2

Microengineering Space Systems

H. Helvajian* and S. W. Janson*

2.1 Introduction

2.1.1 MEMS for Space Systems, an Overview

The evolution of microelectromechanical systems (MEMS) from laboratory curiosities to commercial off-the-shelf components (COTS) is being driven by government investments and strong market forces. These drivers have historically focused on terrestrial applications, which currently dominate MEMS development and usage, and will continue to do so well into the next century. MEMS offers a capability for mass-producing small, reliable, intelligent instruments at reduced cost by reducing the number of piece-parts, eliminating manual-assembly steps, and controlling material variability. These features, together with reduced mass and power requirements, are what space-system designers dream about. To gain an initial understanding of the problems facing spacecraft engineers, consider what your personal computer or other consumer product would look like if:

- The delivery charge to take the product home was between \$10,000 and \$100,000 per kg.
- The delivery truck had no springs or shock absorbers and traveled over really bumpy roads.
- The product kicked itself off the delivery truck and configured itself to receive your commands while the truck drove itself to the junkyard.
- The product ran off of solar cells by day and rechargeable batteries by night.
- The product had to withstand radiation levels that are 4 to 7 orders of magnitude greater than what you face.
- The product had to operate for 3 to 15 yr without maintenance or mechanical upgrades.

No wonder commercial Earth-orbiting spacecraft cost on the order of \$50,000 per kg, not to mention similar costs for the one-shot delivery truck (the launch vehicle). We believe that market forces alone will stimulate the use of MEMS in space systems and foster further development of MEMS specifically for space application. If a commercial space systems provider can use MEMS to save a few kilograms on a spacecraft, perhaps the provider can then justify a low-volume custom foundry run specialized for space-microengineered systems. The saving of tens of kilograms in mass while maintaining capability can result in substantial profit for a provider.

Space systems comprise more than just spacecraft; they include launch vehicles and the ground-based systems used for tracking, command and control, and data dissemination (pictures of the Earth, telephone calls, movies via satellite, etc.). MEMS technology would allow development of new commercial uses of space in the proliferation of miniaturized ground transmitters with on-board sensors. MEMS, coupled with the current generation of digital electronics and telecommunication circuits, can be used for distributed remote-sensing applications. For example, transmitters the size of a fist and smaller can send environmental information, such as local atmospheric pressure, temperature, and humidity, directly to satellites. With Motorola's Iridium or other satellite telephone systems, real-time field data from remote locations can be just a phone call away. Similar remote sensors mounted on launch vehicles can simultaneously monitor

*Center for Microtechnology, The Aerospace Corporation, El Segundo, California.

vibration and acceleration at different locations on the vehicle. MEMS enables mass-production of partially or fully integrated remote sensors inexpensive enough to be "throw-away" add-ons for many aerospace applications. Microengineered devices or application-specific integrated microinstruments (ASIMs) will begin to infiltrate space systems by the end of this decade and become rapidly assimilated during the next. The Aerospace Corporation (Aerospace) coined the term ASIM to define a microengineered instrument designed to fulfill a specific need or solve a specific problem. The ASIM is a conceptual tool enabling the aerospace engineer to solve complex problems by reducing the problem into piecemeal ASIM solution components. The derived benefits of this technology for space systems are quite clear: dramatic cost reductions in manufacturing and operation.[1]

MEMS will also enable a radically new way of building and using spacecraft. Silicon, for example, can be used as a multifunctional material: as structure, electronic substrate, MEMS substrate, radiation shield, thermal control system, and optical material. With proper spacecraft design, it can provide these functions simultaneously. A "silicon" satellite composed of bonded thick wafers could be manufactured by one or more semiconductor foundries. Batch-fabrication would allow mass-production of spacecraft from one-hundred to several-thousand unit lots, which would enable dispersed satellite architectures and spacecraft designs meant for "single-function" and disposable missions. Alternatively, thinned MEMS electronics die, thin-film solar cells, and patterned metal antennas on 10- to 100-μm-thick Kapton™ sheets could permit the development of very large planar-sheet spacecraft for missions where large aperture (power and antenna gain) and low mass are a necessity. A synthetic aperture radar "sail" satellite, proposed by the French Centre National d'Etudes Spatiales (CNES), approaches this goal by allowing the radar sail to provide most of the spacecraft resources, for example, power, payload, and gravity-gradient stabilization.[2]

The chapter is organized into five sections:

- Introduction—Overview of MEMS for space systems
- Applications in which MEMS technology would be useful to space systems
- The silicon satellite concept
- Manufacturing future space systems
- Conclusions

2.1.2 Near-Term Applications of Microengineered Systems in Space

The U.S. National Aeronautics and Space Administration (NASA) and Department of Defense (DOD) have studied the use of microengineered systems for space applications. NASA's Jet Propulsion Laboratory has adopted the technology for producing "smaller, faster, cheaper" space systems to accomplish more interplanetary missions per year in the face of flat or declining budgets.[3] The theory is that many less-ambitious missions spread risk and prevent major program failures; the loss of a single spacecraft is tolerable if several others are in place or soon will be. The Mars Pathfinder mission successfully demonstrated what could be accomplished with "micro" spacecraft that used many COTS components. The "New Millennium"[4] and "X-2000"[5] efforts will utilize more MEMS technology ultimately to produce 10-kg-class interplanetary spacecraft. Most MEMS and ASIM examples discussed in this chapter were developed under some form of U.S. Government funding (e.g., DOD, NASA). In Europe, there is a similar desire to incorporate microengineered systems in space. Space systems development within the European Union (EU) is directed by the European Space Agency (ESA), which in 1997, identified micro/nanotechnology (MNT) as a relevant theme for its future programs. The incorporation of MNT within the ESA program framework is a direct result of two Round-Table meetings hosted by EU industry and

ESTEC representatives in Noordwijk, The Netherlands.[6] These Round-Table sessions established a forum to showcase EU technologies that might be applicable to space systems and to outline the ESA perspective. ESA representatives identified several issues to be resolved before MNT is routinely incorporated into ESA space systems. These same issues have also emerged in the U.S. space community and include the following requisites:

- New ways for designing systems
- Cultural change within the aerospace community to fully exploit the advantages of microsystems technology
- Characterization of materials, systems, and new phenomena at the micron scale
- Customization and subsequent fabrication of space-applicable devices in low-production batches, perhaps necessitating the development of low-cost design, production, and test technologies
- Packaging and interconnection schemes for other than electrical inputs
- Customization of embedded software for space applications
- Development of a new product-assurance philosophy

Examples of microsystem insertion opportunities not readily apparent to the aerospace community but identified by ESA include:

- Low-cost transmission lines, power dividers, phase shifters, and feed horns for frequencies above 100 GHz
- Integration of antennas with solar cells and necessary electronics
- Integration of micro accelerometers, gyroscopes, and charge-coupled devices (CCDs) with small optical apertures

ESA faces the same problem as the U.S. space community: it cannot compete with the blossoming microsystem terrestrial market but must find a way to leverage this technology. As an example, ESA will leverage technology developed under the Brite-Euram projects, which were initially designed to increase the competitiveness of the European industry through targeted research and development on priority industrial objectives. Some of these projects have applications to space systems. As in the United States and Japan, there appears to be considerable industrial interest in the development of micropumps and microvalves with actuation schemes incorporating electrostatics, thermo-pneumatics, shape memory alloys, or the large magnetorestriction effect. The latter approach is somewhat new in that it incorporates the magnetostrictive material (rare earth transition metal thin film) in the microactuating membrane.[7] The major advantages of using these materials over thermal-actuation schemes are the fast response time and noncontact operation. There also appears to be large interest in the development of functionalized materials that can be deposited over large areas. These materials will be useful in future aerospace systems because they enable multifunctionality, thereby reducing the "parts-count." Examples of these novel materials include:

- Thick-film ferroelectric actuators made by sintering ultrafine powder piezoelectric particles that are suspended in a colloid[8]
- Well-established ferrofluids (colloidal suspensions of single domain magnetic nanoparticles, typically 10 nm, in a liquid medium)[9] applied to microinstrumentation
- Low-cost electrochemical deposition (ECD) processes for the production of microstructured permanent magnet devices (CoWPt type)[10]
- Silicates and phosphate glass layers having thicknesses in the 3 to15 μm range for 1.55 μm wavelength waveguiding applications[11]

To accelerate the development of microinstruments and rapid prototyping of designs, the Brite-Euram program has also initiated a commensurate program on developing a versatile electronics package intended to drive/control the microinstruments. Work is being done to fabricate a set of programmable analog cells and routing resources on a chip. The cells include analog interfaces, digital-to-analog and analog-to-digital circuits, amplifiers, and filters. The chip integrates the analog functions of approximately 5-k programmable digital gates, an 8051-based microprocessor core, and program/control memory. A function library also comes with this device to enable a bridge to commercial standard-cell libraries and the migration of programmed prototype segments to hard-wire fabrication using classical application-specific integrated circuit (ASIC) solutions.[12] Examples of space-specific applications sponsored by EU member-state space agencies include the development of a compact ultraviolet (UV)/Vis-spectrometer by the Institute of Microtechnology, Mainz (IMM), Germany. This Hadamard transform optical spectrometer combines the advantages of a diode spectrometer (compactness) with that of a multislit spectrometer (higher signal-to-noise, increased resolution).[13] Other examples include a micro sun-sensor[14] and an infrared (IR) static Earth sensor.[15] There is also ample technology crossover from terrestrial to space applications in the development of compact high-resolution vision systems,[16] microrefrigerators, and microcalorimeters.[17] A specific space application area that cannot readily transfer technology from terrestrial applications is micropropulsion. As a satellite subsystem, propulsion systems are often designed to fit a particular satellite mission and are thus customized. Given that satellites are currently not mass produced in lots greater than 100, there is little incentive to develop standard micropropulsion platforms. However, a group is evaluating the required micro-machined components for developing a miniaturized propulsion platform.[18]

