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Visibility analysis of Phobos to support a science and exploration platform

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Abstract

The surfaces of the Martian moons, Phobos and Deimos may offer a stable environment for long-term operation of platforms. We present a broad assessment of potential scientific investigations, as well as strategic and operational opportunities offered by long-term operation of an instrumented lander. Studies using observations of Mars' moons, and the detailed new findings expected from the JAXA Martian Moons eXploration (MMX) mission, International Mars Sample Return (MSR) Campaign and other upcoming Mars missions, provide a driver for feasibility and trade studies for follow-on missions that would build on the knowledge gain from those missions. We discuss the scientific questions and operational objectives that may be pertinent for landed platforms on the martian moons, including (1) monitoring and scientific investigations of Mars' surface and atmosphere, (2) scientific investigations of the martian moons, (3) monitoring and scientific investigations of the space environment, (4) data relay for Mars surface assets or interplanetary missions and 5) use in a Mars navigation/positioning system. We present results from visibility calculations performed using the SPICE observation geometry system for space science missions, and a Phobos shape model. We compute as a function of location on Phobos, visibility quantities that are most relevant to science and operational objectives. These include visibility from Phobos of the Sun, Earth, Mars surface and atmosphere, Deimos, and Jupiter. We also consider occultation events by the Mars atmosphere of Earth and Deimos that may provide opportunities for radio science. Calculations are performed for a study period spanning one Mars year in a hypothetical future operational scenario (1 Jan 2030–18 Nov 2031). We combine visibility metrics to identify locations on Phobos most suitable for long-term operation of a platform. We find the Mars-facing side of Phobos, and limited areas on the leading and trailing sides, satisfy the most requirements defined for Mars and Phobos science, space environment monitoring, and data relay/navigation. We demonstrate that compliance with requirements related to visibility of Mars and its atmosphere are not mutually exclusive with those that are better satisfied on Phobos' anti-Mars side, such as those aided by maximizing their cumulative view factor to the ecliptic plane (i.e. visibility to the Sun, Earth or outer solar system). Finally, our methodology allows to assess the extent to which combined visibility metrics can meet mission requirements. The process we describe can be used to support landing site identification and selection on planets, moons and small bodies.

Keywords: Phobos, Deimos, Mars, Platform, Visibility

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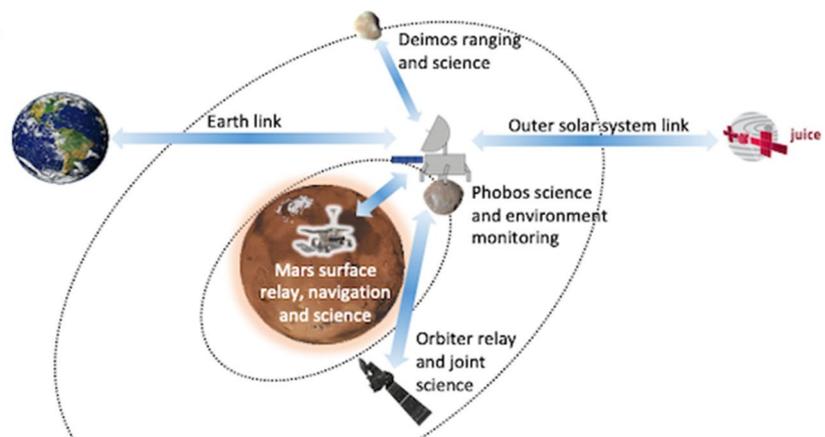
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Graphical Abstract

Visibility computations of Phobos' surface to support objectives in:

- > Science
- > Data relay
- > Navigation
- > Space environment monitoring
- > Future exploration
- > Public outreach



Introduction

Study of the martian moons has persisted since the first images of Phobos and Deimos by Mariner 9 in 1971 (Pollack et al. 1972) and despite enduring study of their characteristics for many decades, from their origin to the grooves on Phobos surface, major questions remain regarding our scientific understanding of the two moons. The dearth of paths to answer these questions has prompted significant lobby from the science community for study of the moons, leading to proposals to space agencies for missions. To address this clear scientific priority JAXA's Martian Moons eXploration (MMX) mission will characterise Phobos and Deimos and their environment in detail, and additionally will return a sample from Phobos (Usui et al. 2020) for analysis in terrestrial laboratories to help determine the moons' origin and answer other high priority questions in Mars and solar system science.

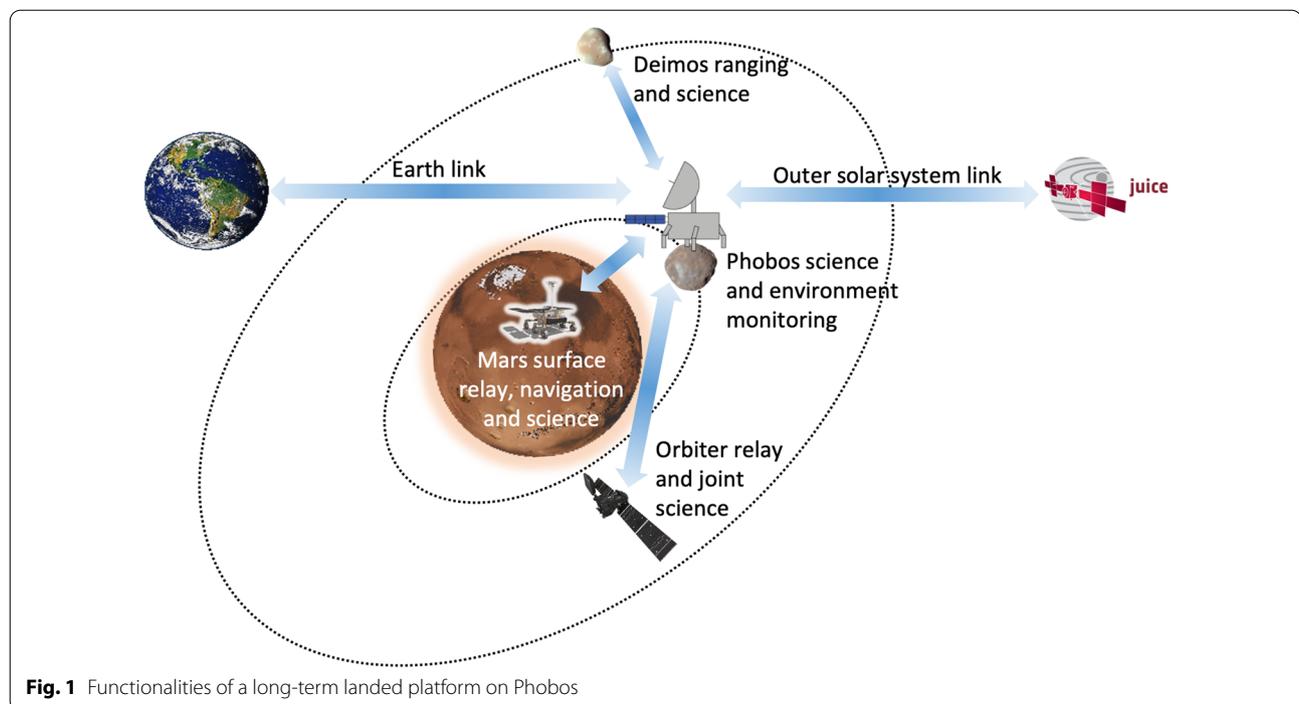
Phobos is in a circular equatorial orbit with mean Mars–surface distance of 5989 km. A platform landed in an optimal location on the surface could provide enduring service in the Mars system for key science and exploration (Fig. 1). Mission activities could include Scientific investigations of Phobos, Deimos and Mars surfaces, monitoring of the martian atmosphere (meteorology, aerosols and dust storms) and space environment (hazards, ionosphere and space weather), data relay for Mars and interplanetary missions (increasing overall bandwidth and reducing lost time during occultations), positioning information as part of a possible future navigation network, support to future human missions to Mars, and public outreach and engagement, for example, via daily images returned of Mars and its atmosphere from Phobos' surface. A landed platform would require no fuel or flight control for station-keeping or orbit changes,

increasing its propensity for a long and cost-effective operational lifetime. A suitable operational phase for such a mission could commence in the 2030s, following the successful completion of the MMX mission, and return of Phobos material to Earth in 2029.

Visibility calculations are an essential part of mission study and design, and can help assess the extent to which mission objectives can be met for different orbits, launch windows and landing sites. To identify and down-select suitable landing sites for a mission, visibility quantities, such as solar illumination, line of sight to ground stations, and observing opportunities to specific science targets (e.g. atmospheric limb, locations on planetary surfaces), may be evaluated and combined over a geographic area. The choice of quantities and their combinations depends on the particulars of the mission under study and various examples are published in the literature (e.g. Chadwick et al. 2005; Flahaut et al. 2020; Lemelin et al. 2021). We present an assessment of the potential scientific and operational application of a hypothetical platform based on visibility calculations on Phobos.

