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SPACECRAFT APPLICATIONS OF COMPACT OPTICAL AND MASS SPECTROMETERS

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ABSTRACT

Optical spectrometers, and mass spectrometers to a lesser extent, have a long and rich history of use aboard spacecraft. Space mission applications include deep space science spacecraft, earth orbiting satellites, atmospheric probes, and surface landers, rovers, and penetrators. The large size of capable instruments limited their use to large, expensive spacecraft. Because of the novel application of microfabrication technologies, compact optical and mass spectrometers are now available. The new compact devices are especially attractive for spacecraft because of their small mass and volume, as well as their low power consumption. Dispersive optical multi-channel analyzers which cover the 0.4-1.1 μm wavelength range are now commercially available in packages as small as 3 x 6 x 18 mm, exclusive of drive and recording electronics. Mass spectrometers as small as 3 x 3 x 3 mm, again without electronics, are under development. A variety of compact optical and mass spectrometers are reviewed in this paper. A number of past space applications are described, along with some upcoming opportunities that are likely candidate missions to fly this new class of compact spectrometers.

I. INTRODUCTION

This paper focuses on two classes of compact sensors, both spectrometers, which are already commercially available or now under development. They are optical and mass spectrometers, both of which have clear promise for use in spacecraft applications. Their smaller weight and lower power requirements, as well as their potentially greater reliability, will clearly have a major impact on new spacecraft. This is true for two reasons: (a) they permit putting greater functionality on conventional spacecraft, for the same weight and power, or reducing the launch and housekeeping needs for the same functionality, and (b) they enable the design of radically new miniature spacecraft which have not been possible before the emergence of microsystems (1).

Microsystems, for example, microelectromechanical systems (MEMS), are particularly attractive for spacecraft. Specifically, the motivations for designing microsystems into spacecraft include the following. Smaller instruments can enable the use of smaller launch vehicles. Smaller launch vehicles translate to lower program costs, more flight opportunities, and possibly less program risk. Microsystems can similarly reduce secondary program costs such as facilities, integration and test, and transportation costs by reducing the physical scale of these operations. Another motivation for using microcomponents is that they permit the collocation of sensors with their electronics, which can yield better signal to noise performance and more efficient packaging. Components and subsystems which are lighter and smaller can relieve a variety of mission requirements. If they require less power, spacecraft can be designed with smaller solar arrays (often the largest single contributor to spacecraft surface area) and smaller batteries (often the largest single contributor to spacecraft mass). Microsystems can improve the capability and performance of a spacecraft by making it possible to fly more sensors, either of the same variety, for redundancy, or of different types, for improved functionality.

Practical factors and limits to miniaturization have to be evaluated. It is only somewhat beneficial if one or more of the smaller or less power hungry subsystems is miniaturized, because the weight and power budget of the entire craft is little reduced. Also, reduction in the size of a component has limits, because of the need for a package which can be handled, fixed in place and connected appropriately. Other limits on microsystems concern their performance, rather than merely their physical characteristics. Several examples of performance limits have been widely discussed. Among them are the aperture limits for small optical systems, the need to match antenna sizes to radio-frequency wavelengths and the fact that the very small proof masses in MEMS accelerometers are limited by thermal (Brownian) noise.

The hardware for any system can be subdivided into a number of subsystems. For spacecraft, these include the structure, power, thermal control, computer, communications and the payload (2). For example, the payload in many cases includes sensors, along with additional control electronics and data storage components. Each of the subsystems on a spacecraft or payload, is a candidate for miniaturization, either in the near term or in the future. Sensors for either housekeeping or as part of the payload are very attractive targets for miniaturization.

II. SPECTROMETERS

Like imagers, spectrometers provide an abundance of data. The spectral lines each have at least a position (energy or mass) and an intensity. For both optical and mass spectra, the position of lines gives qualitative analyses (what is it?) while the intensities yields quantitative analysis (how much?). The continuum in many optical spectra also provides a great deal of information. Both the lines and continuum, properly interpreted, indicate the mechanisms which are active in the production of the observed spectra. Optical spectra can also be used for the characterization of hot or energetic sources. Mass spectra provide data on the makeup of natural plasmas, for example, ionization in the upper atmosphere, and plasmas produced by hypervelocity impact of man-made objects.

The next section deals with compact optical spectrometers, many of which are already on the market. The third section focuses on miniature mass spectrometers which are under development, and may be available in small numbers in the foreseeable future. In both these sections, some background is provided before a review of specific instruments. Then the fourth section reviews some earlier space applications of optical and mass spectrometers, before considering new opportunities for utilization of available and emerging compact spectrometers aboard spacecraft in the fifth section. Special emphasis is given to the coming Clementine II program which might include both optical and mass spectrometers for observation of the impact of microsat interceptors with a sequence of three asteroids.

III. COMPACT OPTICAL SPECTROMETERS

The utilization of optical spectrometers on earth and in space has a long and rich history. There are two major trends now in the evolution of optical spectral instruments. The first is continued reductions in size, which is the focus this paper. The other is full integration of spectrometers with imagers to provide a "cube" of information, namely two spatial dimensions (say, X and Y) and the spectral distribution at each pixel (the wavelength dimension). Such hyper-spectral imagers are instruments which work in a way analogous to our vision, which provides an image with colors. At this time, hyper-spectral imagers have been integrated into aircraft, but not into spacecraft. Multi-spectral imagers, such as on Landsat, which provide images in a few wavelength bands, are really not spectrometer systems in the usual sense. That is, they provide intensities in only a few wavelength bands and not the entire spectrum in a more or less continuous manner.