Microsystem technology has also had an impact on determining the method for developing future space life science experiments. Numerous groups are developing biochemical analysis systems specifically for space life science applications. These microsystems are true complex instruments that incorporate reagants, micropumps (self-priming/bubble tolerant[19]), microvalves, microreactors, microsensors, and microflow control schemes with semiautonomous data acquisition electronics. The sensing techniques include capillary electrophoresis,[20] multisensor array chips (O_2, CO_2, pH, ion-concentrations of for example sodium, potassium, calcium),[21] heterogeneous immunoassay,[22] and measurement of calibrated conductivity.[23] These micro total-analysis systems have a large terrestrial application base as a disposable field instrument, but the deployment of the International Space Station (ISS) in the next few years will stimulate interest in space life sciences, promoting further research and development, and technology cross-over.[24]

An increasing amount of research is focusing on developing components/devices/systems for space missions based on nanotechnology rather than microtechnology.[25] Understanding and exploiting design principles found in nature is key to this technology. Biomimetics is a specialized field devoted to understanding and applying natural principles to develop biolike systems composed of nanostructured macrosystems. In Europe these ideas have been distilled as a mandate for a recently formed independent organization called the International Nanobiological Testbed (INT). The INT conducts policy and specialized research on nanobiological concepts,[26] and as part of its defined mission has investigated a conceptual Mars biophysical station that incorporates the existing and projected developments in micro/nanosystems technology.

Japan also has made strong efforts in nanotechnology, with a probable immediate application in microtechnology. Although not directed toward space applications, Japan's research in this area will have use in future space systems. The Japanese Government has identified micromachine technology as a cornerstone technology for the 21st century. The technology does not ignore semiconductor-based processing technology, but emphasizes the miniaturization of conventional manufacturing techniques like machining, grinding, and electroplating to fabricate micromachines from a wider variety of materials. As an example, the Toyota/Nippon Denso microcar is as tiny as a long-grain rice (7 mm). It is a replica (at 0.001 of the size) of the Toyota Motor Corporation's first automobile, the 1936 Model AA sedan. The minuscule vehicle has 24 parts, including tires, wheels, axles, headlights and taillights, and hubcaps that carry the company name inscribed in microscopic letters. The electromagnetic motor, which is itself made of five parts, is only 1 mm in diameter and can propel the car at speeds of up to 10 cm/s.[27] This micromachined automobile could not easily be fabricated completely of silicon, but with other material microfabrication techniques, it becomes very possible. For space systems, we see applications for micromachines, micromotors (e.g., 1–4-mm-flagella motors [28]), and microbots (e.g., micro-conveyance systems [29]). The Japanese group has designed a variant of the microcar for a small pipe-inspection machine. This application is also of interest to space systems. Examples of other application areas identified for micromachines are transportation safety systems, microsurgery, aircraft engine maintenance, and miniature information devices for appliances.[28]

The authors in collaboration with other scientists from Aerospace have reviewed a number of possibilities for the insertion of MEMS and ASIM components into space hardware. Following is our best estimate of MEMS and ASIM technology that will be inserted in the near term (less than 10 yr). Supporting details can be found in Janson[30] and Robinson.[31]

- Command and Control Systems
  - "MEMtronics" for ultraradiation hard and temperature-insensitive digital logic
  - On-chip thermal switches for latchup isolation and reset
- Inertial Guidance Systems
  - Microgyros (rate sensors)
  - Microaccelerometers
  - Micromirrors and microoptics for FOGs (fiber-optic gyros)
- Attitude determination and control systems
  - Micromachined sun and Earth sensors
  - Micromachined magnetometers
  - Microthrusters
- Power systems
  - MEMtronic blocking diodes
  - MEMtronic switches for active solar cell array reconfiguration
  - Microthermoelectric generators
- Propulsion systems
  - Micromachined pressure sensors
  - Micromachined chemical sensors (leak detection)
  - Arrays of single-shot thrusters ("digital propulsion")
  - Continuous microthrusters (cold gas, combustible solid, resistojet, and ion engine)
  - Pulsed microthrusters (charged droplet, water electrolysis, and pulsed plasma)
- Thermal control systems
  - Micro heat pipes
  - Microradiators
  - Thermal switches
- Communications and radar systems
  - Very high-bandwidth, low-power, low-resistance radio frequency (RF) switches

  - Micromirrors and micro-optics for laser communications
  - Micromechanical variable capacitors, inductors, and oscillators
- Space environment sensors
  - Micromachined magnetometers
  - Gravity-gradient monitors (nano-g accelerometers)
- Distributed semiautonomous sensors
  - Multiparameter-sensor ASIM with accelerometers and chemical sensors
- Interconnects and packaging
  - Interconnects and packaging designed for ease of reparability (e.g., active "Velcro")
  - Field programmable interconnect structures
  - "Smart" interconnects for positive-feedback

2.1.3 Initial Applications to Space Systems—First Steps

The promise of dramatic cost reductions in manufacturing and operating space systems, although appealing, is not a sufficient justification for the wholesale acceptance of MEMS and ASIM technology by the space-systems community. Cost is clearly a driving factor in today's economic environment, but reliability of space systems is the paramount concern and is especially true for both military and civil (i.e., NASA and ESA) space systems. Inserting microengineering technology into current systems can provide better monitoring of system status and health, which can help resolve potential operational anomalies and permit increased functionality with almost negligible weight or power impacts. The latter benefit can enable secondary missions and alternative operational modes to compensate for potential on-orbit failures in spacecraft systems. MEMS and ASIM technology also stands to improve performance and reliability during the other phases of a space-systems life-cycle, specifically, production and logistics (including long-term storage), launch-base facilities and logistic operations, specific prelaunch operations, launch and ascent flight, on-orbit operations involving ground segments, and decommissioning and/or deorbit.[31]

Many aspects of space systems operation actually occur on the ground. Insertion of MEMS and ASIMs into these phases (production, ground operations, logistics) should be somewhat easier as it does not require space-survivable designs. ASIMs that might be important in production and ground operation segments include multiparameter sensors integrated with data loggers and/or wireless (optical or RF) communications. These can be relatively low-bandwidth devices with peak-sensing capabilities to sense, for example, transportation or handling stress variables (e.g., pressure, temperature, humidity, shock, displacement stress, strain, and harmful chemicals) and to ensure that the maximum limits have not been exceeded during production, transportation, and storage operations. MEMS sensors for these parameters already exist and offer mass-production capability for inexpensive and unobtrusive environmental monitoring packs. Typical spacecraft costs range from $1 million for a microsatellite to well over $200 million for a one-of-a-kind geostationary communication satellite; knowing what, when, where, how, and by whom a limit was exceeded is serious business and of importance to setting insurance premiums and liabilities.

MEMS and ASIM technologies can also be used to instrument the launch vehicle. Current launch vehicles such as the Titan IV are often instrumented to measure the lift-off and ascent flight environments. However, these vehicles often have a limited number of channels (<100) to characterize both the dynamic acoustic and vibration environments. By proliferating ASIM units on the launch vehicle, a better characterization of the environment is possible. Similarly, there is a need to instrument the launch site. Ground-based measurement of rocket ignition overpressure and toxic chemical release (e.g., HCl from a solid booster) are needed in conjunction with the launch-vehicle monitoring system to dramatically increase the "awareness" of vehicle status and the launch site environment. MEMS sensors (accelerometers, chemical sensors, etc.) coupled to data transceivers can be used in a wireless network system onboard the vehicle and on the launch site. The telemetry data can channel real-time or near-real-time information to a ground-based data storage system for postlaunch review.

An important role for ASIMs in both satellite and on-orbit manned vehicle operations is enabling a condition-based maintenance (CBM) status and health-monitoring system. These systems could save future costs by fault detection, isolation, and enabling automated self-test and repair actions. The CBM protocol enables safer operations as well as increased system availability compared with a failure-based maintenance protocol scheme. Reusable launch vehicles are prime candidates for CBM. One type of malfunction not uncommon in spacecraft is the faltering of a high-speed bearing, reaction wheel (momentum wheel), or gyro bearing. Bearing degradation can often be anticipated by monitoring vibration signatures, an excellent application for a micromachined accelerometer coupled to digital signal processor or microprocessor in an ASIM. Corrective action could consist of the metered release of lubricant via a fluidic ASIM. Smart bearings, smart structures, and multifunction structures are already being considered by space engineers. These ideas have also been considered in the aerospace community[32] for developing adaptive structures that have imbedded sensors—actuators, controllers and processors.