Science objectives and operations applications

A wide range of instrument types would add scientific value to a long-term landed platform on a martian moon. A mission study for such a platform would necessarily trade off the science potential with engineering, safety and programmatic factors, including mass, power, data, budget and science priorities. For justification and context to the visibility calculations we have performed, in this section we summarise selected opportunities for science and operations, and describe the associated instruments and mission elements required.



Building on MMX science results

The origin of the Mars moons remains a compelling question in Mars science. Characterisation by remote sensing instruments of their morphology (Duxbury 1978, 1991; Muinonen et al. 1991; Duxbury et al. 2014; Willner et al. 2014; Witasse et al. 2014), interior (Pätzold et al. 2014, 2016; Cicchetti et al. 2017; Le Maistre et al. 2019), spectral traits (Ksanfomality et al. 1991; Deutsch et al. 2018; Pajola et al. 2018) and dynamical modelling seeking to explain their orbital elements (Rosenblatt et al. 2016) have thus far have not yielded scientific consensus on their origin. The two leading hypotheses entail that they are either captured asteroids, or remnants of a debris disk generated by a giant impact on Mars (Craddock 2011; Rosenblatt 2011; Rosenblatt and Charnoz 2012).

The importance of this question has provoked advocacy for studies and missions with objectives to elucidate the Moons origins, with particular emphasis on sample return (Galeev et al. 1996; Murchie et al. 2014; Usui et al. 2020). The JAXA MMX mission seeks to resolve this uncertainty with in-situ characterisation using remote sensing instruments and analysis of material sampled from Phobos and returned to Earth.

The MMX spacecraft is scheduled to arrive in the Mars system in 2025. During 2026–2027 the mission schedule involves characterisation of Phobos, selection of a landing site for sampling, deployment of a rover (Ulamet et al. 2021) and Phobos sampling before departure from the Mars system in 2028 for return to Earth in 2029

(Campagnola et al. 2018). The potential for a Phobos platform mission to build on findings from the MMX mission can be described in two main areas.

Firstly, remote sensing observations: Prior to landing on the surface of Phobos, the platform's cruise/deployment stage would be expected to orbit at a low Phobos altitude during a proximity phase, during which remote sensing observations could provide further data to address outstanding questions about Phobos that remain or arise following MMX. This opportunity for observations using science payloads on the platforms' cruise/deployment stage could offer more coverage (spatial, spectral or temporal), use of next-generation instrumentation, larger resources (time, energy, payload mass, etc.) or different orbital characteristics (for example, to observe at specific emission or solar phase angles), to augment the science return from the MMX mission.

Secondly, observations or measurements to support analysis of returned Phobos samples: Following landing of the platform, payloads for in-situ sensing of local regolith, or sampling and analysis, could be operated to provide observations and measurements to support ongoing analysis of Phobos samples returned by MMX and that would be under analysis in terrestrial laboratories. Based on the outcome of MMX, remaining targets of interest that were not able to be sampled could be investigated further in situ. For example, the giant impact hypothesis for the martian moons implies the moons are composed of a mixture of impactor and martian materials (Hyodo

et al. 2015; Rosenblatt et al. 2016). If results from MMX prove this, then the sample mass returned may represent a disproportionate mix relative to the moon’s bulk fractions, and further in-situ analysis may aid to constrain proportions of the progenitors that make up the moon. This example is one of a range of in-situ analysis that could be assessed for their potential to further Phobos science following MMX.

Martian moon surface processes

The long-term operation of a platform on Phobos affords observations with high continuity and long temporal baselines that could be suitable for monitoring surface processes. For example, slow or rare changes in surface properties caused by regolith gardening, mass wasting (Shingareva and Kuzmin 2001) or space weathering (e.g. Nénon et al. 2021) could be observed. Albedo streaks on the slopes of crater rims may be the result of downslope movement and recent geological activity (Basilevsky et al. 2014). Material transport may also be influenced by impact-induced seismicity and thermal cycling. Long-term monitoring of these surface processes and their effects would inform study of surface processes on airless bodies.

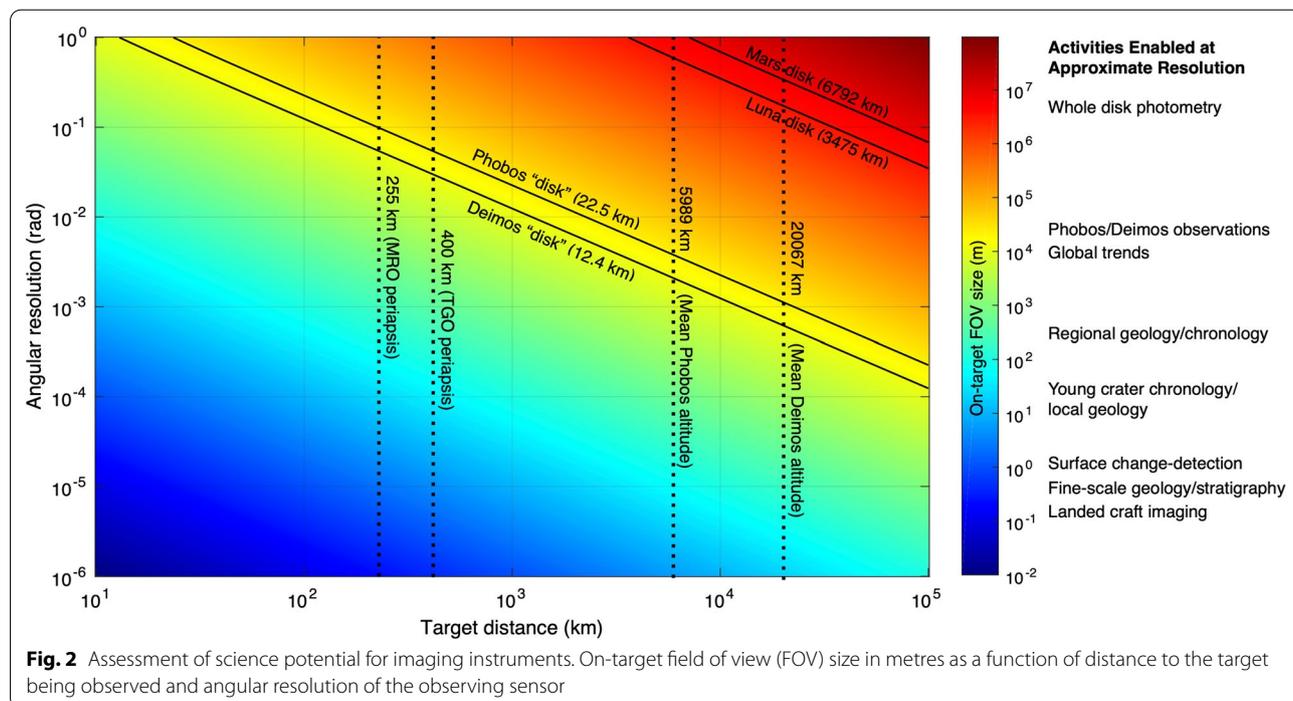
Geodesy and fundamental physics

Ranging capabilities on a landed platform could provide opportunities in geodesy and fundamental physics. Study of an active laser transponder presents a case for Phobos as a platform for measuring space curvature (Turyshev

et al. 2010). Such a system would allow direct measurement of Phobos libration, deformation, gravity field and interior structure. Study of measurement requirements for such a system (Dirkx et al. 2014) concluded that it could produce order of magnitude precision improvements in geodetic measurements of both Mars and Phobos. Radio science investigations make use of existing spacecraft communications systems, though to enable the needed precision, an ultra-stable oscillator (USO) is also typically required on board.

Remote sensing of the Mars atmosphere and surface

Instruments with the ability to spatially resolve features on surfaces or in atmospheres are typically designed and selected with traceability of their science objectives to their specifications and performance. A landed platform on the Mars-facing side of Phobos would provide a vantage point for instruments to observe both globally, studying the full martian disk for meteorology and climate, and at finer spatial scales for study of regional or local atmospheric phenomena and surface features. The angular resolution of an instrument is visualised in Fig. 2, in which we illustrate the types of scientific study enabled as a function of distance to the target and angular resolution of the observing sensor. Phobos’ mean orbital altitude above Mars provides a basis for a wide range of surface and atmospheric observations. Instrument spatial resolutions may be on the order of 10 s to 100 s of metres, sufficient for resolving most atmospheric phenomena, and local to regional-scale geology, though less suitable for



study of fine-detail surface characterisation afforded by high-resolution instruments aboard low-altitude orbiters, such as the High Resolution Imaging Science Experiment (HiRISE) aboard Mars Reconnaissance Orbiter, MRO (McEwen et al. 2007). However, fixed assets observing Mars from Phobos and Deimos could provide frequent, regular observations over long temporal baselines and therefore the potential science return is high for many observation types, e.g. context or survey observations in the visible to far-infrared. The temporal longevity of such an observing platform may be ideal for monitoring seasonal or longer baseline signals of surface change. We do not consider here the technology improvements expected with time, nor the engineering challenges and physical limits in relation to development of high spatial resolution instruments. These may enhance, or limit, science activities that are possible.

