

Multiple Instrument Distributed Aperture Sensor (MIDAS) For Remote Sensing

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ABSTRACT

An innovative approach that enables greatly increased return from earth and planetary science remote sensing missions is described. Our concept, called Multiple Instrument Distributed Aperture Sensor (MIDAS), provides a large-aperture, wide-field, diffraction-limited telescope at a fraction of the cost, mass and volume of conventional space telescopes, by integrating advanced optical interferometry technologies. All optical assemblies are integrated into MIDAS as the primary remote sensing science payload, thereby reducing the cost, resources, complexity, integration and risks of a set of back-end science instruments (SI's) tailored to a specific mission, such as advanced SI's now in development for earth and planetary remote sensing missions. MIDAS interfaces to multiple SI's for redundancy and to enable synchronized concurrent science investigations, such as with multiple highly sensitive spectrometers. Passive imaging modes with MIDAS enable remote sensing at diffraction-limited resolution sequentially by each science instrument, as well as in somewhat lower resolution by multiple science instruments acting concurrently on the image, such as in different wavebands. Our MIDAS concept inherently provides nanometer-resolution hyperspectral passive imaging without the need for any moving parts in the science instruments. In its active remote sensing modes using an integrated laser source, MIDAS enables LIDAR, vibrometry, illumination, various active laser spectroscopies such as ablative, breakdown or time-resolved spectroscopy. The MIDAS optical design also provides high-resolution imaging for long dwell times at high altitudes, thereby enabling real-time, wide-area remote sensing of dynamic changes in planet surface processes.

Keywords: Remote Sensing Space Science, Distributed Aperture Imaging Telescopes

INTRODUCTION

The design concept and key features of an innovative and revolutionary approach to remote sensing imaging systems, aimed at increasing the return on future planetary science missions many fold, are described. Our Multiple Instrument Distributed

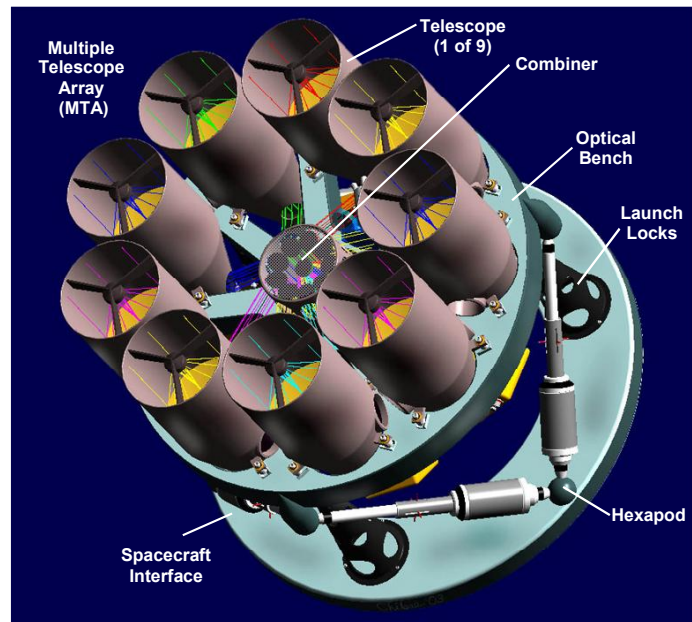


Figure 1 MIDAS Concept

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Aperture Sensor (MIDAS) concept, shown in Figure 1, provides a large-aperture, wide-field, diffraction-limited telescope at a fraction of the cost, mass and volume of conventional telescopes, by integrating patented¹ optical interferometry technologies into a mature multiple aperture array concept that addresses one of the highest needs for advancing future planetary science remote sensing². MIDAS acts as a single front-end remote sensing science payload for common missions, reducing the cost, resources, complexity, and risks of a set of back-end science instruments (SIs) tailored to each specific mission. By interfacing to multiple science instruments, MIDAS enables either sequential or concurrent SI operations in all functional modes. Passive imaging modes with MIDAS enable remote sensing at diffraction-limited resolution sequentially by each SI, as well as at somewhat lower resolution by multiple SIs acting concurrently on the image, such as in different wavebands. MIDAS inherently provides nanometer resolution hyperspectral passive imaging without the need for any moving parts in the SI's. The optical design features high-resolution imaging for long dwell times at high altitudes, <1m GSD from 5000km extent of spiral orbits on the Jupiter Icy Moons Orbiter (JIMO) mission, thereby enabling regional remote sensing of dynamic planet processes, as well as ultra-high resolution imaging at <2cm GSD from the 100km science orbits, enabling remote sensing searches for life sign processes. For NASA's new class of Nuclear Electric Propulsion (NEP) missions, such as JIMO, MIDAS taps the extensive NEP-enable power allocation for science with its active remote sensing modes, using an integrated solid-state laser source, to enable LIDAR, vibrometry, surface illumination, and active or ablative spectroscopy science investigations, integrated with the collection of back-end SI's, as well as optical laser comm for science data return.

DESCRIPTION

1. Overall Description

The MIDAS payload architecture is shown in Figure 2. The MIDAS Science Payload Element is comprised of a Multiple Telescope Array (MTA), a collection of back-end SI's, and a common Command & Data Handling (C&DH) subsystem. The MTA is comprised of its core Mechanical, Optical and Laser subsystems supported by a Pointing Control Subsystem (PCS), Thermal Control Subsystem (TCS) and Electrical Power System (EPS).

