Multiple Instrument Distributed Aperture Sensor (MIDAS) For Planetary Remote Sensing

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ABSTRACT

An innovative approach that enables greatly increased return from planetary science remote sensing missions is described. Our concept, called Multiple Instrument Distributed Aperture Sensor (MIDAS), provides a large-aperture, wide-field 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 future 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 high resolution remote sensing at the diffraction limit of the overall synthetic aperture, 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 subsystem, MIDAS enables LIDAR, vibrometry, illumination, various active laser spectroscopies such as ablative, breakdown, fluorescence, Raman and 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. These remote sensing capabilities significantly enhance astrobiologic, geologic, atmospheric, and similar scientific objectives for planetary exploration missions.

Keywords: Remote Sensing Space Science, Distributed Aperture Imaging Telescopes

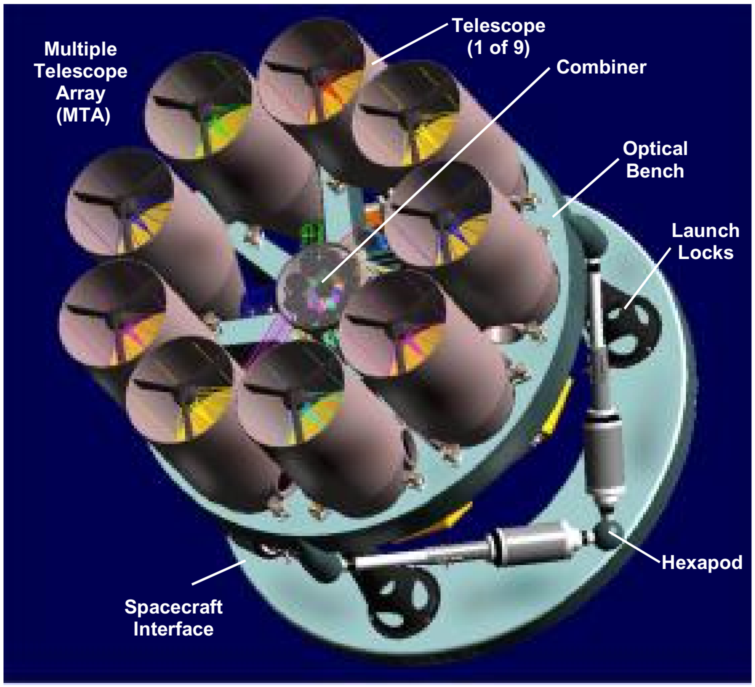

Figure 1 MIDAS Concept

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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 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 patented[1] optical interferometry technologies into a mature multiple aperture array concept that addresses one of the highest needs for advancing future planetary science remote sensing[2]. 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 resolution at the diffraction limit of the synthetic aperture, sequentially by each SI or 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).

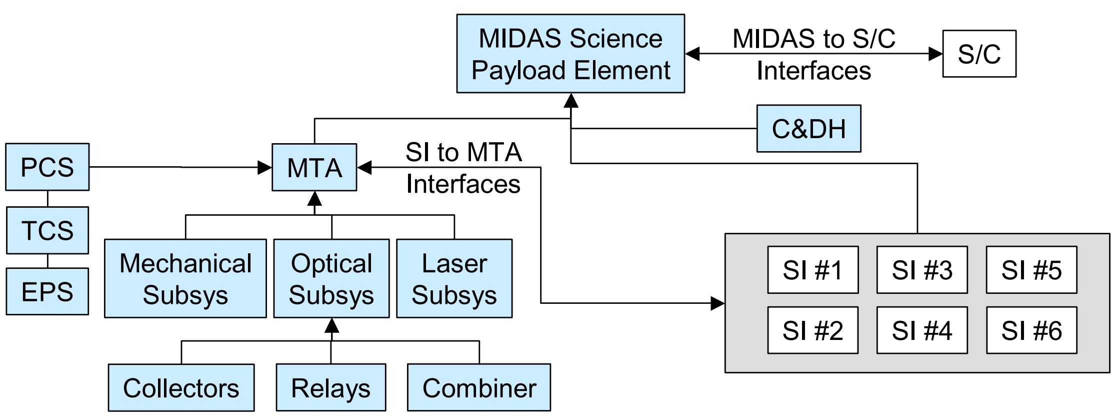


Figure 2 MIDAS Payload Architecture

The MIDAS concept[3] 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 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

