Trends in Instrument Systems for Deep Space Exploration[1]

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Abstract: Instrument systems for deep space exploration have undergone dramatic changes in the last few years. They are smaller, lighter and less power hungry. The line between science instruments and spacecraft sensors is blurring. New vehicles, missions, goals, environments and types of instruments are changing the design of instrument suites. Finally, integrated instrument suites are becoming more common. Using Cassini spacecraft instruments as a benchmark, instrument suites on the DS-1 and DS-2 spacecraft are discussed along with designs for MECA, MER and the Subsurface Explorer, in the context of these trends.

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1. EVOLUTION OF INSTRUMENT SYSTEMS FOR DEEP SPACE EXPLORATION

In recent years there have been an increasing number of space science instruments that are being designed as integral elements in integrated instrument suites as opposed to stand alone instruments. In fact, some instruments are becoming closely integrated with the mobility systems that carry them to their science targets.

This higher level of integration has been motivated by both resource limitations and by an increased focus in science investigations. The reduced size and budget available for individual space science missions combined with the increased complexity of these missions, has encouraged instrument developers to greater integration to reduce mass, volume and power needs.

In parallel, NASA has shifted from flyby and planetary orbiting missions, which included primarily; remote-sensing instruments, to various types of landed vehicles, which include primarily; in-situ instruments. Initial studies of the planets on planetary scales have moved to more detailed ground truth studies on planetary surfaces. The science goals have shifted to focus on specific questions, in the case of Mars, understanding the history of water and the possibilities for life on the planet. This increased science focus has in turn created the need for integrated science suites that can address these questions in ways that stand-alone instruments cannot.

This paper discusses a number of NASA instrument suites, ranging from those currently operating in space to those that are in early study phases. The focus of the discussion is on the trends, including the shift to greater integration, the concomitant challenges that must be overcome to achieve this integration and the benefits that can ensue. This is not intended to be a comprehensive examination of new instrument suites (that would be a much longer paper) rather the example NASA instrument suites discussed were selected, from those that the author had some familiarity with, to include suites representative of the trends in instrument systems for deep space exploration.

2. CASSINI: A BENCHMARK

The Cassini spacecraft (fig. 1), launched in 1997, is currently on its way to explore Saturn and its moons (ref. 1). Like its predecessor, the Galileo mission to Jupiter, Cassini includes many distinct instruments working together to answer broad questions about its targets. The instruments tend to operate independently, with science return typically integrated on the ground. The optical instruments for example, tend to have separate enclosures and separate front apertures and optics for each wavelength region.

While the spacecraft instrument compliments consist primarily of remote sensing instruments, both spacecraft carry probes that are released from the mother spacecraft. In the case of Galileo, the probe entered and examined the Jovian atmosphere and in the case of Cassini, the Huygens

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probe is designed to explore the Saturnian moon, Titan. The instruments on Galileo and Cassini also tend to be distinct from the spacecraft engineering sensors. For the purpose of examining the trends in instruments, I'll use the Cassini spacecraft as the benchmark for comparison.

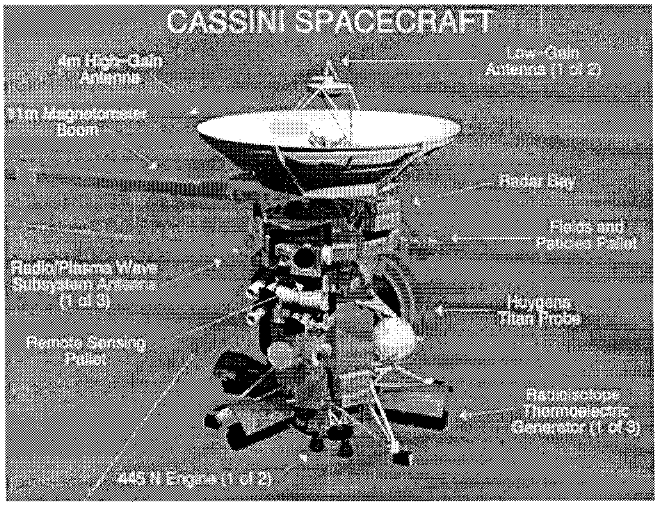


Figure 1. Cassini Spacecraft - Most of the instruments on the, 22 foot tall, Cassini spacecraft are located on pallets, grouped by type so that instruments with similar requirements for resources, including viewing angles are located in close proximity.

3. MICAS: BLURRING THE LINE BETWEEN INSTRUMENTS AND SENSORS

NASA's New Millennium Program (NMP) was created to demonstrate innovative technologies for space flight in space (ref. 2). Deep Space One (DS-1) (fig. 2) is the first NMP spacecraft mission (ref. 3) and was launched in 1998 with twelve new technologies. The Miniature Integrated CAmera Spectrometer (MICAS) (ref. 4) is one of the two instrument technologies validated on DS-1. MICAS has four focal plane arrays (FPAs) covering three wavelength bands (CCD and Active Pixel Sensor (APS) operating from 0.5 to 1 micron, IR spectrometer covering 1.2 to 2.4 microns, and a UV detector at 80 to 185 nm) (fig. 3). In addition to innovative FPA technologies, MICAS uses a single structure, made of Silicon Carbide and a common fore optics. In addition to dimensional stability over time and over temperature variations, the Silicon Carbide structure also provides some of the optical surfaces. MICAS has no moving parts and provides good performance for less mass, volume and power than earlier imaging systems and spectrometers.

