Space-based camera systems

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ABSTRACT

With 40 years of experience with space instrumentation, I reflect on the rigors of designing cameras for stringent environmental hazards. The fundamental knowledge of optics instilled in me as a student at the Optical Science Center gave me the basis for my career. Jim Wyant is the first name that comes to mind from those formative years in the 70's. A decade later, I became an employee of WYKO helping with the phase-shifting interferometers that his company produced. As a final gesture, Jim allowed me to complete my education in 2009 (32 years after my Master's degree) as my PhD advisor.

Keywords: James C. Wyant, space instrumentation, multi-spectral cameras, planetary missions, Mars, Titan.

1. INTRODUCTION

This paper is part of the 'Tribute to James C. Wyant' program and is intended to enumerate the ways that Jim has influenced my career since I first took his class, Interference and Diffraction, at the Optical Sciences Center (OSC) in 1976. Even though I had nearly six years of experience with diffraction gratings and astronomical spectroscopy, I quickly found that Jim provided a depth of knowledge and an intellectual framework that revolutionized my understanding of what was taking place inside a spectrograph. The mathematical description of light beams and their interaction with each other and optical surfaces took my limited experience to new levels as I wrestled with the homework problems and test questions that probed to the inner nature of light.

Of course, as Jim often said, "there is nothing new in optics." His basic starting points were Young's 2-slit experiment and the Michelson interferometer, both invented in the 19th century long before lasers were available. Yet from these basic instruments many variations could be inferred that ultimately encompassed the full range of interferometers still in use today. The invention of the laser in the 60's with its long coherence length made interferometers commercially viable. The addition of a piezoelectric device to one of the mirrors forms the basis of phase-shifting interferometry and ultimately of a highly productive company. WYKO, Jim's company where I worked for 2 years, is just such an example.

During my 2.5 years at OSC, I participated in the Pioneer Jupiter program performing image processing on the recently returned data sets. After graduating from OSC with a master's degree in 1977, this experience helped me qualify for my first job at the University of Arizona (UA). I joined a team that was calibrating a radiometer that was designed and built at OSC and led by Dr. Martin Tomasko from the Lunar and Planetary Laboratory. This instrument, the Large Probe Solar Flux Radiometer (LSFR), eventually was released by Pioneer Venus into the Venus atmosphere and descended slowly under a large parachute to the surface all the while measuring the solar radiation fluxes that were heating the lower atmosphere to extremely high temperatures. As the surface and atmosphere above it tried to cool by radiating heat away from the planet, it was the net flux from the Sun that maintained the hot temperatures at the surface. The atmosphere was so thick and its meridional winds (revolving around the circumference every 4 days) so strong that there was little cooling during the long night times.

With my hard-won knowledge of light and its behaviors and the experience of participating in a space missions, I found my calling. For the next 35 years, I worked on many space missions with various groups at the UA with only a short break spending time at WYKO as an optical engineer. But it wasn't until 2009 after the completion of the Phoenix Mission to Mars that I gained my PhD in optics completing my coursework and writing a dissertation describing the results of the mission for which I was the Principal Investigator. Jim Wyant was my advisor and encouraged me to finish my degree although frankly I was within a few years of retirement.

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Our paths occasionally crossed over the course of my career and there was always the sense that Jim was playing the long game and truly enjoying it. When upon retirement, I started my own consulting company, he gave me sage advice and was very encouraging. I does not surprise me that the OSC that I remember so well is now renamed the James C. Wyant College of Optical Sciences.

2. EARLY SPACE MISSIONS

2.1 Pioneer 10 and 11

These two missions launched in the early 70's to Jupiter were NASA's first attempt to study the outer planets by spacecraft. There were many issues that made this endeavor extremely dangerous which is why they launched two missions instead of one. The distance from the Sun precluded using solar panels, so Radioisotope Thermoelectric Generators (RTG) were necessary and these released high energy neutrons that could damage sensitive instruments. The trajectory went through the asteroid belt about which little was known and one could imagine disastrous encounters. Finally, Jupiter itself was surrounded by high energy magnetic fields with the power to destroy sensitive electronics and darken optical components. These were risky missions, yet expectations were high that major scientific breakthroughs were in store.

