Abstract:
This thesis describes the development of a prototype Confocal Microscope and Raman Spectroscopy Probe for the application of Mars exploration. Raman spectroscopy is a useful identification tool for astrobiologists searching for biomarkers and microbial fossils as evidence of past life on the surface of Mars. Combining Raman spectroscopy with an imaging system gives morphological context to the spectral information that is necessary in order to come to an exobiological conclusion. The confocal microscope and Raman spectrometer use laser illumination at either 852 nm or 1064 nm. A compact probe houses the optical systems and is linked to the laser source, spectrometer, and imaging processing electronics through optical fiber and electronic cable. The probe can be located at the end of a robot arm which facilitates in situ sample investigation during field operation. Integral to system design is the microscope’s MEMS scanning system, the dispersive spectrometer (using an uncooled silicon CCD or InGaAs detector array), and the 150 mW 852 nm DBR diode laser or 120 mW 1064 nm microchip laser. This thesis presents a theoretical treatment of the confocal imaging system, probe design, optical integration with the Raman spectrometer, and experimental demonstrations. The 1064 nm probe has a field of view of 120 microns, a resolution of 1.4 microns, a spectral range from 400-4000 cm⁻¹, measures 9 x 4.5 x 4 cm and weighs approximately 300 grams.
A CONFOCAL MICROSCOPE AND RAMAN SPECTROSCOPY PROBE FOR MARS EXPLORATION

By

Dawn Michelle Crowder

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Two images made of a chrome grating with the deformable membrane inserted into the bench-top proof-instrument. For image (a), the membrane was not actuated. For image (b) the membrane was deflected 1.2 microns. The change in image quality is not noticeable.
This thesis describes the development of a prototype Confocal Microscope and Raman Spectroscopy Probe for the application of Mars exploration. Raman spectroscopy is a useful identification tool for astrobiologists searching for biomarkers and microbial fossils as evidence of past life on the surface of Mars. Combining Raman spectroscopy with an imaging system gives morphological context to the spectral information that is necessary in order to come to an exobiological conclusion. The confocal microscope and Raman spectrometer use laser illumination at either 852 nm or 1064 nm. A compact probe houses the optical systems and is linked to the laser source, spectrometer, and imaging processing electronics through optical fiber and electronic cable. The probe can be located at the end of a robot arm which facilitates in situ sample investigation during field operation. Integral to system design is the microscope's MEMS scanning system, the dispersive spectrometer (using an uncooled silicon CCD or InGaAs detector array), and the 150 mW 852 nm DBR diode laser or 120 mW 1064 nm microchip laser. This thesis presents a theoretical treatment of the confocal imaging system, probe design, optical integration with the Raman spectrometer, and experimental demonstrations. The 1064 nm probe has a field of view of 120 microns, a resolution of 1.4 microns, a spectral range from 400-4000 cm$^{-1}$, measures 9 x 4.5 x 4 cm and weighs approximately 300 grams.
CHAPTER ONE

INTRODUCTION

The study of the climate, geology, and biological history of Mars could provide a valuable link to Earth's past and future. The National Aeronautics and Space Administration (NASA) began an intensive Mars exploration program in the 1990's, aiming to find clues to the origins and history of life in our solar system [1]. In years past, the Viking landers rejected hypotheses that any life on Mars would be confined to surface habitats [2]. Instead, they exposed the surface of Mars to be a hostile environment, with an atmospheric pressure two orders of magnitude lower than that on Earth, extreme UV-radiation, little water, and a strongly oxidizing regolith [3, 4]. Twenty years after the success of Viking, the Mars Pathfinder mission confirmed this void of life at the surface of Mars, leaving future exploration efforts with two options: to search for life in localized, possibly cryptic environmental niches, or to search for the biomarkers or remains of a biological community that once existed on the surface of ancient Mars [1, 2, 3, 5].

If found anywhere, extant life on Mars would be confined to specific environmental niches removed from the harsh surface environment. Astrobiologists have postulated chemosynthetic ecosystems existing far beneath the surface in a biological "oasis" [2, 6]. However, space exploration technology presently precludes
drilling deep into Mars' crust and we are restricted to looking for evidence of present
and past life within several meters of the surface [5]. An exobiological search for
latent or extinct organisms involves looking “for a past atmosphere, past and present
liquid water, organics and fossilized primitive systems. Analysis should be focused
on carbonates, water and organics in Martian subsurface and sediments” (Brack,
1996) [7].

The presence of some form of water on the surface of present day and
historical Mars suggests that though currently impossible, an environment capable of
supporting prokaryotes once existed on the planet’s surface [5]. Mars Global
Surveyor (MGS) determined the north polar cap on Mars to be composed primarily of
water ice, at a volume that is approximately one third that of the Greenland ice cap.
Viking orbiters and MGS have returned thousands of surface images of the geologic
remains of fluvial channels, drainage networks, and floodplains, indicating that
atmospheric conditions may have once been such that liquid water flowed on the
surface. In addition, it is probable that sub-surface water exists in the form of
permafrost in aquifers [4, 8]. These regions are ripe areas for exobiological
prospecting since much of the surface of ancient Mars is still well preserved and
unweathered, and the morphological and chemical evidence of remains of organisms
may still be present [2].

Cyanobacteria are a prime candidate for historical Martian surface habitation
due to their remarkable tolerance of a hostile high-stress environment. On Earth, they
are found in a variety of near-surface, cold desert Antarctic habitats such as on
lakebeds in living stromatolites (laminated structures built mainly by cyanobacteria), on exposed rock ridges in layered communities, and in an endolithic habitat. On Mars, similar communities may be preserved through burial and freezing. Therefore, a surface investigation searching for evidence of photosynthetic life on Mars can concentrate on cyanobacterial residues such as photosynthetic pigments, sunscreens, photoprotective minerals, and stress-protective compounds [5, 9].

Raman spectroscopy is an attractive analytical tool for detecting these organisms and their bio-markers, as it is capable of identifying both organic and inorganic substances. According to H. G. M. Edwards et al. it is unique in that aspect; and therefore well suited to investigate chemically the biology and the geology of its sample concurrently [10, 3]. Many types of spectrometers capable of either elemental or molecular analysis have landed on the surface of Mars to determine surface and sediment composition. Viking landers had two spectrometers included in their scientific payload: a Gas Chromatograph/Mass Spectrometer (GCMS) which performed molecular analysis and an X-Ray Fluorescence Spectrometer (XRFS), which determined elemental composition of samples [2, 4, 11]. The Mars Pathfinder sent an Alpha Proton X-ray Spectrometer (APXS) to the surface of Mars to determine the elemental chemistry of rocks [12]. Athena, which is scheduled to launch in 2003, will send a Miniature Thermal Emission Spectrometer (Mini-TES), a Mössbauer Spectrometer, and another APXS on board a pair of rovers. A non-imaging Raman spectrometer was originally included in the Athena payload but was recently moved to a subsequent mission. The Mini-TES will investigate rocks and soils around the
landing site for mineralogical information based on thermal emission spectroscopy. The Mössbauer spectrometer will investigate the oxidation state of iron, the magnetic phase in the martian soil, and iron-bearing minerals in rocks [13]. When used in conjunction with a Microscopic Imager, the elemental and molecular information obtained by the Athena spectrometers will facilitate a search for evidence of past liquid water. These spectrometers previously mentioned, as well as the spectrometers sent to orbit the planet, are gathering mineralogical, elemental, and atmospheric data which will aid in choosing an appropriate landing site for exobiological research. The next step is to send an instrument to Mars capable of identifying organic compounds (this has not been done since the GCMS, aboard Viking) [1]. Raman spectroscopy is not only suited for this task, it provides mineralogical information at the same time. Comparatively speaking, it is a rapid technique and requires no sample preparation. Raman spectroscopy need not be perceived as a replacement for other mineralogical spectroscopy techniques; rather, it is enhanced by the information provided in both elemental and other molecular techniques [14].

**Raman Spectroscopy**

Raman scattering was discovered in 1928 by two Indian scientists, Raman and Krishnan [15]. When light is scattered by a molecule, a shift in frequency may be observed due to an inelastic interaction with the vibrational modes of the molecule. The frequency shift can be positive or negative, depending on the initial energy state of the molecule. Scattered light that loses energy to the vibrational modes of the atom
is called Stokes Raman-shifted light, whereas scattered light that increases in is called anti-Stokes Raman-shifted light. The Stokes spectrum is much stronger than the anti-Stokes since Stokes scattering involves molecules that are initially in a ground energy state. Because anti-Stokes scattering occurs when light is incident upon molecules already in an excited vibrational energy state (which has a low probability of occurrence) the anti-Stokes spectrum is much weaker. However, both the Stokes and anti-Stokes scatter are dwarfed by Rayleigh scattering, which dominates by at least three orders of magnitude [16, 17, 10].

Raman spectroscopy is a method that uses Raman scattering to identify different materials. A narrow linewidth source illuminates a sample, and the scattered light is collected. Rayleigh scattered light is filtered out and the Raman peaks are recorded as a function of relative energy. The resulting spectrum can be used as a fingerprint to identify materials via their different vibrational energy modes. The vibrational energies of molecules and crystals lie in between zero and 5,000 wavenumbers. A wavenumber represents the number of wavelengths per centimeter and is written as cm$^{-1}$ [16]. A Raman spectrum plots emission intensity versus frequency shift relative to the frequency of the source illumination [18].

Conventional Raman spectrometers use high power lasers in the visible region to near-infra-red region (NIR) and require sensitive, cooled detectors. As a result, most Raman systems are large table-top instruments. Recent technology advances in narrow linewidth high power diode lasers and sensitive CCD arrays have reduced the bulk of spectroscopy equipment considerably. The reduction in size, weight and
power consumption has made them available for in situ field use by consumers, and now for spaceflight and planetary exploration.

Wang et al. at Washington University in St. Louis have developed a breadboard instrument for a Raman spectroscopic sensor designed for in situ planetary surface investigations. Similar to commercial Raman field instruments, a probe illuminates the sample and collects a light signal remotely from the spectrometer and power supply, through optical fiber and electronic cable (see figure 1.1). The visible diode laser source is located in the probe head and illuminates a spot.