In addition to all the innovations in the MICAS design that improve its effectiveness as a science instrument, MICAS also functions as an engineering sensor. It was designed to provide onboard optical navigation to DS-1's asteroid targets as opposed to ground data and control, as had previous spacecraft. In addition to the optical navigation capability, when DS-1's star tracker failed during the mission, MICAS took over the star tracking function, enabling the mission to continue successfully.

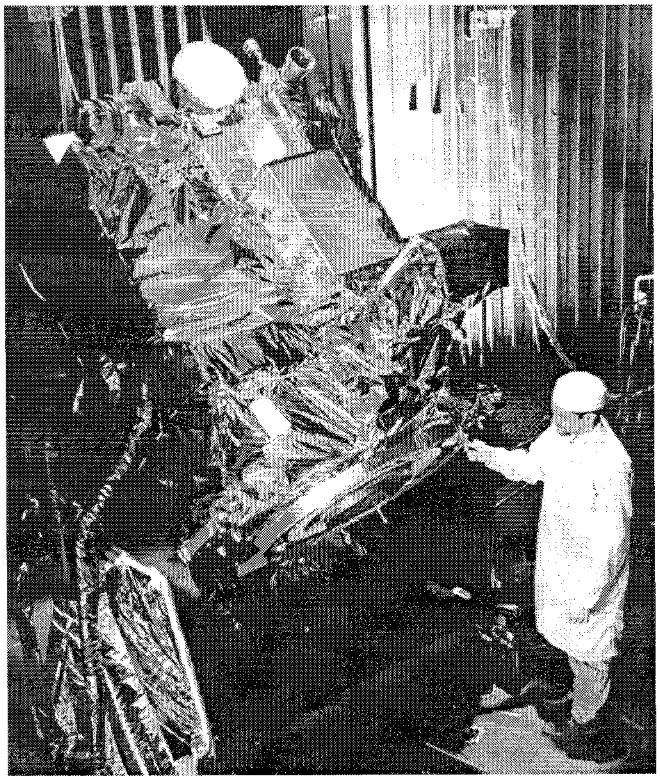


Figure 2. Deep Space One Spacecraft - At under 500 kg, DS-1 weighs less than 10% of the Cassini Spacecraft.

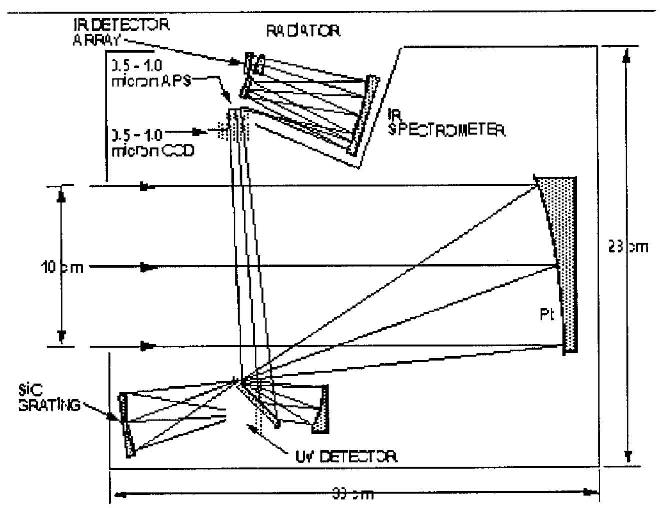


Figure 3. MICAS Optical Ray Trace - indicating common fore optics and separate FPAs, with the UV detector thermally isolated from the visible and IR detector arrays.

While DS-1's MICAS and PEPE are both examples of successful science instrument / engineering sensor combinations, the tradeoffs inherent in dual use are always present. Sharing enclosures and optics between instruments reduces mass and volume but is not generally optimal for the individual instruments. Similarly, specifications for the optimal science instrument generally diverge from the optimal specifications for an engineering sensor. With optical systems, the trade has tended to be between science imagers that want high resolution and thus a small field of view (FOV) and engineering imagers (for navigation or tracking stars, for example) that want large FOVs. As the ability to navigate from smaller FOVs (as for example, with star trackers using large onboard star databases) increases, it will prove more common to have dual use imaging systems. Similarly other types of instruments can be expected, in the future, to perform double duty as engineering sensors.