Within a few decades, thousands of low Earth-orbiting (LEO) satellites will be designed for global communications and general Earth-monitoring missions. Unlike their ancestor satellites, which were primarily used for mass-media communications and national missions, these satellite constellations will enable two-way communication for even simple pedestrian tasks, such as automatically measuring house utility meters; direct tracking of container ships, cargo, and small packages; and monitoring of natural resources and manufacturing facilities that affect the environment. These capabilities become possible with the current development of miniaturized low-power transceivers, which can be integrated with microsensors and data loggers. In the simplest configuration, the satellite constellation operates as a "store-and-forward" communication mailbox; as they orbit Earth, satellites query and gather data from many microtransmitters and forward them to a central ground station. With increasing sophistication, an orbiting satellite can beam down additional data or reprogram a ground unit altogether; for example, it could be sending your utility bill and reprogramming the amount of communication-bandwidth a particular resident address should have (e.g., for pagers, telephone, cellular, television, and other home digital services). A LEO satellite constellation could also provide automatic air-vehicle targeting[33] for special visual or other sensor reconnaissance (civilian applications might include quantifying factory emissions or following news events in near real-time, true global coverage).

Aerospace has been studying the use of micro untethered aerial vehicles (UAV) with a LEO satellite constellation system. The UAVs could provide a local "search and gather" capability that could be initiated from a remote location. For example, a micro UAV transmitting with 0.1 W of RF power using a low-gain monopole or patch antenna could send a 128- × 128-bit visible or IR image to a LEO satellite once per second. If each pixel contained 8 bits of intensity information, and a 15:1 data compression scheme were used, each image would require about 8740 bits. Assume that the following channels were added: 3 channels of 12-bit acceleration, 3 channels of 12-bit angular rate, 1 channel of 12-bit airspeed, and 10 channels of 8-bit health and status data (e.g., voltages, currents, temperatures), all at a rate of 10 Hz. If in addition to these channels, other information such as 264 bits of Global Positioning System (GPS) data (instantaneous true position and velocity) were added, as well as packet and protocol overhead, the total data rate would be about 9600 bits/s. This rate could be accommodated by a 15-kHz bandwidth at 1 GHz that could be received by a 1-m-diam antenna on a LEO micro/mini satellite at a range of 1200 km.

A less complex application using LEO satellites and fixed ground-based tags is the concept being developed by the National Semiconductor Corporation of Santa Clara, California, and Space Quest Ltd. of Fairfax, Virginia. The application is a vehicle tracking system using micro/nanotechnology satellites and wireless "tags."[34]

2.1.4 Spacecraft Orbits, Use, and Basic Design

Satellites are robots that collect and process energy and information. They exploit the strategic position of space to provide communications relay, Earth-observation, and space environment monitoring. LEO satellites orbit 300–2000 km above the Earth in roughly circular orbits that are typically highly inclined with respect to the plane of the equator. LEO orbits are used primarily by high-resolution meteorological and Earth observation satellites, store-and-forward communication satellites, and emerging personal communication satellites. Medium Earth orbit (MEO) satellites orbit 15,000–25,000 km above the Earth where they can "see" about 40% of the Earth's surface at any given instant. The U.S. GPS satellites, the Russian Glonass global positioning satellites, and the upcoming ICO communication satellites are MEO inhabitants. Geosynchronous Earth orbit (GEO) satellites orbit at an altitude of 35,786 km, where the orbit period matches the Earth's rotation rate. Geostationary satellites, which include almost all commercial communication satellites, orbit in the equatorial plane so that they appear to remain almost motionless in the sky; ground-based high-gain antennas for the uplink and downlink can then be fixed in place.

Satellites require a power supply, electronics, sensors, and in most cases, mechanical actuators. Figure 2.1 shows a block diagram of standard spacecraft functions. The white blocks represent functions required for any satellite, while the shaded blocks represent functions required for more advanced satellites. Spacecraft systems are traditionally constructed in individual housings and are electrically connected by a wiring harness. Note that in this packaging approach, the structure and thermal control systems can be separate entities, adding to the parts count, rather than an integrated unit. Within the context of Fig. 2.1, a simple satellite used as a communication relay or

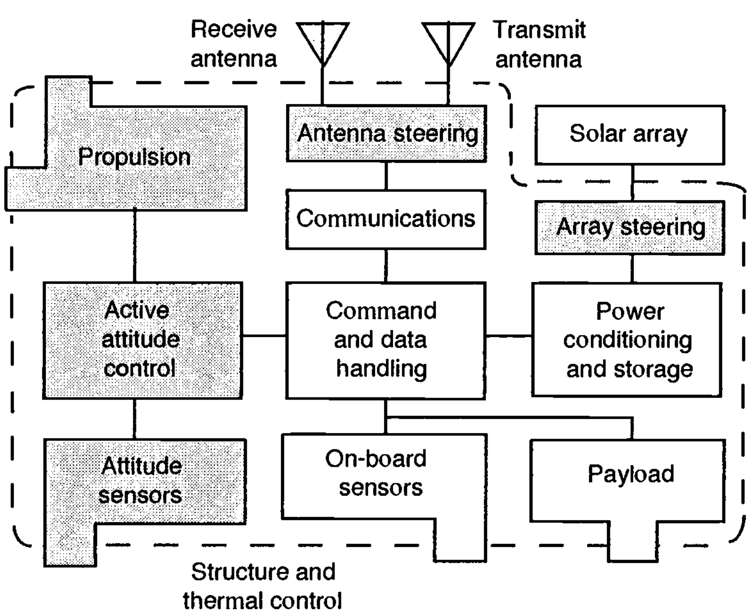

Fig. 2.1. Basic satellite functions.

as a space environment monitor could use fixed on-board antennas for communications and a fixed solar cell array, thus requiring no active attitude control. Examples of this basic spacecraft configuration include the 1960's vintage Courier,[35] the more recent Air Force MACSATs,[36] spacecraft by the University of Surrey, [37] and AMSAT microsats.[38] More advanced satellites require attitude sensing for solar array steering and active attitude control for sensor and antenna pointing. Examples of these spacecraft include GEO commercial and military communication satellites (e.g., Telstar-IV[39] and DSCS-III[40]), weather satellites (e.g., NOAA-14,[41] METEO-SAT[42]), radar satellites (ERS-1),[43] and Earth-observation satellites (e.g., Landsat[44] and SPOT[45]). Payloads can be optical or IR imagers, RF imagers (radar), space science experiments, or communication systems while on-board sensors monitor temperature, voltage, current, etc. While not immediately obvious, MEMS can be used in all spacecraft systems shown in Fig. 2.1.

2.1.5 Getting to Orbit

Spacecraft are placed into orbit using a variety of launch vehicles that currently cost anywhere from $10 to $500 million per launch. Getting to LEO costs between $10,000 and $30,000 per kg; it is a function of launch vehicle, launch site location, orbit inclination, and orbit altitude. Putting a satellite into GEO, MEO, and LLO (low lunar orbit) costs about $50,000 per kg. The cost for putting a satellite into orbit around another planet ranges from about $60,000 per kg for Mars and Venus (with aerobraking) to over $300,000 per kg for Pluto (no planetary gravity assist, no aerobraking).

To get to orbit, the payload must survive various mechanical stresses produced by launch-vehicle acceleration, vibration, and shock from explosively driven stage-separation events. Table 2.1 lists worst-case values within the payload bay for selected launch systems. The Shuttle gives the mildest accelerations to accommodate human occupants; while the Pegasus, at least for this table, gives the highest. Both vehicles have wings that can generate substantial transverse accelerations, and the Shuttle has an additional transverse landing load that can reach 4.2 g.

Launch vehicles have very loud acoustic signatures. At lift-off, large vehicles, such as the Saturn-V, Space Shuttle, and the Titan IV, can generate sound levels up to about 200 dB on the ground (1 million times stronger than what causes pain to an average human, about 140 dB) with an acoustic power of about 10 MW. Payload fairings, located at the top of a launch vehicle, typically incorporate acoustic blankets to protect the payload. Table 2.1 lists the acoustic or sound pressure level in decibels in the payload bays of various launch vehicles. Maximum levels occur

Table 2.1. Worst-Case Payload Ascent Environment for Representative Launch Vehicles[a]

Launcher	Axial loads (g)	Transverse loads (g)	Acoustic level (dB)	Shock (g)
Pegasus	13	± 6	133.5	800 from 1000 to 10,000 Hz
Delta 7925	6	± 2.0	144.5	4100 at 1500 Hz
Atlas IIAS	6	± 2.0	138.4	2000 at 1500 Hz
Ariane AR44L	4.5	± 0.2	142	2000 from 1500 to 4000 Hz
U.S. Shuttle	3.2	± 2.5	140	5500 at 4000 Hz

[a]Data from Isakowitz.[46]

at launch and later during transition through maximum dynamic pressure (Max q). The corresponding vibration environment is also fairly high; power spectral densities between 0.01 and 0.1 g^2/Hz can occur over a 30–3000 Hz range. Finally, pyrotechnic actuators are typically used to separate stages, the payload fairing, and the satellite from the launch vehicle. These devices produce mechanical shocks with maximum magnitudes of 1000 to 10,000 g. Fortunately, these are transient events, and the highest accelerations occur between 1000 and 10,000 Hz. To guarantee that spacecraft will survive these abuses during launch, the spacecraft and major components are often ground-tested on "shaker tables" during the flight qualification stage. Microelectromechanical devices and ASIMs for spacecraft and boosters have to be designed not only to survive these short-term levels of abuse, but also to operate over the entire mission life (e.g., 7 yr).