![Diagram of Raman probe](image)

Figure 1.1 Cross-section diagram of Raman probe built by Wang et al.
size of about 20 microns on the sample. Once the probe is placed on the sample by a robotic arm, the instrumentation inside rotates with respect to the shroud. The objective lens is located off-axis, which enables a scan of the sample and results in a curved line scan of the rock’s mineralogy. Spectra are taken from each point (approximately 20 microns in diameter) along this curvilinear line [14].

Wdowiak et al. at University of Alabama Birmingham also discuss a laser Raman spectrometer system for lander spacecraft, but details of their design are not known at this time [19].

**Combining Raman Spectroscopy with Confocal Microscopy**

Molecular information must be coupled with morphologic evidence and climate information to come to an exobiological conclusion. The Athena payload includes the Microscopic Imager to give context to the spectroscopic data and to look for morphological information [20]. Combining an imaging system with a spectrometer would not only provide two legs of the tripartheid proof needed in exobiology, it could allow for composition to be linked directly with morphology on a microscopic scale.

Our unique instrument designed for Mars surface investigation combines a Raman spectrometer with a confocal laser scanning microscope (CLSM) capable of *in-situ* operation. The CLSM is chosen as the imaging companion to the Raman system because of the compatibility of these two systems. The only fundamental change the confocal microscope makes in the optics of a Raman collection probe is
the scan mirror, which scans the beam to construct an image. The CLSM miniaturizes well (compared to CCD imaging systems) and offers superb resolution with simple optics. The Confocal Microscope and Raman Spectrometer (CMaRS)

![Figure 1.2 Schematic of a fiber confocal optical microscope. Note that the objective lens (and any other necessary light collection optics) are separated from the light source and the detector by some arbitrary length of optical fiber.](image)

...can acquire a reflection-based image of a sample and then take Raman spectra from various locations within the field of view of 300 microns.

The confocal optical microscope differentiates itself from the conventional white light microscope by its shallow depth of focus. This makes it a useful instrument for cross sectional imaging and sample profilometry as well as accurate height and thickness measurements [21]. A pinhole is placed at the illumination and detection points of the microscope which eliminates the collection of any rays that are not scattered from the front focal plane of the objective lens. Thus when an object is...
out of focus, it does not appear at all, whereas with a conventional microscope it would appear blurry. In 1988, Harris invented the fiber-optical scanning confocal optical microscope, in which optical fiber acts as both the source and detector pinhole [22]. This simplification of the optical design not only miniaturizes the microscope as a whole, but also allows the source and detector to be separated from the light collection optics through an optical fiber, as shown in figure 1.2. Consequently, the microscope can be used for in situ investigations, with the source, detector and electronics located remotely from the lens. A confocal optical microscope can image only one point at a time. Consequently, either the sample, the illumination beam, or the objective lens must be scanned in order to obtain an image with an acceptable field of view. However, both sample scanning and objective lens scanning are bulky and slow, and not suited for in situ imaging. Most commercial confocal scanning optical microscopes use beam scanning to create an image. Beam scanning can be achieved by either scanning the pinhole or using a galvanometer mirror [21].

The CMaRS integrates the optical systems of a confocal scanning optical microscope in with a Raman spectrometer, creating an in situ investigation tool for exobiological and mineralogical studies. The microscope and spectrometer share the same source illumination and light collection optics, which keeps size and weight to a minimum. A Micro-Electro-Mechanical Systems (MEMS) two dimensional torsion scan mirror rasters the beam across the sample and the reflected light generates a real time image. Raman spectra can be taken over the entire field of view, a reduced field of view, or from a focused spot within the field of view. Unlike other prototype
Raman spectroscopy instruments proposed for space exploration, the CMaRS combines microscopic imaging with Raman spectroscopy to create a powerful diagnostic tool in both biological and geology investigations.

Figure 1.3 NASA photograph of FIDO. A similar rover will house the CMaRS system with the probe located on the end of the robot arm.

The CMaRS is intended for a robotics exploration of Mars and thus designed for rover-based operation. To achieve this, the bulk of the instrument must reside on the rover body, itself. A compact and lightweight probe contains only the necessary elements for sample illumination and light collection. Optical fiber and electronic cabling will route signals from the probe to the rover body where image processing and spectral analysis take place.

Thesis organization

This thesis will discuss the development of the CMaRS to the brassboard
stage. Chapter two provides a general overview of the entire CMaRS system. The remaining chapters focus on my contributions to this project which include: the CMaRS probe design, operation, and interfacing with the other sub-systems. Chapter three discusses the design of the confocal scanning microscope within the probe, with some theoretical analysis included. The Raman spectroscopy portion of the probe design is addressed in Chapter four. Chapter five includes the specifications for the probe as well as images and spectra taken by the CMaRS. Finally, I will conclude this thesis in Chapter six, discussing the successes and shortcomings of the CMaRS instrument and outlining future instrument development.
CHAPTER TWO

INSTRUMENT OVERVIEW

The CMaRS instrument can be divided into four sub-systems: light launch, probe, image processing and probe control electronics, and spectroscopy system. These sub-systems and their overall integration into the CMaRS instrument are designed for remote field applications. All components except the probe will reside in a compact and environmentally shielded box that sits on a rover body in the case of remote operation or in an operating station. The probe can be deployed to the precise sample location for information collection. Communication from the probe to the

![Block diagram for the CMaRS instrument](image)

Figure 2.1 Block diagram for the CMaRS instrument. Electrical connections are denoted by straight lines, optical connections are shown as curved lines.
CMaRS instrument body is done through optical fiber and electronic cable. Software on a personal computer provides a user interface and displays spectra and images. Figure 2.1 illustrates the links between these systems that make up the CMaRS instrument.

To date, two versions of the CMaRS have been created at two different wavelengths of light. Consequently, each version is unique in its light launch and spectrometer systems. The probe and the image processing and control electronics are nearly identical for both instruments, however. The CMaRS system was originally developed at 852 nm and this thesis will refer this instrument as the CMaRS 852 when the distinction is necessary. The second system constructed uses a 1064 nm laser and will be referred to as CMaRS 1064. Most of the imaging analysis will be treated at 1064 nm, whereas the spectroscopy system will discuss the CMaRS 852.

**Light Launch**

The light launch portion of the CMaRS system encompasses the delivery of illumination light to the probe as well as the returned confocal signal to the photodetector and electronics board. Figure 2.2, is a modification of figure 1.2, where the 3 dB fiber coupler commonly used in a fiber confocal optical microscope has been replaced with a free space beam splitter. The area within the dotted lines is the ‘light launch’ system and will be discussed briefly in this section.
The light source for the CMaRS 852 is an 852 nm distributed Bragg reflector (DBR) diode laser. The narrow linewidth and high power of this laser are essential to the resolution and sensitivity of the spectrometer. The laser light is collimated, travels through a polarizing beam splitter, and is then focused into a polarization maintaining (PM) single mode (SM) optical fiber. This fiber supplies the remotely located probe with illumination light as well as collects the confocal signal. The returning light is cross-polarized to the outgoing light, so when it reaches the polarization beam splitter, it is reflected instead of transmitted. As is shown in figure 2.1, this reflected light is routed through a multi-mode (MM) fiber to the photodetector. At this point, the confocal signal enters the image processing system.

The light launch for the CMaRS 852 is not ruggedized or field-ready. Light launch for the CMaRS 1064, however, was constructed and packaged for field use. The 1064 laser is a diode pumped NdYAG microchip laser coupled directly to the beamsplitter assembly shown in figure 2.2. Replacing the lenses with GRIN (Gradient Index) rods, it essentially uses free space elements that are cemented together and butt-coupled into the optical fiber. The laser system was built by C.P. Yakymyshyn for TRI, Inc.

Polarization optics are used in this module for two reasons. One is to conserve light and avoid loosing 50% of the illumination each way with a regular beam splitter. The second reason is to isolate the laser source from the scattered light. Any feedback into the laser could cause instability in its intensity output.
CMaRS Probe

The CMaRS probe serves two functions: it delivers light to the sample and then collects the backscattered signal, filtering the Raman signal from the imaging signal and sending each to their respective detectors through optical fiber. Figure 2.3, is a conceptual drawing of the basic elements in the probe.

Light entering the probe is immediately collimated and passes through some Raman filters unimpeded. A quarter wave plate (QWP) circularizes the previously linearly polarized light so that upon reflection, the returning confocal signal will have

Figure 2.2 A fiber confocal optical microscope with a free standing polarizing beam splitter (PBS) instead of a fiber coupler. This is the configuration of the confocal imaging portion of the CMaRS instrument. 'QWP' is an abbreviation for 'quarter wave plate.'
an opposite polarization orientation compared to the incoming illumination. Then, a folding mirror directs the beam onto the MEMS scan mirror that rasters the beam in two dimensions, determining the field of view for the microscope. A lens relay magnifies the beam by a factor of 2.3 and images the scan mirror in the back focal plane of the objective lens. The objective lens focuses the illumination light onto the sample. Light that is backscattered off of the sample is collected by the objective lens and retraces the optical path towards the collection fibers. This scattered light contains both spectral and image information from the sample. The elastically scattered light constitutes the imaging signal and is coupled directly into the same single mode fiber from which it originated. A dichroic beamsplitter in the beampath separates the spectral information from the imaging signal by passing the elastically scattered light and reflecting the Stokes Raman shifted light. The Raman shifted light

Figure 2.3 Conceptual drawing of CMaRS probe.
is then routed through a long pass filter before it is coupled into a multi-mode fiber and delivered to the spectrometer.

The MEMS scan mirror (a product of Microvision, Inc., in Bothell, WA) is an essential element for the CMaRS probe, without which this level of miniaturization would not be feasible. It is not only compact and robust, but it outperforms its larger alternatives, scanning in two dimensions fast enough for real time imaging. The two dimensional imaging capabilities of the CMaRS probe are enhanced by a focusing mechanism that provides the third dimension. Figure 2.3 shows a piezo-actuator located in the upper right hand corner of the CMaRS layout. This actuator drives the objective lens forward and backward to allow for one millimeter of focus control. The probe can be pressed up against a sample and the objective lens is moved to find the optimum focus. Together with video-rate two-dimensional imaging, the focus control allows the user to perform image profilometry on a sample. Since confocal microscopes only image one plane at a time, by physically stepping through image planes in discrete increments, CMaRS can investigate the surface relief of a sample. Post processing of the profile images is an option that allows the user to construct a composite image combining the features of each layer into one extended depth-of-field image.