4. PEPE: Challenges Of Miniaturization

The Plasma Experiment for Planetary Exploration (PEPE) is the second innovative science instrument that was validated on DS-1 (refs. 5-6). It combines a miniaturized linear electric time-of-flight (TOF) mass spectrograph that measures energy, mass and angle of incoming ions; with a miniaturized electron spectrometer that measure electron energy and angle. Unlike the corresponding instrument on Cassini, the CAssini Plasma Spectrometer (CAPS) (ref. 7), PEPE has no moving parts and scans the field via electronic deflection. Figure 4 illustrates some of the differences between the two instruments.

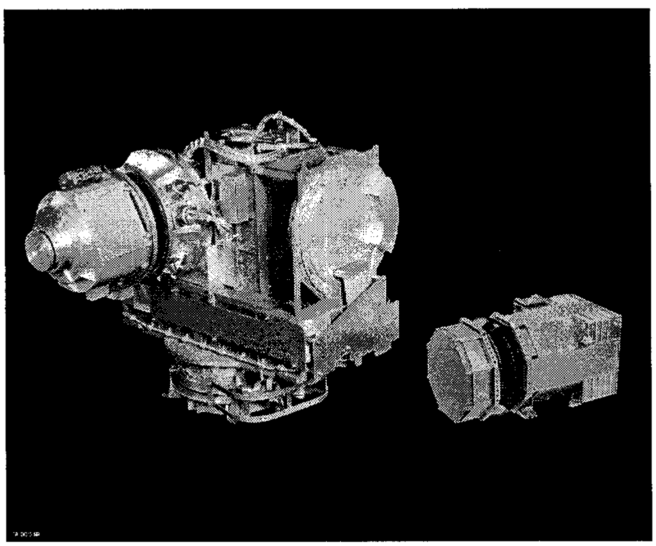


Figure 4. PEPE / CAPS Comparison - PEPE, on the right, with a quarter the mass and half the power requirement of CAPS, has 65% of the energy range and a third of the mass resolution, yet has a 50% greater view, and takes a 3-D spectrum in a third the time.

The greatest challenge in achieving this miniaturization was designing and building the high voltage systems to operate reliably in a confined space. Innovations included replacing the TOF linear electric field rings on CAPS with coated ceramic cylinders on PEPE. Overcoming the miniaturization challenges enables flying additional instruments or using smaller spacecraft.

As with MICAS, PEPE functions as an instrument / sensor hybrid. As a science instrument, PEPE measures the natural electron and ion environment in space and in the vicinity of asteroids. As an engineering sensor, it monitors performance of the ion engine and studies the interaction of the ion engine with the background plasma environment. Finally, it validated the use of plasma instruments on ion propulsion spacecraft.

5. DS-2: New Environments For Instruments

Due to the perceived importance of Martian subsurface samples to understanding the planet, its evolution, the history of its water and the possibility of life, a number of approaches are being developed for deploying science instruments subsurface or returning subsurface samples to the Martian surface for examination. The approach to this problem taken by the DS-2 Mission (ref. 8) was to use penetrators to deliver science instruments 1 to 2 meters subsurface, and to use a drill to obtain a subsurface sample, take it into the vehicle and analyze it there.