When I first started at the UA, both Pioneers had returned their Jupiter images and I was employed to help create high quality images from the data sets. These were not images taken from a framing camera, but instead spin-scan data arrays taken with a single pixel at the focal plane of a lens-prism combination measuring polarization as well as intensity (see Figure 1). The resulting images, if not properly displayed, looked horribly distorted and stretched, sort of like taking a planet grabbing the sides and stretching it into a banana shape. The computer that performed the reconstructions was on the other side of campus so student employees got their exercise hauling computer tapes and boxes of programming cards back and forth. Images were made using a machine that scanned a dot of light modulated by the signal strength across photo paper as it scrolled around a drum. The Imaging PhotoPolarimeter (IPP) had a second pixel, one filtered for blue light and the other for red. By generating a green channel, a combination of red and blue channels calibrated with telescope images of Jupiter, a color image could be made. This was a tiresome process but resulted in many glorious pictures of Jupiter's clouds.

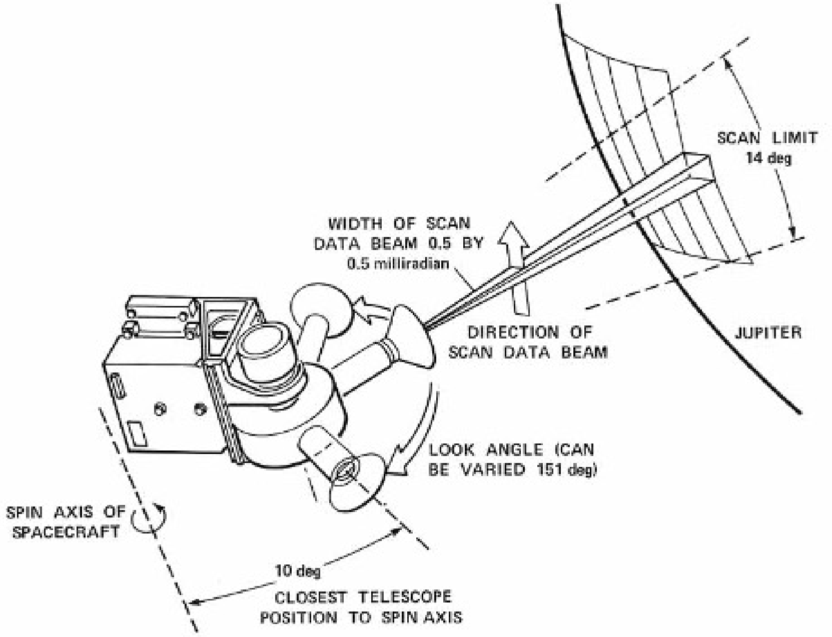

Figure 1. Cartoon of the IPP instrument showing how a single pixel is spin-scanned across a section of Jupiter. The relative motion between the two objects also influences the geometry of the scan.

One task was to make the best possible images of the 4 Galilean moons. The distances were so large that they were necessarily very blurry (a pixel encompassed about 300 km on the surface) and not much could be discerned in terms of surface detail. However, they were useful as measures of the average diameter from which the density of the moon could be calculated, the masses having been measured by their influence on the spacecraft orbit[1]. The resulting paper served as my masters thesis and I was pleased to learn that the results were confirmed within the error bars by the subsequent Voyager flybys with much higher resolving power.

2.2 Pioneer Venus

In 1978, I began at the LPL part time helping to calibrate the Large Probe Solar Flux Radiometer (LSFR, see Figure 2). This was a challenging task since the environments spanned a huge temperature and pressure range. To keep the instrument from overheating a phase change material was used that was chosen to hold the temperature nearly constant during the time of the descent. For calibration this material had to be refrozen each night before tests could be conducted, a special refrigerator was identified and warnings were posted so that no one would put their egg salad sandwiches inside. Things went well up to the point that we tried to calibrate the germanium sensors and found that each day the results were different by a large amount. Time for debugging was short since the delivery date to the spacecraft for integrations was rapidly approaching. With only a few days left, we determined that humidity was the variable that was causing the offsets and by refrigerating the instrument the humidity inside the protective enclosure was somewhat different each day.