For atmospheric studies, Phobos offers a preferential position for a long-term monitoring of the Martian atmosphere on both Mars' dayside and nightside. Additionally, it could permit monitoring auroras (e.g. via UV instrument) and meteor flux (e.g. Christou et al. 2012) on the nightside. On the dayside, observations and retrieval of atmospheric conditions would provide data supporting study of climate and atmospheric processes, as well as monitoring of clouds or dust storms affecting surface missions.

Typical atmospheric parameters of interest include temperature, dust, CO₂ ice, H₂O vapour and ice, CO or CH₄. A summary of the wavelength ranges (from UV to mid-IR) that allow retrieval or detection of these parameters is summarised in Cardesín-Moinelo et al. (2021), with reference to the OMEGA, SPICAM and PFS spectrometers aboard Mars Express, and the NOMAD and ACS spectrometers aboard TGO.

Next-generation instruments may offer improved capabilities for retrievals from Phobos' altitude above Mars. The focus may be on long-term reliable survey and monitoring of atmospheric parameters, though application of cutting edge techniques, such as retrieval of wind speed profiles by measurement of Doppler shift of aerosol backscatter profiles (Cremons et al. 2020). Phobos' orbit would allow atmospheric retrievals at nadir in equatorial regions, with the emission angle of observations increasing with latitude, leading to opportunities for limb observations in polar regions.

A visible wavelength atmospheric imager would follow and build on the datasets provided by The Mars Color Imager (MARCI) aboard MRO (Malin et al. 2008) and the Visual Monitoring Camera aboard Mars Express (e.g. Sánchez-Lavega et al. 2018). Whole Mars-disk

observations would be common at Phobos' altitude, and could provide a basis for regular 'weather reports' and a compelling opportunity for public outreach (Ormston et al. 2011).

Radio occultation of the Martian atmosphere, and most pertinent to this technique—the ionosphere, could be performed between Earth and Phobos, between Phobos and Deimos (assuming a receiver or transmitter on Deimos), or between Phobos and Mars orbiters, to retrieve atmospheric and ionospheric properties. The approach has been successfully demonstrated between the Mars Express and ExoMars Trace Gas Orbiter (TGO) spacecraft (Nava et al. 2020, 2021; Cardesín-Moinelo et al. 2021).

Mars space environment monitoring

The equatorial orbits of Phobos and Deimos offer opportunities for monitoring the space environment and its interaction with the moons. Investigation of the martian magnetotail is of particular interest, since both moons cross the current sheet a few times per day, and Phobos' ~8 h orbital period permits frequent sampling of the martian bow shock, magnetosheath, magneto pileup boundary and terminator-nightside ionosphere current sheet. These are regions of special interest for important plasma processes, such as atmospheric escape, solar wind particle precipitation, solar wind interaction with the induced magnetosheath or crustal field reconnection with the solar wind (e.g. Halekas et al. 2016; Hall et al. 2016, 2019; DiBraccio et al. 2018; Sánchez-Cano et al. 2019). At the time of writing, there are no observations made from an equatorial orbit of these regions of the martian tail. The Indian Space Research Organisation's (ISRO) Mars Orbiter Mission, 'Mangalyaan', has an equatorial orbit, but it does not host sufficient plasma instrumentation. The moon's equatorial orbits around Mars provide an opportunity to investigate the horizontal extent of the martian tail for the first time, and in combination with measurements by polar orbiters. Investigations could focus on energetic particles, magnetic field strength, plasma properties and dynamics of space dust flux/micrometeorite impacts (Zakharov et al. 2014) on the moons. Long-term monitoring investigations of the surface environment could be conducted, for example, on surface charging and sputtering products in response to solar irradiance and solar wind cycles (Dubinin et al. 1991; Cipriani et al. 2011). Measurement of the solar wind at Mars would also provide value as an upstream monitor of space weather conditions to outer solar system spacecraft. Instrument types and investigations

could include plasma packages designed for ionospheric and magnetosheath regions (including atmospheric escape), solar wind and cosmic ray monitoring, seismometers, dust detectors or electric field sensors.

Data relay and navigation

A platform on Phobos could provide relay functionality for spacecraft telemetry and telecommands. Communication would be possible with assets on the surface of Mars, such as rovers, landers or future human missions. Communications capacity similar to or exceeding that of present orbiters (MRO, ExoMars TGO) could be desirable, and could use Ka, X and UHF bands. Data downlinks, e.g. ExoMars TGO, are on average on the order of 10Gib per day, though the link budget varies with Earth–Mars distance.

Relay of data from and to interplanetary spacecraft outside the Mars system, including in the outer solar system (for example ESA’s Jupiter Icy Moons Explorer, JUICE), would also be desirable. This would work to increase the data rates of individual hops and hence the aggregate bandwidth for downlink of science data. Time for mission operations usually lost due to solar conjunction could be regained by the presence of a relay in the Mars system. Risks to spacecraft operations could be reduced by the ability to check spacecraft health and navigation during solar conjunctions.

To fully understand the requirements and feasibility for a communications relay system on a landed Phobos

from orbital positioning systems, for which one or more elements could be provided by equipment on Phobos or Deimos.

Visibility analyses

To assess the potential science return and strategic value of this concept, we assert that a number of key lines of questioning should be pursued to fully elucidate any constraints that are inherent to the geometry of Phobos and Deimos’ shape and orbits. In this study we consider a landed platform on the surface of Phobos.

Method

Due to Phobos’ irregular shape an accurate representation of its topography is critical to providing meaningful visibility results. Shape models of Phobos were first derived using Mariner 9 TV camera images (Duxbury 1974; Turner 1978). Subsequent models with improved spatial resolution and accuracy were derived using Viking Orbiter camera images (Thomas 1989; Duxbury 1991; Simonelli et al. 1993). The availability of images from the High Resolution Stereo Camera (HRSC) and Super-Resolution Camera (SRC) aboard Mars Express has enabled further improvements still. We use the 100 m grid-spacing Digital Terrain Model (DTM) presented by Willner et al. (2014) (Fig. 3), derived using HRSC and Viking orbiter observations and superseding an earlier version of the model (Willner et al. 2010) by using additional HRSC observations. The DTM is published as a gridded

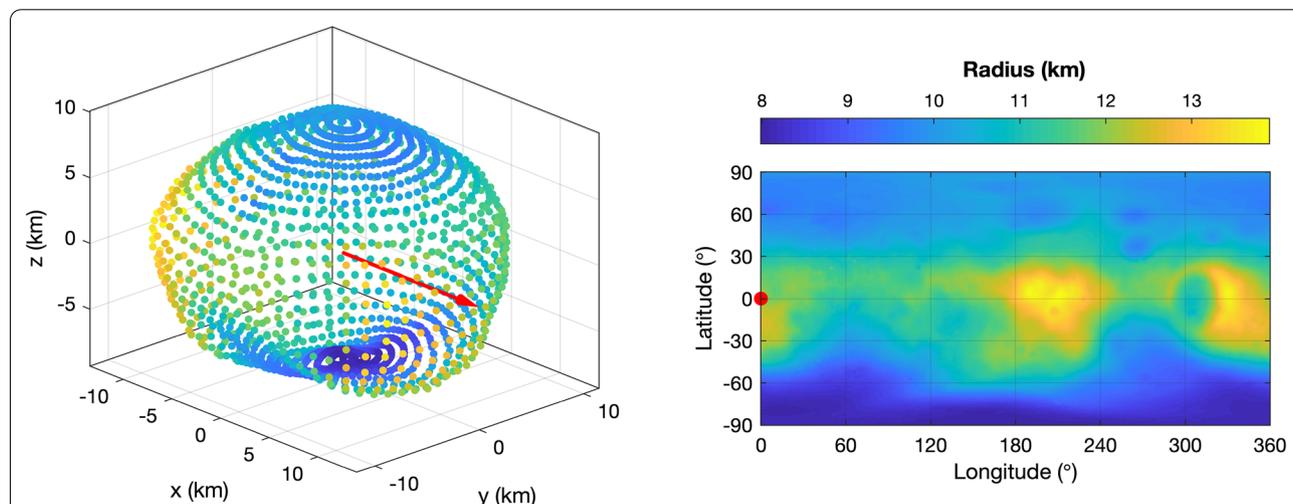


Fig. 3 Phobos DTM by Willner et al. (2014), as published at https://pds-geosciences.wustl.edu/mex/mex-msa-hrsc-5-refdr-phobos-maps-v1/mexhrs_5001/data/dtm/. Colour indicates the radius of Phobos as a function of location. The red arrow indicates the Mars-facing vector, parallel with the positive x axis. Left – Points on a 6° x 6° lat,lon grid sampling the DTM, at which visibility metrics are evaluated in this study. Right – Plate carée projection of the DTM. The Mars-facing vector, at lat=0°, lon=0° is marked by the red circle

platform, a study of the link architecture should be performed. Future Mars exploration may require or benefit

data record (GDR) on NASA’s Planetary Data System (PDS). In visibility calculations performed in this study,

the model is represented as a Digital Shape Kernel (DSK) and used together with SPICE, an observation geometry system for space science missions developed by NASA's Navigation and Ancillary Information Facility (NAIF) (Acton 1996). For computational frugality and ease of displaying global maps in Plate Carrée projection we sample the Phobos DSK onto a global grid of 6° latitude \times 6° longitude. In figures, data points are pixel-centred.