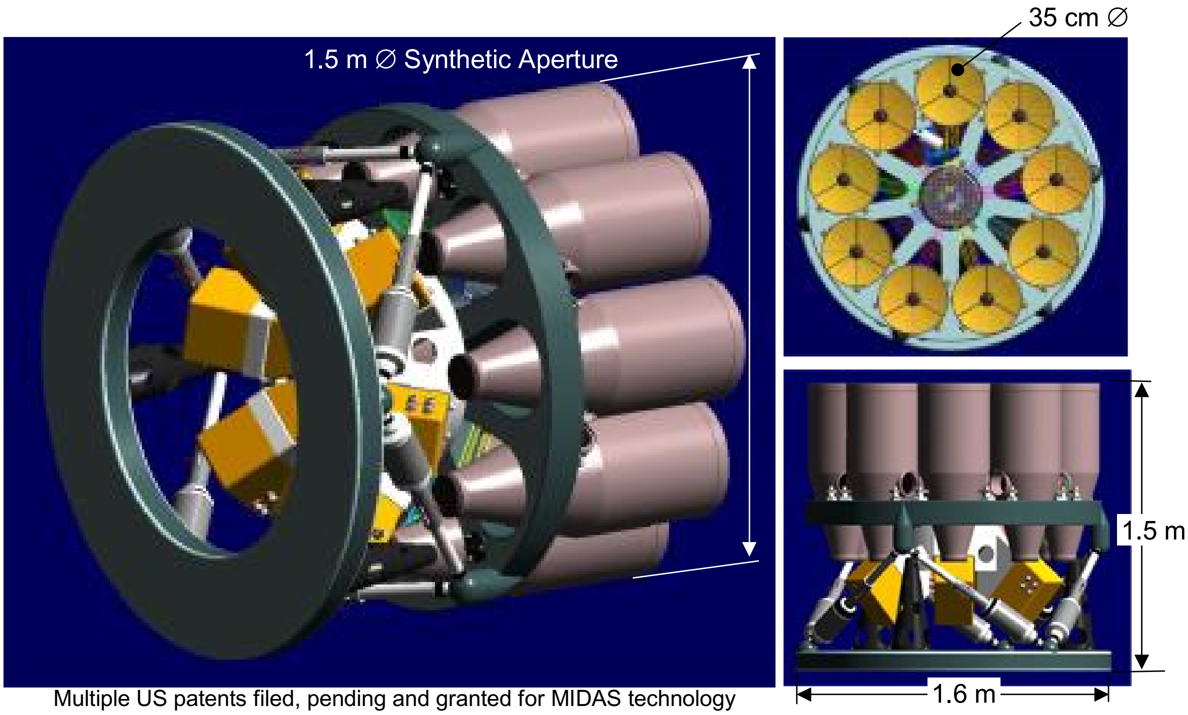


Figure 3 MIDAS Overall Design Concept

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.

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 $\pm$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-Regard (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

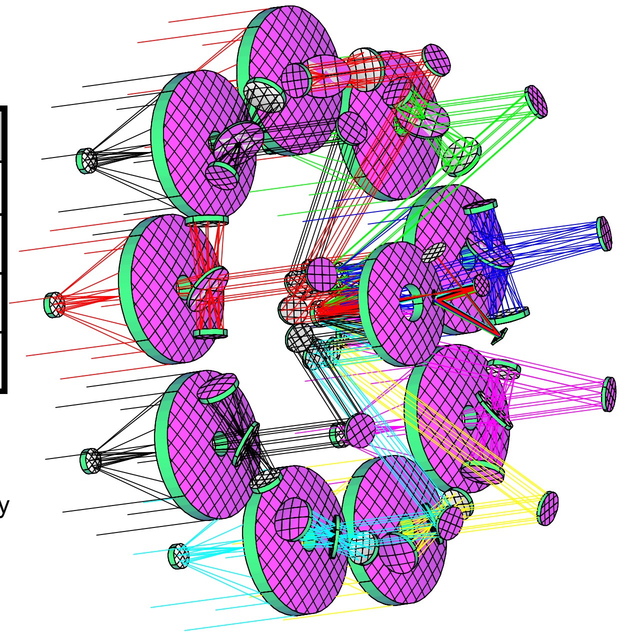


Figure 4 MIDAS Optical Design

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 or fluorescence spectroscopy or enhanced stereo imaging, to ablation of small target areas on the 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, while also enabling use of active remote sensing techniques to probe the geodynamic 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 vibrometery similarly offers the possibility of active remote sensing of dynamic planet processes, such as 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, repeatedly over months of orbits on a JIMO mission.

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.

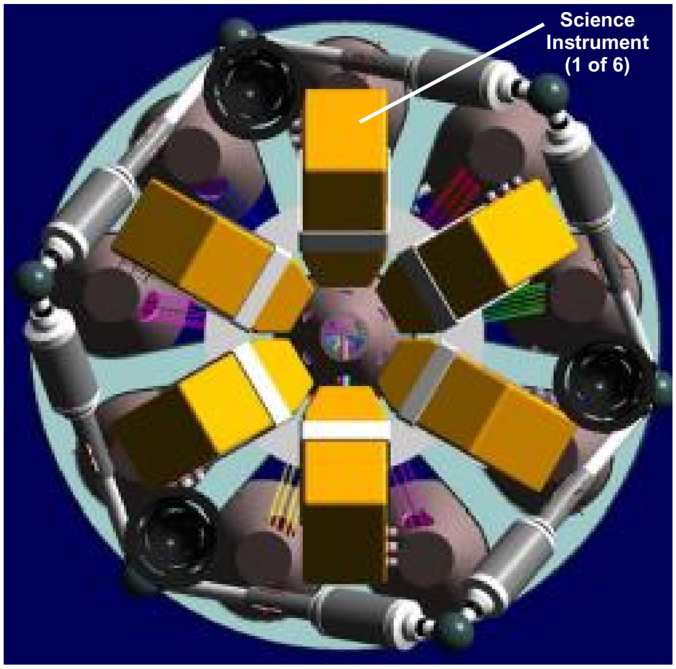


Figure 5 MIDAS Concept Science Instruments

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 concepts[10]. 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.