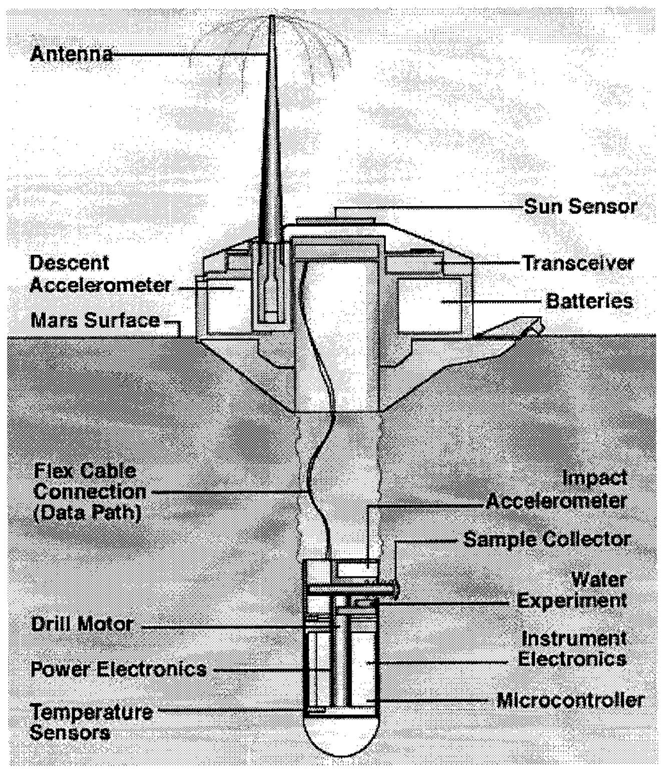


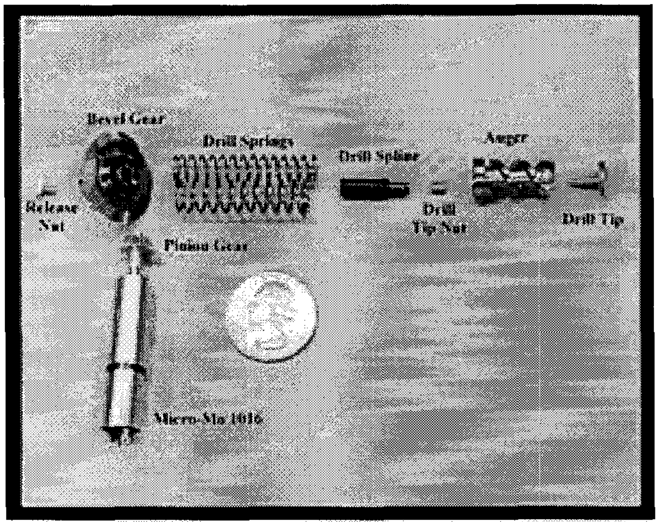
Figure 5. DS-2 - The descent accelerometer, mounted on the aftbody, studies atmospheric densities during descent, while the impact accelerometer, mounted on the forebody, studies regolith densities during penetration. Temperature

sensors are used on the forebody to measure soil conductivity.

The DS-2 Mars Microprobes were two identical penetrators housed in aeroshells and released from the Mars Polar Lander (MPL) Spacecraft prior to its landing on the Martian surface. Unfortunately, signal was lost from MPL prior to its landing and no signal was received from the DS-2 Mars Microprobes. The new technologies developed for DS-2 are however being used in developing future space missions. The DS-2 effort is also proving to be a model for possible future Micromissions to Mars.

The experiments on DS-2 in addition to the sample collection / water experiment (fig. 6-7), included an atmospheric descent accelerometer, an impact accelerometer and temperature sensors for a soil conductivity experiment. All of these, along with DS-2 engineering systems were contained in a compact, coffee-cup-sized forebody and the slightly larger aftbody, which together weighed only 2.5 kg (fig. 5).

The DS-2 microprobes were expected to land at 400 mph. The aftbody was expected to experience 60,000 g and stay on the surface, while the forebody was intended to deliver the experiments a meter or 2 subsurface and was expected to see 30,000 g. The uncertainty of penetration depth is primarily due to our limited knowledge of regolith consistency. Temperatures were expected to be -120 C for the forebody and -80 C for the aftbody.



Motor / Drill Assembly

Figure 6. DS-2 Drill Motor and Sample Collection - The sample collection system was designed to collect a subsurface sample for analysis. Earlier designs were passive collection systems that could not guarantee that the sample collected was subsurface material. In the flight design, the drill moves sample material into DS-2 and deposits it in the sample container.

The DS-2 instruments had to be designed to fit within the tight mass, volume, and power constraints and yet to survive the intense dynamic, thermal and radiation environments. As NASA travels to increasingly tantalizing but equally hazardous new environments, instruments will have to be hardened appropriately. From thermal concerns (Venus), to pressure issues (outer planets), from aqueous environments and radiation extremes (Europa), to dusty environments (Mars), instrument designers will have a challenging job in the future.

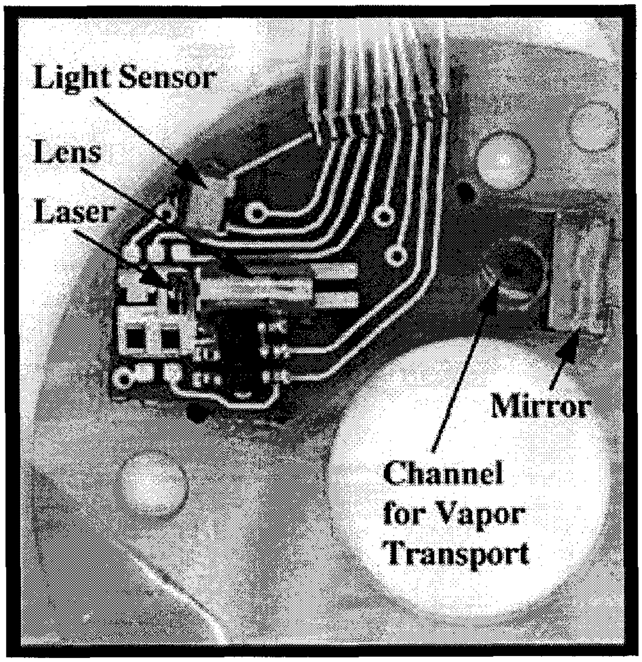


Figure 7. DS-2 Water Experiment - The sample deposited by the drill is sealed in a sample chamber and electrically heated. Vapor emitted from the sample crosses the optical path between the laser and the mirror and the mirror and the photodetector. The tunable diode laser scans wavelength to look for water absorption. The sample temperature at which water absorption is detected indicates the state of the water (i.e. bound water, ice).

6. MECA: NEW TYPES OF INSTRUMENTS FOR SPACE FLIGHT

The Mars Environmental Compatibility Assessment (MECA) (ref. 9) instrument suite was developed as a Human Exploration and Development of Space (HEDS) package for the planned Mars 01 Lander. Since the Mars exploration plans have changed due to the failures of some of the recent Mars missions, it is hoped that MECA will fly on some TBD Mars mission in the near future.