The DTM was constructed using images acquired during Mars Express flybys of Phobos (Witasse et al. 2014) using stereo photogrammetric and bundle adjustment techniques. The images used were acquired of different areas and at different observation geometries; hence, pixel scales of the input data range from 4 to 80 m/pixel. Willner et al. (2014) reported that the DTM's 100 m grid-spacing was selected as a suitable scale to represent the model that was derived, a conservative balance that does not unduly under- or oversample the stereo-reconstruction that was possible given the images available. Our choice of a $6^\circ \times 6^\circ$ grid spacing for visibility calculations, selected to reduce computation time, under-samples the DTM grid spacing by nearly a factor of ten—a 6° arc around Phobos' shortest radius (9.14 km) corresponds to ~ 957 m. Hence, we consider any uncertainties in the shape model, as represented by the residuals on fitting (see Willner et al. 2014), implies that our results likely have spatial uncertainties that are insignificant relative to the grid spacing, and that do not affect the main findings of our study.

For visibility calculations we use the *cspice_illumf* function to determine whether a surface point is visible from the observer. The Mars surface is modelled as the IAU Mars 2000 ellipsoid. We use the *cspice_occult* function to determine if Mars intersects the ray between each grid point on the Phobos surface and the observer under study. Mars is the only possible occulting body that is considered in this study.

We consider a time period covering a complete martian year relevant to an upcoming operational situation, Jan 01 2030–Nov 18 2031. This time period follows the MMX missions' detailed characterisation of Phobos and Deimos 2025–2028, and return to Earth of a sample from Phobos in mid-2029. Additionally, the JUICE mission's scheduled Jupiter orbit insertion in January 2030 supplies an example opportunity for outer solar system data relay. We use a time step of 30 min throughout the study period. For calculations of cumulative visibility, we consider visibility is true at time step t only if the visibility is true also for time step $t+1$. Therefore, our results are subject to time uncertainty of -29 m 59 s. That is, if an object is recorded as visible at time t , then it may have become visible any time in the last 29 m 59 s, and it is definitely visible for at least the next 30 m 00 s (time $t+1$).

Requirements

In order to assess the suitability of locations on Phobos' surface for a landed platform we identify objectives, based on our discussion of science and operational opportunities, and define specific requirements (Table 1) whose compliance may be tested with specific visibility calculations.

Results of visibility computations

Based on the objectives and requirements in Table 1, we present results of visibility calculations performed.

Phobos to Earth

The visibility of a point on Phobos' surface to the Earth depends on the location on Phobos, and the positions of Phobos and Mars in their respective orbits (accounting for seasons and solar conjunctions). Figure 4 shows the result of 2 calculations (i) the mean visibility per day as a function of location on Phobos over the study period (1 Jan 2030–18 Nov 2031) and (ii) the number of days for each location where visibility is ≥ 6 h, according to our data relay requirement shown in Table 1.

The equatorial anti-Mars region of Phobos meets our requirement and has the greatest visibility to Earth. Intuitively, locations in topographic depressions, such as impact craters, have lower visibility in general, caused by the local horizon reducing the view-factor to space.

Phobos to Mars

Visibility to the martian atmosphere and surface from tidally locked Phobos is inherently on the Mars-facing side. Nonetheless, Phobos' non-uniform shape requires quantification of Mars visibility as a function of location and over the study time period. We calculate the number of hours per day, averaged over the study period, for which Phobos sees the centre of Mars (Fig. 5).

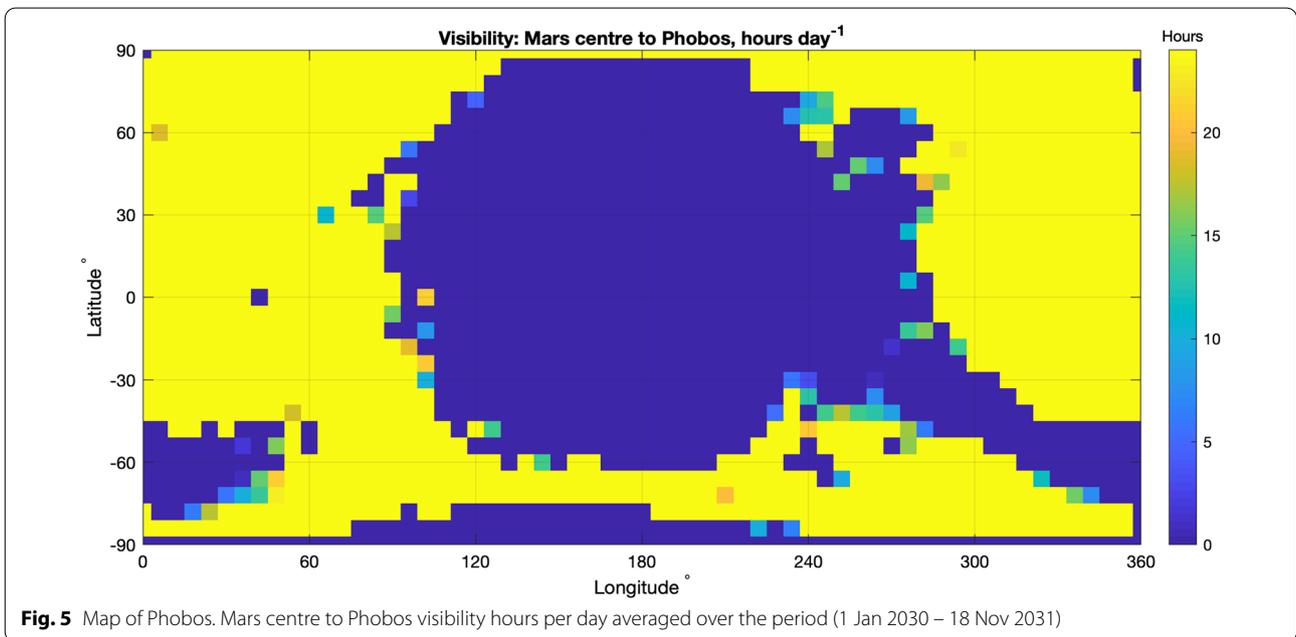
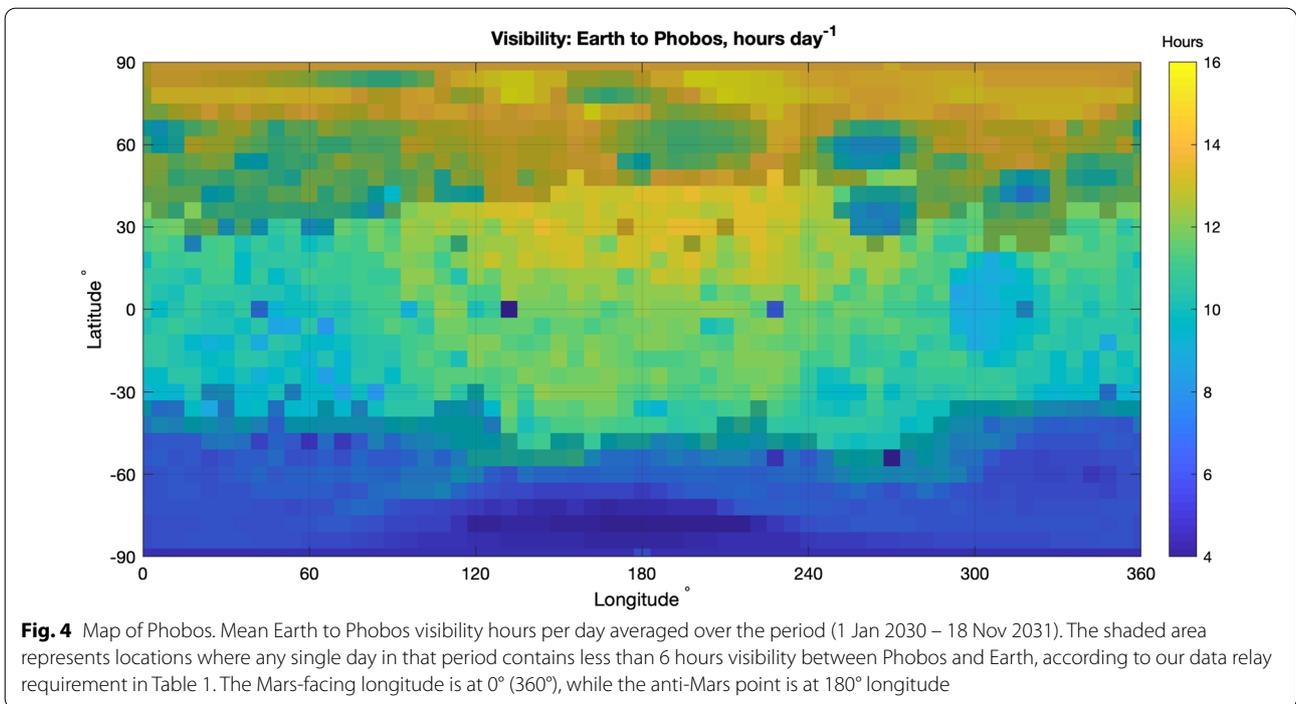
Note this is a simplistic case derived to indicate times when Mars is visible for observations, but that does not include time steps where part of the Mars disk or limb is visible, but the vector to the Mars body centre is occulted by Phobos.