Image Processing and Probe Control Electronics

The hardware and software for the probe are responsible for data signal acquisition, video signal generation, scan mirror control and focus control. This is
accomplished through four separate electronics modules: the Scan Converter (SC), the Microvision Electronics Module (MEM) and the Micropulse Systems Electronics Module (MSEM), and controlled by the user through the Software Control Interface (SCI). The MEM and MSEM receive conditioned power from and are controlled by the SC.

Figure 2.4 Image processing and probe control electronics block diagram

The SC receives the optical image signal and amplifies it, converts it into digital image frames, and then converts these frames into a continuous data stream in an NTSC video signal format. Through the SCI, the user can choose to watch free-running video or individual video frames on a computer monitor. Scan Mirror control is shared between the SC and the MEM. The MEM drives the horizontal axis of the mirror at its natural frequency and provides a horizontal synchronization signal to the SC. The SC uses this horizontal sync signal to generate the vertical scan signal and a frame. The user can power these on and off and adjust the scan amplitude of the
vertical axis through the SCI. The MSEM activates the dynamic focusing system on the probe. Focus control is interfaced from the user to the MSEM through the SCI and the SC. Development and coordination of these systems was done by M. J. Faulhaber, M. T. Wood, and B. Tikalsky.

**Spectroscopy System**

The Raman Spectroscopy System for the CMaRS is developed and built by Top Raman Instruments (TRI) of Laramie, Wyoming. TRI works together with Micron Optical to produce a line of compact, field rugged spectroscopy instruments.

Spectrometer development and availability has governed the CMaRS source illumination choice. TRI manufactures Raman Spectrometers at 633 and 852 nm for commercial use, and a 1064 nm system is currently under development. The CMaRS prototype instrument has been built at both 852 nm and at 1064 nm, thus using the Solution 852, which is TRI’s 852 nm spectrometer, and their development version for 1064 nm. Each spectrometer has its own design, some of which is dictated by wavelength dependent components such as the detector. However, the design concept is comparable for both, based on a Czerny-Turner dispersive spectrometer design.

The Raman filters housed in the CMaRS probe separate the Raman back-scattered light from the confocal signal. This light is delivered to the spectrometer through a multi-mode optical fiber. As Raman scattering is a weak process, it is important to maximize the light collection capabilities of the probe and use a fiber
with a well-matched numerical aperture and a large core size. However, due to spectrometer design in this case, fiber core size effectively dictates spectrometer resolution and a balance is reached using a 50 um core step index fiber for Raman light collection.

The TRI spectrometer design is based on the Czerny-Turner spectrograph (see figure 2.5). Light entering the spectrometer is directed onto a grating. Diffracted light is spread according to wavelength and routed to a detector. The grating is stationary so a position sensitive array must be used as a detector. The 852 system uses a silicon CCD (charge coupled device) camera whereas the 1064 system uses an InGaAs camera. Figure 2.5 shows a zig-zag design which incorporates curved mirrors. The TRI design is a variation of this, using on-axis optics to eliminate astigmatism that would create measurement error with a pixel-based position-sensitive detector.

Figure 2.5 The Czerny-Turner spectrograph.
This thesis will not address spectrometer design in any further detail. Instead, the following chapters will concentrate on how the spectrometer interfaces with the CMaRS system as a whole, and specifically, with the CMaRS probe. Results in chapter 5 will include examples of spectra taken by the Solution 852 using the CMaRS probe as the light collection device.
CHAPTER THREE

CONFOCAL DESIGN

The basic elements required to build a confocal scanning optical microscope (CSOM) are point illumination, point detection, a confocal lens system, and a method of scanning the sample [21]. In the introduction, the basic elements of the CMaRS were discussed briefly. An optical fiber provides the point illumination and point detection for the microscope. A MEMS scan mirror is used to scan the beam across the sample, instead of moving the sample itself. This chapter will address these elements in further detail and introduce the optical system, as well as the general layout and design of the probe. Theoretical performance measures and system simulations will also be presented.

Optical Design

Design constraints

The confocal imaging system is designed to interface with the Raman spectrometer. A several hundred micron field of view would encompass a large enough sample region to determine morphological information. Design goals for the CMaRS are a field of view of 300 microns and a spatial resolution of 1 micron. These design parameters are primarily dependent upon the scanning angle of the scan mirror, and the effective numerical aperture (NA) and focal length of the objective lens.
The image for a confocal microscope is built up point by point using a scanning mechanism; and in the case of the CMaRS, this is accomplished by rastering the beam across the sample with a scanning mirror. The placement of the scanning mirror is critical to the performance of the microscope. To ensure a constant magnification regardless of the focus position, the system is telecentric, meaning the entrance or exit pupil must be located at infinity [23]. Placing the scanning mirror in the back focal plane of the objective lens prevents vignetting of the reflected beam and keeps the image created by the microscope from becoming distorted. (See figure 3.1)

![Diagram](image)

**Figure 3.1** This figure illustrates the telecentric stop and its importance for beam scanning systems. If the scanning element is placed in the back focal plane of the objective lens, or at the telecentric stop, as it is in diagram A, the image is accurate whether the object is in the focal plane or slightly out of focus (depicted by the dotted line). Diagram B illustrates a scanning element that is not placed at the telecentric stop. Note the error in image size when the object is slightly out of focus versus when it is in focus [23].

**Optical Path**

The optical design strives to accommodate these constraints. Light entering the probe from the fiber is collimated and travels a zig-zag path towards the sample.
From the fiber end-face to the folding mirror it travels approximately 4.3 cm, passing through Raman filters and a quarter wave retarder. The folding mirror reflects this light at a 45° angle onto the MEMS scan mirror, 1.5 cm away. The scan mirror redirects the beam parallel to its original path toward the sample. It travels approximately 6.35 cm through a beam expander, the objective lens and a sapphire window before it hits the sample. Light reflected off of the object re-traces its path back to the optical fiber.

The excitation beam and the reflected signal beam are limited in area by the scan mirror, which acts as the aperture stop for the system. This aperture dictates the size of the collimated beam entering the system via the optical fiber and collimating lens. The aperture stop for the system is imaged in the back focal plane of the objective lens, resulting in a telecentric system. The exit and entrance pupils are located at infinity.

Figure 3.2 Optical path for the confocal microscope. (This diagram does not include any interface optics for the Raman spectrometer.)
The following sections will discuss the necessity of each of these elements as well as their specifications and any tolerances involved with their precise location in the optical path (with the exception of the Raman filters, which will be discussed in detail in chapter 4).

**Lens choices**

Though it is desirable to place the scanning mechanism in the back focal plane of the objective lens, due to the geometry of the MEMS scan mirror and its magnetic enclosure and mount, it is physically impossible to do so. To accommodate this, a lens relay images the scan mirror into the back focal plane of the objective lens, concurrently expanding the beam. This beam expansion is desirable to increase the effective numerical aperture of the microscope. The beam is collimated to measure approximately one millimeter in diameter at the $1/e^2$ intensity point. In using a 2.3x beam expander, the beam will be roughly 2.3 millimeters in diameter when it reaches the objective lens.

All lenses used in the CMaRS probe are molded aspheric lenses manufactured by Geltech, Inc. The glass material is a Corning derived C0550 and the difference in index of refraction between the lens design wavelength of 780 nm and the operating wavelength of 852 nm is negligible (0.0018). The lenses are coated with a multi-layer broadband anti-reflection coating that provides less than one percent reflection between 650 and 1050 nm.
The lens relay is made up of Geltech lenses 350240 and 350280. These lenses have effective focal lengths of 8 mm and 18.4 mm, respectively. This creates a beam expansion of 2.3x, and a scan angle reduction of the same magnitude. Figure 3.3 illustrates the placement of the lenses with respect to the scan mirror. The design images the scan mirror in the back focal plane of the objective lens, creating a telecentric system that will produce accurate images consistently throughout the scan range.

The objective lens, Geltech part number 350230, has an effective focal length of 4.51 mm and a NA of 0.55. An incident beam measuring approximately 2.3 mm (at the $1/e^2$ intensity point) reduces the effective NA to 0.25. This focal length provides a compromise between the desired field of view and resolution of the microscope. With this focal length and beam diameter, the theoretical diffraction limited spot waist, $\omega$, is 1.36 microns ($\omega=\lambda/\pi\theta$, where $\theta$ is the angle of the $1/e$ ray relative to the optical axis in the sample space). The field of view is then dependent upon the scan angle of the scan mirror. An optical scan angle of 6°, zero to peak and measured at the scan mirror (which is well within the specifications of the mirror).
translates roughly to a field of view of 475 microns which would meet the design goals for the CMaRS.

Polarization

The CMaRS light launch and probe systems employ polarization controlling optics for two reasons. One is to avoid interference effects in the confocal image due to the long coherence length of the laser. The second reason is to ensure maximum possible light efficiency for both imaging and Raman spectroscopy.

Light leaving the laser diode is linearly polarized, aligned with the short axis of the elliptical beam. It is incident upon a polarizing beam splitter, oriented such that most of the light is coupled into a polarization maintaining (PM) optical fiber and delivered to the probe. As was discussed in the ‘Light Launch’ section of chapter two, the imaging signal that returns through this same fiber will have an orthogonal polarization to the excitation light, thus it will reflect from the polarizing beam splitter instead of passing through and being coupled back into the laser. For the CMaRS 852 prototype instrument, the light launch is a free-space system, and uses a cube beam splitter and conventional bench-top optics. A half wave retarder simplifies launching the linear polarized light into the primary fiber axis. This is a bulky solution with little tolerance for changing temperatures and impractical for field use. As was mentioned in Chapter two, the CMaRS 1064 source environmentally packages the same launch system used for the CMaRS 852. The half wave retarder is not necessary for this system, as once coupling is optimized, the optics are cemented together. Other possible solutions for environmentally rugged light launch
modifications include using a polarization maintaining 3-dB fiber coupler or fiber coupled optical circulator.