The MIDAS concept³ in general, as shown in Figure 3, uses an array of collector telescopes together with relay optics, a combiner, and a set of back-end SI's to form an advanced remote sensing system. The 1.5m MIDAS point design uses nine 35 cm aperture telescopes arranged in a circular sparse array having a 50% fill factor to form a synthetic aperture

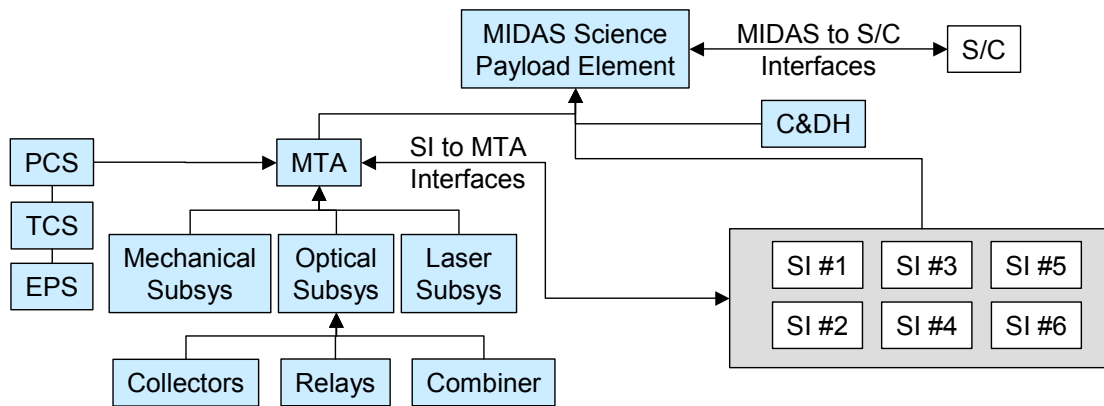


Figure 2 MIDAS Payload Architecture

of 1.5 m that is packaged within a compact payload volume of only 1.6 m diameter by 1.5 m long. A circular optical bench provides a stable reference for the optical subsystem and back-end SI's. When MIDAS is operational the optical bench is supported and pointed by hexapods mounted from the spacecraft interface plate. These hexapods stow the MIDAS payload element against launch locks to provide increased support and rigidity.

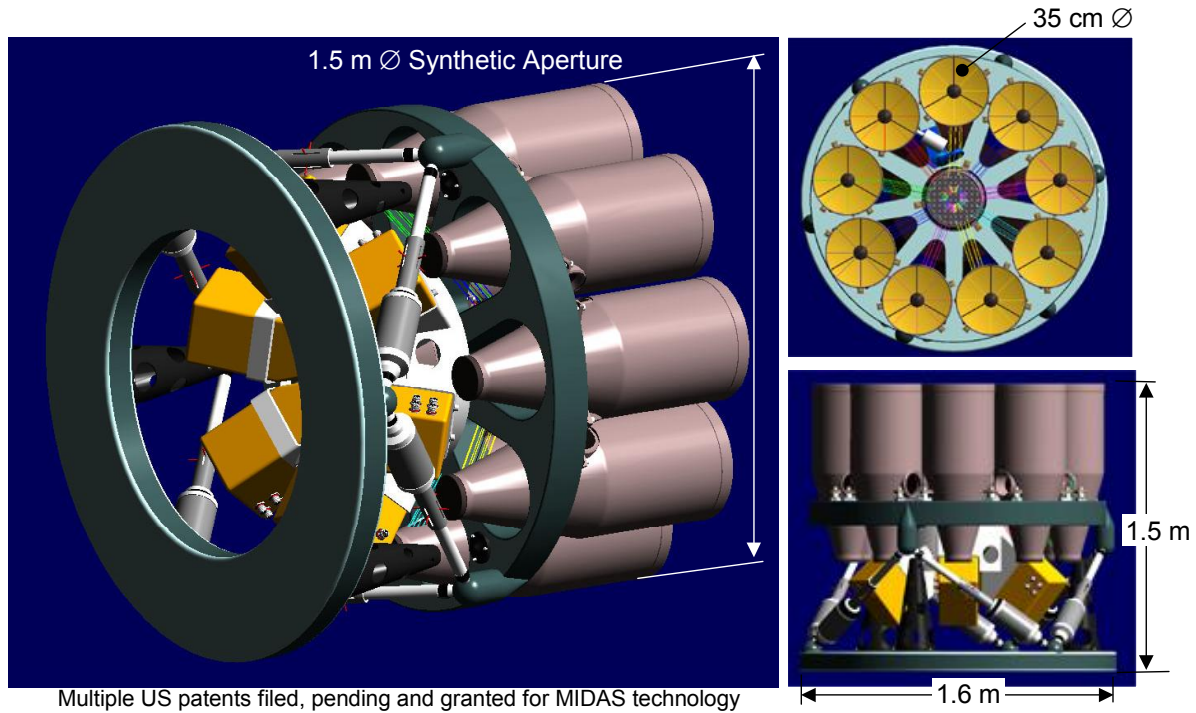


Figure 3 MIDAS Overall Design Concept

2. Mechanical Subsystem Summary

The MIDAS mechanical subsystem integrates the optical, laser and support subsystems. A thermally stable graphite-cyanate circular optical bench meters the telescopes, supports the beam combiner, and interfaces to each of the six back-end science instruments. The optical bench is pointed with respect to the spacecraft via a hexapod assembly, made up of six linearly actuated struts, allowing a ± 15 degree tip/tilt of the entire MTA relative to the spacecraft. The hexapod is also used to stow the MTA onto three launch locks to increase structural rigidity and integrity when desired, such as under launch load conditions. An interface plate mounts to the ends of the hexapod, making for a clean spacecraft interface. All payload electrical harnessing connectors are located on this spacecraft interface plate.