Many good references on the basics of optical spectrometers are available (3,4). There are two main types of optical devices, each with a pair of major variants. The first is dispersive instruments based on prisms or gratings. The second is interferometric spectrometers, such as the Fabry-Perot or Michelson types. Compact optical spectrometers now available commercially employ diffraction grating dispersion elements in reflection geometries. Their description constitutes the body of this section. MEMS spectrometers, with moving components providing dispersion in Fabry-Perot and other designs, are under development. They will be mentioned briefly at the end of the section.

Micro-optical spectrometers behave very much like their larger counterparts. The wavelength of light (from the ultraviolet near 0.2 μm, through the visible 0.4-0.7 μm, to the near infrared around 1.0 μm) is small compared to geometries in even compact spectrometers. The light collection efficiency depends on optics external to the spectrometer, the size of the entrance slit, and the angular acceptance (called the f number). The ability of the spectrometer to register photons, namely its efficiency, varies across the spectrum and depends on the individual efficiencies of the grating and the detector. The resolution is determined by the size of the entrance slit, the geometry of the grating and spectrometer, and the size of the detector elements (pixels).

The range over which a given spectrometer works depends on its design, the grating ruling density, and the size of the instrument. When only point electronic detectors were available, grating spectrometers had to be scanned to record an entire spectrum sequentially (serial readout). With the availability of solid-state detector arrays, such as charge-couple devices (CCD) and photo-diode arrays (PDA) in the 1980s, it is possible to capture an entire spectrum simultaneously (parallel readout). This mode, the so-called optical multi-channel analyzer (OMA), is similar to the way in which photographic film was used to record spectra before there were any electronic detectors.

Many standard, laboratory-size OMA spectrometers and spectro-photometers are on the market. Three commercial grating optical multi-channel analyzers, which are compact and relatively inexpensive, will now be described. To our knowledge, none of these has been flown on a spacecraft, but all are candidates for missions to be described in the fifth section.

A spectrometer which literally fits in the palm of a hand is shown in Figure 1. It, and variants of it, are manufactured by Ocean Optics, Inc. (5). Light arrives at the instrument in an optical fiber, the end of which serves as the entrance slit. Hence, one can trade resolution (linear in the fiber core diameter) for intensity (quadratically dependent on the diameter) in a straightforward manner. The instrument is assembled from separate components, a folding mirror, grating and detector array, and then sealed. That is, switching of internal components is not possible in the current versions. The company offers several different input fibers and gratings so that the buyer can tailor the intensity, resolution and range to the application. It is possible to cover a 500 nm range, say, from 250 to 750 nm, with 2.5 nm resolution, or a 125 nm region with 0.7 nm resolution. The detector is a CCD containing 1024 elements. Spectra can be collected in as little as 8.2 msec, that is, it is possible to record over 100 spectra per second. As illustrated, the instrument is mounted on a half-board which fits a standard PC. The computer performs both control and data recording functions, with subsequent spectral analysis being readily performed with either the vendor supplied, or third party, software. The cost of the spectrometer on the board, input fiber, and software is about $2000.

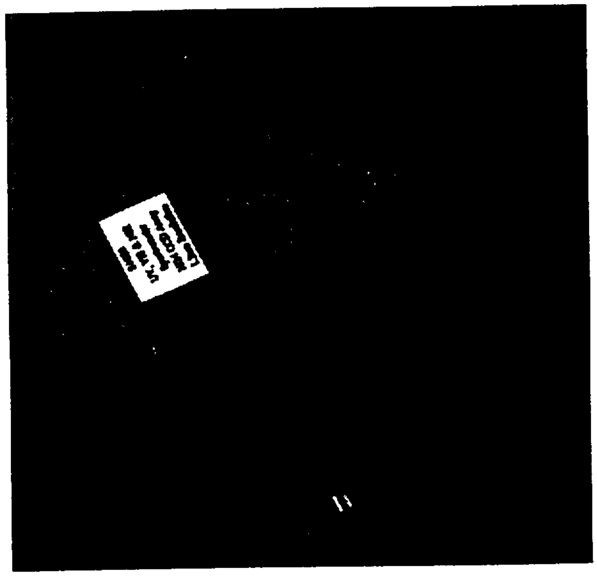

Figure 1. Optical grating spectrometer, fed by the optical fiber shown at the bottom, covers half a short board for a PC.

Another compact grating OMA is made by Carl Zeiss (6) and pictured in Figure 2. This system, which contains a grating and a diode array, is also fixed in construction. It is offered in two versions. One covers the 190-735 nm region with 2.2 nm resolution, while the second is good for the 320-1100 nm range with 2.2 nm resolution. The detector is a PDA with 256 elements. It can provide 12 bit information in 10.5 msec or, with different electronics, 14 bit data in 9 msec. While the spectrometer itself is quite compact (24 mm diameter body 28 mm long), it is mounted in a housing so that the entire unit is 40 mm x 50 mm x 65 mm in size (for the longer wavelength version). In addition, a separate external electronics box 60 mm x 100 mm x 100 mm is needed between the spectrometer and a PC plug-in board. The entire basic system including the spectrometer with the housing, 12-bit electronics box and PC board, and connecting cables costs $3000. The 14-bit electronics are an additional $2850.

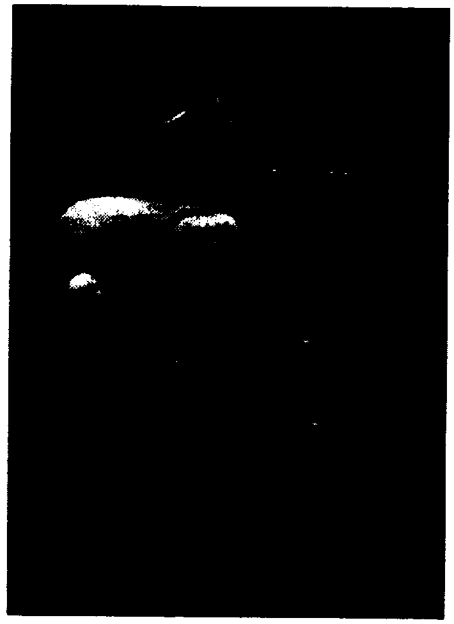

Figure 2. Compact optical spectrometer, with the input optical fiber, a grating under the curved top and detector array near the output pins.