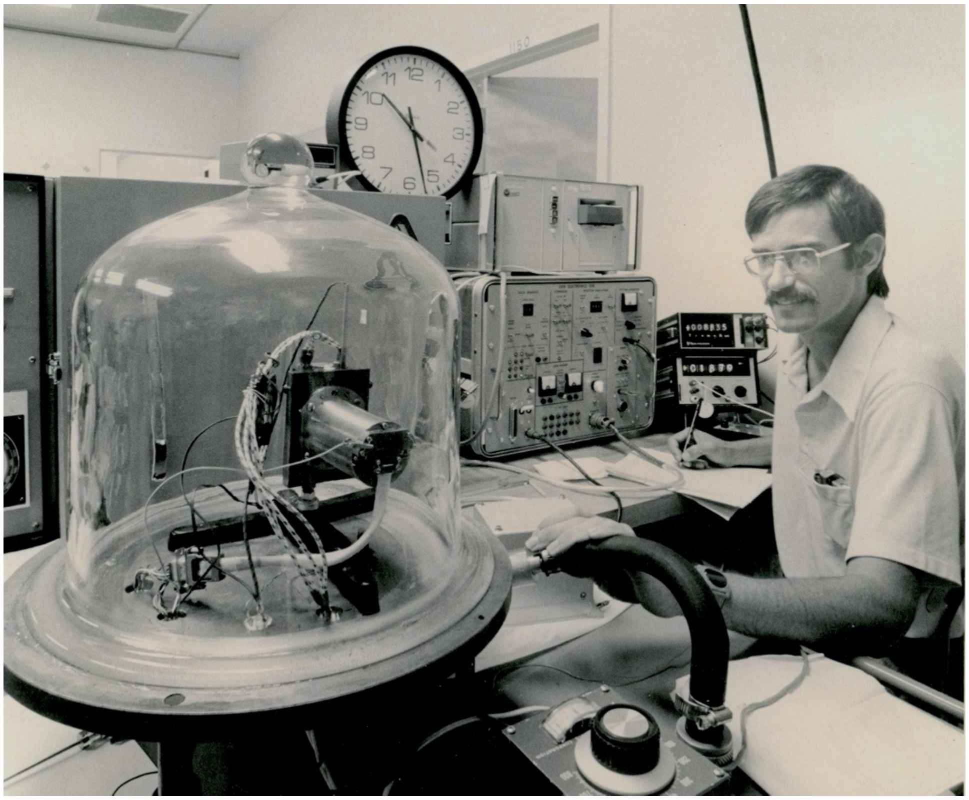

Figure 2. Smith in Spring 1978 gathering calibration data for the LSFR on Pioneer Venus. The radiometer is inside the bell jar where its temperature and pressure are being controlled.

Correcting for humidity gave us reproducible results and we were able to meet our deadline. In August, the spacecraft was launched from Cape Canaveral and in early December the mission was carried out and data returned. To support, the operations our team went to Ames Research Center and watched as the printer spewed out the data sets. We rushed into our temporary office and made our first assessment of the results. The upward looking channels and downward looking channels behaved as expected and we were thrilled that we had a data set that could be analyzed to learn some of the secrets of the Venus atmosphere. Within a few months we had published our first results in Science[2] and I became enchanted with the rapid progress from instrument development to new understanding.

2.3 Pioneer Saturn

Pioneer 11 had been redirected to Saturn after its successful Jupiter flyby and after a year of analyzing the Venus data, our group led by Tom Gehrels turned our attention to the IPP operations as the spacecraft approached the Saturn system. We relocated to the Bay Area and were given a portion of the operations center to set up our IPP station. Commands to the instruments were sent on a daily cadence and data retrieved on the downlink channel. The commands were being formulated in an office nearby and compared with the downlinked data to be sure that the instrument and the Saturn system behaved as expected. The round trip light time was about 3 hours so there was no hope of live operations.

Several weeks were spent approaching the planet and watching it grow ever larger in our images. There were only a few opportunities to take data on the Saturnian moons with Titan being the largest target. These data sets would be analyzed for years to come for they showed a featureless, thick atmosphere that could be modeled with the atmospheric models that we had built for the Venusian data sets. However, the models could never converge due to the incompatible discrepancy between their forward scattering nature—the new moon, backlit by the Sun, was just as bright as the full moon Titan—associated with large particles and its high polarization that implied small Rayleigh-scattering particles. This paradox would not be resolved for many years.

Encountering Saturn, the focus turned to the rings. They were magnificent and seen from the viewpoint of the spacecraft there appeared an unknown outer ring later named the F ring. I take some pride in this discovery because I wrote the sequence of commands that allowed this discovery and started the sequence far outside the radius where we thought the rings began.

3. SEARCHING FOR EXOPLANETS

As planetary exploration wound down during the Reagan presidency, I joined the radial velocity spectroscopy project tasked with finding exoplanets by observing their gravitational pull on the central star. Jupiter imparts a velocity of 13 m/s with a period of 5 years on our Sun. If Jupiter were closer, then larger velocities and shorter periods are predicted. At the time in the early 80's the best radial velocities published were in the 100 m/s range, so the challenge was to develop and instrument with both the needed precision as well as the stability to create a multi-year timeline. Kristof Serkowski, a Polish astronomer at the UA formulated a solution: use the high order interference terms from a Fabry-Perot (F-P) interferometer and remove the Earth motions by inducing a tilt that acts as a velocity shift. The stability could be achieved by placing the Fabry-Perot in a vacuum chamber with precise temperature control. The orders could be separated using an echelle spectrograph and the instrument housed on an optical table with a special optical fiber connecting the input optics to the telescope focus.