3. Optical Subsystem Summary

The MIDAS concept further advances multiple telescope array optical systems. As shown in Figure 4, the 1.5m MIDAS optical design uses a series of individual afocal collector telescopes, followed by a relay section with fixed and active plano mirrors (all located in nominally collimated light), and finally a central combiner telescope to merge the light from all apertures into a single phased image. The degree of aberration correction demanded for a distributed telescope array to form an extended field image with proper phasing has been well investigated^{4,5,6,7}. The MIDAS optical design has a number of unique features that provide significant benefits to planetary science remote sensing. It has a large optical Field-Of-View (FOR) that is well corrected and it is capable of steering the detector's field of view (FOV) over this FOR with internal steering optics. MIDAS can also be used as a very high resolution imaging Fourier transform spectrometer^{8,9}, as it has internal pathlength control over each of its individual collector apertures.

MIDAS Optical Characteristics	
Diameter ⁽¹⁾	1.5 m
Fill factor ⁽¹⁾	50%
EFL & F/no.	39.1 m, f/26
Length ⁽²⁾	0.8 m

Notes

1. Based on circumscribed aperture
2. Collector secondary to combiner tertiary

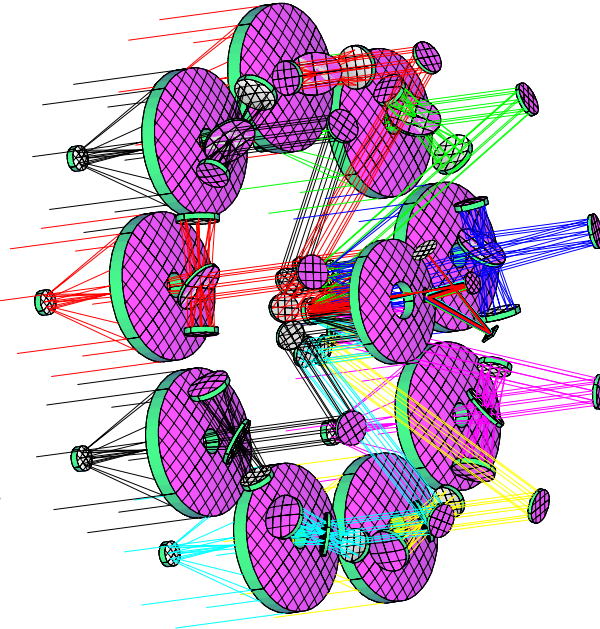


Figure 4 MIDAS Optical Design

4. Laser Subsystem Summary

The MIDAS laser subsystem provides integral solid-state laser assemblies that can be used in planetary science missions to provide varying degrees of active remote sensing. These capabilities range from broad area illumination at one or more specific wavelengths of interest, such as for remote Raman spectroscopy or enhanced stereo imaging, to ablation of small target areas on the planet surface, such as for ablative spectroscopy by the MIDAS back-end science instruments. The laser subsystem enables the MIDAS array to illuminate portions of the planet surface for active imaging. The laser subsystem also enables using active remote sensing techniques to probe the geomechanic characteristics and behavior of the planet surface and its processes. MIDAS enabled LIDAR can significantly enhance the surface coverage and accuracy of topographic measurements by means of the large effective aperture and collecting area of the array. MIDAS enabled vibrometry similarly offers the possibility of active remote sensing of dynamic planet processes, such as the fluctuation of the planet surface due to tidal forces, by enabling not only high resolution topography but doing so from high altitudes with large dwell times and repeatedly over the course of years of spiral orbits on a mission like JIMO.

5. Pointing & Control Subsystem Summary

The MIDAS pointing & control subsystem (PCS) is comprised of a hexapod architecture scan platform consisting of six actuated struts. Each strut contains a linear actuator with sufficient travel to allow the MTA an overall 15° FOR. The actuator contains a preloaded, recirculating ball nut device utilizing either a low outgassing liquid or solid lubricant. The actuator motor can be of the DC variety with an integral brake or stepper drive. The actuator is located between graphite cyanate composite structural tubes. At the ends of each strut are flexured fittings used to reduce motion deadband. One significant advantage of using a hexapod architecture is that it provides six degree-of-freedom motion of the base with graceful degradation should any of the actuators fail. In this application the hexapod scan platform is required only to provide overall tip and tilt control of the MTA, and its six available degrees of freedom are thus very redundant. Any one failed actuator does not degrade pointing capability of the MTA at all, because the other five struts fully enable tip and tilt control of the MTA through its entire FOR. Additional strut failures begin to limit the range of MTA tip and tilt motions, to a degree that depends on which of the multiple actuators fail.

The hexapod assembly drives the MTA to be supported on three launch locks in the stowed configuration. This allows the hexapod to be free of the additional requirement of supporting the MTA through severe environments, such as for the rigors of the launch environment. By doing this, the hexapod assembly can be made lighter while the stowed MTA can be made more compact, stiffer and stronger for severe environments. The launch lock supports are manufactured out of graphite cyanate composite and bolted directly to the spacecraft interface plate. The redundant launch locks can be any of the standard types: paired squib pin pullers, nut separators or shockless paraffin actuators.