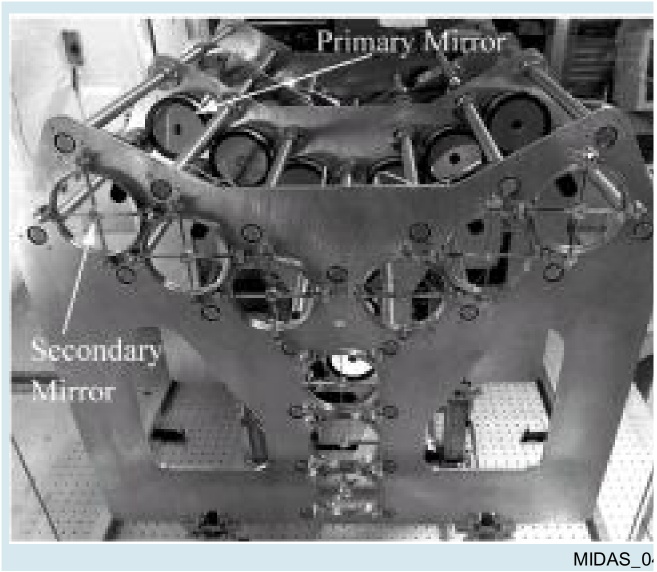


Figure 6 LM-ATC Radial Telescope Array Testbed

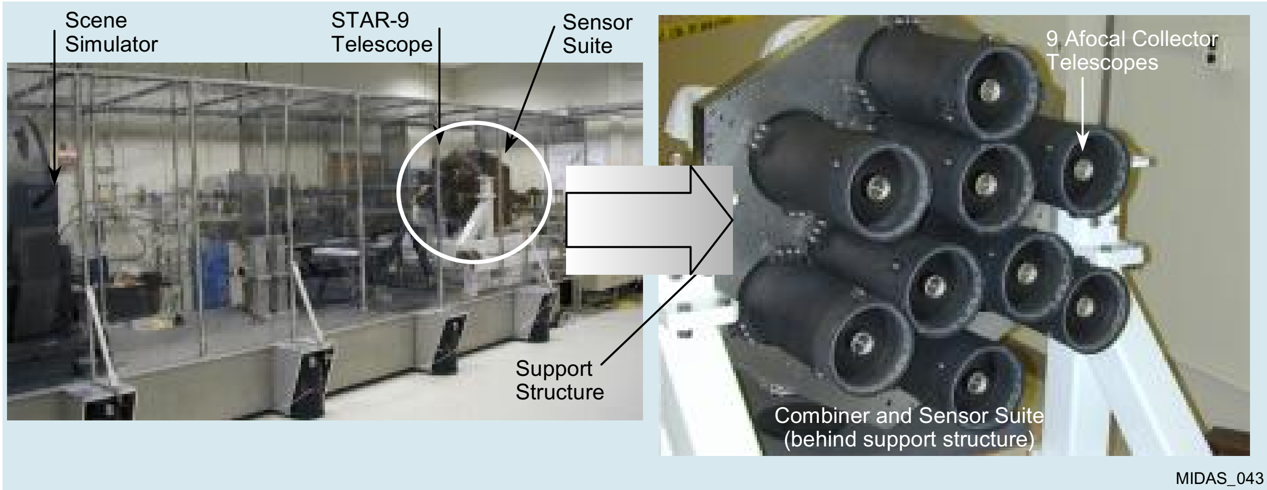


Figure 7 STAR-9 Distributed Aperture Testbed at LM-ATC

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 m^3 of volume (including a total science instrument volume of 0.125 m^3), and measures 1.63 mϕ 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.