The computation performed in Fig. 6 indicates when any of Mars is visible from Phobos, but we also compute the visibility to a specific point on the surface of Mars. This represents the location of a landed spacecraft or human presence requiring data relay or navigation services. As an example, and for simplicity, we select the approximate landing location of NASA's Mars Science Laboratory rover in Gale Crater (5.4°S , 137.8°E).

A similar spatial pattern is obtained for visibility to a fixed point on Mars as for any view of Mars centre, as

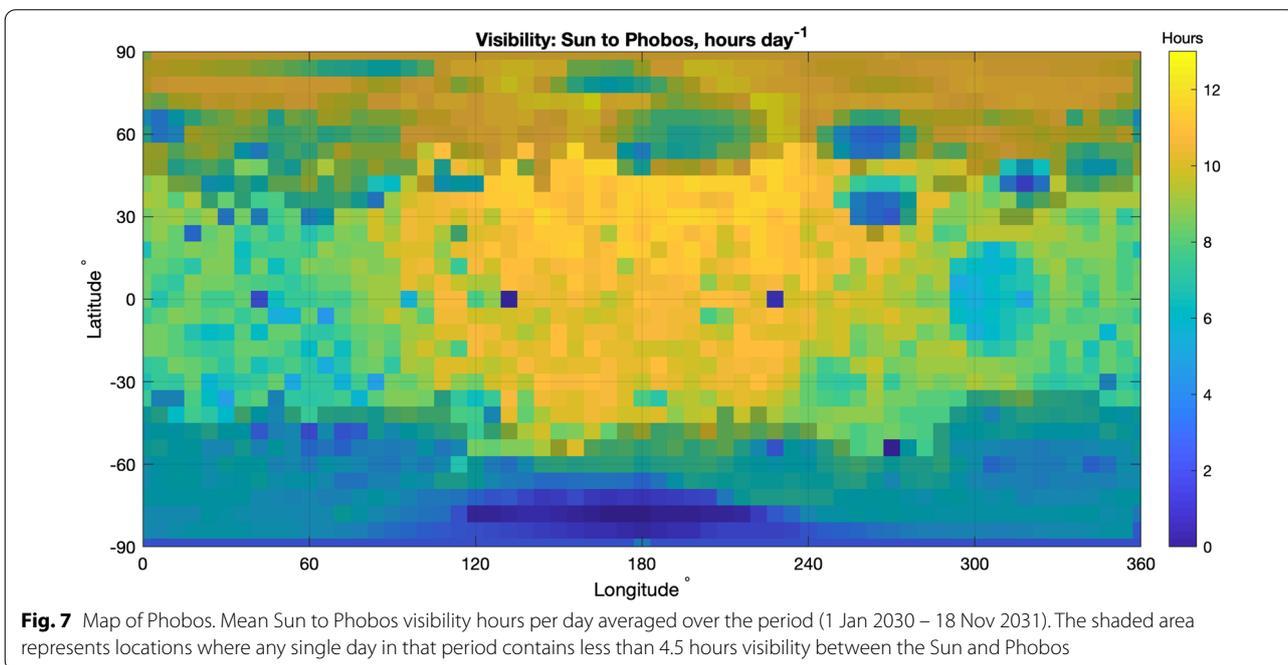
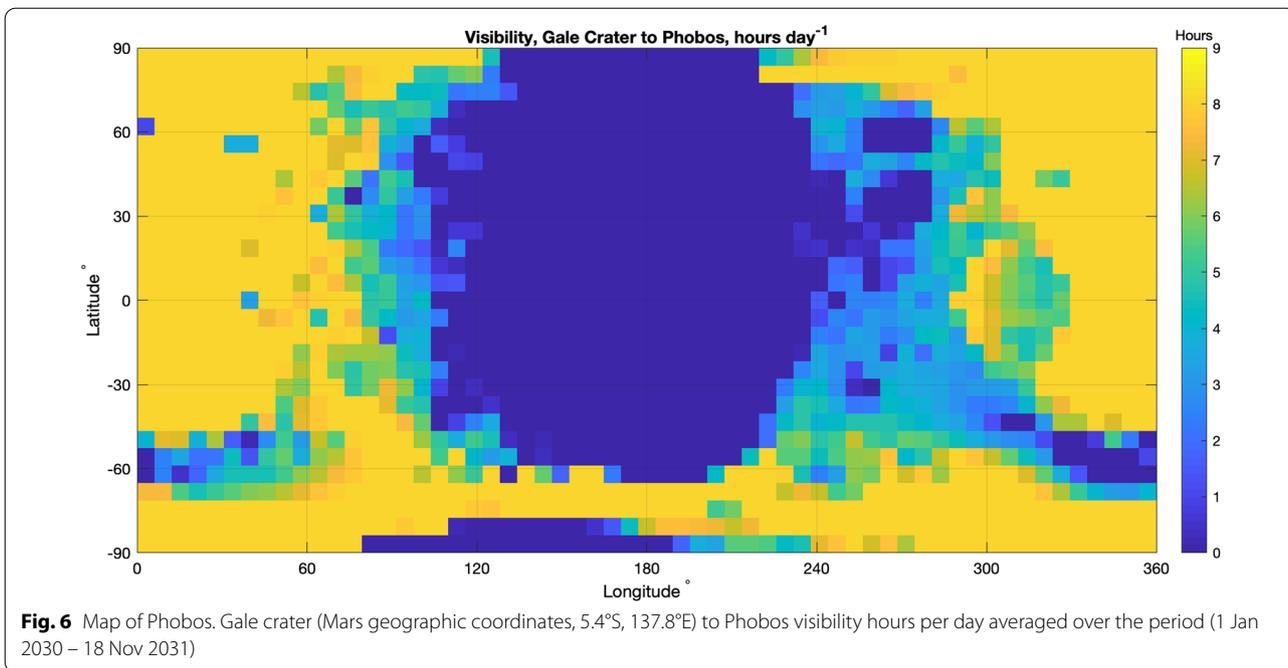
Table 1 Objectives and requirements for visibility calculations

Objective	Requirement	Justification	Data
Remote sensing of the Mars atmosphere and surface	Visibility of Mars > 0 min	Visibility of Mars dayside and nightside	No map required due to Phobos' tidal lock and equatorial orbit. All Mars local times are covered equally. Dayside and nightside are both observed ~ 3 h 50 min per orbit
Radio/ranging science: Geodesy, dynamics, gravity, fundamental physics	Visibility from Deimos during Mars occultation	If stations are located on both Phobos and Deimos, attenuation of a signal transmitted between the two captures information about Mars' atmosphere and ionosphere	Map of Phobos quantifying the number of occultation events showing locations where the line of sight to Deimos intersects Mars' surface
	Visibility from Deimos: ≥ 2 h per day	Both cases are mostly covered by the GPS requirement	Boolean map of Phobos true where visibility from Deimos is ≥ 2 h per day
	Visibility (laser ranging) from Earth ≥ 2 h per day		Boolean map of Phobos true where visibility from Earth is ≥ 2 h per day
Phobos in-situ science	No requirements	All locations on Phobos have science potential	-
Mars space environment monitoring	Visibility from Sun (solar wind) 2 h per day	Solar wind monitoring	Boolean map of Phobos true where solar visibility ≥ 2 h per day
Data relay	Visibility from Earth ≥ 6 h per day, except during solar superior conjunction	6 h is considered a basic requirement (including consideration of eclipses) for ESA planetary missions	Boolean map of Phobos true where Earth to Phobos visibility ≥ 6 h/day
	Visibility from Mars > 0 min	Link to surface rover for data downlink or telecommanding. As an example, we use the NASA Mars Science Laboratory landing site at Gale crater: 5.4°S, 137.8°E	Boolean map of Phobos true where a rover landing site to Phobos visibility > 0 min/day (accounting for a buffer in elevation of + 10° above horizon)
	Visibility from Jupiter: at least 3 h per day, during solar superior conjunction (Earth-Jupiter)	3 h per day is estimated to provide sufficient data volume for downlink of housekeeping data and uplink of telecommands from and to the JUICE spacecraft	Boolean map of Phobos true where Jupiter to Phobos visibility ≥ 3 h, there is a solar superior conjunction
Global Mars positioning system	Visibility from Deimos ≥ 2 h per day	For positioning, laser ranging, radio tracking	Boolean map of Phobos true where Deimos to Phobos visibility ≥ 2 h per day
	Visibility to Phobos from Mars and Deimos simultaneously	Concurrent visibility of Phobos and Deimos from the surface of Mars allows better positioning	Map of Mars showing hours per day where Phobos and Deimos are concurrently visible
Power (assuming solar power system)	Solar illumination should be ≥ 4.5 h per day	This time duration is estimated based on previous studies (ESA Concurrent Design Facility Study Report: Phobos Sample Return 2014)	Boolean map of Phobos true where visibility from Sun is ≥ 4.5 h per day
Public outreach	Visibility from Mars: once per day on the day-side of Mars	Public outreach 'Phobos-webcam'	Visualisation to demonstrate outreach potential