6. Science Instruments

The 1.5m MIDAS concept design accommodates up to six back-end science instruments, as shown in Figure 5, that can each sense and interrogate the optical image provided by the MTA. The science instruments are individually, and if need be also collectively, enclosed in one or more shields for enhanced detector cooling and, when necessary, for radiation protection. These science instruments can be configured unique to the remote sensing needs of a specific science mission, while using the same MTA and pointing platform hardware that is common to a range of planetary science missions, providing a balance between maximizing science return on specific missions like JIMO while minimizing nonrecurring development and qualification costs for a collection of missions, such as for the Prometheus project.

The back-end SI's occupy a volume dictated by a constraint on minimizing the overall science payload volume, consistent with current JIMO resource allocations. For somewhat larger science payload volume allocations, the individual SI's can readily extend aft much further, with an associated increase in the spacecraft interface ring diameter.

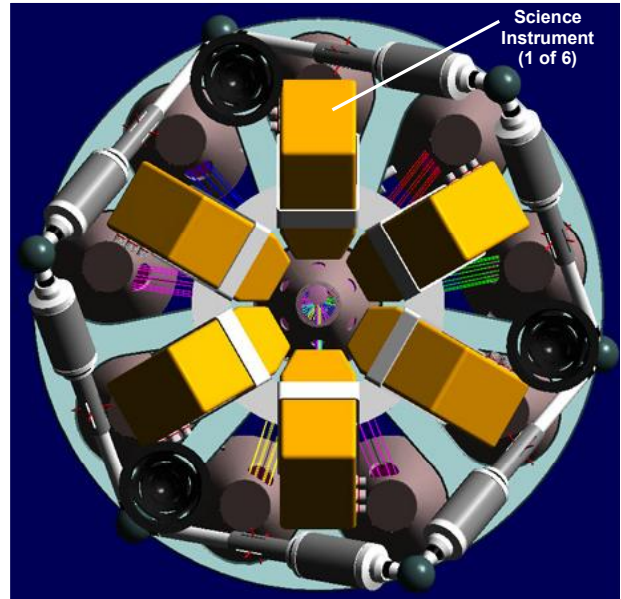


Figure 5 MIDAS Concept Science Instruments

HERITAGE

Figure 6 shows a full-scale lab testbed of a predecessor radial telescope array developed at our Lockheed Martin Advanced Technology Center (LM-ATC), used in experiments to confirm performance and sensitivities of multiple aperture concepts¹⁰. Many years of technology development work on sparse aperture arrays^{11,12,13}, including advances at the LM-ATC such as the nine-aperture testbed shown in Figure 7, have matured the integration of optical interferometry technologies by demonstrating diffraction-limited imaging with dilute arrays, controllability of the entire optical system, sensitivities, and practical aspects of design, packaging and space-flight qualification. These and other testbeds together with supporting component technology development investments and advances have advanced the application of distributed aperture sensing approaches such as MIDAS to the needs and goals for many-fold increased science returns on future planetary science missions, such as the Prometheus class of NEP-powered missions to the outer planets, led by JIMO.