The most compact commercial spectrometer is made by a German company called MicroParts Gesellschaft fur Mikrostrukturtechnik mbH (7) using the LIGA technique (8). This extraordinary device is sketched in Figure 3. The holder for the input optical fiber, the grating, and a 45 deg. mirror which deflects the light down into the horizontally mounted array are produced as a unit. It provides 7 nm optical resolution over the wavelength range from 370 to 850 nm. The spectrometer itself is only a few mm thick, 6 mm wide and 18 mm long. It costs about $600, including the 256-element PDA, without electronics. The electronics board permits spectral acquisition times variable from 40 to 1256 msec, with 16-bit resolution. The entire system, spectrometer with PDA, electronics, software, and power supply costs about $4100.

The focus in this section so far has been on available instruments. However, since tomorrow's product is commonly a recent or current research prototype, we will briefly survey some other reports of microsystem optical spectrometers in the remainder of the section.

An infrared spectrometer on a chip was fabricated with integral light guides and grating (9). It consisted of an InP substrate, an intermediate layer of InGaAs and a top layer of InP through which the radiation traveled. That is, the layout is generally similar to the commercial spectrometer shown in Figure 3, in which the optical radiation travels in air. The infrared transmissivity within a solid semiconductor was exploited in this developmental device. Radiation in the 1.48 to 1.59 µm region was dispersed with 3.75 nm resolution.

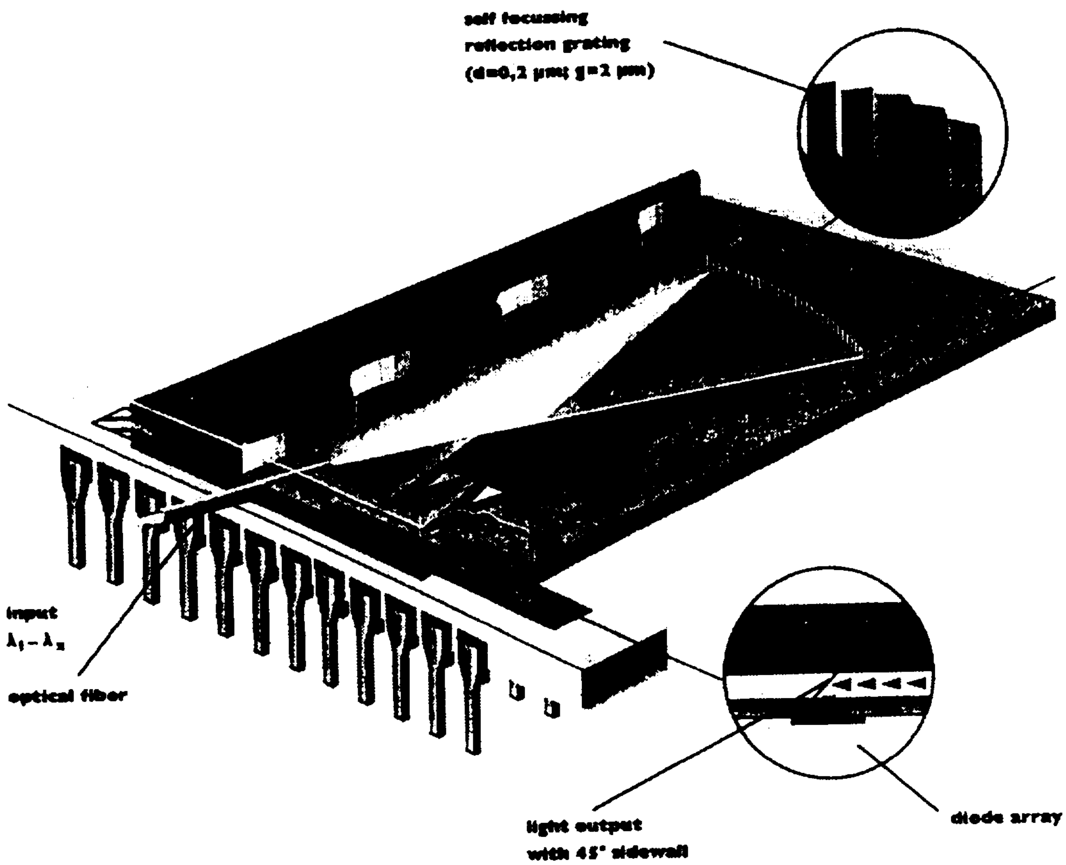

Figure 3. Micro-optical-spectrometer, 18 mm in length and 6 mm wide, with fiber optic input and a silicon diode detector array.

A silicon spectrometer was fabricated by deep etching of two wafers and their subsequent bonding to form an integrated device with a 4 mm total optical path length (10). Dispersion was obtained with a 32-slit transmission diffraction grating on the same wafer as a 200-element PDA.

There have been at least four reports of MEMS Fabry-Perot interferometric components. The first two came from the same group, which used electrostatic tuning of bulk micromachined and bonded structures. They achieved tunability in the 1.30-1.38 µm range by applying voltages up to 70V. The optical resolution was 0.9 nm (11,12). A similar approach in the visible region yielded 1.6 nm resolution at 450 nm (13). A process and design study for surface micromachined silicon tunable interferometric arrays is also available (14).

A tunable, high-pass infrared MEMS filter based on deformable metallic structures was produced by the LIGA technique (15). Spectral resolution can be attained with this device by scanning the cutoff. Variation in the cutoff, which is similar to the waveguide cutoff at radio frequencies, from about 5 to 25 μm has been demonstrated.