When I joined the group, the fiber concept had not been added and the instrument was compromised by the need to suspend it from the rear of the telescope. So many optical elements crammed into a small volume swung high in the air at the end of a telescope spelled disaster. My job was to upgrade and re-design the concept adding the fiber link and simplifying the layout. Having never worked with the F-P interferometer, I turned to my notes from Wyant's class and rederived all the equations for the spectrometer. It was a beautiful concept, but one could get lost for a lifetime in the analysis of the hundreds of orders spaced along the stellar spectrum. While considerable effort had been made to provide analysis software, it was still a daunting task for a small team. It occurred to me that by tilting the F-P a small angle and introducing a wavelength shift that the derivative of each order with wavelength could be derived. This number gave the sensitivity of an order to radial velocity shifts. Some points had no sensitivity and others were highly sensitive.

Stability could be achieved by using the insensitive lines for continuity between observations and comparing them to the sensitive lines to derive a radial velocity. After much effort this was made to work in the lab, with no large motions possible. Connecting our instrument to the fiber and the fiber to a Celestron 14" telescope placed in a parking lot outside and pointing it toward Arcturus, a red giant, gave us our first stellar source. We hoped to show that night after night the star maintained its zero velocity. We were sure that our method was working because we could track the Earth's rotation velocity over several hours of observation with error bars less than 10 m/s. Unfortunately, we were shocked to find night-to-night variations of around 100 m/s and carefully searched for error sources in our admittedly crud set up. Over time, we determined that Arcturus was a variable star and one of the graduate students, Bill Merline, did his dissertation on the long-term fluctuations of the stellar surface. As often happens, enhancing our sensory abilities leads to new discoveries.

Many years were devoted to observing a set of 20 stars thought not to be variable and of approximately Sunlike properties[3]. The observing program was tedious as we needed to staff the 1-meter telescope on Kitt peak for 2 weeks per month. With a small group there was no support staff, just a few of us so the designated observer was left alone on 14-hour long winter nights in a huge dome with the lights off and a long set of observing tasks. Slowly, point by point graphs for each of our stars unfurled. The brighter stars, our limit was sixth magnitude, gave the smallest error bars and we could quickly see that there were no large planets close to the main star. However, there was still the chance that we were looking at a Jupiter-like 5-year period. After a few years of this, I had enough observing and needed to return to my first love of optical design. I left the UA to join Wyant's new company, WYKO.

4. WYKO

Wyant was the principal owner of a small and growing start up across Campbell Avenue from the UA. Their primary products were phase-shifting interferometers used to evaluate surfaces in comparison to a known surface like a flat or a spherical mirror. Interferometer configurations varied depending on the purpose of the measurement. The workhorse of the company was the SIRIS used to test small optics. Competition was tough between WYKO and ZYGO, a similar company based in Middlefield, CT, and eventually the animosity built to the point where a lawsuit was filed against WYKO and years of bitter court battles took place.

I was hired in 1988 as an optical engineer and tasked with creating reference sources for a laser diode test station called Ladite. My direct supervisor was John Hayes, a partner in the company, and he taught me the pathways from bright idea to marketable product. New inventions were being breadboarded regularly and testing rarely met expectations so I learned not to fall in love with the concepts but rather to treat them like stepping stones. The phase-shifting technology was such a powerful tool that the search for new applications was very fruitful. Add-ons to the basic interferometer seemed endless and customers desires were carefully considered with new products or upgrades in mind.

Several of the calibration sources that I developed came to market for the Ladite interferometer after about 1.5 years of development during which time the devices had been promised and sold many times (see Figure 3). But by the time the reviews were coming back to the company, I had been offered another space project at the UA and decided to accept it.

Figure 3. The Ladite laser diode tester made by WYKO in the late 1980's. The calibration devices in front of the interferometer were designed by the author while an optical engineer working with Jim Wyant and John Hayes.

5. BUILDING A DESCENT IMAGER

Martin Tomasko had a small grant to develop a near IR spectrometer to fly into the atmosphere of Titan and descend by parachute to the surface measuring the atmospheric properties on the way down. He had been stalled by design issues with his team at OSC and asked if I could bring my experience to bear to solve the design problem. We were told that the spectrometer had to be large to meet our specifications, but since large in this case meant it would not fit into the spacecraft, another approach had to be found.