would be expected for a tidally-locked body. Aside from the obvious reduction from Figs. 5 to 6 in the time per day, due to the constraint on visibility to a fixed geographic location on Mars, the fringes of the visible areas on Phobos from Gale Crater are more spatially dispersed. This is attributed to the fact that a fixed and near-equatorial location on Mars is seen by Phobos’ leading, then trailing, sides as it passes over the location. Accordingly,

terrain on Phobos near its 90° and 270° longitude meridians, even if in the anti-Mars hemisphere, also has frequent visibility to fixed surface locations on Mars. We find that a platform on the Mars-facing side of Phobos would be able to observe a near-equatorial point on Mars’ surface for 8 h 7 m per day. For our example case of MSL, each orbital pass would permit a 3 h 33 m communication window.



Phobos to Sun

Insolation is critical for solar powered spacecraft. Visibility to the sun and solar wind presents science opportunities. For both factors, objectives and requirements are derived in Table 1. Our requirement of $\geq 4.5 \text{ h day}^{-1}$ of insolation is based on a previous study (ESA 2014) and does not consider any effects other than tracing a single ray. A mission study would

incorporate consideration of incidence angle, scattering and other effects influencing power generation capability of photo-voltaics. Similar to the data in Figs. 4, 7 shows the result of two calculations, (i) the mean visibility per day as a function of location on Phobos over the study period and (ii) the number of days for each location where solar visibility is $\geq 4.5 \text{ h}$.

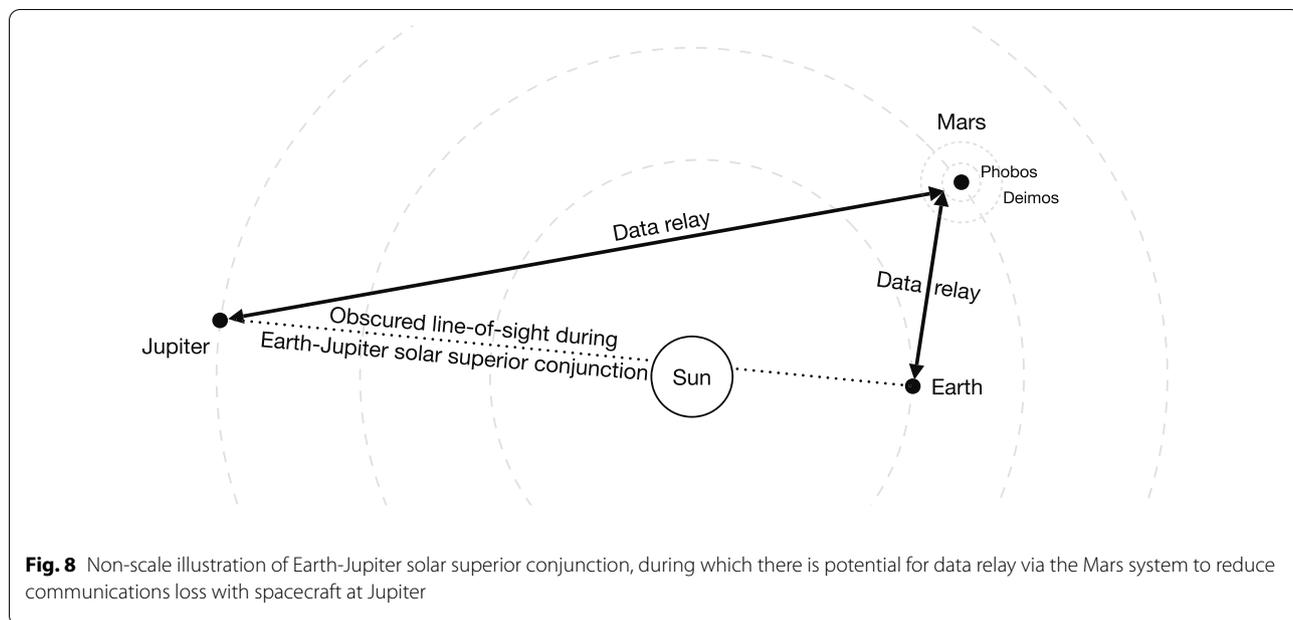


Fig. 8 Non-scale illustration of Earth-Jupiter solar superior conjunction, during which there is potential for data relay via the Mars system to reduce communications loss with spacecraft at Jupiter

Solar visibility over Phobos ranges from near-permanent shadow to 12 h day⁻¹ (Fig. 7). The anti-Mars hemisphere spends more time illuminated by the sun, because while everywhere on Phobos is shadowed from the sun every orbit, the sun is also occluded by Mars every orbit in Phobos’ Mars-facing hemisphere. A band of sub-equatorial latitudes -30° – 30° has ≥ 4.5 h solar illumination for each day in the study period.

Phobos to Jupiter

To demonstrate the potential of a Phobos platform to perform data relay for outer solar system spacecraft, we select the JUICE mission (Grasset et al. 2013) as an example. During the year 2030, JUICE will reach the Jovian system, which will experience a solar superior conjunction with Earth (Fig. 8) from 26 Nov 2030–4 Dec 2030, assuming corona radius 12 times larger than the solar

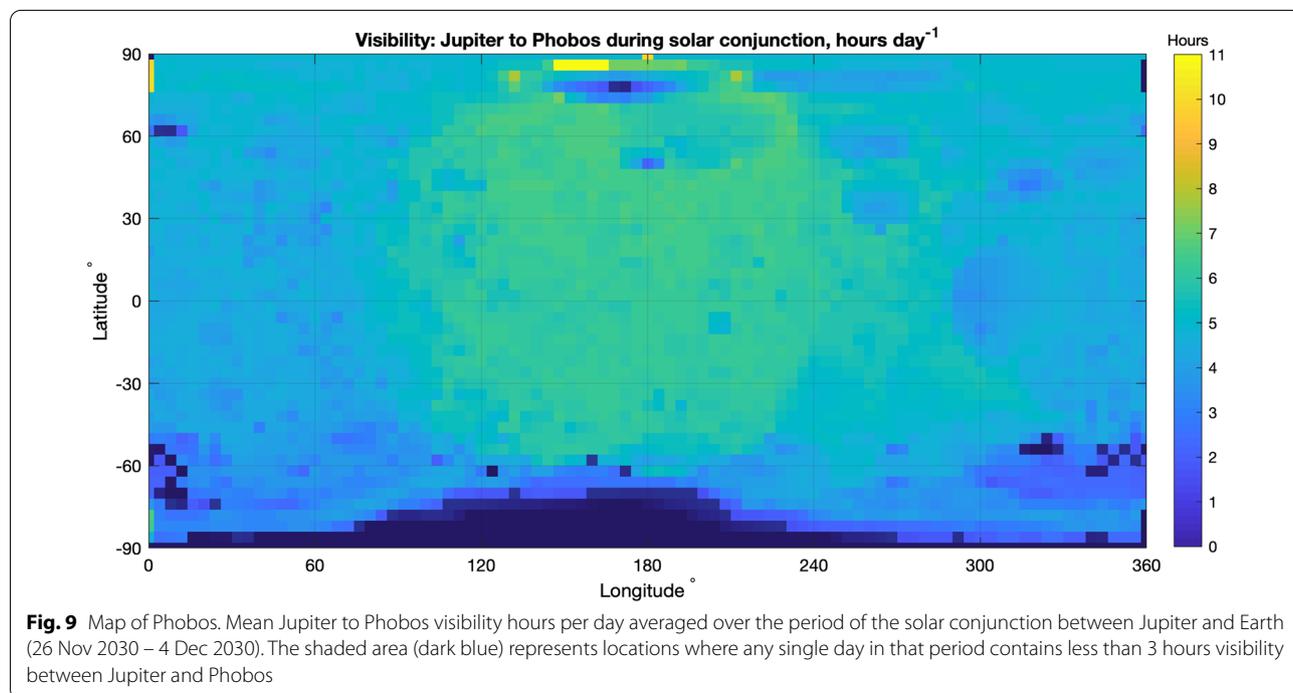


Fig. 9 Map of Phobos. Mean Jupiter to Phobos visibility hours per day averaged over the period of the solar conjunction between Jupiter and Earth (26 Nov 2030 – 4 Dec 2030). The shaded area (dark blue) represents locations where any single day in that period contains less than 3 hours visibility between Jupiter and Phobos