The other Mars 01 instrument packages included MARIE, a radiation instrument, MARDI, a descent camera, and MIP, a series of experiments to test approaches to in-situ propellant production, so that the propellant needed for return flights from Mars can be manufactured using indigenous materials.

All of the HEDS instruments are intended to study aspects of Mars that could impact future manned flights to the planet. MECA consisted of four instrument suites to examine chemical, microscopic and electrostatic properties of Martian soil. The microscope suite incorporated optical and atomic force microscopes to image mineral and rock grains, and measure morphology, hardness and magnetic and electrostatic properties. Samples were to be transported to the suite by the Mars 01 sample arm and once within the suite, a sample wheel brought the samples to the foci of the microscopes.

The MECA wet chemistry cells or "labs in a teacup" performed analyses of pH, redox, conductivity and dissolved salts, in a soil-water mixture using 26 ion selective electrodes. Each of the four wet chemistry cells (fig. 8) were able to analyze a single sample.

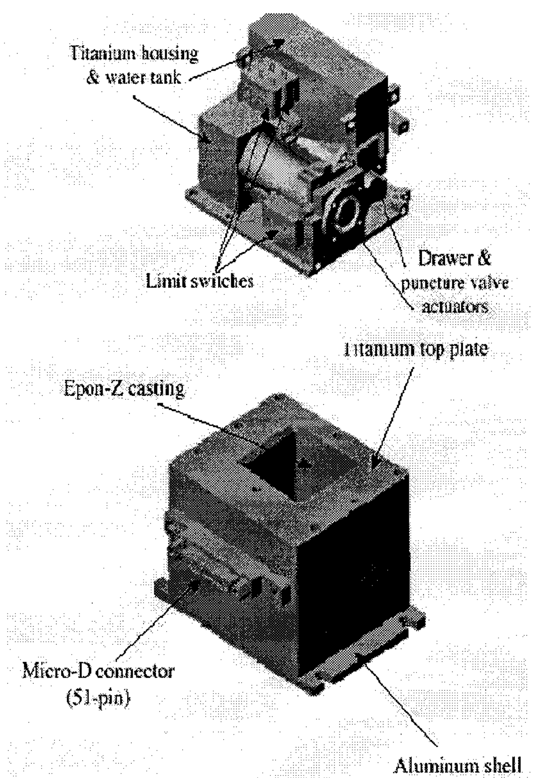


Figure 8. MECA Wet Chemistry Cell - The Mars 01 sample arm was to deposit samples in the sample drawer, which would then bring the sample into the sample chamber and release it. The sample was then mixed with the leaching solution and reagent pellets. The response of the 26 electrochemical sensors was then used to analyze the sample.

The MECA electrometer used multiple sensors, mounted on the sample arm, to measure electric fields, radiation and triboelectric charging. The MECA adhesion patch plate contained nearly 100 samples of various materials, whose reaction to Martian conditions was to be observed by the Mars 01 camera to measure any visible changes, including fluorescence and adhesion of Martian dust to different materials.

MECA is a great example of the new types of instruments that are being used on spacecraft. Some of these new instruments are enabled by new technologies to make familiar measurements in innovative ways, while others enable new measurements that have never been made in space and are intended to answer specific scientific questions. As MEMS, nanotubes and TBD move from speculation to flight instruments, the shape and focus of science instruments will broaden dramatically.

7. FIDO / ATHENA: INTEGRATED INSTRUMENT SUITES WITH A COMMON GOAL

The Mars Exploration Rover (MER) Project (ref. 10) is preparing two rovers for launch in 2003. Each of these rovers will be much larger than the Pathfinder Sojourner rover (150 kg vs. 11 kg) and will replace the rover with a single instrument, that is reliant on a lander, with an independent rover with an integrated instrument suite, called Athena. The MER rovers will start science operations by raising their masts and using mast mounted instruments to survey the scene and select targets. The rovers then move to, and deploy instrument arms to perform detailed in-situ investigations of these targets.

The mast mounted and arm mounted instruments, though distinct instruments, function as a coordinated suite. The mast mounted Panorama Camera (Pancam) photographs the surrounding terrain in multiple wavelengths, which allows for preliminary identification of the local geology. The IR Spectrometer then takes remote spectra of targets of interest identified by the Pancam. The data from these instruments is then used to select targets for in-situ study. During traverse to the target, the Pancam is used as needed to take closer images of the target area. Finally, the Pancam is used to guide instrument arm placement.