Approaching the design from a different perspective, I was able to miniaturize it and build a breadboard instrument. With this experience behind us Tomasko and his team were able to write a proposal to ESA for an instrument that combined imaging and spectroscopy into one package that met the requirements specified. Because Huygens probe was a European contribution to the CASSINI mission, we went to Europe to recruit co-investigators who could provide hardware components. The Paris Observatory agreed to contribute both an infrared spectrometer and science support, they had worked on similar instruments with Russian missions. The Max Planck Institute for Aeronomy would provide the CCD sensor for the cameras along with image compression software to reduce the data volume. The instrument itself would be built and tested at Lockheed Martin in Denver.

With a team together, the proposal was submitted and approved in 1989. Once we were selected, I became the Project Manager of the Descent Imager/Spectral Radiometer (DISR), it was a position that scared me to death. I knew nothing about contracting, project management, negotiating strategies, or the inner workings of a large aerospace company. At the same time the UA needed a contract with NASA, managed through JPL, to produce the necessary documents and track the progress against the expenditures. Our progress was also overseen by a team at ESA and they had a long list of required documents from their side. Tomasko and I were overwhelmed with management tasks and at the same time had to deal with engineering issues that were a constant headache at Lockheed. These sorts of distractions were what Wyant was dealing with at WYKO where he grappled with fire regulations, insurance, human resource issues, legal issues, and building maintenance.

The instrument design matured and it was clear to see that it included most of the optical components that I had worked with throughout my career. The CCD was multiplexed through a complex optical fiber bundle so that a single chip was the sensor for three cameras and several visible spectrometers. There was an internal calibration system that fed all thirteen subsystems through another fiber package and bled light into their optical paths through tiny fold mirrors. The complexity of the packaging problem is hard to comprehend and the mechanical engineer at Lockheed was pulling his hair out to get everything fit into a tiny package that would sustain the vibrations of launch and entry as well as the large temperature ranges that would be experienced (see Figure 4). Calibration through all the environments would be a nightmare[4].

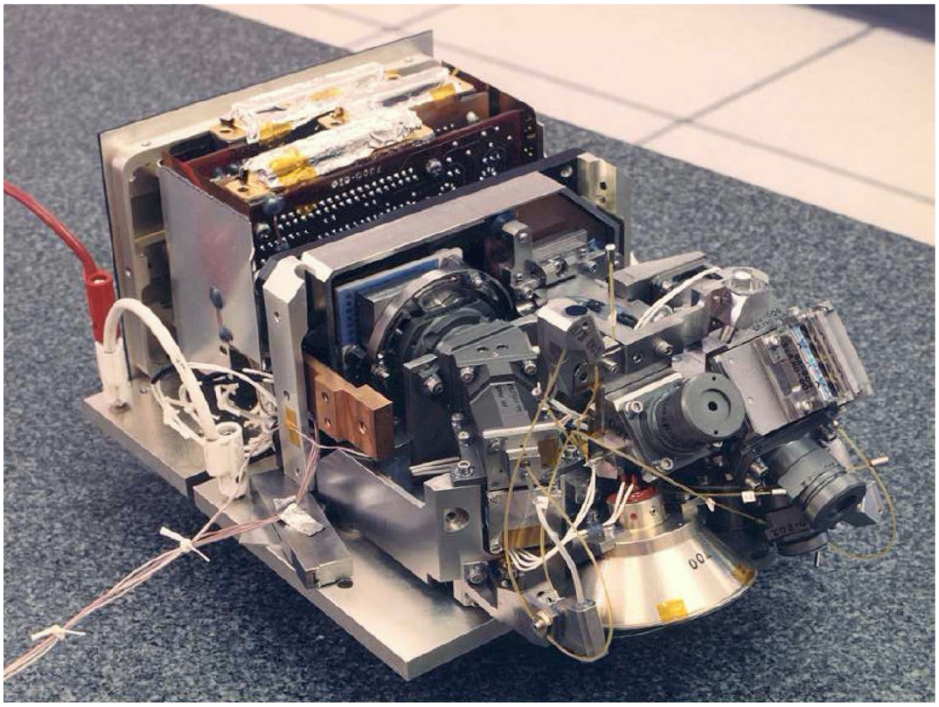

Figure 4. The DISR with its protective cover removed. This complex instrument had three imagers sharing the same CCD through a fiber optic bundle and both visible and near IR spectrometers. During the 2.5 hour descent through the atmosphere, the structure and composition of the gases and aerosols was recorded and then the lamp shown on the lower portion of the instrument illuminated the surface for the final images.