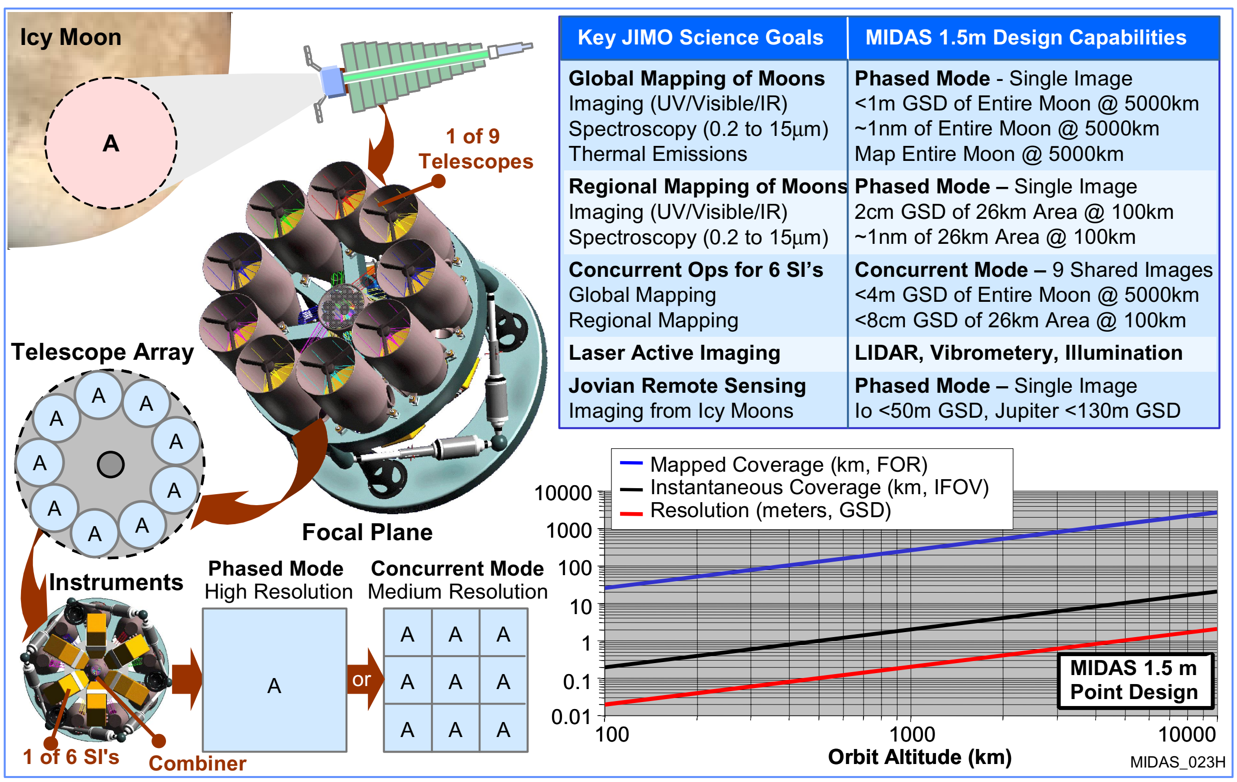
2. Growth and Scalability

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 concepts[14].

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 systems[15]. 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.

3. Remote Sensing of Planetary Surfaces

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 requirements[16] by providing high-resolution wideband imaging of the geology and glaciology of the surface[17,18], high spectral resolution to help determine the geochemistry of surface materials[19], active spectroscopy techniques[20] to help in the search for signs of life processes[21], active imaging to help conduct seismic and tidal studies[22], and high optical throughput to enable laser comm approaches for science data return. The MIDAS



Key JIMO Science Goals	MIDAS 1.5m Design Capabilities
Global Mapping of Moons Imaging (UV/Visible/IR) Spectroscopy (0.2 to 15μm) Thermal Emissions	**Phased Mode** - Single Image <1m GSD of Entire Moon @ 5000km ~1nm of Entire Moon @ 5000km Map Entire Moon @ 5000km
Regional Mapping of Moons Imaging (UV/Visible/IR) Spectroscopy (0.2 to 15μm)	**Phased Mode –** Single Image 2cm GSD of 26km Area @ 100km ~1nm of 26km Area @ 100km
Concurrent Ops for 6 SI's Global Mapping Regional Mapping	**Concurrent Mode –** 9 Shared Images <4m GSD of Entire Moon @ 5000km <8cm GSD of 26km Area @ 100km
Laser Active Imaging	**LIDAR, Vibrometery, Illumination**
Jovian Remote Sensing Imaging from Icy Moons	**Phased Mode –** Single Image Io <50m GSD, Jupiter <130m GSD

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

concept helps maximize the science data return on future planetary science missions such as JIMO, 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, MIDAS maximizes the value of remote sensing science by enabling not only orders of magnitude better resolution of the surface 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 of the planet surface during the spiral orbits around each icy moon at Jupiter.

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 1 nm spectral resolution 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 taken at <1m GSD resolution achieved during the inward and outward spiral orbits extending to 5000km altitude, as well as remote sensing at higher altitudes during the entire four years spent in the Jovian system, with resolutions of 2cm to 200m GSD for each Icy Moon, 50m to 300m for Io and 150m to 400m for Jupiter, as shown in Figure 11.

