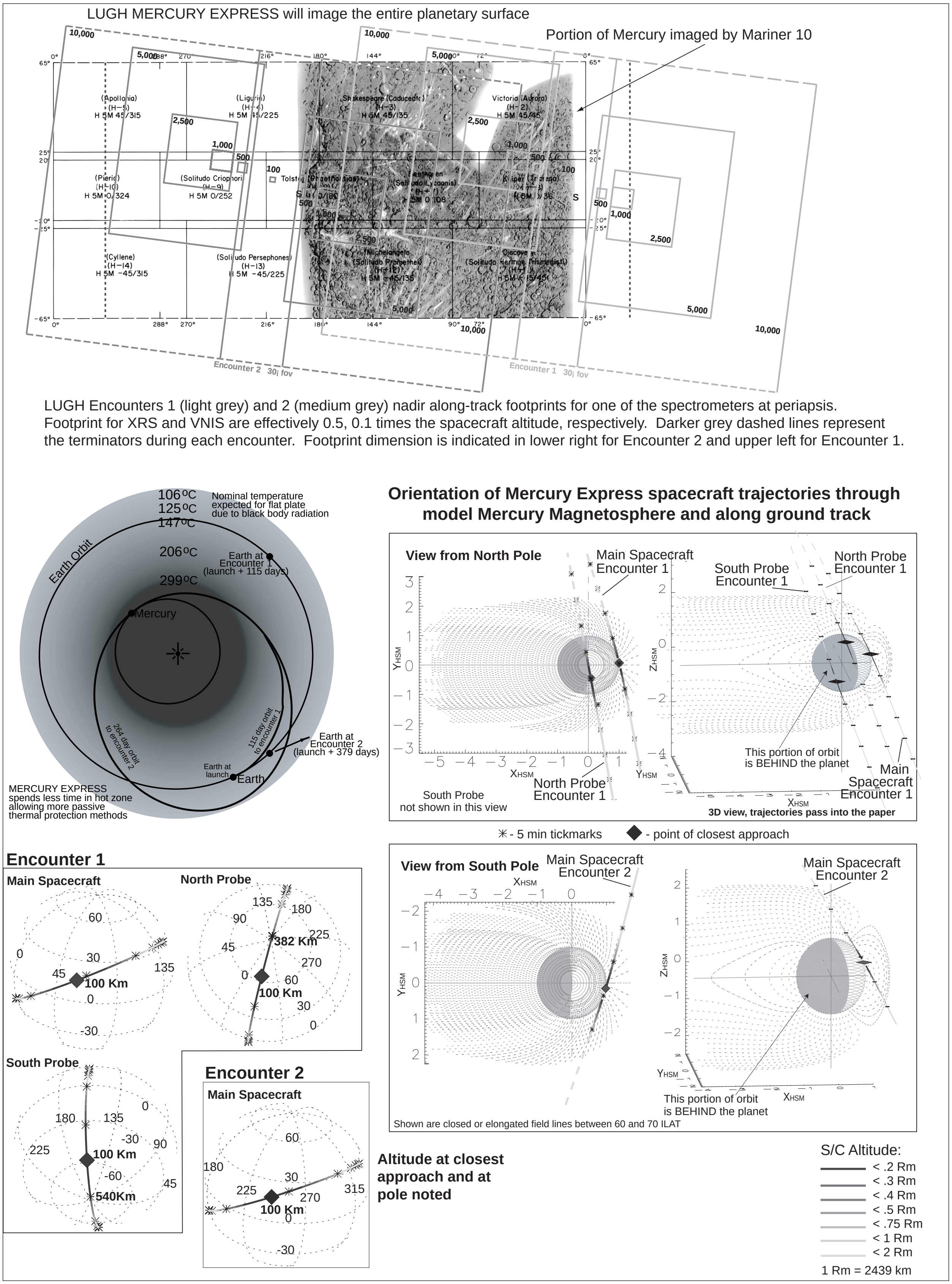

Figure 5: Trajectory Tracks for Overall Mission, Main Spacecraft, and Probes.