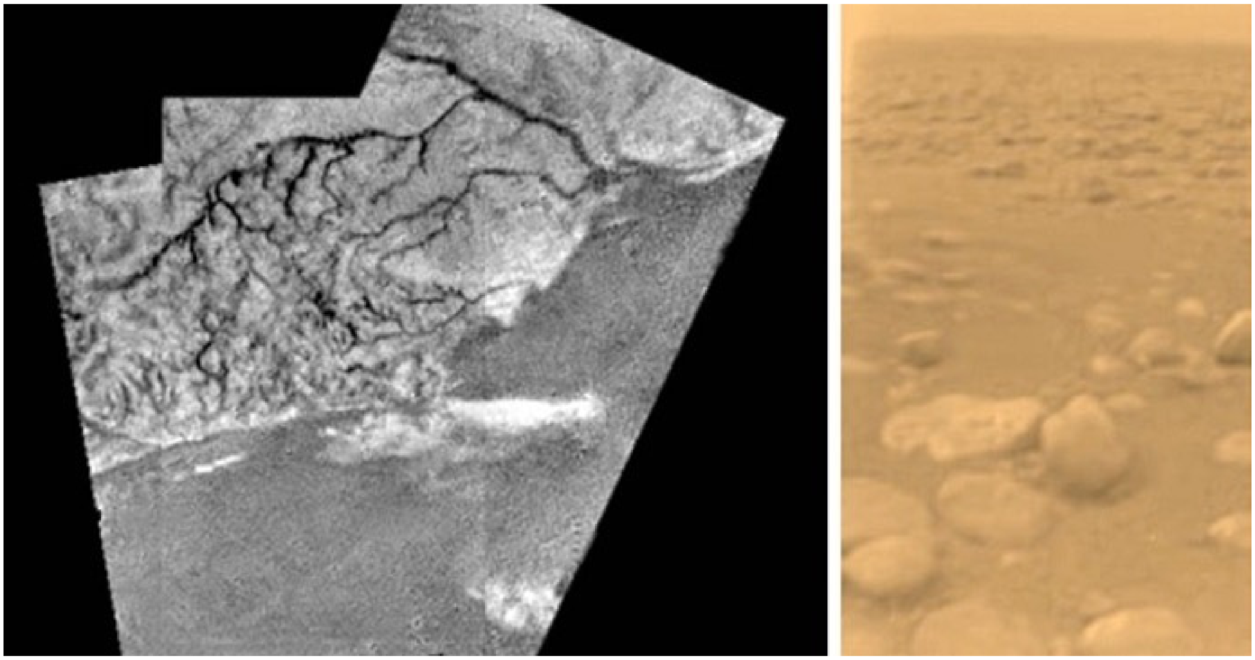

Figure 5. Several descent images mosaicked together illustrate the similarity of the Titan surface to the Earth's with river systems and lakeside hills. The difference is that the liquid is methane and the hills may well be constructed of water ice. On the right, the final image taken at the surface shows rounded rocks probably composed of water ice and weathered by methane flow.

The nightmare took place at the UA in our test facility: a hyper clean room with optical benches and specially designed fixtures and a team of test engineers. However, by the time calibration was underway, I was no longer the Project Manager. The project was successfully completed in January 2005 when the Huygens Probe entered the atmosphere of Titan and descended to the surface. Figure 5 shows an image during descent and another at its resting place on the surface.

6. CAMERAS TO MARS

In December 1992, an Announcement of Opportunity was released by NASA for a Mars surface camera as part of the Pathfinder Project. This was to be the first of many landers sent to the Martian surface to restart the exploration of our neighboring planet that had been neglected since the Viking landers of 1976, the lack of life signatures in the returned data had disappointed Congress and the world to the point where there was no appetite for expensive new missions. Therefore, to start anew, a low-cost landing system was being developed with just a basic camera to track a small rover named Sojourner. I dreamed of taking the next step in my career and proposed as a Principal Investigator.

Following a vision that captivated me one night, I put together a camera concept that used parts from the DISR instrument developed for Titan to keep costs low for the Mars camera. I could include the German team to provide another CCD and compression software and take a lens design from one of the imagers. A Fosters-beer-can-sized housing would hold the fold mirrors for two "eyes" to share the sensor and provide stereo images. Each optical path would contain filters to provide both RGB color imagery and multi-filter spectro-photometry from 450-1050 nm. Additional filters were added to look directly at the Sun to study the atmosphere. With no need for short exposure times, a large f/# reduced the need for active focusing on the Martian surface, diopter lenses allowed focus onto the lander deck. Thus, the Imager for Mars Pathfinder (IMP) was born.