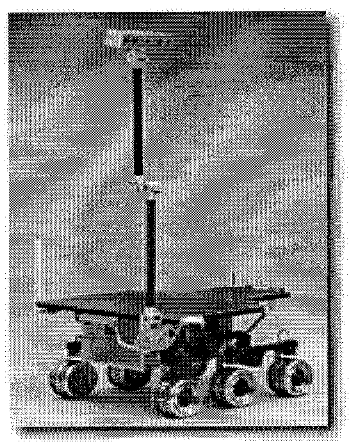
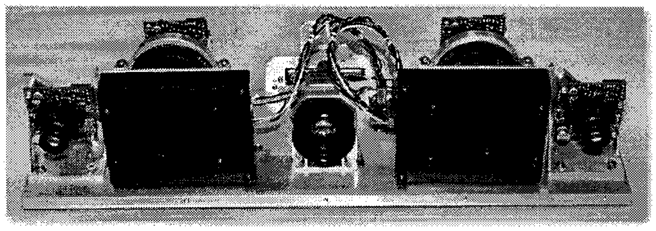


Figure 9. The FIDO Rover - The five apertures in the mast

head correspond to the stereo navigation cameras, the stereo Pancam and the feed optics for the spectrometer.

The arm mounted microscope is typically deployed first to visually examine the target up close. Depending upon the target and the portion of the mission, an arm mounted Moessbauer Spectrometer and an Alpha-Proton-X-Ray Spectrometer are used to provide in-situ mineral identification. This real time use of instruments as a coordinated science suite to locate, identify and classify minerals can be contrasted with most previous instrument situations, where the instruments take separate data, which is at best correlated months later on the ground.



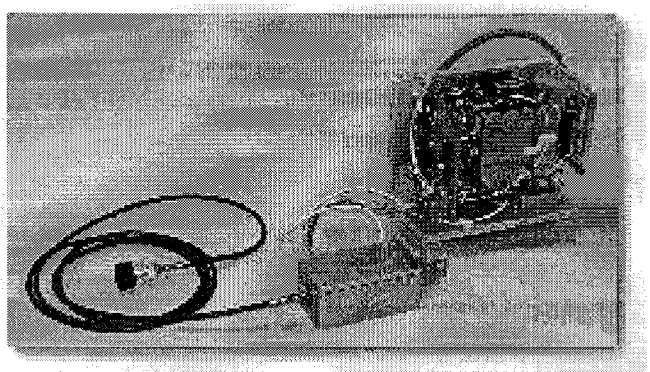


Figure 10. FIDO Mast Instruments - The upper photograph is the inside of FIDO's mast. The outer cameras are navigation cameras. The rectangular elements are the Liquid Crystal Tunable Filters (LCTF) in front of the Pancam cameras and the center element is feed optics for the Infrared Point Spectrometer (IPS). The lower photograph shows all the IPS components: feed optics, fiber cable, Acousto-Optical Tunable Filter (AOTF) spectrometer and electronics.

To better understand the operation of a coordinated instrument suite and to train the Athena science team, a terrestrial test rover was developed and instrumented with a suite of instruments selected to simulate Athena operations. This Field Integrated Design & Operations (FIDO) rover (fig. 9) has been outfitted with analogues of the Athena instruments (ref. 11). FIDO has a Pancam (fig. 10 top) that operates in three near IR bands, centered on 650, 750 and 850 nm using LCTF filters to simulate operations of the Athena Pancam which has a filter wheel with a much larger number of bands. The mast spectrometer on FIDO is an AOTF based near-IR point spectrometer, operating from 1.2 to 2.4 microns, which is capable of commanded raster scanning (fig. 10 bottom). In contrast, the Athena spectrometer is a mini-Thermal Emission Spectrometer (mini-TES) operating at longer wavelengths.

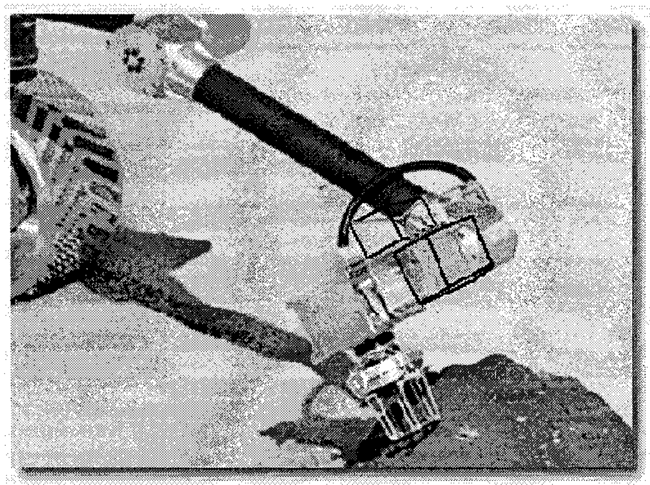


Figure 11. FIDO Arm Instruments - The upper photograph shows the microscope with its fixed focal length standoff with illuminator ring placed against a target. The black lines indicate position for a possible third arm instrument. The lower photograph shows the Moessbauer Spectrometer placed on a target.

FIDO's arm mounted microscope is simpler than the Athena microscope, while FIDO's Moessbauer spectrometer is almost identical to the Athena flight version (fig. 11). FIDO does not have an Alpha-Proton-X-Ray Spectrometer, since it would not operate without near vacuum conditions. To adequately simulate flight operations with FIDO, all the instruments are fully integrated with the rover; all are completely housed within the rover and are powered by the rover. Commanding is via Web Interface for TeleScience (WITS) (ref. 12) from researcher home organizations.