The PM fiber is connectorized such that light enters the probe polarized in a horizontal direction. For the purpose of this thesis, this axis will be referred to as the x-axis, and we can call this TM polarization. TM polarized light is preferred (over TE) because the transmission curve through the dichroic filter versus angle of incidence is consistently higher than that of the TE light. The transmission is also more constant over a larger span of incidence angle for TM than for TE, which is important since precise angular alignment of this filter is not guaranteed. This will be discussed further in chapter 4, where the Raman filters are examined in detail.

Inside the probe, a quarter wave plate in the beam-path circularizes the polarization of the beam. With each reflection along the optical path, the polarization changes handedness. The beam reflects off of the folding mirror, the scan mirror, and finally off of the sample before returning to the quarter wave plate (via another reflection off of the scan mirror and the folding mirror). Thus when the beam passes through the quarter wave plate a second time, it has opposite handedness with respect to when it came out of the quarter wave plate. The quarter wave plate converts it back to linearly polarized light, but now it is of the opposite orientation from the incoming light. Thus the excitation light that is delivered to the probe through the PM fiber is horizontally linearly polarized, whereas the elastically scattered confocal signal that enters the fiber is vertically polarized. When the confocal signal light has traveled through the fiber and is incident upon the polarizing beam splitter within the
light launch system, it will be transmitted instead of reflected, as it is cross polarized opposite to the laser light.

In practice, tracking the polarization of the beam is a bit more complex, as the quarter wave plate is not the only optical element modifying the polarization of the beam. A window in the probe housing is necessary for environmental protection of the instrument. Sapphire is our the material of choice with its hardness properties and scratch resistance, however its birefringence adds to the retardance of the quarter wave plate and complicates alignment.

**Imaging Capabilities**

A simplified confocal microscope model is useful for a theoretical performance analysis. A complete mathematical treatment will not be discussed in this thesis. The reader can refer to Dickensheets [24], Gu, Sheppard and Gan [25] and Wilson and Sheppard [26] for an involved study of image formation for the confocal microscope. For the simplified diffraction limited confocal microscope it can be shown that:

\[ I = \left| p^* \ast s \right|^2 \]  

(3.1)

where \( s = s(x,y) \) is the sample reflectivity and \( p = p(x,y) = p(r) \) is the field of the optical beam in the sample plane (let \( r^2 = x^2 + y^2 \)). If we assume the sample to be a perfect point reflector, then \( s(x,y) \) becomes a delta function and \( I = \left| p(r) \right|^4 \). This is the intensity point spread function (PSF) of the simple fiber confocal optical microscope.
FCOM as shown in figure 3.4. Considering a gaussian beam input to this system, the PSF becomes [25]:

\[
I(r) = \left| \int \frac{2 \pi a_0^2 \omega_0}{\lambda f_\omega} e^{-\left(a_0 r / \omega_0\right)^2} J_0(2 \pi a_0 r p / \lambda f) \rho d\rho \right|^4
\]  

(3.2)

This is essentially the Hankel transform of a Gaussian field distribution at the pupil [24]. In this equation, \( a_0 \) is the radius of the pupil at the objective lens, \( \omega \) is the Gaussian beam field 1/e radius at the objective lens, \( \omega_0 \) is the mode field radius of the beam measured at the fiber endface, \( f \) is the focal length of the objective lens, and \( \rho \) is a unitless aperture variable (\( \rho = 1 \) at the edge of the aperture). \( I_0 \) is the on-axis intensity at the fiber end-face and the quantity \( I_0 \omega_0 / \omega \) is the peak field strength at the pupil center where the beam has expanded to a width, \( \omega \). The field at the pupil can be found from the field at the fiber end-face, indicated in figure 3.4.

A parameter

Gu, Sheppard, and Gan of the University of Sydney in Australia introduced a dimensionless parameter, the ‘A-parameter’ which simplifies a transfer function.

Figure 3.4 The simplified fiber confocal optical microscope. The pupil is between the two lenses, indicated by the arrows, with radius \( a_0 \).
analysis of a fiber confocal microscope. [25] They define ‘A’ as:

\[
A = \left( \frac{2a_{\text{mirror}}r_0}{\lambda f_c} \right)^2 = 2\left( \frac{a_0}{\omega} \right)^2
\]  

(3.3)

where \( r_0 \) is the intensity 1/e radius \( (r_0 = \omega_0 / \sqrt{2}) \) and \( f_c \) is the focal length of the collimating lens and \( a_{\text{mirror}} \) is the aperture radius at the scan mirror. The A-parameter can be conceptually considered as a dimensionless parameter proportional to the square of the ratio of the pupil radius to the Gaussian beam 1/e field radius.

Theoretical analysis of a fiber confocal microscope’s performance in terms of the A parameter is convenient for design. This section will address the point spread function, the axial response and the efficiency of the microscope with respect to A via a numerical analysis using MATLAB.

For the CMaRS probe, the aperture stop is at the scan mirror. Though the mirror is square, the rest of the system exhibits circular symmetry and in order to simplify calculations, the mirror is often considered as a circular aperture within the scope of this thesis. The length of one side of the square mirror (1.4 mm) is taken as the diameter of the pupil (as opposed to using the diagonal of the square.) The physical aperture stop (radius \( a_{\text{mirror}} \)) is imaged into the back focal plane of the objective lens by the beam expander, and this image can be considered the effective aperture for our system, \( a_0 \), and is used for image analysis. See figure 3.4 for a graphical representation of this. For the CMaRS probe, \( a_{\text{mirror}} = 0.7 \text{ mm} \), and \( a_0 = (2.3)a_{\text{mirror}} \), where 2.3 is the magnification of the beam expander. These aperture dimensions are fixed, therefore, control over the \( A \) parameter resides in varying the size of the
incoming collimated beam. The beam waist at the pupil behind the objective lens is found to be \( \omega = 2.3(f_c)/\left( \lambda \omega_0 \right) \), where \( f_c \) is the focal length of the collimating lens and \( \omega_0 \) microns is the mode field radius leaving the fiber. For our microscope, \( f_c = 4.51 \) mm and \( \omega_0 = 3.3 \) microns.

\( A = 0 \), \( A = 2 \), \( A = 4.57 \), and \( A = 8 \) microns.

Figure 3.5. Normalized confocal point spread function for different values of \( A \), NA = 0.25. The solid line indicates the actual curve for the CMaRS when \( A = 4.57 \).

Considering these two apertures, \( a_{\text{mirror}} \) and \( a_0 \), and their respective beam waists, the \( A \) parameter and the numerical aperture can be calculated for the CMaRS. For \( \lambda = 1064 \) nm, \( A = 4.57 \) and when \( \lambda = 852 \) nm, \( A = 4.6 \). The numerical aperture (NA) for the CMaRS can be approximated as \( NA = a_0/f_{\text{obj}} = 0.335 \). The beam waist does not
fill this aperture, however, so the effective numerical aperture is found to be NA_{eff} = \omega / f_{obj} = 0.25.

Point Spread Function

The confocal point spread function (PSF) is a measure of the resolution of the microscope. Substituting the $A$-parameter into equation 3.2 causes the intensity PSF to be [25]:

$$I(r) \propto \left| \int_0^1 e^{-\frac{r^2}{2}} J_0 \left( \frac{\omega}{f\lambda} r \rho \right) \rho d\rho \right|^4$$

Figure 3.5 shows the theoretical intensity PSF ($\|p(r)\|^4$) plotted versus the focal plane radial coordinates normalized to $\lambda$. Each curve corresponds to a different value of $A$.

Note that for the case where $A=0$, the first minimum point is at 1.8 microns at $\lambda=1064$ nm. An $A$ parameter equal to zero corresponds to an infinitely wide beam waist, or a 'top-hat' illumination. The Fraunhofer diffraction pattern for a uniformly illuminated circular aperture is an Airy pattern. This pattern predicts the first minima (or zero point) in the intensity distribution to be located a distance, $r=(0.61)\lambda/NA$. In this case, for $\lambda=1064$ microns and NA=0.335, $r=1.9$ microns. We must remember that the Fraunhofer diffraction pattern is a paraxial approximation. With a fully illuminated pupil, the NA for the CMaRS is 0.335 (this is far from the paraxial case) and this explains the small difference between this prediction and the results shown in figure 3.5.

From the plot shown in figure 3.5, we predict that for $A=4.57$, the $1/e^2$ confocal intensity beam waist is 1.15 microns at 1064 nm and the confocal PSF full
width at half maximum (FWHM) is 1.38 microns. From this point response, we can generate a line or edge response of the system that we can compare to actual measurements. Figure 3.6 displays the confocal edge response for the CMaRS for \( A=4.57 \). The 20-80% rise for this edge is equal to 1.12\( \lambda \) when normalized to the wavelength. At 1064 nm, the predicted edge response is 1.19 microns.

![Figure 3.6 Edge response (intensity) for the simplified confocal microscope plotted versus \( x/\lambda \) (where \( x \) is a radial dimension in the focal plane). \( A=4.57, \text{NA}=0.25 \).](image)

**Axial Response**

The cross-sectioning abilities of a confocal microscope are dependent upon its depth of focus or axial response, also called \( V(z) \). Intuitively, we know that high NA objective lenses will have a tight focus and therefore a narrow axial response.

\[
I(u) = \frac{A^2}{\pi^2} \frac{(1-e^{-2A} - Ae^{-A} \cos u)}{\pi^2 - 2A \sin^2 u - A^2}
\]

(3.5)
Equation 3.5 shows the axial response of the ideal FCOM to a perfect plane reflector [25].

where \( u = 2kz(1 - \cos \theta) \) is a dimensionless defocus parameter and \( \theta \) is the angle corresponding to the numerical aperture of the microscope such that \( NA = \sin \theta \). Figure 3.7 is a plot of equation 3.5 for four different values of \( A \). The FWHM at 1064 nm is 14.3 microns.