2.1.6 Surviving on Orbit

Surviving on orbit requires attention to the packaging of both MEMS and electronics. While the human-occupied portions of the Space Shuttle, the Russian MIR space station, and the ISS are relatively benign, the outside space environment is much harsher; it significantly exceeds the design parameters for most terrestrial consumer/MEMS products. For example, local vacuum precludes the use of ambient convection cooling schemes; a modern fan-cooled microprocessor would quickly expire of "heat stroke." Spacecraft thermal management requires conductive heat transfer through circuit boards, structure, etc.; convective heat transfer through sealed "heat pipes"; and radiative heat transfer to and from the Earth, sun, and deep space. In general, internal spacecraft temperatures typically range from −10°C to +40°C, with the exception of RF power amplifiers like traveling wave tubes (TWTs) that can reach 70°C. External temperatures on the other hand (i.e., on a deployed solar array) can range from −50°C to +100°C.

Other drawbacks of operating in vacuum are outgasing of high-vapor-pressure materials, such as oils, plastics, and rubbers, and the lack of aerodynamic damping of moving components. Many MEMS devices such as accelerometers are designed to operate at atmospheric or reduced pressure. The surrounding gas provides mechanical damping and decreases the effective Q-factor (Q = frequency of resonance/bandwidth of resonance) to make simple electronic feedback control possible. Any MEMS device that requires gas-dynamic damping or includes high-vapor-pressure materials has to be hermetically sealed.

While the LEO environment is considered a "hard" vacuum by terrestrial standards, it is not a perfect vacuum. At altitudes between 200 and 650 km, the local pressure ranges from 10^{-6} to 10^{-10} mbar, and atomic oxygen is the dominant species. Figure 2.2 shows the atomic oxygen density as a function of altitude for "quiet" and "active" solar conditions. The ultraviolet output of the sun follows the 11-yr sunspot cycle, and during active times the rarefied upper atmosphere heats and expands further into space. Note that local O-atom densities differ by orders of magnitude between quiet and active solar conditions for altitudes above 400 km. At the present time, solar activity is increasing, and we expect to enter the next active phase by the year 2001.

Spacecraft in low Earth orbits are bombarded by atomic oxygen since the atmosphere is fixed with respect to the Earth. This results in aerodynamic drag forces, orbital decay, and surface erosion for orbiting structures. In the "ram" (along the velocity vector) direction, atomic oxygen impacts spacecraft surfaces with kinetic energies up to 5 eV. At these energies, chemical reactions with organic materials, composite structures, and metallic films are possible. This leads to surface modification and erosion, which can destroy micron-thick coatings and structures on the exterior of spacecraft. The most rapid erosion mechanism is surface oxidation into volatile byproducts. Kapton™, a DuPont Corporation polyimide that is used on many spacecraft, erodes at 3 μm per atomic impingement fluence of 10^{20} atoms/cm^2, which translates to an average erosion rate of

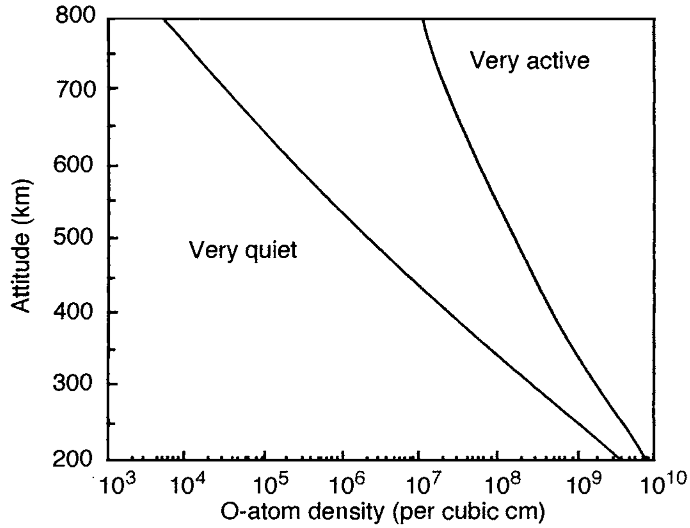

Fig. 2.2. Atomic oxygen density as a function of altitude under very quiet and very active solar conditions.

90 μm per year at a 400-km altitude for average solar activity. Figure 2.3 shows worst-case (surface normal always pointing in the flight direction) calculated erosion rates of Kapton as a function of altitude for very quiet and very active solar conditions.

Below 400–600-km altitude orbits, use of polyimide materials on exterior surfaces is not recommended, as a consequence of the high erosion rate. However, silicon dioxide (SiO_2), if deposited without surface defects or large internal stress, has an atomic oxygen erosion rate that is more than 3000 times lower than Kapton's.[47] For applications where surface charging may be a problem, somewhat thicker germanium or indium tin-oxide coatings can be applied. A 1-μm-thick layer of SiO_2 would last for at least 4 yr at an altitude of 400 km under active solar conditions. Coating thickness of at least 1 μm should be sufficiently durable for exterior and exposed

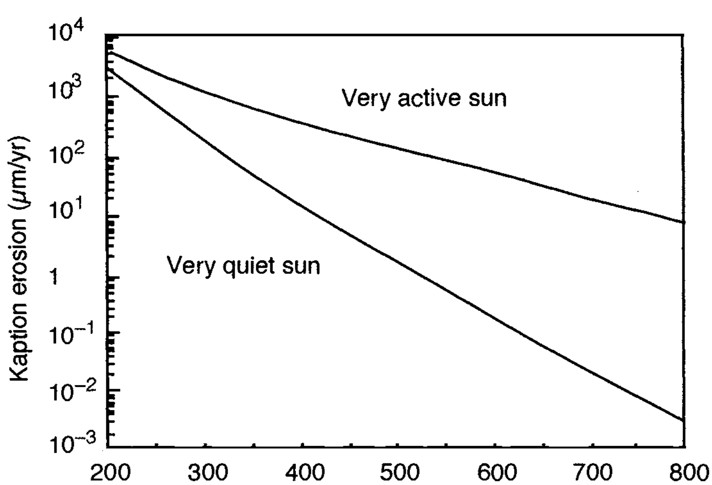

Fig. 2.3. Kapton erosion rate as a function of altitude under very quiet and very active solar conditions.

micromachined components (i.e., for microengineered active thermal surfaces, optical surfaces, and uncovered phased-array switches).

The "vacuum" of space has yet another important inhabitant: trapped ions and electrons that make up the Van Allen radiation belts. Damage in materials via defect formation can occur by the inelastic scattering of the high-energy particles. Defects in materials can form by atomic displacement, secondary particles, "showers" that create daughter products by fission, or by the ionizing tracks left in the wake of the particle pass-through. The latter type of damage can create abnormal charge concentrations. For MEMS, insulating surfaces can build up charge, which may upset electrostatic actuator and sensor operation. Similar effects on semiconductor circuits range from a temporary change in logic state, because of the sudden local appearance of charge, to permanent substrate atom and charge dislocations that produce altered current-voltage characteristics and possible device failure.[48] Single-event upsets (SEUs) are particle-induced "bit-flips"; while latch-ups are more serious high-current flow conditions generated by new low-resistance paths created by particle-induced ionization trails. Both SEUs and latch-ups can be controlled by appropriate choice of semiconductor technology, "watchdog" and error-correction circuits, and error-correction software. Continual accumulation of radiation damage, however, ultimately results in device failure.

Table 2.2, adapted from Griffin and French,[49] gives rough radiation hardness levels for different types of semiconductor devices. A rad is the amount of particle radiation that deposits 100 ergs of energy per gram of target material, and the radiation hardness level represents total dose required for device failure. In the spacecraft industry "total dose" is defined as the total dose absorbed and is therefore a material-dependent parameter. Typical low-power consumer electronic components, incorporating complementary metal oxide semiconductor (CMOS) technology, are designed to operate in our low-radiation biosphere (roughly 0.3 rad/yr) but can tolerate 1–10 kilorad integrated radiation doses. Unfortunately, the radiation tolerance varies widely from

Table 2.2. Radiation Hardness Levels for Semiconductor Devices

Technology	Total Dose in rads (silicon)
CMOS (soft)	$10^3 - 10^4$
CMOS (hardened)	$5 \times 10^4 - 10^6$
CMOS (silicon-on-sapphire: soft)	$10^3 - 10^4$
CMOS (silicon-on-sapphire: hardened)	$> 10^5$
ECL	10^7
I^2L	$10^5 - 4 \times 10^6$
Linear integrated circuits	$5 \times 10^3 - 10^7$
MNOS[a]	$10^3 - 10^5$
MNOS (hardened)	$5 \times 10^5 - 10^6$
NMOS	$7 \times 10^2 - 7 \times 10^3$
PMOS	$4 \times 10^3 - 10^5$
TTL/STTL	$> 10^6$

[a]Metal-nitride-oxide semiconductor.

design to design, so radiation testing should be performed on selected components. The particular semiconductor foundry process used also impacts radiation hardness; the 0.5-μm Hewlett-Packard CMOS process, as currently performed, can tolerate in excess of 100,000 rads.[50] Transistor-transistor logic (TTL) and emitter-coupled logic (ECL) circuits are inherently more radiation hard than CMOS, but they require more power. NMOS (n-type minority charge carrier MOS), PMOS (p-type minority charge carrier MOS), I^2L, and silicon-on-sapphire MOS circuits can be fabricated to be fully immune to latchup. CMOS circuitry fabricated onto silicon-on-sapphire substrates has traditionally provided radiation-tolerant electronics for space applications. The use of thin silicon over an insulator reduces the volume for charge collection along an ionizing particle track, thus reducing the amount of charge introduced into random gates. Thin-film silicon-on-insulator (TFSOI) technology is now being considered for commercial electronics because it can provide enhanced low-voltage operation, simplified circuit fabrication, and reduced circuit sizes relative to bulk silicon counterparts.[51] TFSOI would be particularly interesting for MEMS space applications because of its inherent radiation tolerance and its built-in etch stop for bulk silicon etching.