Telemetry is likewise distributed to JPL and the scientists' universities via the web. The FIDO instruments were hardened to function within the electrical environment of the rover, to withstand the temperature variations of desert field testing and the dynamic shocks of travelling on rough terrain. The highly integrated FIDO instrument suite has since undergone extensive testing in JPL's Mars Yard and in multiple desert field tests (refs. 13-14).

8. Subsurface Explorer: Concurrent Development Of Innovative Instruments And Mobility System

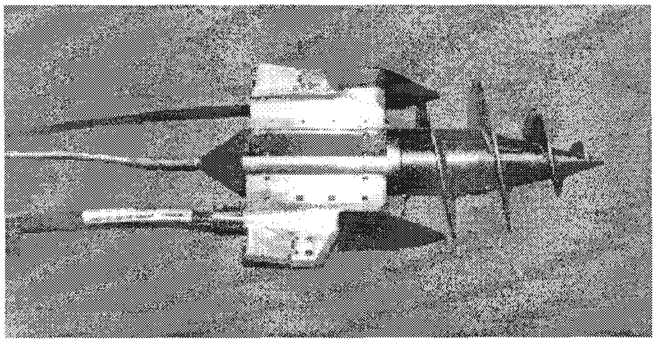


Figure 12. Early Prototype of the Subsurface Explorer - To either side of the vehicle are vanes with triangular tips in which the instrument fore optics were placed behind specially hardened windows. The instrument fiber cables are on top left (imager) and bottom left (Raman Spectrometer) of the photograph.

The Subsurface Explorer Vehicle, which is in an early study phase, takes a different approach to subsurface science than the DS-2 Microprobes. The early versions of the Subsurface Explorer moved beneath the surface carrying instruments within it. The latest version of the vehicle instead envisions returning samples to the surface. Both approaches pose distinct challenges to the associated instruments. For instruments to be integrated within the Subsurface Explorer requires miniaturization, new designs to fit the vehicle design and the ability to survive the vehicle environment.

The early prototype of the Subsurface Explorer (fig.12), which was used to demonstrate initial feasibility of a subsurface mobility system, had fins in which instruments could be mounted. The initial instruments selected were an imager and a Raman Spectrometer (fig. 13). Optical heads for both these instruments were mounted in two of the vehicle fins, and fiberoptic umbilicals were used to send the Raman exciting laser beam subsurface and to send images and the Raman signal to the surface where the rest of the instruments were housed.

This prototype vehicle and instruments demonstrated feasibility of the concept. To improve mobility, the vehicle was redesigned to a cylindrical configuration with percussive propulsion and to improve science return and increase the unboard capability, a Raman Spectrometer optical head was designed that fit the new vehicle design and integrated an imager with the spectrometer.

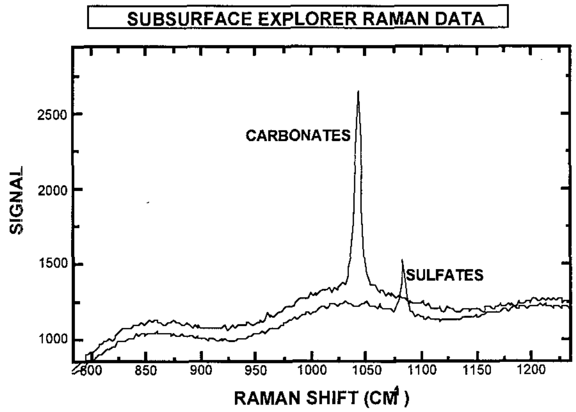


Figure 13. Raman Spectra from Subsurface Explorer - This spectra was taken of sample materials as the Subsurface Explorer drilled through them.

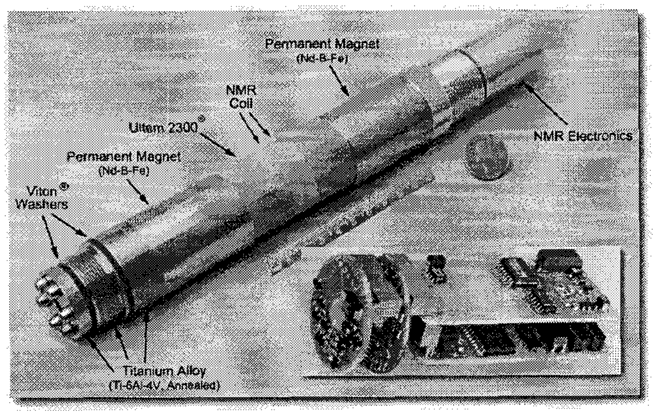


Figure 14. NMR Designed for Subsurface Explorer - The NMR magnets and coil element double as portions of the outer wall of the vehicle.