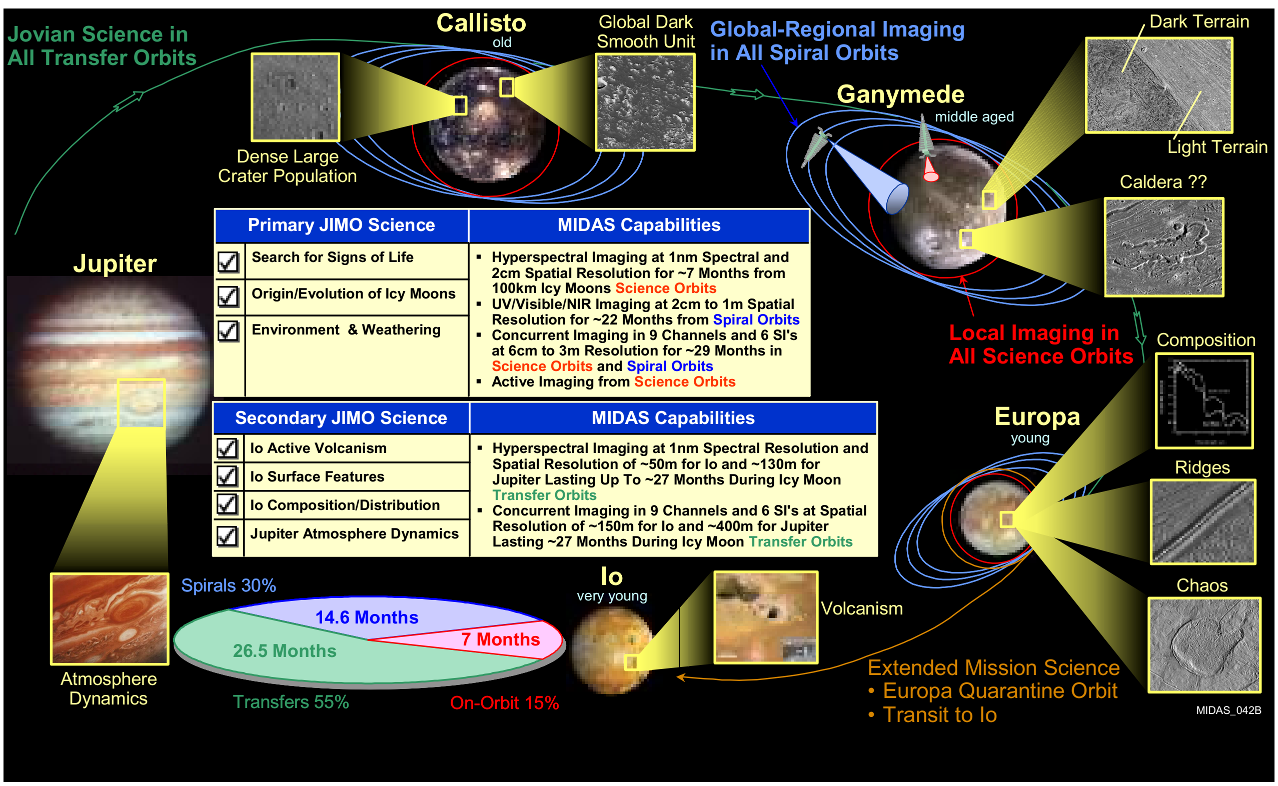


Figure 9 Reference JIMO Mission Spends About 4 Years in Near-Continuous Science Data Taking Modes

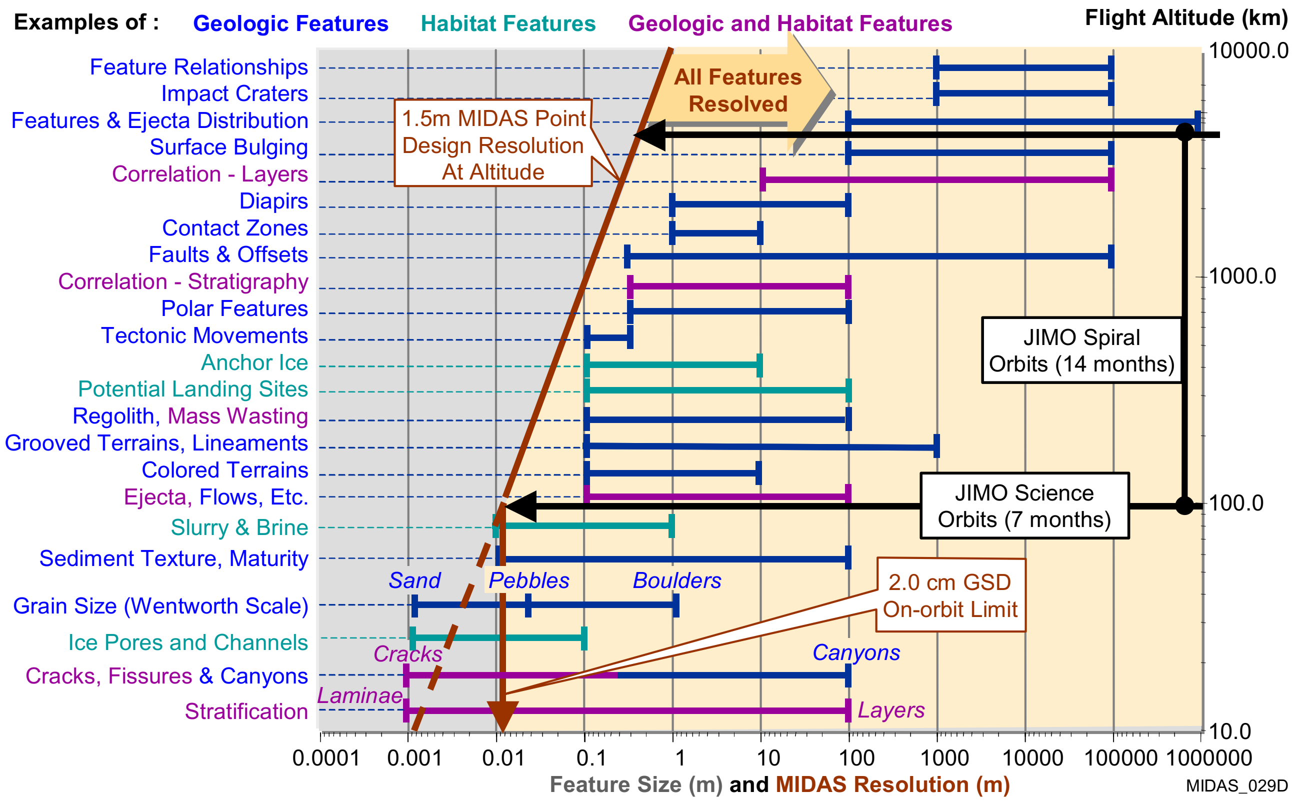


Figure 10 Geologic and Astrobiologic Features of Interest are Resolved with MIDAS for the Entire 4-year JIMO Science Mission, Because Ultra-High Resolution Leverages the Value of Time Spent at High Altitudes