![Figure 3.7 Normalized projected axial response of a confocal microscope for different values of A, NA=0.335. The horizontal axis is in units of mm/\( \lambda \).](image)

Efficiency

It is clear from the theoretical axial response and the PSF that a value for the \( A \)-parameter smaller than 4.57 is desirable. However, these performance measures are a trade-off with light efficiency. As \( A \) decreases in size, the beam waist is getting
much larger than the pupil, thus decreasing the amount of light allowed through the system. Figure 3.8 shows the round-trip efficiency for the CMaRS 1064 as the waist of the incoming beam is varied and incident upon a square aperture. This plot assumes that the only losses in the system are due to the limiting size of the aperture. The beam is assumed to be a Gaussian. The zig-zag in the beam path is taken into account, as the 22.5° angle of incidence effectively reduces the size of the scan mirror with respect to an incoming beam. The actual beam waist ($1/e^2$ intensity radius) of 0.5 mm corresponds to an efficiency of 97% round-trip for 1064 nm. This high efficiency was chosen at the expense of spatial resolution and axial response for the Raman spectroscopy portion of the system. Light collection is an important parameter to enable quality spectra and this governed the value of $A$ that was chosen.
Other factors that influenced this choice were the off-the-shelf optics available, the fixed size of our scan mirror, and the trade-off between the field of view vs. N.A. An $A$ parameter equal to 4.57 balances all these considerations well.

**Zemax simulation**

Zemax is an optical design software program used to simulate the optical performance of the CMaRS. This is particularly valuable in addition to the MATLAB analysis because it allows us to insert the actual aspheric lenses used by the CMaRS into a simulation. Figure 3.9 shows the layout of the optical system considered and optimized with the scan mirror taken as the aperture stop. Analysis was performed at 852 nm and at 1064 nm, both on-axis and at two different scan angles corresponding to fields of view of 100 microns and 300 microns. The 1064 nm data will be presented since experimental verification of these performance measures will be presented for 1064 nm in Chapter 5.

![Figure 3.9 Zemax layout for performance optimization and simulation of CMaRS.](image)
Figure 3.10 Optical path difference plots for on and off-axis beam paths in the 1064 lens system.

Optical Path Difference The optical path difference (OPD) is plotted for the on-axis case as well as for two different scan angles in x and in y (see figure 3.10). These optical scan angles are 1.26 and 3.8 (0 to peak, measured at the mirror) which correspond to a field of view of 100 microns and 300 microns, respectively. The maximum on these axes is 0.5\(\lambda\), which indicates a reasonable performance of the system. In the case of axial propagation, path differences are within 0.1\(\lambda\). For the small scan angles (1.26 optical deflection, 0-peak, at the mirror), there is little change from the on-axis case. However, for the larger field of view, especially the axis that is not being scanned begins to exhibit path differences approaching 0.3\(\lambda\). We can expect to see some change in the image quality at the edge of the field of view for a 300 micron image.
Spherical Aberration The spherical aberration coefficient (as calculated by Zemax) varies from \(-(0.1188)\lambda\) to \(-(0.1190)\lambda\) as the objective moves through its range of focus. These coefficients are very small and show that there is very little spherical aberration in our image, over the full focus range.

Variable Focus Performance The focus control steps the objective lens forward and reverse along the axis of the beam. At either extreme, the PSF shows no noticeable change. Other issues that could change the PSF are de-centration of the lenses. The lens mounts are subject to human error in fabrication, which ensures that axial alignment will be less than perfect. Zemax simulations showed little difference in performance with a de-center of 0.1 mm (or 4 thousandths of an inch). Mounts for these lenses were given 2 thousandths of an inch tolerance for critical dimensions. This holds the y-axis (vertical) accurately on center, but precision in horizontal alignment is reliant upon assembly.

Opto-mechanical Design

Design Constraints

The CMaRS was conceived as a part of the Mars Instrument Development Program (MIDP). With a surface exploration of Mars as its goal, primary design concerns are size, weight and power. The CMaRS instruments described in this thesis are breadboard instruments, which means they are prototypes in the development towards a flight instrument. The design has attempted to minimize volume, mass, and
power consumption while serving as a proof of concept and leaving room for any minor adjustments and additions.

This prototype does not take into consideration many of the environmental factors a flight instrument must be prepared for. The temperatures a Mars science instrument will be exposed to both in flight and on the surface of Mars (at the middle latitudes) are between -110° C and +40° C. [27] These are not necessarily operating temperatures, but temperatures the instrument must be able to withstand and under which the instrument must maintain its structural and operational integrity.

Considering the locations on the surface of Mars where the CMaRS would likely be sent, the operation range for the CMaRS is between -80° C and -10° C. It is possible to use a thermal insulation system and heating element inside the probe to raise the lower end of these specifications to -40° C. The CMaRS 852 and CMaRS 1064 prototypes are designed for operation at room temperature and have yet to undergo thermal modeling and testing for the extreme temperature swings it must withstand for a Mars mission. The optical mounts and the probe exterior have been constructed almost entirely out of aluminum to minimize thermal expansion differences, and adhesives and electrical components have been chosen which can cycle to -50° C, but the instrument has not yet been thermally cycled.

Other environmental concerns which this version of the CMaRS does not address and would need to be considered for a planetary exploration instrument are outgassing, vibrational testing, acoustic testing, and sealing.

For any type of remote application, simplicity in design is most efficient for statistical reasons. Since repair operations on Mars are not feasible, it is important to
minimize opportunities for failure. The CMaRS design avoids moving parts when possible, but a purely rigid instrument was not possible by definition of a confocal scanning microscope.

![AutoCAD drawing of probe layout](image)

**Figure 3.11(a)** AutoCAD drawing of probe layout

![Photograph of CMaRS before any electrical connections were made.](image)

**Figure 3.11(b)** Photograph of CMaRS before any electrical connections were made.
Probe Layout

The probe layout is designed to conserve volume while providing a means of making simple adjustments and alterations to the parts involved. A rectangular base-plate is the foundation, and all pieces are mounted to this base-plate from above or below. Aluminum was chosen as the fabrication material for its ease of acquisition, low density and non-magnetic property. Additionally, aluminum is relatively easy to machine.

Figure 3.11(a) shows an AutoCAD drawing of the probe layout from a top view. It identifies most of the individual parts in the probe and their relative location. This section will discuss in detail the integral mechanical elements in the probe, such as the scan mirror, the collimation unit, and the focus control. Additionally, the mounts for all elements, both optical and mechanical will be described briefly.

Mechanical Elements

MEMS Scan Mirror The MEMS scan mirror, built by Microvision, Inc. is a bi-axial scan mirror fabricated from single crystal silicon via bulk micromachining technology. Figure 3.12 shows the mirror’s general architecture. The system consists of two hinged concentric plates, which operate simultaneously and perpendicularly to each other to give the mirror a full range of motion around the x and y axes. The inner plate scans the beam horizontally (as the mirror rotates about the vertical axis) and is driven electrostatically. This axis is driven at resonance (approximately 19 kHz) and thus referred to as the ‘fast scan.’ The outer plate is rotated via a magnetic
drive, scanning the incident laser beam vertically. This axis is driven off-resonance at 30 Hz, thus referred to as the ‘slow scan’.

The bulk silicon layer is epoxied to a ceramic or glass substrate which provides structural support and contacts for electrical connections. Including the substrate, this MEMS device measures 12.8 mm x 7.2 mm x 1 mm thick, though the mirror, itself, measures only 1.4 mm x 1.4 mm. The size of the overall system is most affected by the magnetic drive, which requires relatively large rare earth magnets to generate a constant magnetic field across the mirror [28]. Including the magnets and aluminum mount for the mirror, the scan mirror system measures 1.1” x 1.1” x 0.55 “ deep.

The slow scan is driven by an alternating current passing through a magnetic field. The NdBFé24H magnets and their stainless steel return path (manufactured by Magnet Applications, Inc.) envelop the mirror, creating a constant magnetic field of approximately 5 mGauss across the face of the mirror. The outer plate of the machined silicon acts as a substrate for a current coil as shown in figure 3.12. The CMaRS SC module generates a sawtooth waveform which drives an alternating current through the coil and torques the mirror. Driving the slow scan off-resonance not only keeps the part from self-destructing due to enthusiastic scan angles, it puts the mirror in a linear region of its frequency response curve and allows the slow scan to be controlled open-loop.
The electrostatic drive requires a high voltage sinusoidal signal sent alternately to the two electrodes located on the ceramic substrate directly beneath the scan mirror. This scan axis has an extremely high Q factor, due in part to the high resonant frequency at which it is run. Because of this, if the resonant frequency of the mirror were to change due to environmental factors while the scan is running, the scan angle would lose amplitude very quickly. To avoid drastic changes in scan amplitude, Microvision has incorporated a sensing system and feedback control of the drive frequency [28].

The Microvision MEMS scan mirror meets all of the required specifications for use in the CMaRS instrument. Mechanical scan angle (MSA) measures the amplitude of the angle, 0 to peak, that the mirror moves while scanning. Microvision, Inc. reports achieving a MSA of 6.7° on the fast scan axis and 4.8° on the slow scan axis [28]. This deflection is more than adequate for the CMaRS imaging system.
Images from the CMaRS table-top proof instrument have a field of view of 300 microns, corresponding to a MSA of only 2°. The CMaRS system is therefore not limited by the scan mirror.

Focus Control  Control of the depth of focus is achieved using a piezo driver built by Micropulse Systems, Inc. (located in Santa Barbara, CA) to move the objective lens along the z-axis. The L-104 driver (diagram in figure 3.13 and photograph in figure 3.14) is designed to operate in pairs to achieve linear or rotary motion of a separate element. However, the CMaRS probe uses only one L-104 driver to move a conventional linear slide back and forth. The objective lens mount is secured to the top of the linear slide, and mechanical stops ensure a maximum of one millimeter of total motion.

The L-104 driver consists of a spring loaded stainless steel block adhered to

![Diagram](image)

Figure 3.13  Diagram of L-104 piezo driver and linear slide. The objective lens mount is fastened to the top of the linear slide through the holes shown. The slide and the objective lens then move in the direction of the arrow.
two piezo blocks attached to either side of an alumina wedge. The alumina makes contact with the element that moves, and the piezo blocks are activated individually to make the slide move in one direction or the other. ‘Activating’ the piezo block consists of sending it a 134 kHz sine wave at approximately 600 volts peak to peak.