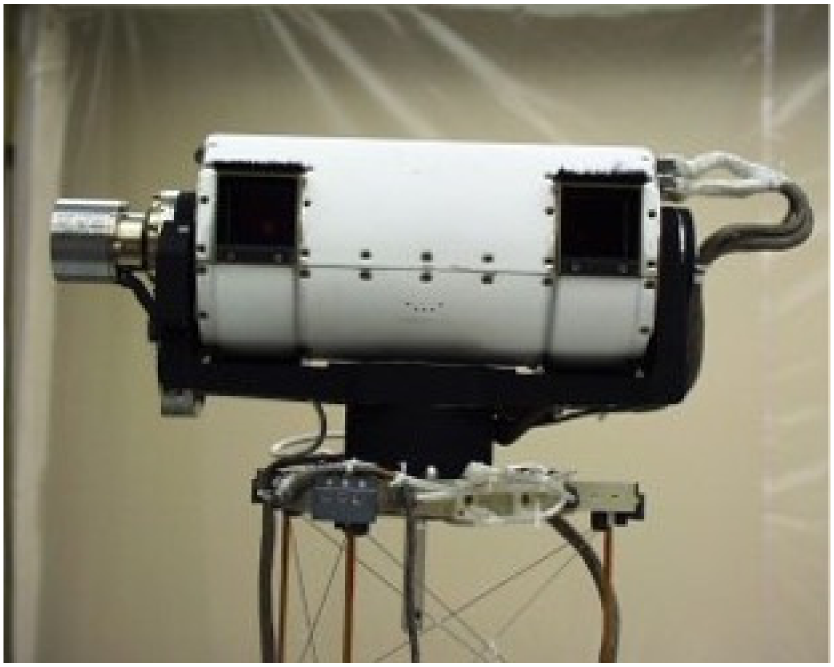

Figure 6. The IMP camera head at the top of its extendable mast. The two "eyes" allow for stereo views important for tracking the rover's progress. The white cylinder is 8 inches long and the pointing is driven by two motors in an alt-az mount configuration.

With a deployable mast and alt-az motor system the camera gave a humanistic view of the surroundings looking up and down and around at about five and a half feet above the surface. We won the proposal and started construction, with Lockheed Martin in 1994. There was little time and with a tight budget no chance for mistakes. However, mistakes were made and to save the budget the project was moved to the UA where a team was quickly formed to meet the manufacturing specifications of a NASA flight project. Our motor system was the last to meet requirements and after seeking the help of Tony Spears, the Project Manager at JPL, we changed providers with months left before delivery. This new company working out of a garage gave us fully functioning motors with approved lubricants with a month to spare. Compressing the calibration procedures to a minimum set, we were able to deliver the Imager for Mars Pathfinder (IMP) on New Years Day 1996. The launch was set for December 1996.

There was much to do in the year before launch since we now had a contract to build a camera system for the next mission: Mars Polar Lander (MPL) that would study an ice-rich area near the southern polar cap. In addition to an IMP camera, there was a need for a Robotic Arm Camera to help guide the arm to gather samples to provide to instruments on the lander deck. For this project we again partnered with the German group but did not contract to Lockheed Martin. The cameras were built between the two groups and for much less money than the first one. This time things went smoothly and there was more time for calibration and testing. By the time that Pathfinder was prepared to land near Ares Valles, the camera was in full calibration mode. This split our small team between Tucson and Pasadena with constant telephone calls between.

On July 4, 1997 the year that the UA basketball team won the NCAA tournament, Pathfinder began its Entry Descent and Landing (EDL) sequence with a huge national audience watching. Landing on Mars is perhaps the most difficult in the solar system. To land on the Moon, only thrusters are needed and guiding the spacecraft to the surface seems like something pilots can easily learn. For the Earth, there is the additional danger of entering the upper atmosphere at high speed and generating tremendous heat that must be shunted using an ablation shield or tiles. Once through that entry phase, a shuttle-like descent or parachuting to the surface has become routine. Mars is different. The atmosphere entry requires the same heat shield, but parachutes only slow the descent speed to 100 mph or so requiring a third braking system. Pathfinder, and now Polar Lander, use airbags and bounce onto the surface, Viking uses thrusters, and lately the large rovers use a complex sky crane mechanism. The entire EDL operation is called the "7 minutes of terror."