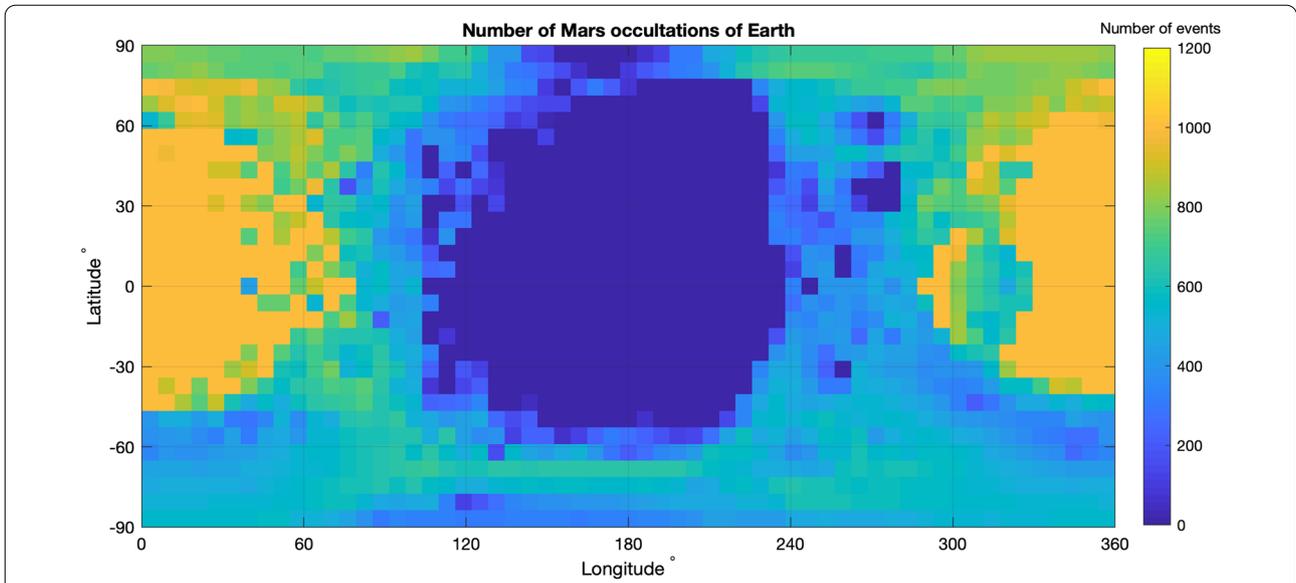


Fig. 10 Map of Phobos. Number of Mars occultations of Earth during the period 1 Jan 2030 – 18 Nov 2031

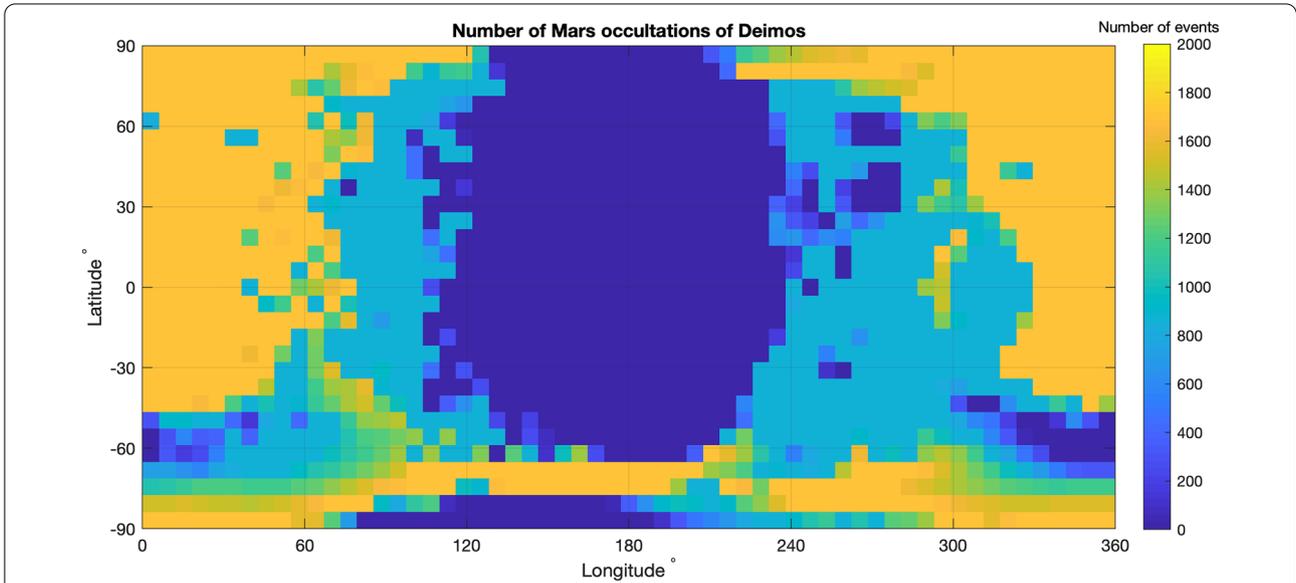


Fig. 11 Map of Phobos. Number of Mars occultations of Deimos during the period 1 Jan 2030 – 18 Nov 2031

photosphere (Srivastava et al. 2016). Thus, mission planning must normally account for a loss of communication with JUICE during the conjunction. We compute the visibility of Jupiter from Phobos during the conjunction to assess the opportunities for data relay (Fig. 9).

We find that almost all locations on Phobos exceed our minimum requirement of 3 h per day visibility to Jupiter (Table 1), estimated to provide sufficient link budget to JUICE at least for downlink of housekeeping data and

uplink of telecommands. A few crater interiors and the south polar region, in particular on the anti-Mars side, do not meet the requirement due to limited visibility of the ecliptic plane.

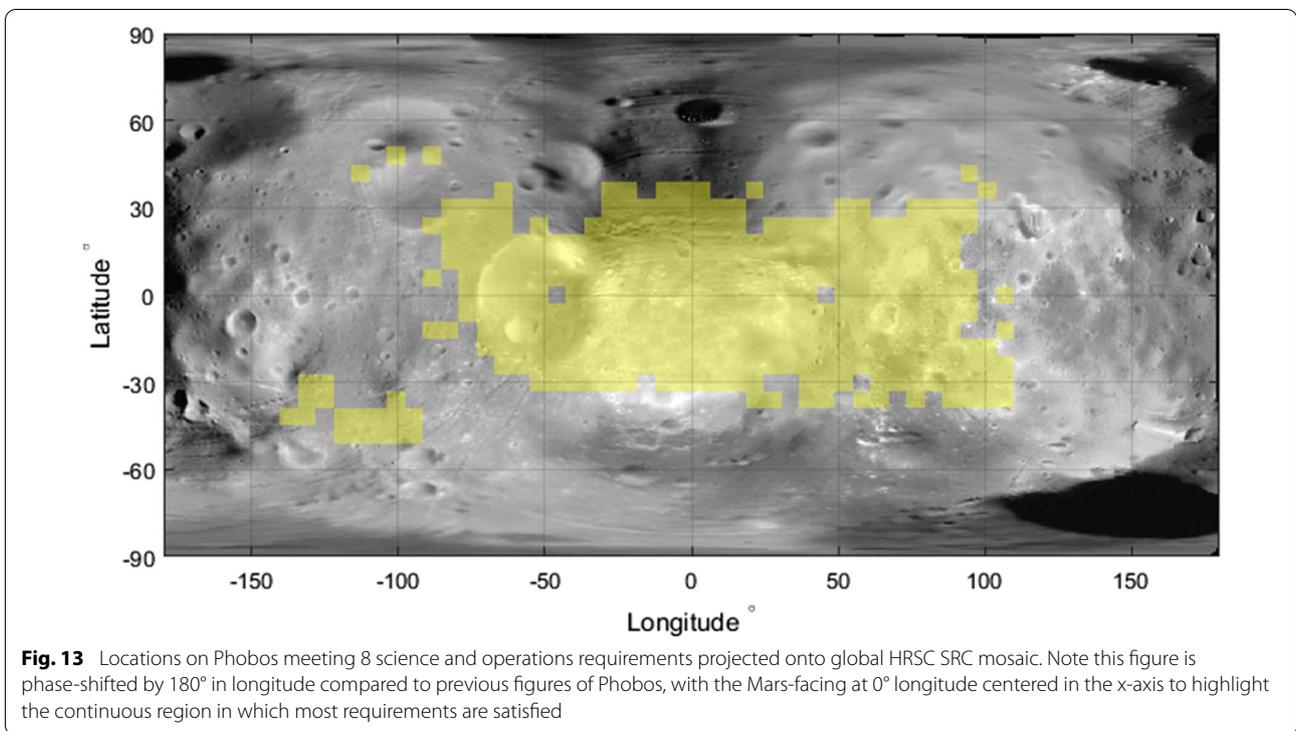
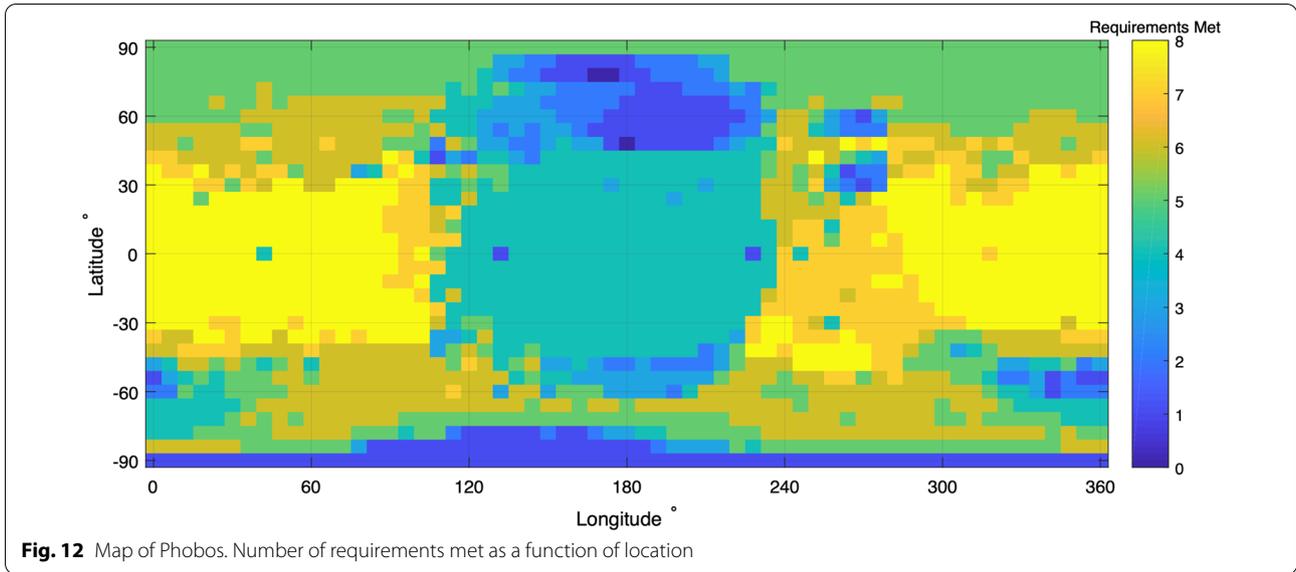
Mars atmosphere radio occultations