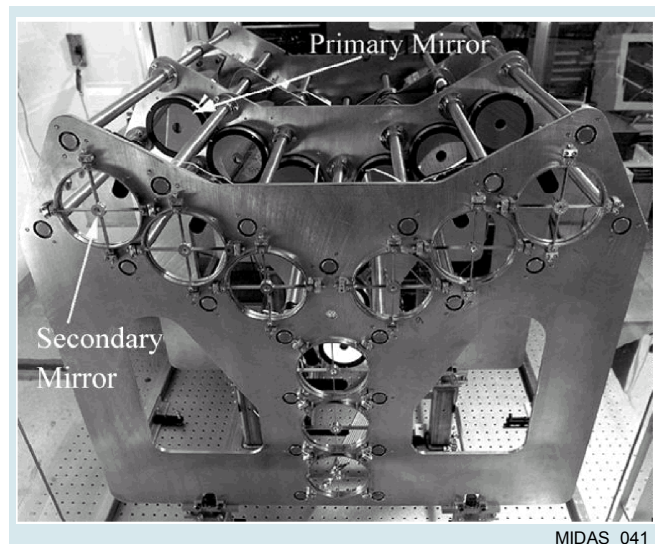


Figure 6 LM-ATC Radial Telescope Array Testbed

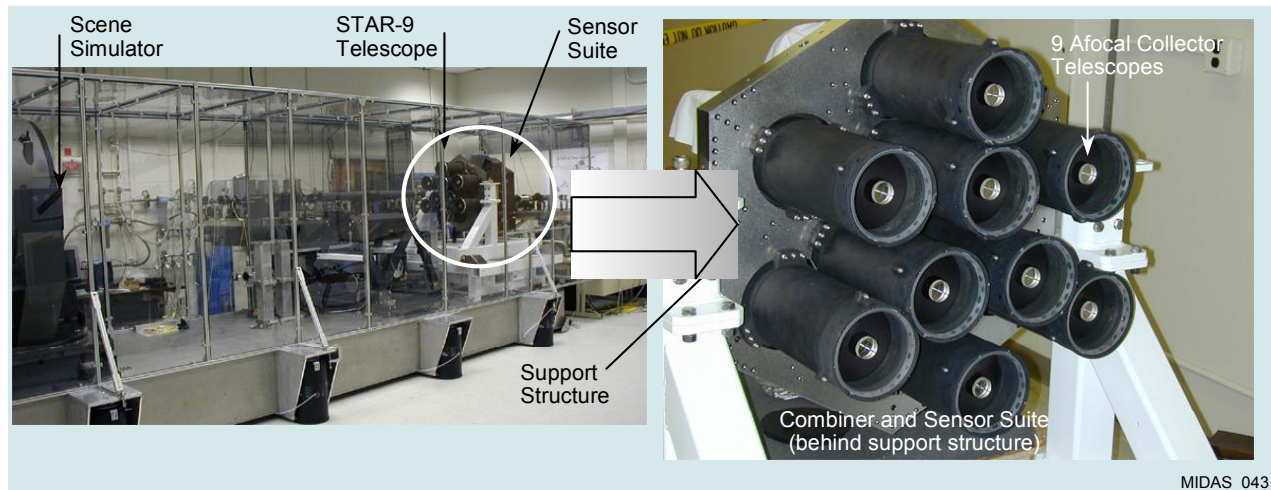


Figure 7 STAR-9 Distributed Aperture Testbed at LM-ATC

KEY FEATURES AND BENEFITS

Key features and benefits of applying our MIDAS concept to planetary remote sensing are summarized in Table 1.

1.5m MIDAS Feature	Remote Sensing Benefit
Large FOR with steerable telescopes and MTA hexapod	Global planetary surface mapping from high altitude
High resolution telescope with 1.5 m synthetic aperture	Regional planetary surface mapping from science orbit
Six synchronized SI's operating concurrently	Multispectral imaging, SI redundancy
Fine UV/Vis/NIR hyperspectral imaging	Global precise measure of planet surface composition
Active imaging modes (spectroscopy ,LIDAR, vibrometry)	Remotely determine features, composition, topography
Large aperture collecting area of 1.8 m ²	Greater throughput enables active imaging/spectroscopy & laser comm
Compact length less than 33% of a comparable aperture TMA	Enhances structural efficiency, packaging, and pointing stability
Nine 35 cm telescopes form a 1.5 m effective aperture	Lower cost than 1.5 m primary and lower risk than TMA secondary
Staring optical system, compared to scanners	High quality and high rate planetary science data return
Modular design with clean interfaces to SIs and S/C	Simplifies Integration & Test activity cost and schedule
Extensive use of heritage components	Reduces recurring cost and development risk
Highly scalable design for specific mission needs	Enables incremental payload development toward complex missions

Table 1 Key Features and Benefits of Applying MIDAS to Planetary Science Missions

1. Resource Requirements

The 1.5m MIDAS MTA estimated mass (sized to accommodate and support six back-end SI's) is about 250 kg, depending on specific mission environments and requirements. The 1.5m MIDAS occupies 3.1 m³ of volume (including a total science instrument volume of 0.125 m³), and measures 1.63 m ϕ by 1.53 m long. Extending the instruments aft past the spacecraft interface plane can provide additional science instrument length, if needed. By comparison, for any given aperture size, a conventional monolithic telescope (such as a Three-Mirror Anistigmat, or TMA) of equivalent resolving power occupies three times the total volume of the MIDAS concept. In the axial direction of the launch vehicle the MIDAS concept is three times more compact than a TMA, for a given aperture size, simplifying packaging and integration.