There are many other papers on optical MEMS, where the components do not act as spectrometers. Functions such as light modulation, coupling of fiber optics and formation of beams for displays are being aggressively pursued. A review of optical MEMS is in preparation (16).

IV. COMPACT MASS SPECTROMETERS

Mass spectrometry has a long and rich terrestrial history, which can be traced back to around 1910. However, mass spectrometers have not been used in space anywhere near as much as optical spectrometers. Because they require contact with the material to be analyzed, mass spectrometers are limited to direct rather then remote sensing, both of which are possible with optical spectrometers. Mass-resolving instruments are evolving in the direction of smaller devices without much loss of capability. This is making them increasingly attractive for a wide variety of space missions, as will be discussed in the fifth section.

Good references on the fundamentals and applications of mass spectrometers are available (17,18). As with optical spectrometers, there are a few basic types of instruments which can be used to distinguish the masses, and therefore type of atoms and molecules. A conceptually simple approach to mass separation is taken in time-of-flight devices. In these, diverse ions are given the same energy by pulsed electron or photon (laser) excitation. They then move through a drift region in the instrument at different speeds because of their different masses. The drift region can be one directional, or can include an ion mirror, which serves to shorten the overall length of he instrument. The varying arrival times at the ion detector provides the mass spectrum.

The second class of mass spectrometers involves the use of time-varying, often radio-frequency, fields. Three major versions of these systems exist. In one variant, called fourier-transform ion cyclotron resonance mass spectrometry, a radio-frequency field is applied to a vacuum trap containing the ions to be analyzed. Image charges in nearby plates provide a signal, which is fourier transformed to obtain the mass spectrum. In another, termed a quadrapole mass filter, four electrodes are biased with both steady and varying electric fields in such a way that specific masses can transit the filter. Recording a mass spectrum requires scanning of the pass band of the quadrapole analyzer. The third RF variant has multiple deflection plates along the track taken by he ions to be analyzed. The plate geometry and RF frequency are chosen so that the mass of interest will pass to the detector, but all other material will be shunted aside. Hence, this is also a sequential method of mass spectrometry.

The final class of mass spectrometer employs magnetic fields, either separately or in combination with electric fields, to disperse charged species with missing or added electrons. This approach can be used in either a scanning (series) mode, if the fields are varied appropriately, or for simultaneous (parallel) acquisition of a spectrum, if an array of detectors is available. The latter is amenable to either pulsed operation, as in a time-of-flight instrument, but it can conveniently be operated in a DC mode to accumulate a spectrum.

Development of smaller mass spectrometers requires shrinking all of the needed components, notably the source of ions, the means of dispersal in space or time and the detector. The method of ionization varies widely, depending on the material to be analyzed (gas, liquid or solid, and the chemical makeup) and the source of energy for the production of ions (optical, electrical or other means). The collection efficiency of the system is set by the external optics (if any), the size of the entrance slit and the geometry. The spectrometer efficiency depends on the quality of the internal vacuum and the efficiency of the detector. Mass resolution, the ability to separate neighboring isotopes different by only one atomic mass unit, is determined by the slit widths, dispersion element(s) and the detector pixel size. The mass range over which a particular device is useful depends on the design, the dispersion element, and the size of the key components. All of the different classes of mass spectrometers described above, except of the fourier-transform ion cyclotron resonance approach, are being made more compact with conventional technology or being designed anew with micro-machining technology. Some commercially-available, relatively-compact mass spectrometers, and small instruments under development, will be described in the remainder of this section.

A few companies offer time-of-flight mass spectrometers for laboratory applications. Comstock, Inc. is an example (19). They sell both linear and reflection models in which the drift region is 1 m. Now, they are offering more compact 450 mm drift region devices in field-portable configurations. Adaptation of the new designs to space missions is more attractive, because of the lower mass in the smaller instruments.

A compact time-of-flight spectrometer is under development at the Johns Hopkins Applied Physics Laboratory (20). The mass analyzer is 200 mm long, 6000 mm^2 in cross section and weighs 500 grams, with the system weight being greater due to electronics, vacuum pumps and computer. Spectra from the prototype instrument have been measured in the mass-to-charge range of 0-500. This device is also being aimed at field use and is a candidate for space missions.

Quadrapole mass analyzers are widely available commercially because of their use in leak detectors for vacuum systems. Miniature quadrapole mass spectrometers are under development at the Jet Propulsion Laboratory (21). Unit mass resolution has been demonstrated from 4 to 86 amu. Large arrays of small, lithographically-produced mass filters are being envisioned for planetary, near comet and space plasma measurements.