4. Remote Sensing of Planetary Atmospheres

MIDAS capabilities flown on JIMO enable significant increases in our understanding of key Jupiter atmosphere science, as summarized in Table 2 against the JIMO SDT science goals and measurement requirements[23]. One area of interest is the state of the weather-layer winds – jets, vortices, turbulence, hemispheric asymmetries, heat and mass transport. The combination of spatial resolution, pointing errors and short time duration over which Jupiter atmosphere observations have been obtained to date prevent us from quantitatively measuring atmospheric velocities in the weather-layer except for the largest features: zonal winds, Great Red Spot, White Ovals, some anticyclones at 41°S and some barges. The measurements have ~10% uncertainty, implying the uncertainties in the horizontal derivatives of those velocities and the vertical vorticity (derivative of the velocity most useful in characterizing atmosphere dynamics) has an uncertainty of ~50%. Spatial resolution of 10 km/px over ~2 weeks of continuous observations, which is readily achieved with MIDAS any time during the JIMO mission, would allow the horizontal velocities and their horizontal derivatives to be measured with uncertainties of 3% and 12% respectively. Uncertainties this small will allow us to determine eddy stresses, which in turn supply the rates at which the eddies receive and give energy to the ambient zonal flow. This fine spatial resolution for long duration observations will also allow us to determine the velocities of most of the large, cyclonic, filamentary regions, and with repeated observations over a year, we can determine their robustness, the relationship between their instantaneous winds velocities and cloud morphologies, and their longevities. This will give us a better understanding of the overall vortex dynamics of the weather layer. For example, we will be able to determine the ratio of the populations of the robust cyclones to the robust anticyclones, a ratio crucial to understanding the atmosphere and determining the dominant physics. Currently, there are two very different, competing models of the Jovian atmosphere. To determine if this ratio is small or of order unity would immediately eliminate one of the models.

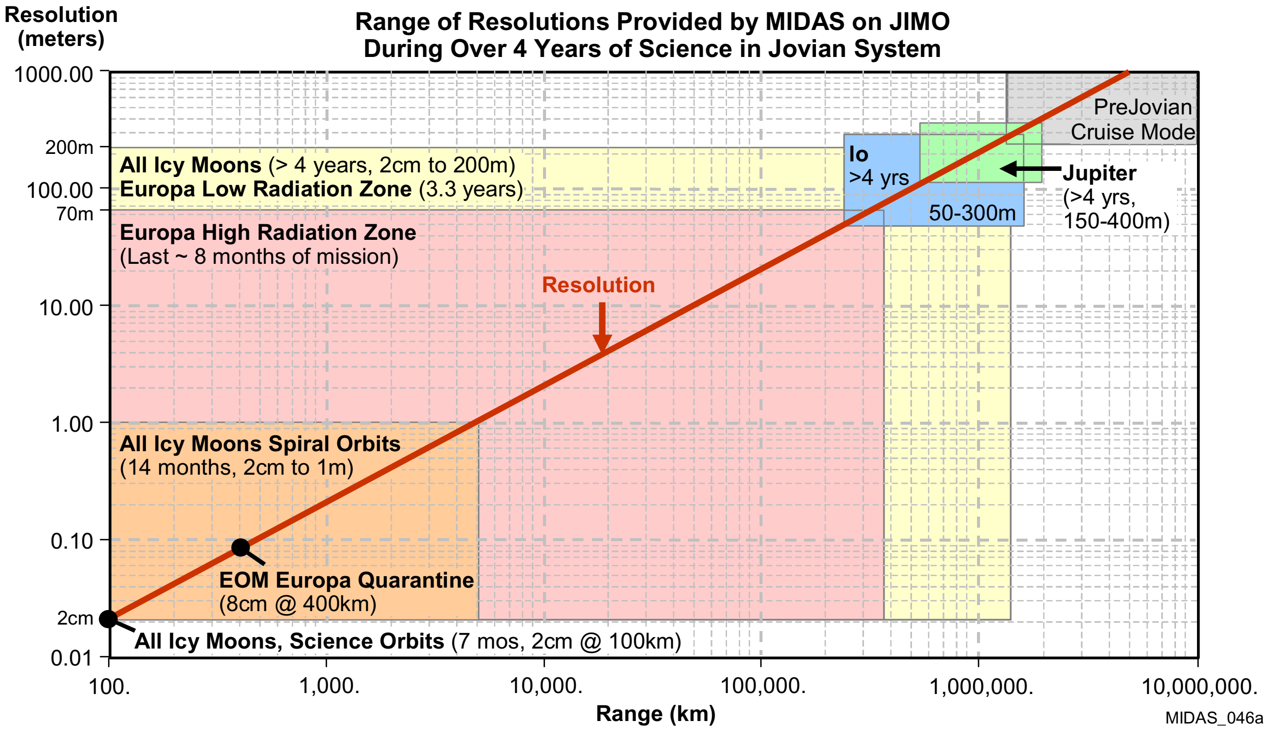


Figure 11 During Four Years of Science in the Jovian System on JIMO, MIDAS Enables Remote Sensing of Not Only Each Icy Moon at 2cm to 200m GSD, but also Io at 50-300m GSD and Jupiter at 150-400m GSD.