The mission lasted nearly three months and successfully drove the Sojourner Rover around the spacecraft inspecting the field of rocks that surrounded the lander. The IMP worked flawlessly throughout the mission until communication was lost and the mission ended[5]. Pathfinder showed the way for future missions to Mars and the IMP camera has been duplicated many times with higher resolution, but basically the same attributes. The advances made to atmospheric science, local morphology, mineralogy as revealed by the visible-near infrared spectra, and magnetic properties were published in a large edition of the Journal for Geophysical research. A copy of IMP was installed on the Mars Polar Lander and launched to Mars in 1998.

Figure 7. A view of Mars taken by the IMP camera showing the Sojourner Rover measuring the composition of Yogi rock. The deployed ramp that allowed access to the surface is shown in the lower left.

The MPL mission also had a robotic arm camera to aid in digging samples from the local soil. This camera was a joint effort with the German Space Agency and had a focusable double Gauss lens along with a bank of multi-colored LEDs to illuminate the scene and create color images. The camera pair was fully tested and calibrated, but no images were ever received from Mars. The mission entered the atmosphere and was never heard from again. The loss of MPL plus its companion orbiter caused a complete reorganization of NASA's Mars exploration strategy. The future missions that I had proposed for and won instruments on were all canceled. At the start of the 21st century, I was left with no projects and little resources for the future, my team of 35 highly trained camera experts were all terminated. Fortunately, recovery came quickly.

7. THE PHOENIX MISSION

In 2002, our Phoenix team competed with more than twenty other groups to win the first PI-led Scout project to Mars, all types of mission were open to consideration and there was a broad range of mission types proposed. By the end of the year our polar lander was one of four missions selected for a phase A study. As the PI, I had chosen a team of JPL management and Lockheed Martin as the aerospace house along with a payload of instruments and a science team to interpret the data. The UA provided an operations facility and was prepared to support two of the major instrument builds.

We were chosen in the summer of 2003 and had four years before launch to build and test the spacecraft. This seemed reasonable since the name Phoenix came from the idea of refurbishing and flying the 2001 spacecraft that had been canceled after the MPL debacle. Our plan was to follow up on the Odyssey discovery of near-surface ice surrounding the permanent polar ice cap and determine whether this ice-soil boundary could be a habitable zone. After four long years of developent, our spacecraft was deemed ready for launch and on August 4, 2007 we left the Earth from Cape Canaveral on our way to Mars.

The world was watching on May 25, 2008 as we endured the terror of landing in and unknown landscape. It went perfectly and images were quickly returned showing a permafrost shaped landform with polygons surrounding low hummocks formed by the underlying ice[6]. In fact one of first images showed that the thrusters had scrapped away the soil cover and exposed the underlying ice sheet. Our activities over the next few months before winter set in were to examine the soil-ice boundary testing the chemistry and composition of the soil.

Figure 8. The robotic arm camera peered underneath the Phoenix lander to find that the thrusters (shown at the top of the image) had cleared away the overlying soil during final descent. From the curvature of the strut shadow the depth to ice can be estimated as 5 cm.

The soil chemistry is most interesting. The discovery of perchlorates in the soil implied that the freezing point of water could be significantly lowered; it also raised a caution that the soil could be toxic to humans. Fortunately, when wet the soil has the pH of salt water and is a fine growth medium for many vegetables. As winter approached snow was observed falling from the thin clouds and a few microns of water ice dusted the surface. Calcium carbonate was identified and the ice layer determined to be within a few inches of the surface. If the upper layer could be brushed off the northern plains are similar to an ice-skating rink.

8. CONCLUSIONS

With the lost of the Phoenix mission in November 2008, members of our team joined with the OISRIS-REx (O-R) mission as part of the camera team. This allowed us to continue occupying the Michael Drake space operations building and increased the interaction between Space Sciences and the College of Optical Sciences. The O-R cameras were designed and built at the UA and involved personnel from Optics. The days of relying on aerospace companies for space cameras and other instruments were over. Of course, they would always have an important role in designing and building the spacecraft.

My interaction with Jim Wyant continued as I furthered my education to obtain a PhD in Optics with Jim as my advisor. I had completed nearly all the coursework and only lacked a dissertation. Fortunately, the paper recently published in Science with the results of the Phoenix mission[6] served that purpose and in the Spring of 2009 after passing my dissertation defense, I received a PhD in Optics 32 years after being awarded a Masters. Space Sciences finds a rewarding partnership with the optical sciences and my career illustrates that there is a bounteous future as the departments find new opportunities together.

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