How much radiation shielding, that is, local packaging plus spacecraft structure, is required for a given mission? Dose rates for a silicon target are usually given as a function of grams/cm^2 or thickness of spherical aluminum shielding required for a given orbit and given solar conditions (i.e., for minimum or maximum solar activity). Figure 2.4 shows the yearly dose rate as a function of aluminum shielding thickness (full sphere shielding) for 700-km altitude orbits with orbit inclinations of 28.5 and 98.2 deg. CMOS circuits with an assumed total radiation dose tolerance of ~3000 rads will require at least 0.3 g/cm^2 aluminum (or 1.3 mm of silicon thickness) shielding for a 1-yr on-orbit lifetime in a 700-km, 28.5-deg inclination orbit. For the more interesting sun-synchronous (98.2-deg inclination) orbit, about 0.8 g/cm^2 (or 4-mm silicon thickness) is required for a 1-yr lifetime and about 3 g/cm^2 (1.3 cm silicon) for a 10-yr lifetime. At lower altitudes, significantly less shielding is required; while at higher altitudes, significantly more shielding may be required. Note that shielding effectiveness is not really linear with respect to thickness, especially

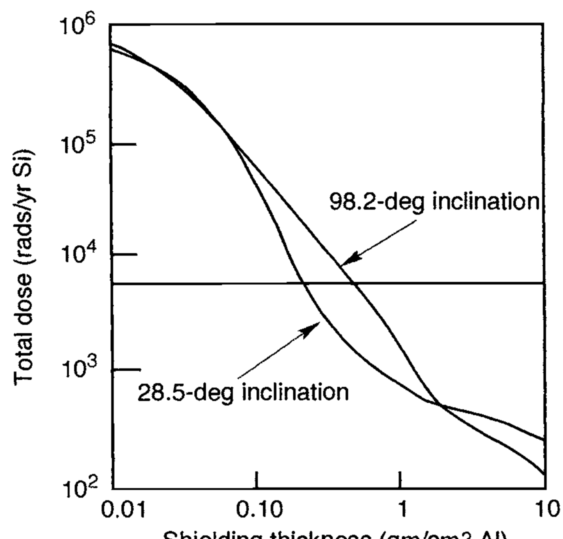

Fig. 2.4. Total yearly dose, under solar maximum conditions, in silicon as a function of aluminum shielding thickness for 700 km circular orbits.[52]

for low-inclination orbits. Use of more radiation-resistant technologies is the only solution for some orbits.

Figure 2.5, from Griffin and French,[49] shows the dose rate dependence as a function of circular equatorial orbit altitude inside spherical aluminum shields with densities of 0.5 g/cm^2 (0.18-cm-thick aluminum or 0.21-cm-thick silicon) and 3.0 g/cm^2 (1.1-cm-thick aluminum or 1.3-cm-thick silicon). Note the rapid rise in dose rate with altitude above about 2000 km and below 20,000 km; a hard-to-shield proton belt exists at ~4000 km and an easier-to-shield electron belt exists at ~20,000 km. At geostationary Earth orbit (GEO; 35,786-km altitude and 0-deg inclination) with a maximum dose of 3000 rads, 0.5 gm/cm^2 (0.22-cm silicon) and 3.0 gm/cm^2 (1.3-cm silicon) shielding give lifetimes of roughly 11 days and 3 yr, respectively. The real significance of Figs. 2.4 and 2.5 is that normal CMOS circuitry should be used only for low-altitude LEO missions; when designing smart MEMS and ASIMs for general space applications, hardened processes and designs must be used.

In addition to causing electronic upsets, on-orbit ions and electrons can also induce spacecraft charging of external surfaces. High-inclination orbits and high-altitude MEO and GEO orbits are particularly susceptible to this phenomenon. Without a slightly conducting path to spacecraft "ground," surface dielectric surfaces can charge up to kilovolt levels, resulting in a rapid local electrostatic discharge and potential device failure. Micron-scale MEMS structures probably will not tolerate this abuse; MEMS structures on exterior spacecraft surfaces should not be completely electrically isolated from their substrates. Resistive substrates and coatings should be used whenever possible. Additional information on launch system and space environment interactions with MEMS can be found in Muller *et al.*,[53] Barnes *et al.*,[54] and Stuckey.[55]

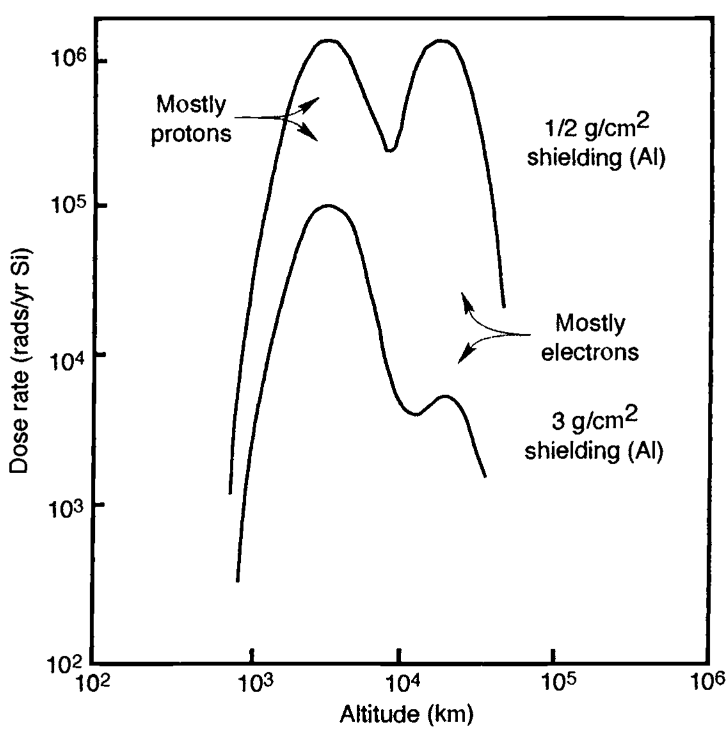

Fig. 2.5. Radiation environment for circular equatorial orbits.[49]

2.2 Spacecraft Applications

2.2.1 Electronic Systems

Electronics pervade almost all spacecraft systems. Individual electronic components can be classified as purely electronic or electromechanical. Purely electronic components (e.g., inductors, transistors, resistors) do not require any physical movement for proper operation; while electromechanical components (e.g., quartz crystal oscillators, relays, surface acoustic wave [SAW] filters, variable capacitors, and potentiometers) require translation, rotation, or vibration. Cofabrication of both purely electronic and electromechanical components on the same substrate is possible using a combination of MEMS and semiconductor fabrication techniques. This approach leads to a reduced parts count, volume, and the number of macroscopic electrical interconnects.

Resistors, capacitors, and inductors are typically considered passive components; whereas transistors and diodes are active components. MEMS changes the rules by allowing the fabrication of active capacitors, inductors, and resistors, and by offering micromachined switches and relays that could potentially compete with transistors in functionality for many applications. These "MEMtronic" devices are particularly interesting for space applications because they are inherently radiation-hard and could operate over a much wider temperature range (i.e., less than 50 K to more than 1500 K) than conventional circuitry.

Consider the active capacitor shown in Fig. 2.6.[56] This is a 190 × 190-μm-sq parallel plate capacitor with a nominal 1.5-μm variable air gap between the plates and a 300-fF capacitance. By applying a dc potential between the plates, the plates move closer together (normal to the page in Fig. 2.6), and a significant increase in capacitance results, that is, a 25% increase with a 4-VDC potential. This device can be used in an on-chip LC (inductor-capacitor) circuit to create variable frequency oscillators or filters. On-chip inductors will still need to be fabricated. Low-inductance spiral windings can be deposited on silicon substrates, but low-resistance silicon substrates produce capacitive loading. By fabricating the spiral inductor over an anisotropically etched pit, as shown in Fig. 2.7, much higher inductance and resonant frequencies are possible.[57] By exploiting MEMS cantilevered structures, variable-inductance coils are also possible.