Pulsing this signal for a known time increment moves the slide a discreet distance.

The L-104 driver operates on frictional principles. With each oscillation, the piezoceramic element is stretched and compressed, pushing the alumina wedge against the slide and then pulling it away. In effect, the slide is hammered (in very small increments) in one direction, and then the opposite piezo block is activated, and it is hammered back to its starting point [29]. This constant hammering makes it necessary to choose a material with like hardness to the alumina wedge for the driven face of the slide. The slide is made of aluminum, which is extremely soft when compared to alumina, so a piece of alumina was epoxied to the side of the linear slide.

Micropulse Systems specifies their L-104 driver pair to have a resolution of two micro-inches (0.05 microns) [29]. Since the CMaRS does not use the L-104 driver in its intended fashion (we are using one driver instead of a pair) these
attempt to keep the motion of the lens as linear as possible. One full revolution of the screw moves the lens 0.0125 inches.

Control over z-axis position is achieved similarly. The x-y mount shown in Figure 3.15 is attached to the end-plate of the CMaRS via the three mounting holes and a piece of steel shim and a ‘spacer block.’ The end-plate is the piece the optical fibers and electrical cable are connected to, and also serves as one of the exterior walls for the probe. A translation screw maintains a set distance between the end-

![Collimation lens mount for x-y positioning of lens.](image)

piece and the collimating lens mount. The shim acts as a hinge and translation of the lens is achieved by turning the screw and pushing the lens away from the end-plate. The shim steel piece is bent to oppose this motion before assembly, and is an effective spring.

This collimation assembly is a functional solution for the application. It is not an answer for a situation desiring frequent adjustments of the collimation or beam position as fatigue in the hinges would quickly become a problem.
Optics mounts

The elements of the CMaRS probe remaining to be discussed in this section are the mounts for the following optical devices: the Raman filters, the quarter wave plate, the folding mirror, the scan mirror, the lens relay, the objective lens and the sapphire window. These mounts are all machined out of aluminum. Whenever possible, clearance holes are used instead of threaded holes so they can be mounted to the baseplate from the top and adjusted easily. Tolerances are generally between 2 and 5 thousandths of an inch. Optics are held in place with Loctite E30CL epoxy. Figure 3.16 shows all of these mounts in place from a top-view.

The folding mirror mount is a simple L-shaped piece with only one clearance hole in its base to mount it to the base-plate. The folding mirror rests on a lip which
ensures proper mirror height and is epoxied into place. It does an adequate job of directing the beam onto the scan mirror, but leaves no room for tilt adjustments. For future versions of the CMaRS, this is a desirable feature to have, especially with the focus control modifications discussed in Chapter 6.

The sapphire window is mounted directly into the nose-piece for the CMaRS. The nosepiece is the exterior of the probe which faces the sample directly. It is basically a flat aluminum piece with a protruding cylindrical snout. There is a counter-bored hole for the sapphire window and it is epoxied into place. As was discussed earlier in this chapter, the orientation of the sapphire window is critical to the polarization and therefore the return signal of the microscope. Alignment during assembly is a coarse and difficult process. Future designs should take this into consideration.

The mount for the MEMS scan mirror is an ‘H’ shaped aluminum piece with small flanges for mounting it to the base-plate. Figure 3.17 displays a photograph of this mount from the front with the mirror and jumpers epoxied in place (shim pieces for strain relief are not shown). At the center of the mount is a recessed area slightly

Figure 3.17 Scan mirror and mount. Off to the right and left of the mirror are ‘jumpers’ for electrical connections.
larger than the ceramic mounting plate for the scan mirror. Along the sides of the mirror, space is left for electrical connections to the mirror, and rectangular pieces of shim stock are mounted with hex head screws to secure the wires in place and provide strain relief.

The filter block has counter-bored spaces for the filters, with the angles pre-cut. Therefore, the relative angles between the long pass filter, the band-pass filter, the dichroic beamsplitter and the second folding mirror are pre-set. The angle of the entire block can be coarsely adjusted with the mounting screws.

The quarter wave plate (QWP) mount provides coarse axial rotation control. The QWP sits in a short cylindrical tube, which in turn slides into a counter-bored mounting block. The cylinder can be rotated to the desired position and then secured by tightening a set screw which sits in the mounting block. This allows for adjustment of the polarization state of the beam during assembly and testing.

The lens relay mount is an aluminum tube mounted to a rectangular block with phalanges for mounting to the baseplate. The lenses are epoxied into each end of the tube. This mount fixes the lens separation of the relay and therefore the axial dimensions are held to tight tolerances of 2 thousandths. Height and centration are also crucial, as they are for all lenses. The mounting holes in the base allow for slight translation and angular adjustment. The height, however, is once again dependent upon machining tolerances.

The objective lens mount is a long tube with a recessed area for the lens at one end. The other end is fixed to an L-shaped piece that mounts to the linear slide. The
odd shape of this mount was chosen to accommodate the lens relay tube and to provide a ‘snout’ at the end of the CMaRS.

Connections and Packaging

The optical mounts are fastened to a quarter inch thick aluminum base-plate and then enclosed on all four sides and from above by aluminum plates, also fastened with screws. The plate that is put in contact is the ‘nose-piece’ and holds the sapphire window. The opposing plate, the end-piece, is where the light enters and leaves the probe, where all optical and electrical connections are made. Figure 3.16 shows the optical and electrical cables coming into the assembled probe.

The illumination fiber is connectorized with a FC angle polished connector (APC) to eliminate back-reflections from the end-face of the fiber and try to minimize interference effects in the imaging system. Because this is a polarization maintaining (PM) fiber whose orientation in non-trivial and the angle polish of the connector also dictates a particular orientation, the fabrication of this fiber patch-cord is an involved procedure. The 1064 fiber patchcord used with the CMaRS probe to generate the data presented in chapter five is made from Corning Puremode fiber for 980 nm and Molex APC connectors. It maintains a polarization ellipticity equal to 0.023.

The Raman collection fiber is a much less sensitive endeavor. The multi-mode fiber patch-cord uses FC connectors which makes fabrication a routine process.
The optical connections are made through bulk-head connectors which were milled down to an appropriate size and fastened to the end-plate. The bulk-head connector for the PM fiber matches the angle polish of the connector.

Electrical connections are made through a miniature 25 pin connector manufactured by Nanonics Corporation. The scan mirror requires eight wires, two of which are high voltage. The piezo driver necessitates three wires for operation, two of which are also high voltage. A 25-pin connector accommodates these high voltage lines, by alternating between active and inactive pins. Few manufacturers carry electrical connectors small enough for the CMaRS application. While this Nanonics connector meets the size requirement, it lacks robustness for repeated connecting and disconnecting. A future version of the CMaRS should consider another solution.

With the optics enclosed in its aluminum box and the optical and electrical [Figure 3.18 CMaRS probe mounted to the tri-pod.](#)
connections made, the CMaRS probe is prepared for field operation (in moderate, dry weather). While image acquisition is fast (approximately 70 milliseconds), depending on the sample, Raman spectra can take seconds, minutes, and even hours to acquire. This fact demands a rigid mount which can hold the CMaRS probe up to the sample for an extended period of time. In the event of rover-based operation, this would be achieved using a robotic arm. For current field testing, a commercially available tripod has been modified and put to use. Mounted to the tripod is an x-y translation stage and a sliding rail for z movement. This gives the user coarse adjustment for the placement of the CMaRS on the sample. Figure 3.18 displays the CMaRS probe mounted to the tripod.
CHAPTER FOUR

RAMAN DESIGN

The spectrometer for the CMaRS system is a commercial, field rugged instrument built by Top Raman Instruments (TRI). The system they provide includes the spectrometer and controlling electronics, a fiber-optic probe, and a portable personal computer with interfacing software. The CMaRS instrument uses the spectrometer and electronics of the original TRI system, but has incorporated the fiber optic Raman probe with a confocal microscope in the CMaRS probe.

The CMaRS probe has been built at two different wavelengths and researched and proven at a third. These wavelength choices and changes have been driven by the spectrometer, as source wavelength is not crucial to the imaging system. During the developmental stages of the CMaRS, TRI manufactured spectrometers at two different wavelengths: 633 nm and 852 nm. The CMaRS proof instrument initially used a 633 nm source. However, at this excitation wavelength, some biological samples are extremely fluorescent and this overpowers the significantly weaker Raman signal. At 852 nm, even though the longer wavelength decreases the Raman scattering cross-section, spectral information is obtainable from a wider variety of samples.

The CMaRS 852 made an improvement upon the 633 nm proof instrument in its obtainable spectra. However, through collaboration with the British Antarctic
Survey and HGM Edwards at the University of Bradford in the UK, it became clear that using a 1064 nm source could further improve the spectroscopy capabilities of the instrument. The 1064 spectrometer was built by TRI for the CMaRS 1064. It is still undergoing testing and in its final phase of completion, so this chapter will concentrate on the ‘Solution 852’, which is TRI’s 852 nm spectrometer. It will discuss the spectral characteristics of the source and the incorporation of the essential elements of the Solution 852 Raman probe into the CMaRS probe.

**Source**

Essential to any Raman spectrometer is a source with a narrow linewidth and high optical power. The resolution of the spectrometer is directly proportional to the linewidth of the source, and the sensitivity of the spectrometer directly proportional to the light intensity delivered to and collected from the sample. The source used for the compact CMaRS is an 852 nm laser diode manufactured by SDL (now JDS Uniphase) that is no longer in production. It is a distributed bragg reflector (DBR) laser diode, meaning it has a frequency selective feedback mechanism (a Bragg grating) located at each end of the laser gain medium [30]. Figure 4.1 shows the spectrum of the laser. The Bragg grating selects a narrow peak at 852 nm out of the broadband emission. This peak has a measured 3 dB linewidth of 0.08 nm. Not only does this source provide a narrow linewidth, but DBR diodes provide an inherent internal frequency lock that prevents mode hopping without the use of any external optics. Frequency stability is also ensured via a thermo-electric cooling system. The DBR source puts out approximately 150 mW optical power.
Figure 4.1 Spectra of the 852 nm SDL Laser Diode (the source illumination for the CMaRS instrument). The bottom curve is merely a zoom-in of the top curve. Note the span for the top is 100 nm whereas the span for the bottom graph is 2 nm. These spectra were taken with a Hewlett Packard Optical Spectrum Analyzer.
Filters

The probe delivers the illumination light to the sample and then filters the Raman signal from the confocal signal. A set of interference filters are necessary not only to split the Stokes-Raman signal from the Rayleigh scattered light, but also to ensure the integrity of the illumination laser light. Figure 4.2 displays the basic configuration of the Raman filters within the CMaRS probe. The accuracy of a Raman spectrum is dependent upon the spectral quality of the excitation light. Figure 4.1 shows the broadband emission from the diode laser, and though much weaker than the peak at 852 nm, this broadband illumination can destroy the sensitivity of the spectrometer at low wavenumber shifts if not properly suppressed or filtered out.