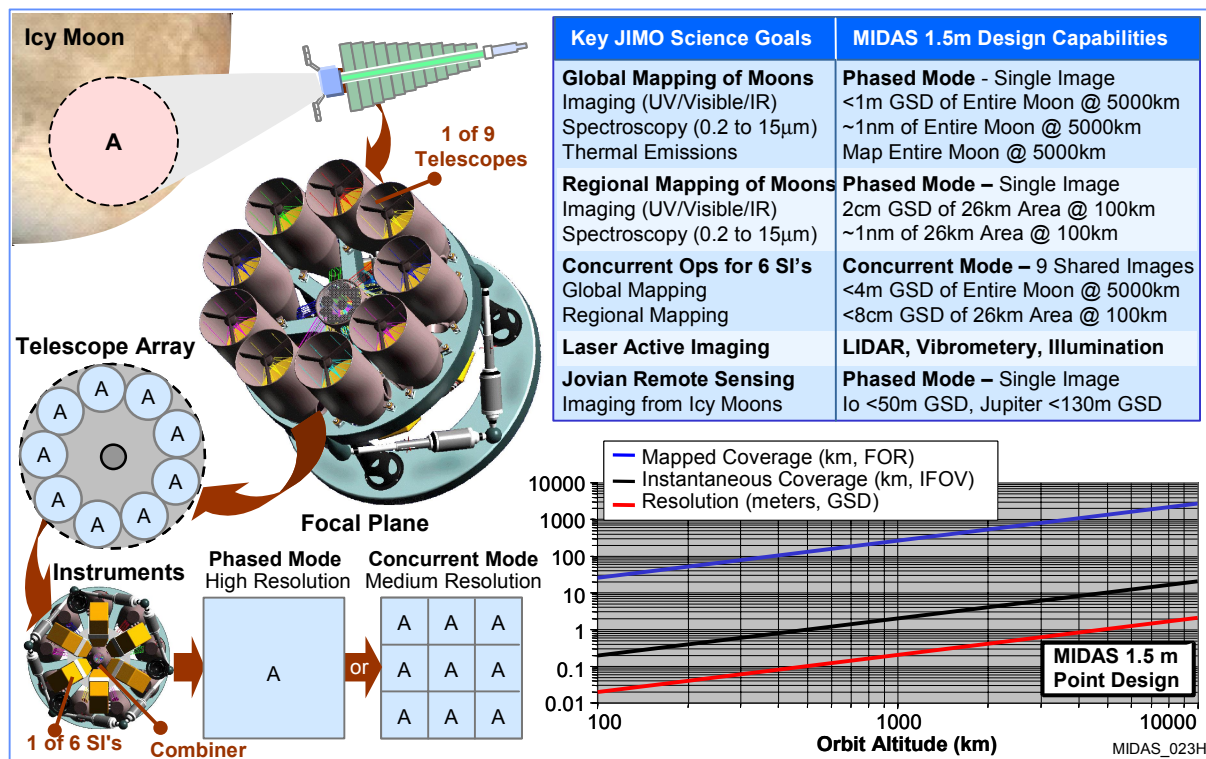


Figure 8 MIDAS Key Features & Benefits to Planetary Science Remote Sensing

2. Planetary Science Remote Sensing Capabilities

Implementing a MIDAS approach for future planetary remote sensing missions, such as the Prometheus class, enables a wide range of science operating modes, features and capabilities. Implementing these capabilities depends on the science-driven needs that determine the selection of a mission-specific collection of back-end SI's, and the end-to-end optical system features chosen for performance optimization. The combination of MIDAS passive and active modes, each with sequential or concurrent SI operations, offers the opportunity to increase potential science return for planetary science missions many fold. For example, on a mission to the icy moons of Jupiter as shown in Figure 8, MIDAS aligns well with top level science requirements¹⁴ by providing high-resolution wideband imaging of the geology and glaciology of the surface^{15,16}, high spectral resolution to help determine the geochemistry of surface materials¹⁷, active spectroscopy techniques¹⁸ to help in the search for signs of life processes¹⁹, active imaging to help conduct seismic and tidal studies²⁰, and high optical throughput to enable laser comm approaches for science data return. The MIDAS concept helps maximize the science data return on future planetary science missions such as JIMO, one of the Prometheus-class missions planned by NASA to use NEP. This potential increased science return is made possible by NEP enabling significantly increased mass and power resources allocated to the science payload, as well as enabling extended duration of near-constant remote sensing science data taking, which is about 4 years in the Jovian system for the current JIMO baseline mission, as shown in Figure 9. These missions use NEP to achieve relatively large amounts of propulsion capability at the outer planets, allowing an advanced remote sensing approach like MIDAS to have extended and extensive observation campaigns from a range of altitudes and phase angles, aligning very well with the primary and secondary science objectives. By featuring such fine spatial and spectral resolution capability, Figure 8, MIDAS maximizes the value of remote sensing science by enabling not only orders of magnitude better resolution from the 100km science orbit than previously obtained at the outer planets, but also about 2 years of science data taking at better than 1m resolution during the spiral orbits around each icy moon at Jupiter.