Miniaturized communication systems may also use SAW devices for bandpass filters and time delay (or phase shift) generation. SAWs are usually discreet components composed of a piezoelectric substrate, quartz or lithium niobate, with patterned metallic electrodes acting as acoustic

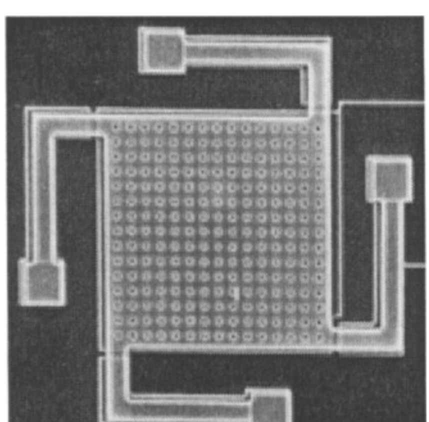

Fig. 2.6. Micromachined parallel plate capacitor with variable separation. (Courtesy B. Boser and D. Young.[56])

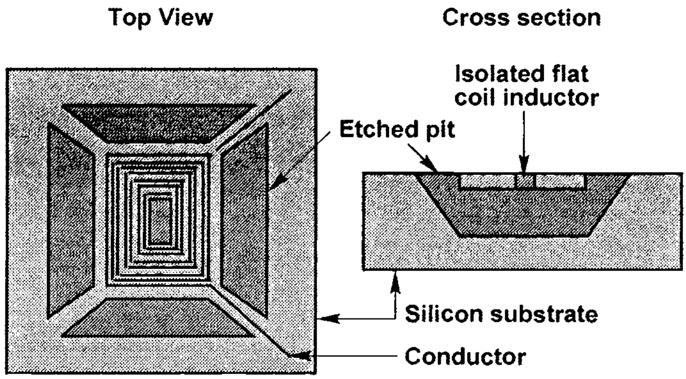

Fig. 2.7. Schematic design of low-capacitance coil for silicon substrates.

wave launchers, diffractors, and detectors.[58] The metallic patterns are created using photolithography, and a wide range of signal-processing functions can be accomplished by controlling electrode and surface geometry. A possibility for integrating SAW devices with silicon is to create an oxide layer on a silicon substrate, cover it with a piezoelectric layer such as zinc oxide, and top it with an appropriate metallization pattern.

Timing references are a key component of computer and communication systems. Quartz crystal oscillators consist of a specially cut crystal sandwiched between electrodes, which provides timing accuracy to better than 50 parts per million. An ultrastable quartz oscillator constructed by the Johns Hopkins Applied Physics Laboratory has a frequency stability of 7×10^{-14}, which is many orders-of-magnitude better than a digital watch oscillator. This device has a mass of 0.64 kg, a power requirement of 0.9 W, and a volume of 720 cm^3.[59] It may be possible to drastically reduce the volume, mass, and power requirements for precision oscillators using MEMS techniques to create single-crystal silicon resonators with mechanical isolation and micro heaters for precise temperature control. Cofabrication of the oscillator and electronics is also highly desirable to minimize the number of piece-parts and macroscopic interconnects. Designs for microheaters and hot plates compatible with CMOS processing can be found in Marshall *et al.*[60] Micromachined capacitively activated torsional resonators with Q factors greater than 500,000 in vacuum have also been demonstrated.[61] DARPA (Defense Advanced Research Projects Agency) currently sponsors a number of programs at the University of Michigan, Rockwell Science Center, and the California Institute of Technology[62] in the development of micromechanical filters and oscillators for communication systems operating at VHF, UHF, and S-band frequencies (100 MHz through 2500 MHz). Another option is to develop a miniaturized atomic clock that uses an atomic beam or static gas (for lower resolution units) in a cavity, an electromagnetic trap, and a scheme for excitation and sensing a resonance at a hyperfine splitting frequency (e.g., Mg^+ and Be^+ at 300Mhz, Hg^+, 40 GHz).[63]

Higher frequencies require smaller MEMS devices or nanoelectromechanical systems (NEMS). NEMS are MEMS with critical dimensions below 100 nm (0.1 μm). Current NEMS research uses specialized fabrication techniques to create submicron scale lengths in at least two dimensions. The semiconductor fabrication industry now fabricates devices with feature sizes down to 0.25 μm and is expected to break the 0.1 μm barrier in approximately the year 2007. Nanoelectronics will become commonplace, and mass-produced NEMS will become possible.

Microwave and millimeter-wave communication systems may use active antennas that integrate oscillators, amplifiers, or frequency conversion systems with microstrip antennas.[64-66]

The advantages of active antennas are reduced transmission line losses (which increase with frequency), and isolation of sensitive (low-noise preamplifier) or interference-generating (output amplifier) RF components from the digital electronics in the spacecraft. The individual radiators can be low-gain patch or micro stripline antennas, or they can use micromachined silicon horns or reflectors to boost gain.[67,68]

Phased-array systems take the active antenna concept one step further by using phase-controlled multiple transmit/receive antennas to produce and detect custom wave fronts.[69,70] This capability allows a fixed array of elements to simulate a single antenna of equivalent area with variable focusing characteristics; it allows electronic steering of a narrow beam, formation of multiple narrow beams, and controllable gain. Phased-array antennas add another degree of flexibility to communication systems by using fixed complex hardware under software control. Micromachined RF switches can be used to build true time delay lines and transmit/receive couplers for phased-array antennas.[71,72] In this application, micromachined switches can outperform transistor counterparts because of their inherent high bandwidth and low insertion loss.

MEMS switches can also replace transistors in digital circuits. The Air Force Institute of Technology (AFIT) has produced microrelays and microlatches for possible space applications.[73] Bimetallic (e.g., silicon and aluminum) thermal switches can be imbedded into electronic die to provide local overheating and latch-up protection. Figure 2.8 shows a schematic design of a simple MEMS switch designed at Northeastern University that is functionally equivalent to a field-effect transistor (FET) used in a digital mode; the gate potential determines if current can flow between the source and drain.[74] Figure 2.8 shows at the right a four-terminal microrelay version of this design, and Fig. 2.9 shows a scanning electron micrograph of the microswitch. Figure 2.10 shows a comparison between a FET-based dual-input NOT-AND (NAND) gate and a MEMtronic NAND gate based on the microswitch from Fig. 2.8. Note that they are almost identical. However, the same MEMtronic logic gate could operate deep within the Van Allen belts, on the surface of Venus, or within the icy fringes of our solar system. The disadvantages are the relatively slow speed (typically less than 100 MHz operation for MEMS, perhaps higher for NEMS), high operating voltages (tens to hundreds of volts using current technology), and increased surface area (the switches discussed in Zavracky, Majumder, and McGruer[74] are 30 × 65 μm in area). These disadvantages can be overcome by utilizing thinner structural layers and smaller device dimensions.

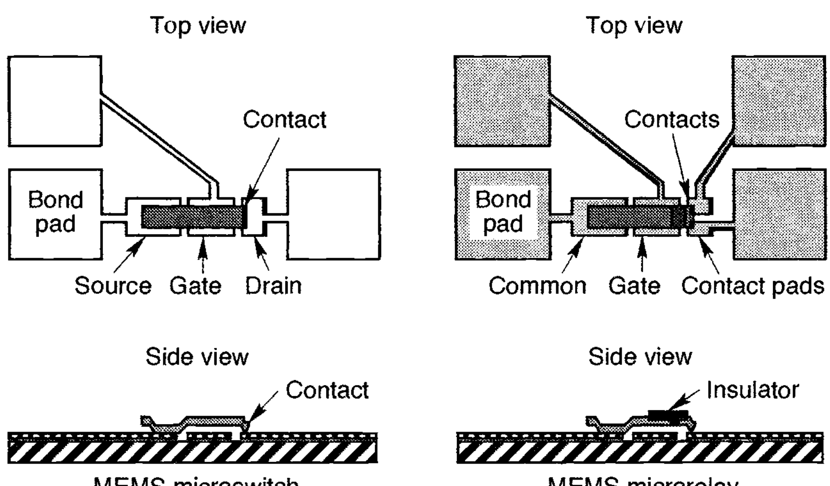

Fig. 2.8. Schematic of MEMtronic components.[74]

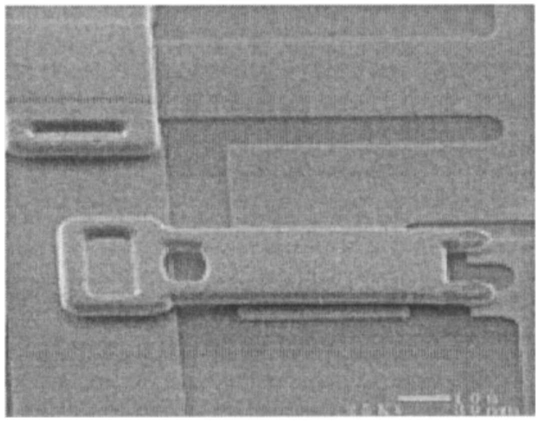

Fig. 2.9. Scanning electron micrograph of a MEMS microswitch. The "source" contact is on the left, the gate is in the middle, and the drain is under the two prongs. (Photo courtesy P. M. Zavracky.[75])

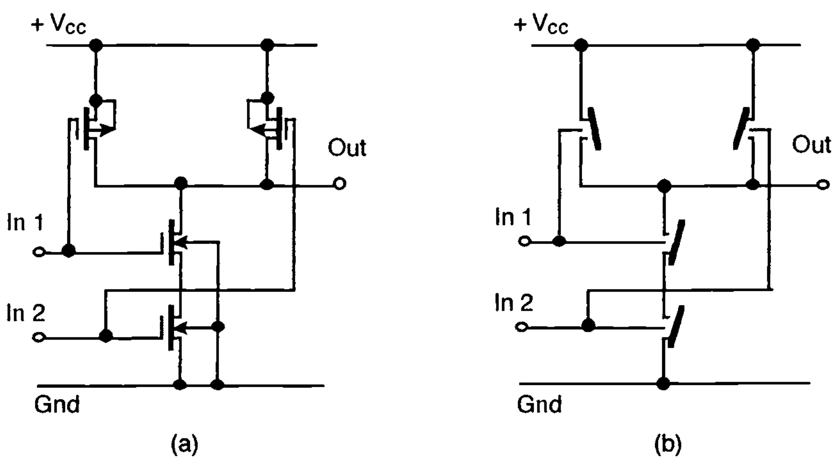

Fig. 2.10. Comparison of FET-based electronic and microswitch-based MEMtronic dual-input NAND gates.