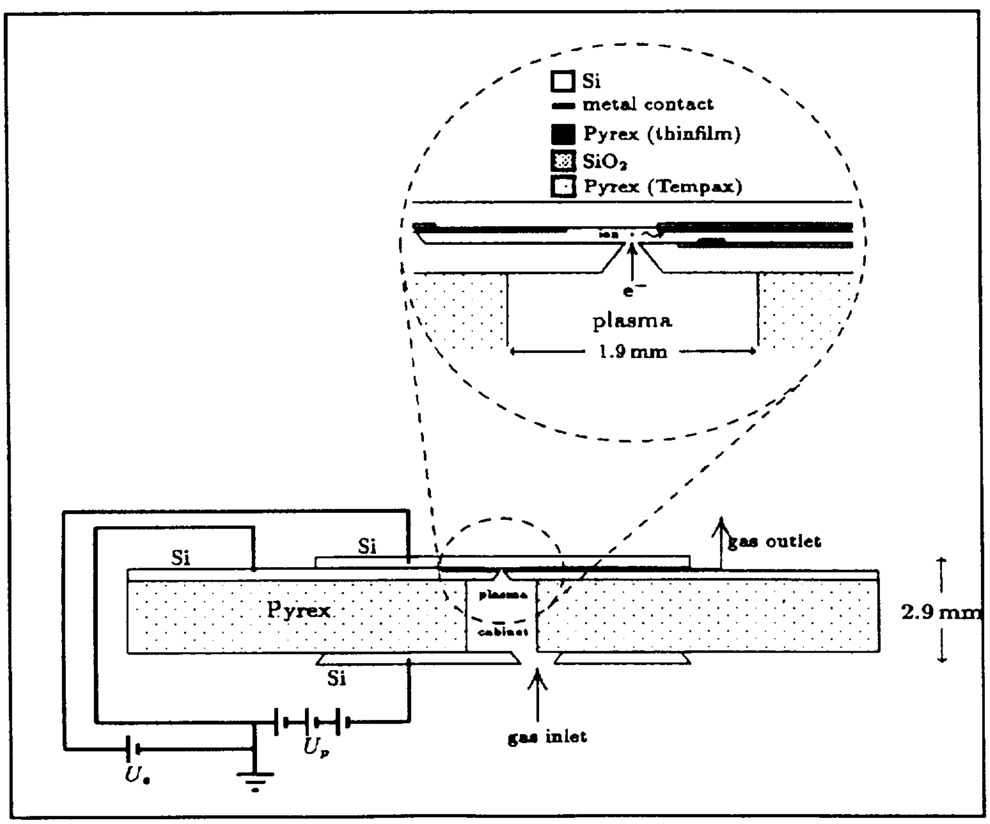

Figure 4. Cross section of a compact RF mass spectrometer.

Two current projects are seeking to build mass spectrometers "on a chip". In one of them, a combination of lithography, anisotropic etching of silicon, thin film deposition and anodic bonding of wafers is being used (22). The spectrometer, shown in Figure 4, included a plasma electron source, an ionization chamber and a mass separator in a (3 mm)^3 volume. The separator consists of a series of plates to which an RF is applied (around 50 MHz). Data published one year ago showed a modest mass resolution of 18 (mass/delta mass) in a separator length of 2 mm.

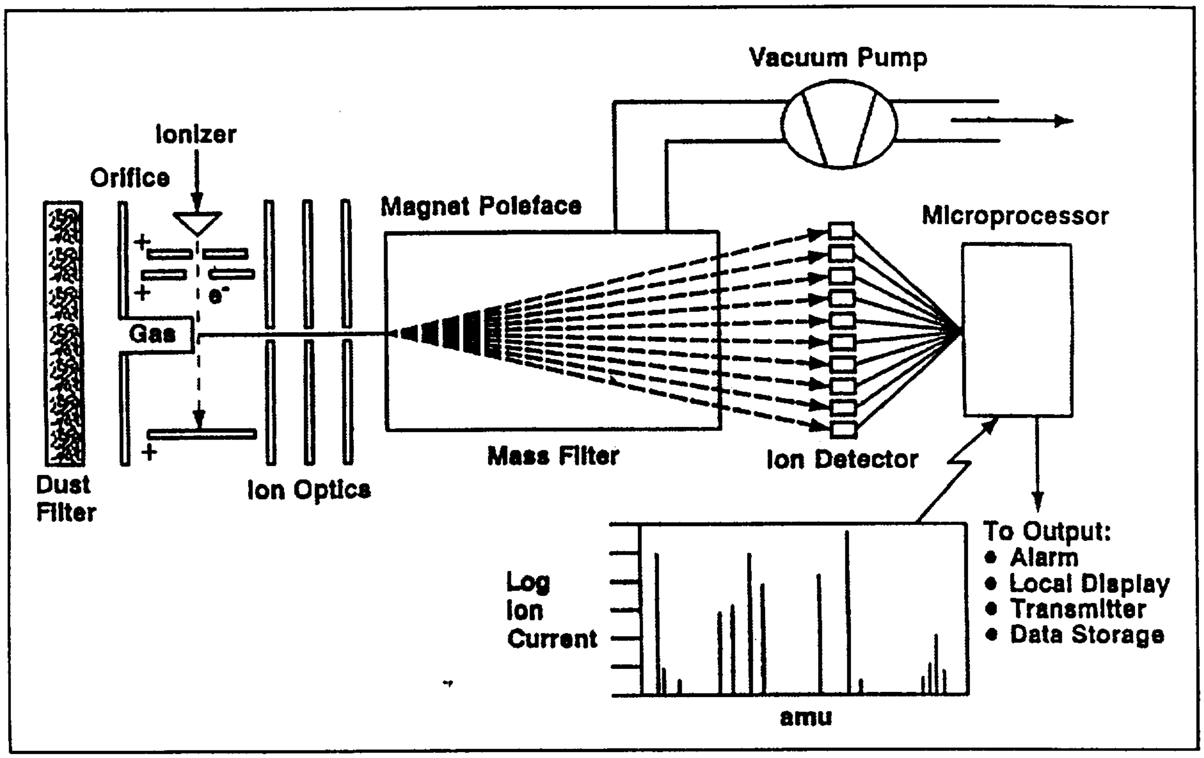

Figure 5. Plan view of a mass spectrometer on a chip.

An ambitious development project for a very small mass spectrometer is underway at Westinghouse, Inc (23). It involves producing four key components by silicon processing technology: (a) the electron ionization source, (b) a mass analyzer with crossed magnetic and electric fields, (c) an array of charge collection devices, and (d) micro-machined vacuum pumps. Production of pumps in series which are capable of achieving vacuum conditions in the atmosphere are a stressing aspect of this project.