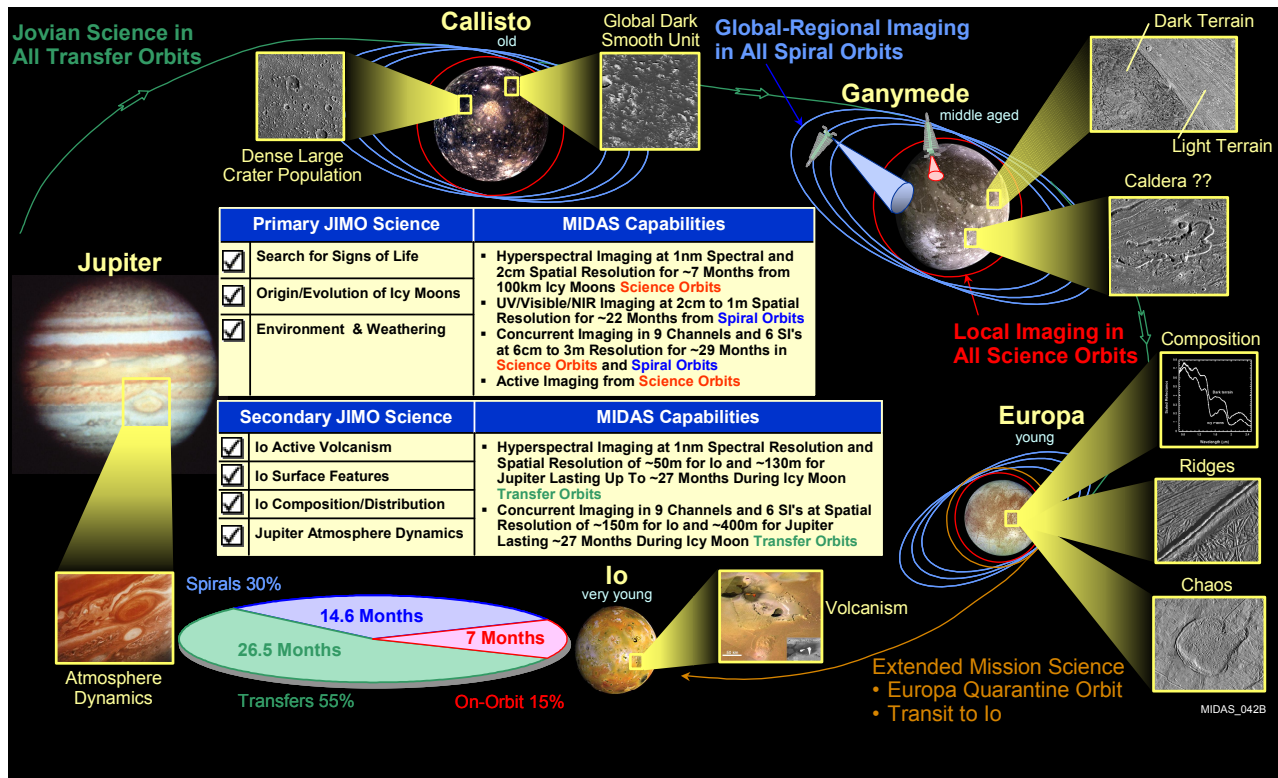


Figure 9 Reference JIMO Mission Spends About 4 Years in Near-Continuous Science Data Taking Modes

When considered in the context of the astrobiological search for signs of life processes, for example on Jupiter's icy moon Europa, the MIDAS approach shines, as captured in Figure 10. Because the reference JIMO mission while in the Jovian system spends much of its time in steadily decreasing and then steadily increasing altitude spiral orbits at each of the icy moons, very high resolution systems like MIDAS can enable a strategy of undertaking high-altitude <1m resolution global and regional imaging and spectral characterization for months while in spiral orbits, followed by spending time understanding the results of those observations to guide subsequent months of regional and local remote sensing down to 2cm resolution spectral imaging and characterization of features having the most value and interest from the science orbit at each moon. The power of 2cm GSD resolution from a 100km science orbit at each of Jupiter's icy moons is highly leveraged by proceeding and following each of those science orbits with months of observations taking at <1m GSD resolution achieved during the inward and outward spiral orbits extending to 5000km altitude.

3. Growth and Scalability

The MIDAS concept is highly scalable to a wide range of growth configurations. For space-based science mission applications, MIDAS readily scales with very little change to about 5m in synthetic aperture, with the upper end limitation imposed by existing launch vehicle payload fairing diameters. This upper limit could readily grow to about 7m if industry efforts now underway at developing 7m diameter fairings prove successful. Above this limit imposed by launch vehicle payload fairing diameters, MIDAS scales readily to well over 10m synthetic apertures by implementing a change from fixed to deployable collector telescopes, such as put forth in one of our prior concepts²¹.

Indeed, applications of MIDAS technology are not limited to only space-based science missions, as evidenced by continued interest and development of concepts for terrestrial-based distributed aperture optical systems²². The advantages afforded distributed aperture approaches to the ever-increasing desire for higher resolution and total optical throughput, including their compact volume, lower mass, reduced cost, and modularity benefits for maintenance and upgrades, extend across the entire spectrum of planetary science remote sensing future needs.