![Diagram of the Raman filter arrangement inside the CMaRS probe.](image)

**Figure 4.2** Diagram of the Raman filter arrangement inside the CMaRS probe.

Another issue related to the integrity of the illumination light is Raman scattering in the fused silica optical fiber, itself. In the CMaRS system, as in many other remote Raman probes, the source light is delivered to the probe through optical fiber instead
of placing the source inside the probe. Laser light and Raman scattered light in the illumination fiber result in a background spectrum which must be filtered out before the light is delivered to the sample [31].

After light is collimated upon entering the probe, it immediately passes through a bandpass optical filter, which attempts to isolate only the 852 nm light and subdue all other wavelengths. Spectral information about the bandpass optical filter is shown in figure 4.3. This measurement was taken using a Hewlett Packard Optical Spectrum Analyzer (OSA). The white light source from the OSA was sent through a MM fiber, collimated and passed through the bandpass filter, then coupled into
another MM fiber and sent to the OSA for analysis. The peak of the filter is well centered at 852 nm, and the 3 dB bandwidth is approximately 7 nm. The span on the graph for figure 4.3 is identical to the span of the top curve in figure 4.1. In comparing the two spectra, it is easy to see that while the bandpass filter will suppress much of the broadband radiation emitted from the laser diode, it is not narrow enough to cut out all of it. As a result, a fair amount of broadband laser light leaks into the Raman system, and with certain samples this decreases the sensitivity of the instrument. This will be discussed further in the results section of Chapter 5.

After passing through the bandpass filter, the excitation light encounters a dichroic beam splitter (see figure 4.2). The transmission through this dichroic beam splitter is dependent upon both the angle and polarization orientation of the incoming light, as well as its wavelength. Figure 4.4 displays a transmission curve for transverse electric (TE) and for transverse magnetic (TM) incident polarization. The data was taken with the 852 nm DBR laser source and a rotation stage and a silicon photodetector. The x-axis of these graphs is scaled in relative incidence angle. This is a non-calibrated angular measurement where the center of the curve is at approximately 45° to the incident light and all measurements are relative to this. There is a noticeable difference between the maxima of these two curves. For TE polarization, the maximum was 78% and for TM polarization, 88%. However, the pass-band nature of the curves is quite different. The TM curve is not only
Figure 4.4 (a) Transmission of TM polarized light through the dichroic beam splitter versus angle.

Figure 4.4 (b) Transmission of TE polarized light through the dichroic beam splitter versus angle.
considerably flatter, but it has nearly twice the width. This gives it a large tolerance to any angular slop in the filter block, where it is mounted. The TE curve is considerably narrower and dips down to only 55% transmission at the center of its angular variation. For this reason, the PM fiber is connectorized such that light entering the probe is linearly polarized in the horizontal direction.

Light scattered off of the sample retraces its path until it is once again incident upon the dichroic beam splitter. The dichroic splitter has a pass band centered at 852 nm and reflects all other wavelengths. As has been mentioned previously, the Rayleigh scattered light will pass directly through the dichroic splitter and the bandpass filter and be coupled into the PM fiber it came from. The Stokes-Raman scattered light, however, will be reflected off of the dichroic splitter, then off of a folding mirror and sent through a long pass filter (see figure 4.2). The long pass filter serves to isolate the Stokes Raman-shifted light from the anti-Stokes scatter and any Rayleigh scatter that may have leaked through the system to this point. Since the reflectance of the dichroic splitter only partially suppresses the shorter wavelength light, it is essential that the dichroic beamsplitter is followed by a long pass optical filter. Figure 4.5 and 4.6 show the cut-off curves for the long pass filter. These graphs were experimentally found using the OSA and its internal light source just as they were for the band pass filter. The 3 dB cutoff wavelength for the bandpass filter is approximately 870 nm. In figure 4.6, note the ringing at the edge of the filter. This ringing is visible in the spectra taken with this spectrometer and will be discussed further in chapter 5.
Figure 4.5 Transmission through the long pass filter. Note the span is 1100 nm for this graph and the center is at 1150 nm.

Figure 4.6 Transmission through the long pass filter. Note the span is only 100 nm and the center wavelength is 852 nm.
The Stokes Raman scattered light is coupled into a multi-mode step index fiber with a 50 μm core size. This increases the sampling size for the Raman portion of the probe when compared to the confocal sampling size. Because the effective ‘pinhole’ is ten times larger for the Raman collection fiber, it will not be so sensitive to depth of focus and could actually acquire a stronger spectrum when slightly out of focus.

Another asset of using multi-mode fiber is the effective reduction in the instrument’s sensitivity to chromatic aberrations in the imaging system. The spectrometer is sensitive to wavelengths between 880 nm and 980 nm, which scales to a spectral shift in the wavenumber range of 400 to 1500 cm$^{-1}$ (see figure 4.7). Using multi-mode fiber ensures that no photons are lost in coupling into the fiber due to chromatic aberrations in the optical system.

![Figure 4.7](image.png)

**Figure 4.7** Wavelength to wavenumber shift (relative to 852 nm excitation) conversion chart.
CHAPTER FIVE

RESULTS

CMaRS Proof-Instrument

The CMaRS 852 and 1064 compact probes were preceded by a bench-top system that demonstrated proof of concept. This bench-top system included the

Figure 5.1 Diagram of the optical set-up for the bench-top proof instrument. This diagram includes the instrumentation housed in the probe and within the light launch of the compact CMaRS.
elements belonging in both the probe and light launch of the compact CMaRS. The optics used were functionally equivalent though not identical to those in the probe, and conventional bench-top mounts were employed. Image acquisition employed a Datel data acquisition card and MATLAB code. The spectrometer was the same spectrometer as used by the probe. Images and spectra taken from this proof instrument served to de-bug the design and sleuth out potential problems while generating preliminary data on samples provided by our collaborators. This section of this thesis will present some representative images and spectra taken with this bench-top proof instrument.

Figure 5.2 displays an image of a cleaved calcite sample along with different spectra taken within that field of view. The field of view of 300 microns is

![Figure 5.2 Image of a cleaved calcite sample with corresponding spectra taken with the bench-top 852 system. The x-axis scale for these spectra is 400 to 1600 wavenumbers, and the y-axis is arbitrary. The field of view for this image is 350 microns.](image)
sufficiently large to present a varying morphology in that region of the sample. Spectra taken from different regions in the sample are varied: some display a conclusive calcite signature (bottom left) and some are overshadowed by sample reflectance and residual laser emission (bottom right). For this reason, it is often advantageous to turn off the scan-mirror and steer the beam to small regions of the sample to take a spectrum, as opposed to taking a spectrum of the entire region while scanning.

Figure 5.3 displays a ‘through-focus series’ of cleaved calcite. Images (a), (b), and (c) are taken as the axial position of the objective lens was translated, and different portions of the sample clearly move in and out of focus with each step. The composite image can be created with post processing techniques. It essentially forms
a superposition of the other three images and may be more useful to the user than several images at different depths of focus.

Figure 5.4 shows an image and spectra of a methamphetamine crystal. This data was taken to demonstrate possible applications of the instrument in the field of forensics. The two spectra were taken with TRI spectrometers operating at 852 nm. The comparison demonstrates the compatibility of the microscope optics as they are used for light collection for the spectrometer. At the higher wavenumbers, the spectrum on the top of figure 5.4 appears to have reduced sensitivity when compared to the spectrum beneath it. This is because the spectrometer's silicon CCD detector loses sensitivity at longer wavelengths and an excitation wavelength of 852 nm is already nearing the edge of the silicon responsivity curve. At 633 nm excitation (see the bottom spectrum) silicon provides ample sensitivity at the longer wavenumbers.

Figure 5.4 Image and two comparative spectra of a methamphetamine crystal. The top spectrum was taken with the CMaRS table-top proof instrument at 852 nm while the bottom spectrum was taken with a commercial TRI instrument at 633 nm.
Figure 5.5 is a comparison of two spectra taken of Acarospora chlorophana. Acarospora is an epilithic desert lichen from Victoria Land, Antarctica. Such an organism is under study (along with other cold-desert micro-organisms) by astrobiologists searching for links to life on Mars through pigment analysis. These two spectra were taken at different wavelengths with entirely different apparatus. The top spectrum in figure 5.5 was taken with a commercial Fourier-transform Bruker FRA 1064 Raman spectrometer. This is a table-top instrument using a high power Nd/YAG laser at 1064 nm and a liquid nitrogen-cooled germanium detector. The spectrum displayed at the bottom was taken with the CMaRS’s bench-top proof-instrument at 852 nm [32].

![Figure 5.5 Comparison of spectra taken from Acarospora chlorophana. The top spectrum was taken with a Bruker FT Raman spectrometer at 1064 nm. The bottom spectrum was taken with the bench-top system at 852nm [32].](image-url)
Spectra taken from many biological samples revealed significant autofluorescence at our excitation wavelength of 852 nm which was not present at 1064 nm. *Acarospora chlorophana* produced a clean Raman signature on top of this autofluorescence, but attempts to generate useful spectra from Nostoc, *Xanthoria elegans*, and cryptoendolithic lichen samples were not successful. This makes a longer excitation wavelength attractive, particularly for biological samples.