One serious difference between optical and mass spectrometers for ordinary uses deserves emphasis. Optical devices do not require a vacuum, as do mass spectrometers. For terrestrial uses, the need for a vacuum system can be the factor limiting the overall system size, weight and power. Micromechanical pumps are under development (24). However, these small pumps, and associated micromechanical valves, are mainly for the movement of gases against modest pressure differentials or for transporting liquids at pressures near one atmosphere. The potential application of compact mass spectrometers in the natural vacuum of space could reduce or obviate the need for the vacuum system normally associated with a mass spectrometer. This is especially attractive for the spectrometers "on a chip".

This completes our review of the compact optical and mass spectrometer technologies. Examples of past use of conventional spectrometers in space will be examined in the next section. Future possibilities for the exploitation of the emerging technologies discussed above will be presented in the following section.

IV. PAST AND CURRENT SPECTRAL MEASUREMENTS IN SPACE

Remote sensing is used to provide information about an object without being in physical contact with it. One way that information can be gathered is by measuring changes in the electromagnetic field associated with the object. Different parts of the electromagnetic spectrum are utilized for remote sensing (i.e. visible, ultraviolet, infrared). Spectrometers are used to remotely measure the spectral content in and near the visible region of the electromagnetic field of interest. In addition to spectral data, spatial or intensity information may also be required. Hybrid systems that provide both spectral and spatial information (imaging spectrometers) or spectral and intensity information (spectroradiometers) are in use today (25).

A variety of space related applications exist where spectrometry has, and will continue to play a significant role, see Table 1. Spectral imaging of the earth provides data on numerous environmental factors such as ozone depletion, vegetation characterization, ocean color (chlorophyll levels), and soil moisture content. Spectral characterizations are made of the earth's surface, both dry land and oceans, as well as the atmosphere at various elevations. Similar types of measurements can be made on other celestial objects including planets, comets, and asteroids. Lunar and planetary measurements can be made from orbiting platforms or surface landers.

	Optical Spectrometry	Mass Spectrometry
Earth Sensing		
• Earth Observation (Imaging Spectrometers)	X	
• Remote Sensing (Surface)	X	
• Atmospheric/ Ionospheric Mapping	X	
Planetary Sensing		
• Orbital Survey	X	
• Atmospheric Probes	X	X
• Landers	X	X
• Rovers	X	X
• Surface Penetrators		X
Asteroid / Comet Sensing		
• Orbital Survey	X	
• Landers	X	X
• Rovers	X	X
• Surface Penetrators		X
Solar Sensing	X	
Stellar Sensing	X	
Deep Space Sensing		
• Space Chemistry	X	X
• Plasma Characterization	X	X

Table 1. Summary of space applications for optical and mass spectrometers.

Earth observation from space offers a number of advantages compared to airborne and ground based techniques, including larger field of regard, synoptic coverage over that field of regard, some immunity to local disturbance effects, and the potential for continuous coverage (geostationary systems). There are several significant disadvantages to space-based earth sensing including severe weight and volume restrictions for payloads due to launch vehicle limitations, no access to sensors for maintenance or repair, and harsh operating environments (radiation dose, atomic oxygen, thermal cycling). The fact that several hundred earth sensing satellites have been launched by more than 20 countries indicates that often the benefits outweigh the disadvantages.

Life cycle cost is another important factor in evaluating space-based systems. Launch vehicle costs are extremely high, \$15M - \$400M, so program life cycle costs are high. Payload development costs are high due, in part, to very high reliability requirements for space systems that, once launched, cannot be repaired. The aerospace industry has become very sensitive to these cost concerns and the current trend is towards smaller, cheaper, and in some cases less capable satellite systems (away from larger, expensive, infrequently flown, but very capable systems). This trend is an ideal opportunity for the introduction and use of compact optical and mass spectrometers for remote and direct sensing.

Space-based platforms have been used for remote sensing for years. One of the first remote sensing platforms, Tiros 1, was launched by the United States in 1960. Tiros 1 was a meteorological satellite which returned more than 22,000 images to earth. The Tiros satellites were the precursors to the National Oceanic and Atmospheric Administration (NOAA) Geostationary and Polar Operational Environmental satellites (GOES and POES) (26) .

The European Space Agency (ESA) is currently flying a number of environmental sensing platforms. The Envisat 1, scheduled for launch in 1998, will be flying a medium resolution imaging spectrometer. The instrument will work in the visible and near IR ranges and will be used for water and land quality measurements such as plankton content, water depth, bottom type classification, and pollution monitoring (27).

The Total Ozone Mapping Spectrometer Earth Probe (TOMS-EP) will be launched by the US in 1997 to continue monitoring of atmospheric ozone levels. The instrument is a 308.6-360 nm Fastie-Ebert Monochrometer used for ozone content characterization in six wavelength bands. This program uses small satellite technologies throughout the spacecraft and is further indication of the current trend in the aerospace industry towards smaller, cheaper satellites (28).

Various spectrometric systems have also been used on planetary and lunar probes. The latest lunar mission, Clementine, was launched in 1994. The mission profile included a lunar mapping phase and a near earth asteroid fly-by. The program was designed to be a flight demonstration for a set of light weight space based sensing technologies developed by the Ballistic Missile Defense Office (BMDO).The satellite was successfully launched on schedule in January 1994 and completed the lunar mapping phase in May 1994. During the mapping phase Clementine produced 1.8 million multi-spectral digital images (visible, ultraviolet, and infrared) of the moons surface (29).

Optical spectroscopy has long contributed to solar and stellar astronomy. Solar spectral studies at wavelengths below 200 nm, necessarily done from space because of atmospheric absorption, probe the appropriate range of temperatures (30). Stellar and other deep space spectral measurements are epitomized by current results from the Hubble Space Telescope (HST).