2.2.2 Attitude Sensors

Spacecraft usually need to know their orientation in space to obtain maximum power from sunlight and to point high-gain communication antennas. Orientation can be determined by sighting against known references such as the sun, Earth, and stars; by measuring the local magnetic field vector; or by monitoring the phase shift in multiple antennas from different GPS satellite signals. Table 2.3 gives typical accuracy, mass, and power requirements for spacecraft attitude sensors. Optical sensors for locating the sun, Earth, and stars can have absolute accuracy much better than 0.1 deg and can operate from LEO to beyond GEO. Magnetic field sensors, on the other hand, work best in LEO and depend on a well-characterized magnetic field; above LEO they become more susceptible to transient magnetic events. GPS-based attitude determination is a promising technique that can provide absolute attitude and position determination. Once a "fix" has been established, on-board inertial navigation sensors can be used to estimate position and attitude at later times.

Table 2.3. Existing Attitude Sensors for Spacecraft[a]

Sensor	Accuracy (deg)	Mass (kg)	Power (W)
Sun sensors	0.005–3	0.05–2	0–3
Earth (horizon) sensors:			
Pulse generators	0.1–0.5	0.05–1	1
Passive scanners	0.5–3	1–10	0.5–14
Active scanners	0.05–0.25	3–8	7–11
Star Sensors	0.0003–0.1	1.5–10	1.5–20
Magnetic field sensors	0.5–5	0.6–2	0.5–2
GPS	0.1	2–10	15

[a]Data from Eterno *et al.*,[76] Pritchard and Sciulli,[77] and Johnson.[78]

Microoptoelectromechanical systems (MOEMS) can significantly decrease the mass, volume, and power requirements of optical navigation sensors, while MEMS could have a similar effect on inertial navigation sensors. A conceptual design for a single-chip, micromachined, single-axis sun sensor, designed by one of the authors, is given in Fig. 2.11.[30] The aperture is a slit 90 μm wide by 1.1 cm long, and the drive electronics are integrated with photodetectors. Photodetectors composed of n-doped regions in p-type silicon, or vice versa, are easily fabricated using

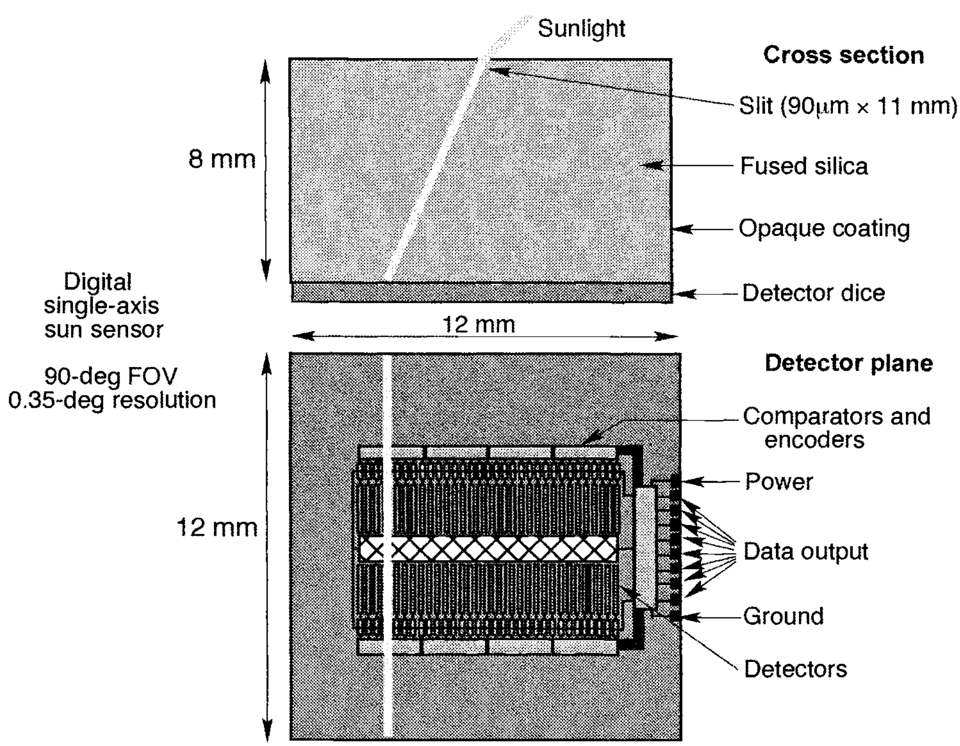

Fig. 2.11. Design of a micromachined sun sensor for a nonspinning satellite with a 90 deg field-of-view.

conventional CMOS processes. The large center detector provides a reference output against which the individual outputs of the 64 smaller interdigital detectors are compared. Coarse position (1.4-deg resolution) is determined in digital mode by locating which interdigital detector has the highest output; fine position (0.35-deg resolution) is determined in analog mode by ratioing the output powers from neighboring detectors. The fused silica provides radiation shielding for the detector electronics, and the opaque coating should be covered by a thin layer of aluminum, which oxidizes quickly and provides resistance to further atomic oxygen reactions. Estimated mass and power for a two-axis version are 5.5 g and 40 mW, respectively.

LEO spacecraft typically use flux-gate magnetometers to measure local magnetic field strength and direction. Flux-gate, magnetoresistive, and Hall-effect sensors are all suitable for developing microengineered magnetometers. The Honeywell HMC2003 is a three-axis magnetic sensor hybrid based on magnetoresistive transducers with a minimum detectable magnetic field of 100 μg and a range of ±2 g.[79] Nonvolatile Electronics, Inc., manufactures application-specific magnetic sensors based on the giant magnetoresistive ratio (GMR) effect, one of which has a ±10 g range.[80] Note that the Earth's magnetic field is less than 0.5 g in LEO. A novel magnetometer concept is being developed at Johns Hopkins University.[81] The operating principle of the magnetometer utilizes the Lorentz force to measure vector magnetic fields and is based on a classical resonating xylophone bar. The design is ideally suited for miniaturization, and the device has the potential for wide dynamic range and sensitivities down to applied fields of 1 nT. Figure 2.12 shows a scanning electron micrograph (SEM) of a polysilicon xylophone bar designed for capacitive pick-up. Although the device works, the high sheet resistance of the structural polysilicon layer limits the current-carrying capacity and sensitivity. An alternative material combination being considered is a metal/piezoelectric/metal (e.g., Pt/PZT/Pt) system.

Accelerometers and gyroscopes are key components of spacecraft inertial measurement units (IMUs). Spacecraft or launch vehicle accelerations can range from below 10^{-6} g to about 5000 g (the high levels are transient shocks), where g is the value of gravitational acceleration at the

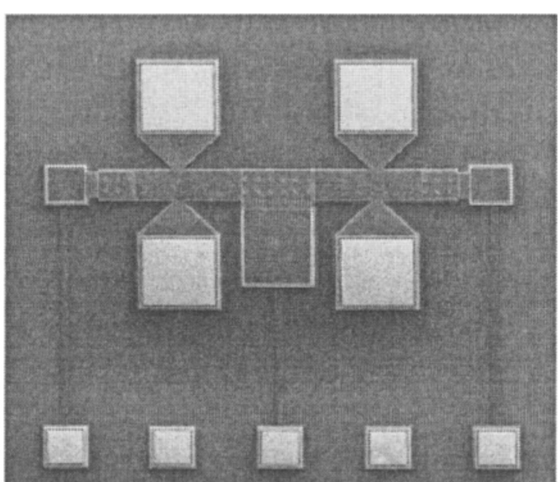

Fig. 2.12. Polysilicon xylophone magnetometer device fabricated by the MCNC MUMPS process. The poly0 layer is removed. The bar (poly1) dimensions are 1000 × 100 μm with the support legs 10 μm wide. The poly2 layer capacitive plates are placed at the ends and in the middle to enable differential capacitance measurements. (Photo courtesy D. K. Wickenden[81])

Earth's surface. Micromachined accelerometers monitor either the motion of a constrained proof mass or the force required to maintain an unconstrained proof mass at a fixed location within the instrument. The second approach usually provides higher bandwidth and accuracy. High sensitivity micromachined accelerometers such as the *Centre Suisse d'Electronique et de Microtechnique* (CSEM) ACSEM02-S and ACSEM02-T/6 force balancing sensors[82] or the silicon electron tunneling sensor built at NASA Jet Propulsion Laboratory (JPL) (sensitivity of 10^{-9} g/Hz$^{1/2}$)[83] offer micro-g and better sensitivity for on-orbit applications. This performance level requires temperature stability to within 1°C, which could be accomplished through integration of microheaters, silicon temperature sensors, and control electronics next to the sensing element. To survive launch loads and launch-related shock events, a safe "park" position may be required for the tunneling sensor. For launch vehicles and on-orbit propulsion monitoring, micromachined accelerometers in the range of 1 to 40 g can be used. A large number of such accelerometers are commercially available from a number of manufacturers, including Analog Devices, Kistler, Motorola, Silicon Designs, and EG&G IC Sensors.