We currently have very limited understanding of Jovian turbulence, except for the fact (based on the observed vortex interactions) that it is unlike classical 3D, 2D, or shallow-water turbulence and also unlike the turbulence of Earth's atmosphere or ocean. The key to characterize the turbulence, which is tied to the transport of heat and mass throughout the planet, is to measure the turbulent energy spectrum as a function of wavenumber. With spatial resolutions better than 1 km/px with MIDAS, we should be able to obtain energy spectra between the largest scales (20,000 – 30,000 km – the size of the largest coherent features such as the longitudinal widths of the zonal flows and of the horizontal extent of the Red Spot) down to 50 km or smaller. Paradoxically, the length of the smallest measurable scale in the energy is not only a function of spatial resolution and observing time, but also of the velocities of the smallest scales and their variances, both of which are obtainable from the energy spectrum that is currently unknown. Knowledge of the energy spectrum is the most fundamental piece of information needed in analyzing a turbulent flow. To put the determination of Jupiter's energy spectrum in context, it would vary by a factor of 400 or more between its largest and smallest scales. Typically, state-of-the-art laboratory measurements and 3D numerical simulations of turbulence vary at most by a factor of 100 between the largest and the smallest features (uncontaminated-by-numerical-dissipation). Measuring the spectral index (the relation between energy at a length scale and the local wavenumber) over a range of 100 is sufficient to characterize and understand turbulence. Other information derived from the energy spectrum is a determination of the spatial scales over which energy is transferred to and from the weather layer and atmospheric variability.

A fundamental question mostly ignored by Jovian scientists, yet perhaps one of the most frequently asked questions by the larger atmospheric community, is why Jupiter's northern and southern hemispheres appear so different. One plausible explanation is that they are not, or at least not considering their largest scales. The southern hemisphere is characterized by its large number of big, coherent vortices. Both their associated clouds and the temperature anomalies between them and the ambient flow can immediately identify them. Recent numerical simulations of the vortices embedded in a background of turbulence produce clouds and temperatures consistent with the observations. However, a small increase in the amplitude of the turbulent energy at scales below those measured to date, readily measured with MIDAS sub-km resolution, change the picture entirely. Without destroying or appreciably changing the large vortices, a small increase in the small-scale turbulence creates cloud patterns so that most traces of the underlying vortices disappear. An observer would not know the vortices were there. A similar change occurs in the temperature anomalies; turbulence transports heat so efficiently that the warm or cool cores of the vortices are mixed quickly into the ambient atmosphere. The same simulations show that highly intermittent turbulence, on occasion and for short times lasting weeks, produce temperature anomalies that are confined to the vortices, and on those occasions appear as a latitudinal row of hot or cold spots. The latter phenomenon has been observed in Jupiter's northern hemisphere. Measurements of Jupiter's energy spectrum and its variability are key to understanding Jupiter's hemispheric asymmetries.

MIDAS remote sensing capabilities of the Jovian atmosphere during JIMO also enable increased understanding of the vertical velocities, energy balances, heat and mass transport, and relation between weather layer and underlying convective zone. Another fundamental question about the Jovian atmosphere is why its radiated heat flux is nearly independent of latitude. On Earth, the weather is driven by the temperature differences between the equator and poles, which is due to differential solar heating. This engine drives the winds and storms, so an understanding of why the Jovian weather appears so isothermal in latitude, how energy is transported in the weather layer and how it is energetically tied to deeper layers, including the underlying convection zone, is crucial. There are at least two ways that sub-kilometer spatial resolution provided by MIDAS can be used to make direct observations of transport and of vertical velocities that connect the weather layer to the convection zone. If the underling convection has a direct influence on the weather layer it is via narrow plumes that can overshoot from the convective zone into the overlying stratified fluid and possibly up to the tropopause. Vertical plumes stop rising and spread horizontally outward (like a mushroom cloud from a rising fireball) due to the stable stratification of the atmosphere. The horizontal spreading produces a horizontal divergence in the velocity. Like the vertical vorticity, the horizontal velocity divergence depends on derivatives in the horizontal direction of the horizontal velocity. Vertical velocities can be inferred immediately from the horizontal velocity divergence, and those vertical velocities provide an unambiguous and quantitative measure of the coupling of the weather layer to the convection zone. However the horizontal divergence is much more difficult to measure than the vertical vorticity because the two derivative terms that make up the divergence nearly cancel, so a 50% uncertainty in computing a derivative of the velocity makes an order unity error in the divergence, making the measurement worthless. Spatial resolution of <10 km/px would allow for the quantitative measurement of divergences of big features, and sub-kilometer resolution such as provided by MIDAS for over 4 years on JIMO would allow the detection of vertical plumes from the convective zones and bounds on their velocities. If in addition, near simultaneous measurements of temperature anomalies correlated with the plumes were made, we would have a quantitative and direct measure of the coupling of the dynamics that we see directly in the weather layer to the underlying convective zone.

It is possible that the coupling to the underlying convection zone is too weak to account for the nearly uniform radiated thermal flux from the weather layer. In that case, mixing within the layer must be responsible, and that can be accomplished in at least two ways. The small-scale turbulence could transport the heat from the equator to the poles. Just as increased spatial resolution permits the determination of an energy spectrum, it also allows for the temperature variance spectrum, and two correlation spectra between the temperature and the two horizontal components of the velocity. From these the role of the small-scale turbulence in heat transport can be determined. These same spectra can also be use to compute the transport due to the large vortices, and in particular the large-scale temporal chaos of the velocity field (distinct from turbulence) that they create might be responsible for the heat transport in the weather layer. Chaotic mixing can be efficient in transporting heat, and to understand the energetics of the atmosphere, it is necessary to understand how big or small a role it plays. For example, with the recent mergers of the White Ovals, there is much less large-scale chaos in the weather layer at 34°S, and therefore less chaotic mixing. If, at that latitude, chaotic mixing is the main mechanism for transporting heat southward from the equator to the pole, then there will be an abrupt warming of the weather layer on the equatorial side of the latitude and a corresponding cooling in the poleward side.