Since plans for Martian exploration are focused on the search for water, it was decided to design an NMR instrument for the Subsurface Explorer. The challenges here were to develop an NMR that could function within the Subsurface Explorer and that could survive the shock and vibration of the Subsurface Explorer's propulsion system. An external detection magnet was designed that fit within the cylindrical vehicle and a special sleeve was designed to house the instrument and connect with the Subsurface Explorer elements. The magnet and the electronics boards, in addition to fitting the cylindrical cross section, had holes concentric with the cylinder axis to allow the vehicle's electrical umbilical to pass through. Shown in figure 14 is the NMR along with its vibration isolation elements.

The current design for the Subsurface Explorer contains within its umbilical a tube through which samples are returned to the surface. This design has removed the subsurface instruments in favor of increased mass and volume for vehicle systems, enabling deeper subsurface exploration. However, one could easily imaging a hybrid Subsurface Explorer (fig.15) that incorporates nose sensors, science instruments within its body and a science suite on the surface analyzing samples returned from the vehicle.

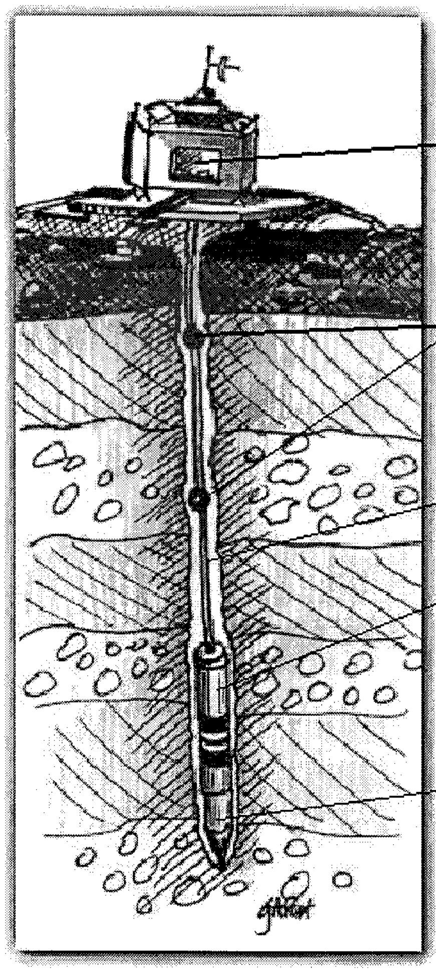


Figure 15. Artist's view of Subsurface Explorer and possible integrated instruments.

The Subsurface Explorer is a good example of a prototype mobility system whose instruments are designed concurrently with the vehicle and are physically integrated with it. As the vehicle design and its mission profile mature, the instrument suites are being designed to evaluate its performance as a mobile science platform.

9. Concluding Remarks

Tables 1 and 2 summarize the types of integration and the new aspects of the instrument suites discussed here.

Integration:	MICAS	PEPE	DS-2	MECA
Instrument / Sensor	X	X		
Shared Resources	X	X		X
Single Science Focus				
New:				
Technology	X	X	X	X
Mission Environment			X	X
Vehicle Environment		X	X	
Instrument Types			X	X

Table 1. Trends in Some Existing Flight Instruments - In addition to higher levels of integration to aid in miniaturization, MICAS and PEPE integrate science instrument functions with engineering sensor functions. They along with MECA, share instrument resources to a large extent, with all of them, for example, sharing front apertures with multiple instruments. Three of these four suites function in a mission environment and / or a vehicle environment that has not been seen by similar instruments in the past. Half include new types of instruments that have never flown before and all rely heavily on new technology to achieve their objectives.

Integration:	FIDO	Athena	Subsurface Explorer
Instrument / Sensor			TBD
Shared Resources			TBD
Single Science Focus	X	X	
New:			
Technology	X	X	X
Mission Environment			X

Vehicle Environment			X
Instrument Types			

Table 2. Trends in Some Demonstration or Development Instruments - The integration aspect of the rover suites is interesting in that they are much more oriented than past instrument suites towards a single science goal, with instruments commonly being used to help select targets for other instruments, and all instruments evaluating the same target. As with the flight instruments, the use of new technology to achieve goals is present in all of these instruments.

Not included in the tables but certainly worthy of note is the trend to greater autonomy for both vehicles and instruments. With the increasing capability of onboard databases it is expected that instrument suites will learn from early data collected and recommend new objects for observation to the science teams.

Also of note is the impact of future mission architecture on instruments and sensors. Separated spacecraft missions along with the use of sensor arrays are becoming more common and will certainly greatly influence design of future instruments and sensors.

With all the changes, we can rely on a number of constants. First, even with all the new exotic instruments, we will always want to make key measurements that we relate to as human beings (e.g. what does it look like? fell like? Is it hot or cold?) and those that we have become comfortable with (e.g. what are its electrical characteristics? its velocity?).
Second, the space environments, with radiation, thermal extremes, shock, solid particles, pressures ... will always prove challenging. Finally, due to the lack of repair people, exceptional reliability will always be required of instrument designs.

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