The HST, launched in April 1990, is the largest optical telescope and the largest civilian payload ever flown on the shuttle. Of the five primary scientific instruments integrated on the HST two were spectrometers. The Faint Object Spectrograph uses the full HST resolving capability and operates in the 115 - 850 nm range allowing for measurements of stellar objects up to 14 billion light years away. The High Resolution Spectrometer is optimized for higher resolution observations in the UV (110 - 320 nm). This device has experienced operational difficulties due to power supply fluctuations on orbit. The Near-IR Camera & Multi-Object Spectrometer (NICMOS) will be integrated onto the HST during a later shuttle servicing mission scheduled for 1997. NICMOS will use three separate grating spectrometers operating in the 1.0 - 3.0 μm range to simultaneously observe different portions of the instrument field of view (31).

Direct measurement of materials using mass spectroscopy has not been employed in space to the same extent as optical spectrometry. However, in-situ measurements on planets and other celestial bodies are possible. A current example is the Galileo mission, now on its final leg to Jupiter. The Heavy Ion Counter on the Galileo spacecraft uses direct sensing; it registers the characteristics of ions in the spacecraft's vicinity which enter the instrument. It does not form an image of the ions' source. In addition, the Galileo mission will be the first mission to make in-situ measurements of an outer planet's atmosphere. A separate atmospheric probe will be deployed from the Galileo spacecraft into the Jovian atmosphere to evaluate chemical composition at various altitudes. The probe uses an 11 kg neutral-ion mass spectrometer (1-150 amu) (32).

V FUTURE OPPORTUNITIES

A Clementine II mission has been proposed and is currently being studied by the Naval Research Laboratory and Phillips Laboratory. The Clementine II mission, see Figure 6, would involve three asteroid encounters and the use of "micro-satellites" as asteroid interceptors. The plan is to develop and launch an upgraded Clementine bus, sketched in Figure 7, that can support multiple interceptor micro-satellites. When the primary spacecraft is in close proximity to a selected asteroid a micro-satellite will be deployed. The micro-satellite will navigate to the asteroid using an onboard suite of imaging sensors. Any devices on the micro-satellites will have to be very compact since the weight of the entire micro-satellite will be on the order of 20 kg. The micro-satellite will impact the asteroid, generating a cloud of debris through which the primary spacecraft will fly using a suite of sensors to make various measurements.

Near each asteroid optical spectrometers would be used to characterize the composition of the asteroid surface by measuring the asteroid in various spectral bands. Once an impact occurs on the asteroid surface, spectroscopic measurements of the internal asteroid structure can also be made. Mass spectrometers could be used to characterize some of the debris created by the impact if a means of capturing the material safely can be developed.

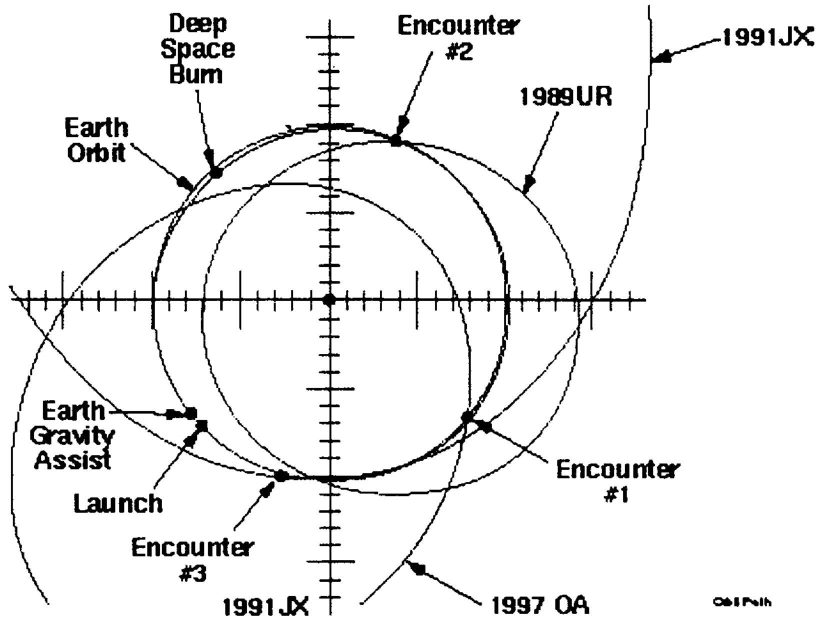

Figure 6. Clementine II Mission Profile

A presidential mandate requires that the current NOAA satellite programs be combined with the Defense Meteorological Satellite Program (DMSP). The data collection requirements of these two individual systems have significant overlap. Many of the observational parameters, such as ocean chlorophyll content and moisture profiles, require spectroscopic measurements. The combined program, the National Polar-orbiting Operational Environmental Satellite System (NPOESS), is currently evaluating instrument technologies for the future flight systems (33). While the present performance of compact optical spectrometers is not adequate for the primary systems, potential secondary applications are being discussed.

The NPOESS primary satellite constellation will consist of several large multi-instrument platforms. One possible application for compact spectrometers is as spares, either resident on the large primary host vehicles or on subsequently launched small satellites. As a secondary instrument on the host the compact devices could be bore-sighted with the primary systems and used in case of primary instrument fails to provide some data at degraded levels. A proposal is