Characterization of these same plumes could shed light on another long-standing problem in the observed ammonia abundance, namely the large global depletion of ammonia gas below the cloud layers (0.5-~5 bar) relative to that observed in the deep atmosphere (>8 bar). If most of the air ascends in isolated thunderstorms and about half the ammonia abundance is lost by rainout or downdrafts to the deep layers, this overall depletion can be modeled. Although lightning, indicative of thunderstorms, has been seen primarily in the belt regions, the small-sized thunderstorms theorized to exist have not. Atmospheric monitoring of Jupiter for the long durations enabled by the JIMO mission, at the sub-km spatial scales afforded by MIDAS resolution, would help confirm or refute such models.

Jupiter Atmospheric Science (From JIMO SDT Report of 2/13/04)		MIDAS 1.5m Point Design Capabilities on JIMO
Goals	**Measurement Requirements**	
Jovian Atmospheric General Dynamics Investigations		
Detect and monitor individual thunderstorms • Characterize convective cells (including hot spots) and lightning on a global scale	Broadband visible and near-IR imaging Local and global coverage at ~10 km/px resolution Sampling rate ~10^3 sec	Jupiter remote sensing images: • 6 km/px to 400m/px for ~7 years of cruise from 34M to 2M km approach • 400 to 150m/px for >4yrs within Jovian Jupiter imaging spectroscopy: • 0.2-15 µm with ~1nm resolution
Characterize abundance and variability of water at and above the clouds	5 µm imaging spectroscopy, $\lambda/\Delta\lambda$~3000 Global coverage at 100 km/px	Imaging spectroscopy: 5 µm $\lambda/\Delta\lambda$ ~5000 Global coverage during entire mission: • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian
Presence and distribution of Ammonia	Mid-IR imaging at 200 km/px resolution, $\lambda/\Delta\lambda$ ~2500, depth range 0.01-0.5 bars	10 µm imaging spectroscopy $\lambda/\Delta\lambda$~10,000 • <6km/px for ~10yrs cruise & Jovian • 150-400m/px or less for 4yrs in Jovian
Temperature and Energy Balance of Jupiter, role of solar insolation, magnetospheric interaction, winds and eddies in atmospheric circulation and convection		
Provide global temperature maps from 0.001 to 0.5 bars, 100 km spatial resolution Determine eddy heat fluxes	Wind, temperature maps, 7-8 µm @ 100 km spatial resolution, $\lambda/\Delta\lambda$ >1000; 14-40 um: $\lambda/\Delta\lambda$>50 Limb sounding with 20-40 km vertical resolution	Imaging spectroscopy 7-8 µm, ~1nm spectral resolution, • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian 14-40 µm coverage with active cooling
Characterize Jovian aurora and correlate with simultaneous plasma and field measurements	Multispectral imaging of Jovian aurora in IR, Optical, and UV over varying timescales ranging from minutes to days	Simultaneous broadband imaging spectroscopy in visible/IR with ~1nm spectral resolution in concurrent mode Simultaneous single aperture separate spectrometer for UV coverage
Vertical structure in composition, clouds, hazes, disequilibrium species dynamics (including sources, sinks, moist convection, precipitation)		
Determine global and regional cloud vertical structure from 0.1- to 5-bars	Simultaneous visible and near IR spectral imaging with comparable spatial resolutions, and sufficient $\lambda/\Delta\lambda$ to resolve molecular absorption bands • Near-IR: $\lambda/\Delta\lambda$ > 300 • Mid-IR (~8 µm): $\lambda/\Delta\lambda$ > 1000 • Far-IR: $\lambda/\Delta\lambda$ > 500.	Simultaneous broadband imaging spectroscopy in visible/IR with ~1nm spectral resolution. Sequential SI investigations: • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian Far IR imaging with active cooling.
Characterize photochemical hazes	UV, visible/IR imaging and (visible) polarimetry over 0.3-5 µm at varying phase angles with $\lambda/\Delta\lambda$ ~50-500 and 100 km/px spatial resolution	Visible/near IR polarimetry Spectral imaging 0.3-5µm at ~1nm at all phase angles from Icy Moon orbits • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian
3-dimensional distribution of disequilibrium species and para-H2 fraction above the clouds	Image mid-to-far IR at 100-km/pix, $\lambda/\Delta\lambda$ > 2000 to 5000	Mid-IR imaging with ~1nm resolution; extension to far IR with active cooling • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian
Global 3-D distribution of organic (hydrocarbon) molecules (including auroral emissions).	Global coverage at 100 km/px at 8-16 µm, $\lambda/\Delta\lambda$ > 10,000 Limb spectroscopy with 20-40 km vertical spatial resolution.	Spectral imaging $\lambda/\Delta\lambda$ >10,000 10-16 µm Global spatial resolution • <6km/px for ~10yrs cruise & Jovian • 150-400m/px for 4yrs in Jovian

Table 2 MIDAS Capabilities on JIMO Meet or Exceed All SDT Goals for Jupiter Atmospheric Science

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, various 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.

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