In considering figure 5.5, it is evident that the TRI system at 852 nm is much more sensitive at the lower wavenumbers where it still lies well within the silicon detector’s responsivity curve. Between spectral shifts of 1200 and 1600 wavenumbers it becomes difficult to distinguish the peaks from the noise level. Switching to a detector with a broader responsivity curve at these longer wavelengths could eliminate this limitation. The 1064 nm Bruker spectrometer is sensitive out to 4000 wavenumbers (beyond the axis of the graph in the figure) because of the responsivity of Germanium, and this is particularly helpful with a sample like *Acarospora* that has lots of activity at these longer wavenumbers.

Considering this comparison with the Bruker 1064 system, the we decided to switch the CMaRS spectrometer detector to an InGaAs array for a wider spectral range, and the entire system moved to a 1064 excitation source in an effort to avoid fluorescence with biological samples. In moving to a longer wavelength, the Raman scattering efficiency decreases (since the scattering cross section is inversely proportional to $\lambda^4$), but this is decrease in scattering intensity is outweighed by the capabilities available with a reduced fluorescence contribution [32].
Compact CMaRS

The compact CMaRS is not yet fully operational. Images have been taken with the CMaRS probe at both 852 and 1064 nm, but only with an alternate image acquisition board and software. The SC control modules and compatible systems are still undergoing final testing and integration. Spectra have been taken with the CMaRS probe and the TRI 852 spectrometer. However, the 1064 nm spectrometer is still in its final development stages. Figure 5.6 displays the CMaRS 1064 in its soft sided carrying case (which attaches to a back-pack frame for long term portability). The laser source and spectrometer are located left of the computer in the carrying case.

This section will discuss the imaging and spectral capabilities of the compact probe and demonstrate the level of progress that has been attained.

Figure 5.7 shows an image taken with the CMaRS 852 of a 10 micron period chrome grating. The period of the grating along the horizontal axis is not spaced.
evenly for two reasons: there was tilt in the sample that caused certain portions to be out of focus, and the horizontal scan is sinusoidally driven, so the image stretches out at the turn-around points of the mirror. This image demonstrates a field of view of 140 microns, which is the largest field of view we have seen with the compact probe. Due to capacitance in the electrical cable, the fast scan signal is smaller than is possible with the mirror located at the electronic control module. After the image is “cleaned-up” and we keep only the data in the linear region of the mirror motion, the remaining field of view is in between 100 and 120 microns. In comparison to a 300 micron field of view in the table-top set-up, 100 microns is quite small and should be improved.

Spectra

Figure 5.8 displays spectra taken with the CMaRS 852 probe and the 852 TRI spectrometer. Spectrum (a) is of Benzene, which is a material that has a strong Raman peak and therefore useful for calibration purposes. The peak is located at the

Figure 5.7 Image of a chrome grating taken with the CMaRS 852.
Figure 5.8 Raman spectra taken with CMaRS 852 probe and the TRI spectrometer. Spectrum (a) is of Benzene, spectrum (b) is of Acorospora chlorophana, and spectrum (c) is of nothing (the spectrometer is looking at air and the laser is on).
superimposed upon the light throughput to that point results in the background shown in figure 5.8 (c). Efforts have been made to subtract this background out from the signal, but an effective technique has yet to be found. The intensity of the background varies with sample reflectivity, making the scaling coefficient different with each spectrum.

**CMaRS Probe Performance Measures**

In order to compare the actual microscope to the theoretical development discussed in Chapter 3, the edge response, axial response, and light through-put were measured for the CMaRS microscope.

**Edge response**  Edge measurements for the CMaRS 1064 were performed on the horizontal and vertical axes in the center of the field of view. These measurements were made with a chrome grating target while scanning the beam to a field of view of approximately 100 microns. The edge measurement was made off of the edge of the chrome while the mirror was in the linear region of its scan. Figure 5.7 shows the vertical edge for the CMaRS probe. The 20% to 80% falling distance is 1.16 microns when the maximum is taken to be the extreme maximum in the curve shown, and the minimum taken to be the extreme minimum. This agrees closely with the results of the theoretical simulation presented in chapter three, which was 1.19 microns.
Figure 5.9 Edge response for the CMaRS Probe

**Axial response** The axial response (or V(z) response) of the CMaRS was measured by translating the sample through the focal plane with a differential micrometer and recording the return signal intensity as a function of sample position. Figure 5.9 shows a plot of the measured axial response of the CMaRS 1064. The full width half maximum (FWHM) spans 20 microns. The theoretical prediction for the simplified fiber confocal optical microscope yielded 14.3 microns at full width half maximum.
Figure 5.10 Axial response of the CMaRS 1064.
Though the compact CMaRS has yet to be demonstrated in its entirety, each aspect has been proven individually, and the performance of the optical systems has been verified. Future advancements will entail gathering a better understanding of current obstacles and moving from the breadboard phase into the brassboard phase of development.

**Breadboard Modifications of the CMaRS System**

Improvements can still be made in some aspects of the current optical systems before moving on to brassboard development. Interference in the image and laser noise at 1064 nm occurs due to feedback into the laser source. In the 852 nm system, this interference was eliminated once polarization control optics were introduced into the optical path. Why this is occurring with the 1064 laser source is not yet fully understood, though one solution may involve inserting an optical isolator into the beam path.

The 1064 nm spectrometer is still under development at TRI and has yet to be tested with the CMaRS probe. Operation of the CMaRS probe at 852 nm with the TRI spectrometer successfully identified calibration materials, but artifacts in these
spectra were observed and never addressed by TRI. Successful operation of the probe with the spectrometer is essential to the appeal of this system and a milestone of this phase of development.

The electronic control of the imaging system is currently in its final testing phase. One remaining task in this category is to insert a transformer into the probe to step up the voltage sent to the scan mirror. The scan signal for the MEMS mirror loses amplitude due to capacitive loading of the two-meter cable to the probe, which limits the field of view of the microscope. Locating the voltage step-up transformer in the probe is a simple solution to this problem.

Once the entire CMaRS system demonstrates functionality at room temperature, environmental and field-testing are remaining tasks. Collaboration with the British Antarctic Survey (BAS) will send the CMaRS to Antarctica for a field trial. In addition to this, basic temperature, vibrational, and impact testing needs to be completed. Information gathered from these tests will aid in the design alterations for a brassboard instrument.

Brassboard Modifications of the CMaRS Probe

Once the CMaRS prototype is ready to move into the brassboard phase of development, the major improvements that must be made are in environmental preparedness and volume and mass reductions.

Focus Control One proposal that would slim down the size of the probe considerably and improve mechanical reliability involves the implementation of another method of
focus control. Replacement of the piezo driver with an optical MEMS (also called MOEMS) device for dynamic focus control would not only reduce the volume of the probe by a third, but also provide a faster and more robust method of controlling the focus position [34]. This MOEMS device is a deformable silicon membrane with a gold-coated mirror surface that has undergone development by Dickensheets, Himmer, and Friholm at Montana State University [33]. This micro-machined device is circular in shape with two electrodes on its surface. When activated properly, the membrane is capacitively pulled into a parabolic shape. This changes the wavefront shape of a reflected beam and thus can be used as a dynamic focusing element.

Replacing the folding mirror in the CMaRS with a deformable mirror has been demonstrated to provide dynamic focus control, both theoretically and in the bench-top proof-instrument [34, 35]. This would remove the piezo driver and linear slide from the ‘floorplan’, effectively streamlining the CMaRS and making it more dependable by eliminating the major mechanical moving parts from the system.

A 750 um diameter membrane was inserted into the bench-top proof-instrument discussed in Chapter Five and demonstrated 75 microns of focus control. The membrane was imaged onto the MEMS scan mirror (which, in turn, is imaged into the telecentric stop for the microscope). Figure 6.1 displays the optical set-up for this experiment. The 3:2 beam expander was used to downsize the one mm diameter beam so that it would appropriately fill the 750 micron diameter membrane. Seventy-five microns of focus control was observed with only a 1.2 micron deflection of the membrane. This was a maximum deflection for that particular device, but larger
devices have proven capable of up to 3.6 microns of deflection. Friholm suggests that a 1500 micron diameter membrane inserted into the compact CMaRS probe would generate 200 microns of focus control with only a 4 micron deflection of the membrane [35].

As part of this proof-of-concept demonstration, the edge response of the microscope-and-membrane system was evaluated with the membrane both actuated and static, and this was compared to the edge response without the membrane. Figure 6.2 contrasts these edge responses graphically. Figure 6.3 shows images captured
Figure 6.2  Edge response comparison of membrane–controlled focus with the edge response without the membrane in place.

Figure 6.3  Two images made of a chrome grating with the deformable membrane inserted into the bench-top proof-instrument. For image (a), the membrane was not actuated. For image (b) the membrane was deflected 1.2 microns. The change in image quality is not noticeable.
with and without focus control (200 V and 0 V applied, respectively) and demonstrates visually that the quality of the image is not lost with this alteration to the wavefront.

Further Miniaturization

Once the piezo driver is eliminated, other elements that could be downsized are the filter block, scan mirror assembly, and collimation systems. Smaller magnets would reduce the size of the scan mirror assembly, and therefore the height of the entire probe. As the MM fiber is less sensitive to coupling than the SM fiber, the x-y collimation mount for the multi-mode fiber could be replaced with a GRIN lens which would occupy much less space. Most of the optics mounts, especially the Raman filter block, could be reduced in size if the over-all probe lay-out required it.

Summary

This thesis has presented the development of a confocal imaging and Raman spectroscopy instrument intended for remote field investigations, ultimately the surface of Mars. The CMaRS successfully integrates MEMS beam-steering technology into a compact confocal imaging probe suitable for in situ investigations. Furthermore, the instrument has demonstrated concurrent confocal imaging and Raman sampling of various test specimens. Using a simple optical system we demonstrated 1.4 micron resolution and field of view of 120 microns capable of taking spot Raman spectra or spectra from this entire field of view. This prototype instrument is the first compact imaging Raman spectrometer capable of field use.
Because the CMaRS system in its entirety has yet to complete the breadboard phase of its development, it is pre-mature to assess its potential value to a Mars mission. The instrument’s performance for a Mars surface investigation will depend on the performance of the spectrometer and its capabilities in delivering molecular composition information to the user. The confocal microscope provides the context for this information. Further development of the CMaRS will follow instrument performance evaluation during an upcoming field trial.
REFERENCES CITED