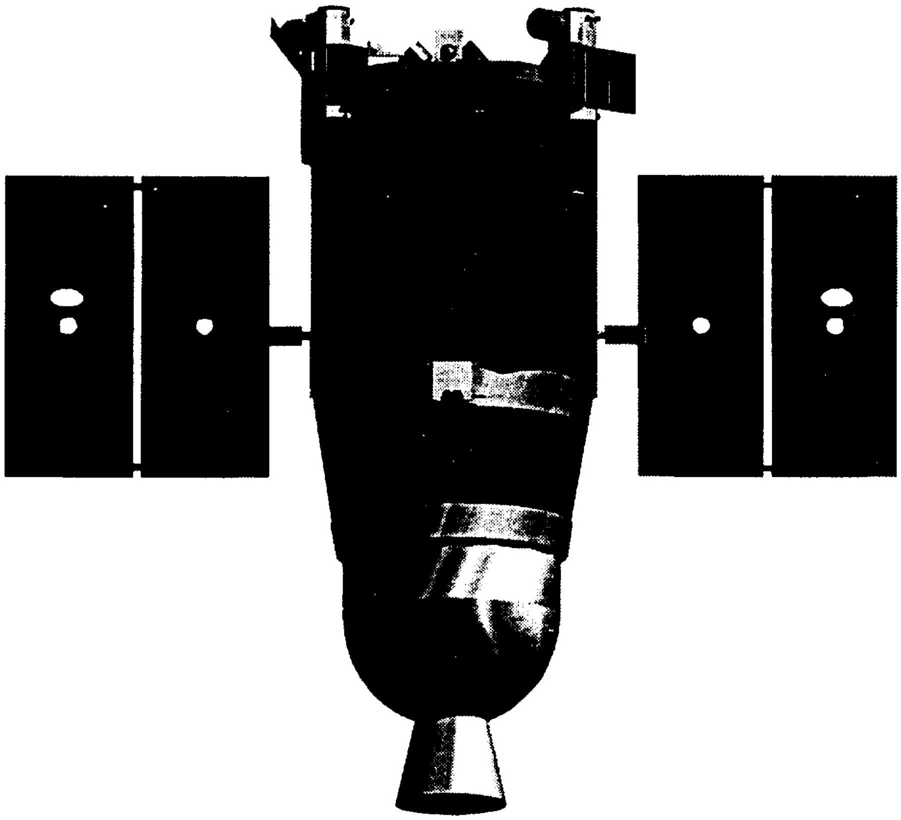

Figure 7. Clementine Spacecraft (2 Micro-Satellites Shown)

being investigated for using small satellites launched only after a primary instrument failure in order to supplement the larger vehicle system. This approach would allow instrument replacements to be delivered without replacing the entire primary satellite. The concept would require constellation maintenance to ensure that the original vehicle and the small satellite carrying the spare instrument remain in close proximity to each other (requirements exist for measurements from several instruments at the same time and location).

In general, the use of smaller satellites is a trend in industry, especially in remote sensing platforms. In the last two years several small imaging (< 500 kg) systems have been proposed: the CTA World View venture which uses a 235 kg satellite planned for launch in 1995 will provide 3 m resolution; the Lockheed Commercial Remote Sensing Satellite (CRSS) venture which delivers 4 m multi-spectral resolution and will be launched on an LLV2; and the Orbital Sciences Corporation (OSC) Eyeglass venture, which will provide 1 m panchromatic resolution, is slated for a Taurus vehicle. All three systems could benefit from adding on a small spectrometer payload to provide additional wide area (lower spatial resolution) coverage in other spectral bands.

The New Millennium Program (NMP) is an effort by NASA to provide frequent flight opportunities for new enabling technologies. The program started early in 1995 and is managed by the Jet Propulsion Laboratory, will create collaborative partnerships among NASA centers, government agencies, industrial firms, nonprofit research organizations, and academic institutions (34). Partners will participate in NMP teams from proposal, development and implementation through design, launch, and operation of validation flights. Five technology areas were selected as the focus of the project, one of which was Microinstruments and MEMS. All the technologies enable smaller, more capable spacecraft

NMP will fly several technology qualification flights per year and also transition newly flight proven technologies to operational systems in a timely manner. One of the first operational systems to take advantage of this process will be the Pluto-Express mission. The Pluto mission plan calls for launch of two spacecraft early in the next decade toward encounters with Pluto around 2010 or later. The mission objective is a low cost, initial reconnaissance of the Pluto system which would include: geology and morphology - high resolution global maps of the planet; surface composition - global composition maps of Pluto; and atmosphere composition - composition with vertical temperature and pressure profiles of Pluto's atmosphere. Optical and mass spectrometers are potentially applicable instruments, keeping the mission relatively low cost by assuring a small payload weight.

VII. CONCLUSION

Spacecraft applications for recently available and emerging compact spectrometers are abundant. Such instruments can yield a great deal of quantitative information in support of diverse space missions.

Optical spectrometers have a history in space spanning almost half a century. Compact devices now available sacrifice some performance, mainly resolution, because of their small scale. However, they are light-weight, small, require relatively little power, and are easily integrated into a spacecraft (because of their common integration with microcomputers for control and data acquisition). Current small commercial optical systems cover only a few of the design options; that is, it is straightforward to tailor the designs of compact spectrometers to the needs of a given mission.

Mass spectrometers have neither so long nor rich a history in space as do optical spectrometers. Nor are compact mass spectrometers as available commercially today. However, their increasing availability, capabilities, and the design flexibility they enable, all bode well for further utilization. This particularly true for planetary exploration missions such as Galileo.

This paper has focused on applications of compact spectrometers for spacecraft sensors applications. There is also a potential for uses in support of space missions. For example, the condition of exterior materials, such as reflectivity, can be tracked with optical spectrometers. The Long Duration Exposure Facility could have provided dynamic degradation data if it had been equipped with small optical spectrometers. Diagnosis of in-flight ascent, or on station, conditions are also possible when the monitoring instruments are small and light weight Mass spectrometers could be used to monitor environments within spacecraft, either prior to launch or on station, and might be used as a quality assurance tool. Potential applications include the Space Station Freedom. In short, it seems reasonable to expect that truly compact spectrometers will be an enabling technology for a number of new spacecraft operational and supporting applications.

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