We assess the extent to which surface locations on Phobos provide opportunities for radio occultations by the

Mars atmosphere to retrieve properties, in particular of Mars' ionosphere. We compute for each location on Phobos the number of times in the study period that a ray from Earth drawn to the location is intercepted by the Mars limb, a proxy for the number of opportunities to observe radio occultations by the Mars atmosphere (Fig. 10).

Similarly, we consider the case where a receiver or transmitter is stationed on Deimos as well as Phobos

(Fig. 11). In this case, occultations of Deimos by the Mars limb are either preceded or followed by an opportunity for observing signal transmitted between the moons and attenuated by Mars' atmosphere. In this case, retrieval of properties is restricted to the line of sight between Phobos and Deimos, which aligns very closely with the Mars equator due to their equatorial orbits. Mars atmosphere/ionosphere occultations of Earth from Phobos would also be restricted in Mars surface latitude, but within a



seasonally cycling, sub-equatorial latitude range, governed principally by Mars' axial tilt.

In both cases, opportunities to perform occultation measurements of Mars' atmosphere are clearly highest on the Mars-facing side, though roughly half a number of opportunities also exist surrounding Phobos' leading and trailing meridians.

Discussion

The Phobos platform concept predicates accomplishing multiple science and operations objectives from a single location on Phobos' surface. Via computation of visibility quantities over a time period relevant to a conceptual operational environment, we demonstrate the extent to which locations on Phobos meet requirements devised for the objectives we have identified in Table 1. We select the following eight quantities and requirements to combine for assessment of landing site preference: (1) visibility to Earth ≥ 6 h day⁻¹, (2) visibility to Mars > 0 h day⁻¹, (3) visibility to Deimos ≥ 2 h day⁻¹, (4) visibility to Gale Crater (an example of a fixed location on Mars with a landed mission) > 0 h day⁻¹, (5) visibility to Sun ≥ 4.5 h day⁻¹, (6) visibility to Jupiter ≥ 3 h day⁻¹, (7) radio occultation events with Earth > 0 and (8) radio occultation events with Deimos > 0 . Figure 12 illustrates the number of requirements met as a function of location. We project a map of fully compliant grid points on the global image mosaic produced using HRSC images (Willner et al. 2008) (Fig. 13, note that in this figure the Mars-facing meridian is centred, at 0° longitude).

The largest number of requirements is met in a region on the Mars-facing side spanning approximately $\pm 30^\circ$ latitude of the equator, and $\pm 100^\circ$ longitude of Phobos' sub-Mars meridian. Notably, several smaller regions also comply that are at higher latitudes (30–50° N/S) and further west. Those in the northern hemisphere appear positioned on a crater rim, increasing their overall view factor to space. A more extensive area of higher visibility is centred around 40°S and spans 230–270° longitude.

We acknowledge several areas in which future studies could advance from this work. Firstly, our spatial sampling of the Phobos shape model was designed to keep computation time manageable for calculations over the study period. The geographic grid (6° × 6° in latitude and longitude) does not provide equidistant spacing, and under-samples the information contained in the Phobos shape model. Grid points spaced 6° around the equator of a roughly Phobos-sized (22.5 km) spherical body would be separated by ~1.2 km, while those at 80° latitude would be spaced closer to ~200 m. Future studies could use more uniform spatial sampling, and at a resolution equivalent to the shape model data (~100 m) in order to

better quantify effects on visibility of local topographic features.

Secondly, while the DTM used (Willner et al. 2014) provides an excellent topographic basis for visibility calculations, given the historical progressive improvements to DTMs (see Sect. "Method"), future studies using this technique would benefit from using the most high spatial resolution and accurate DTM available at the time, e.g. using HiRISE images (McEwen et al. 2007), in order that fine topographic features that may be critical to the safety and operation of landed missions are fully resolved at spacecraft-relevant spatial scales. In addition, given that Jupiter, Mars, Deimos, Phobos, Earth and Sun position data in this study are produced using SPICE, we acknowledge that the outcome of visibility calculations depends on the ephemerides used, which may be subject to change in future releases of SPICE's Spacecraft and Planet Kernels (SPKs). However, we do not expect future updates of ephemerides to significantly affect our results because orbits are already well-quantified over the period in study, and because our results concern cumulative statistics, rather than individual events, so are only minorly sensitive to small changes in orbit parameters that may occur in the future.

Thirdly, our study does not consider surface attributes that are pertinent to landing safety and operations, such as regolith properties or features contributing to short-baseline roughness (boulders, slopes). Mission studies would necessarily take these into account.

Finally, our choice of study period was to evaluate metrics in a time period pertinent to potential platform objectives, in 2030–31, when follow-on Phobos science may build on analyses of samples returned by MMX in 2029, when the JUICE spacecraft would benefit from data relay during an Earth–Jupiter solar conjunction and when infrastructure for Mars science and exploration may be in consideration for support of future human activities at Mars. Naturally, any future studies focusing on specific mission opportunities for a landed platform on Phobos would use timings specific to the mission opportunity under study.

Conclusions

Using a shape model of Phobos, by performing visibility calculations in a relevant time period, we have assessed the extent to which locations on the surface of Phobos meet science and operations requirements identified for a long-term surface platform. We find that the Mars-facing side of Phobos permits mutual satisfaction of requirements that we have defined for Mars and Phobos science, space environment monitoring and data relay/navigation.

Several areas on the leading and trailing edges of tidally-locked Phobos also comply completely with our requirements. Intuitively, terrain with high relative elevation compared to the Phobos mean provides a higher view factor with respect to a larger number of visibility metrics, compared to terrain that is shielded by local horizon, such as crater interiors. Future studies of the suitability of the martian moons for landed science, exploration and data relay/navigation support will build on the knowledge gained from current and upcoming missions. Specifically, the JAXA-conceived and led Martian Moons eXploration mission is expected to provide detailed characterisation of Phobos and Deimos, and profound results on their nature and origin, providing a path for establishing new science and exploration objectives for future missions.

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Authors' contributions

GT developed code and ran visibility calculations with supervision by OW and ES-N, and prepared a report on findings. Inputs on plasma science were provided by BS-C, Mars science and spacecraft science operations inputs by AC-M, and space environment and spacecraft operations by DK. ES-N adapted and created figures, and prepared the manuscript with inputs from all co-authors. All authors read and approved the final manuscript.

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Availability of data and materials

Code and data for visibility calculations are available in the following repository: <https://github.com/elliotsn/phobos-platform-visibility-study-2021/>.

Declarations

Competing interests

The authors are aware of no competing interests for this manuscript.

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