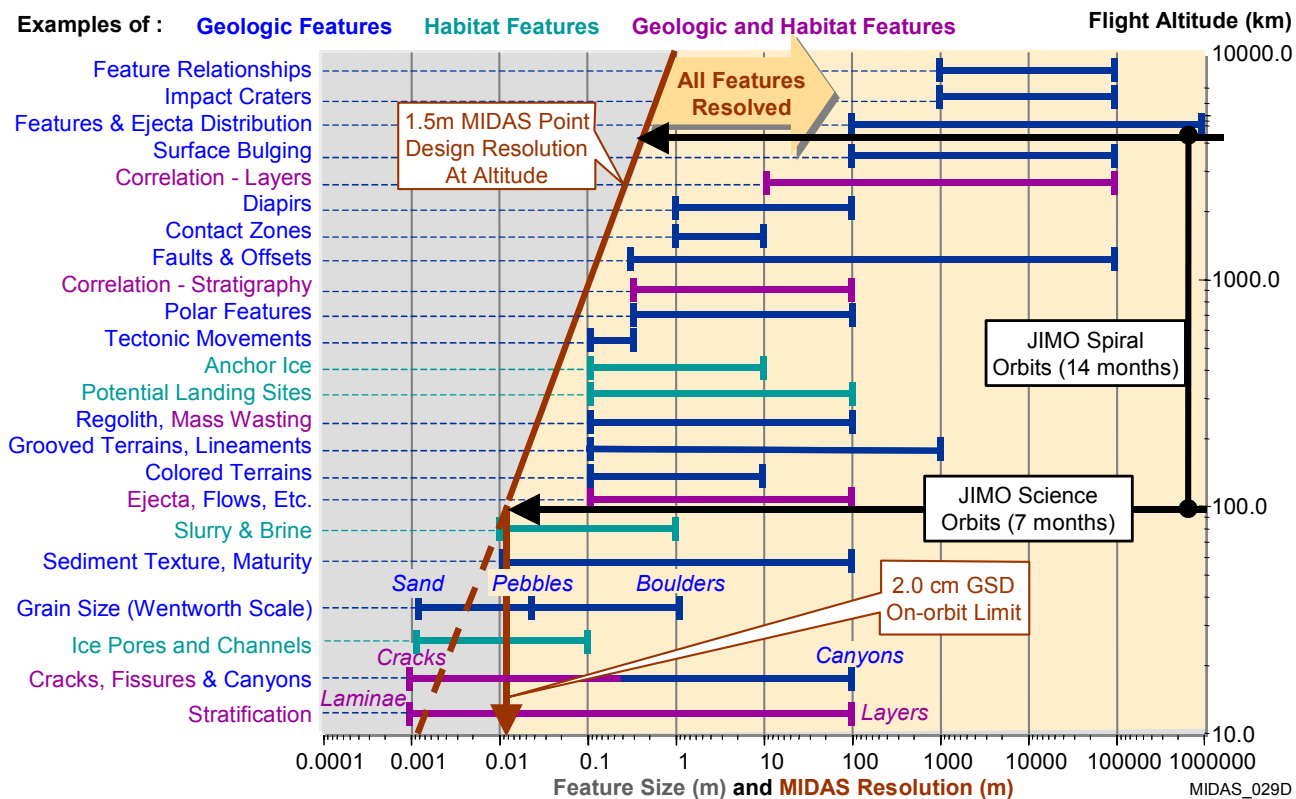


Figure 10 Geologic and Astrobiologic Features of Interest are Resolved with MIDAS for the Entire 4-year JIMO Science Mission, Because Ultra-High Resolution Leverages the Value of Time Spent at High Altitudes

SUMMARY

We have described our Multiple Instrument Distributed Aperture Sensor (MIDAS) concept, which represents an innovative approach to future planetary science mission remote sensing that enables order of magnitude increased science data return. With its large-aperture, wide-field, diffraction-limited telescope packaged at a fraction of the cost, mass and volume of conventional space telescopes, MIDAS helps advance the application of integrated optical imaging interferometer technologies toward the goals of many-fold improved science data return on future planetary science missions such as the Prometheus class of outer planet explorations, led by JIMO. The combination of ultra-high resolution passive imaging, hyperspectral imaging, multispectral imaging, and various active sensing modes including LIDAR, ablative spectroscopies and vibrometry, along with the ability to support active laser communication with high optical throughput, make MIDAS the ideal choice for an integrated remote sensing science payload on future planetary science missions to the outer planets.

REFERENCES

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- ¹ Duncan, A., Sigler, R., Kendrick, R., *Multi-Aperture Imaging System*, US Patent number 5,905,591, 18 May 1999.
- ² Meyer, C. et. al. (1995) *Planetary Surface Instruments Workshop* [LPI Pub 95-05](#).
- ³ Stubbs, D. et. al., *Multiple Instrument Distributed Aperture Sensor (MIDAS) Science Payload Concept*, SPIE paper 5487-201, June 2004.
- ⁴ Lucke, R. L., *Fundamentals of Wide-Field Sparse-Aperture Imaging*. US Naval Research Lab.
- ⁵ Harvey, J. E., et. al. (1995) *Image Characteristics in Applications Utilizing Dilute Subaperture Arrays*, Applied Optics, Vol. 34, No 16.
- ⁶ Fienup, J. R. (2000) *MTF and Integration Time versus Fill Factor for Sparse-Aperture Imaging Systems*, SPIE Vol. 4091.
- ⁷ Angel, R. (2002) *Sensitivity of Optical Interferometers With Coherent Image Combination*, SPIE Vol. 4838.
- ⁸ Kendrick, R., Smith, E., and Duncan, A. (2003) *Imaging Fourier Transform Spectrometry with a Fizeau Interferometer*, pp. 657-662, Interferometry in Space; M. Shao; Ed., SPIE Vol. 4852.
- ⁹ Kendrick et al. (2003) *Imaging Fizeau Interferometer: Experimental Results*, submitted to Frontiers in Optics conference.
- ¹⁰ Zarifis, V. et. al. *The Multi Aperture Imaging Array*.
- ¹¹ Lucke, R. L., *Fundamentals of Wide-Field Sparse-Aperture Imaging*.
- ¹² Fienup, J. R. (2000) *SPIE V4091*, 657-662.
- ¹³ Harvey, J. E., et. al. (1995) *Applied Optics*, V34, N16.b
- ¹⁴ Greeley R., et al. (2003) [JIMO Forum Compiled Results](#).
- ¹⁵ Carlson, R. W. (2003) LPI 1163, [Abstract #9042](#).
- ¹⁶ Lipps, J. H. et. al. (2003) LPI 1163, [Abstract #9088](#).
- ¹⁷ Dalton, J. B. (2003) LPI 1163, [Abstract #9051](#).
- ¹⁸ Hibbits, C. A. et al, *High-Spectral Resolution 6 to 12- μ m Reflection Spectroscopy of the Icy Galilean Satellites*, LPI 1163, Abstract #9040
- ¹⁹ Lipps, J. H., *Astrobiology of Jupiter's Icy Moons*, SPIE Denver 2004, in press.
- ²⁰ Moore, W. B. et al. (2000) *Icarus*, V147, 317–319.
- ²¹ Duncan, A., Sigler, R. and Stubbs, D. (2002) *Multiple Aperture Telescope Array with a High Fill Factor*, pp. 257-268, Highly Innovative Space Telescope Concepts, H. A. MacEwen, Ed, SPIE Vol 4849
- ²² Kuhn, J. R., et. al. (2001) *Concepts for Large-Aperture, High Dynamic Range Telescope*, pp. 1486-1510, PASP Vol 113.