Interestingly enough, within a three-axis-stabilized or rotating spacecraft, microaccelerometers with 10^{-7} g and better resolution can be used to determine spacecraft orientation by monitoring the gradient of the Earth's gravitational field. The radial component of the gravitational gradient, da/dr, is given by

$$\frac{da}{dr} = -2GMr^{-3} \tag{2.1}$$

where a is the local value of gravitational acceleration, r is the radial distance from the Earth's center, G is the gravitational constant, and M is the mass of the Earth ($GM = 3.98602 \times 10^{14}$ m^3/s^2). Values of $\|da/dr\|$ as a function of altitude above the Earth are given in Fig. 2.13. Note that the gravitational gradient is of the order of 10^{-6} m/s^2 per meter in LEO all the way down to the Earth's surface. Therefore, a 10^{-7} g resolution accelerometer could theoretically measure altitude to 1 m, if it was stationary with respect to the Earth's surface.

For the measuring of spacecraft orientation, consider an accelerometer mounted near the center-of-mass of a nonspinning spacecraft. The satellite is in free-fall, but the net local acceleration forces are zero, because of the balance between gravitational and orbit centrifugal forces. If the

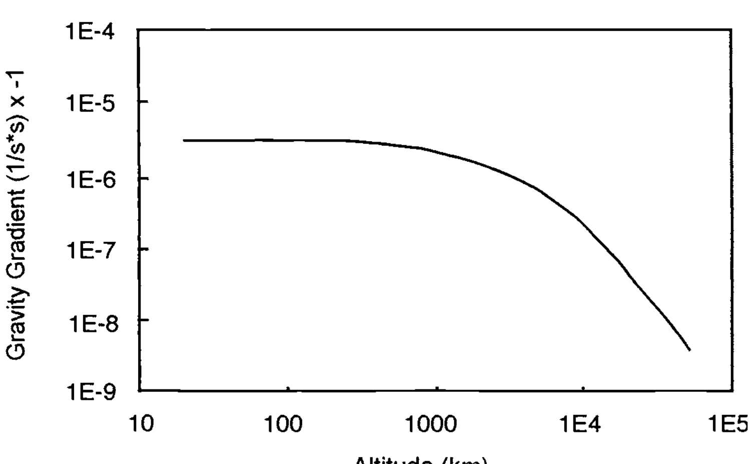

Fig. 2.13. The absolute value of the radial gravity gradient produced by the Earth as a function of altitude.

accelerometer is moved within the spacecraft radially outward from the Earth, the local gravitational acceleration is lower and the centrifugal acceleration is higher (larger orbit radius but higher velocity because the orbit period is the same), which results in a local tidal force directed away from the Earth. Similarly, a local tidal force is directed toward the Earth if the accelerometer is located closer to the Earth than the spacecraft center-of-mass. Figure 2.14 gives the radial tidal accelerations as a function of radial displacement from a spacecraft's center-of-mass for different orbit altitudes. If accelerometers could be produced with these sensitivities, determination of spacecraft orientation with respect to the Earth would be possible without using optical or RF (GPS) sensors. A gravity gradiometer with a sensitivity of 10^{-9} m/s^2/m was designed for the now-canceled ESA's ARISTOTELES mission.[84] This extraordinary sensitivity was to have been produced by 4 electrostatically controlled 320-g proof masses at the corners of a 1 m sq. If micromachined gravity-gradient sensors could approach this level of performance, batch-fabrication would allow proliferation of standardized attitude determination sensors across many LEO spacecraft series.

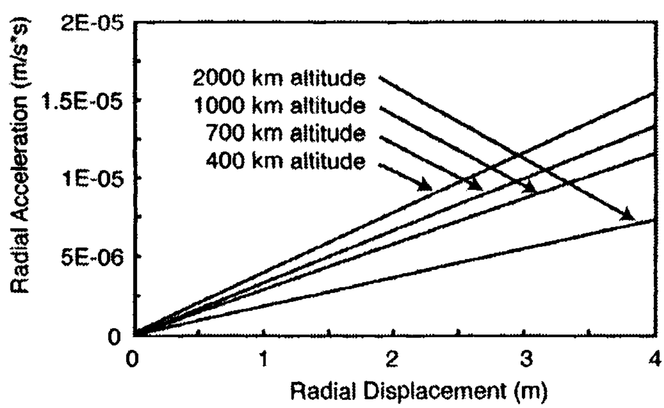

Fig. 2.14. Radial tidal accelerations as a function of radial separation from the center-of-mass of a spacecraft in circular orbit at different altitudes.

The established means of monitoring spacecraft attitude is to use rate gyros (gyroscopes) with optical sensors for absolute calibrations. Spacecraft gyroscopes are typically based on a rotating mass, a vibrating fork, or the continuous circulation of light around a closed loop (ring laser or fiber-optic gyros). Typical launch-vehicle or spacecraft-propulsion applications require drift rates of 0.1 deg/h or less, and typical spacecraft pointing requirements are at least an order of magnitude more demanding.[85] Micromachined gyros are based on "tuning forks" or vibrating structures that are excited in one plane and monitored for vibration at right angles to this plane. The Coriolis force, which is proportional to the angular rotation rate, generates these out-of-plane oscillations.

The Charles Stark Draper Laboratory has tested micromachined silicon gyroscopes with drift rates below 1 deg/h (at 0.1 Hz bandwidth).[86] Continuing research at Draper laboratories, JPL, and University of California, Berkeley, may drive drift rates down to 0.03 deg/h within a few years. If this performance cannot be obtained on a single gyro, perhaps applying signal-averaging techniques and a large number of gyros can reduce the drift rates. This approach is feasible if the drift is dominated by random factors. Drifts resulting from temperature changes are not random. Fiber-optic gyros (FOGs), which are replacing ring-laser gyros and spinning-mass gyros for many terrestrial applications, constitute the main competing technology for space applications. For example, Fibersense Technology offers a single-axis sensor with a 0.01 deg/h drift rate that consumes 5 W and weighs 10 oz.[87] The unit dimensions are 3.75 in. in diameter by 1.25 in. wide.

2.2.3 Propulsion

Propulsion is required for orbital maneuvering and can also be used for spacecraft attitude control. Once spacecraft attitude, position, and velocity are known, propulsion can be used for orbit raising, adjustment, and position maintenance. Currently, position and velocity are usually determined by ground station data and orbital mechanics. The range and the range-rate measurements are determined by radar or by relaying a known signal from a ground station, through the satellite's communications system, back to the ground station.

Propulsion requirements are expressed as a velocity increment (ΔV or delta-V) and the basic figures-of-merit for propulsion systems are thrust, minimum impulse bit, and specific impulse (I_{sp}), which is defined as the thrust divided by the mass-flow-rate of propellant through the thruster. If a time limit is imposed on a given mission, the minimum thrust can be determined from the ΔV, the mass of the spacecraft, and the thrusting time. Table 2.4 gives representative maneuvering missions, their associated ΔV, and the minimum thrust required in newtons per kilogram of spacecraft mass for two different mission times.

The mass of propellant to be expended is determined using the rocket equation:

$$\Delta V = g_o I_{sp}\, ln\left(\frac{m_i}{m_f}\right) \tag{2.1}$$

where g_o is the gravitational acceleration at the Earth's surface (9.8 m/s^2), m_i is the initial spacecraft mass, and m_f is the final spacecraft mass ($m_i - m_f =$ propellant used). Figure 2.15 shows the propellant mass fraction (required propellant mass/initial spacecraft mass) as a function of specific impulse and ΔV. High specific impulse is desirable to minimize propellant mass or to maximize ΔV.

Table 2.4. Propulsion Requirements for Representative Missions

Mission	Time	ΔV (m/s)	Minimum Thrust (N/kg)
Increase altitude from 700 to 701 km	2 h	0.53	74.0
Increase altitude from 700 to 701 km	2 days	0.53	3.0
Move 10 km ahead at 700 km altitude	2 h	5.20	1100.0
Move 10 km ahead at 700 km altitude	2 days	0.04	8.3
Change inclination by 1 deg at 700 km altitude	2 h	131.00	40,000.0
Change inclination by 1 deg at 700 km altitude	2 days	131.00	2000.0
Change inclination by 1 deg at GEO	2 days	54.00	7500.0
Change inclination by 1 deg at GEO	2 days	54.00	750.0
Boost altitude by 100 km at GEO	1 day	3.65	42.0
Boost altitude by 100 km at GEO	1 week	3.65	6.0

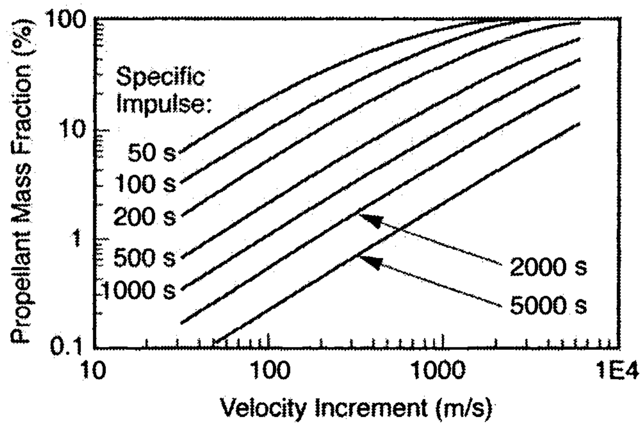

Fig. 2.15. Propellant mass fraction as a function of mission ΔV requirement for different I_{sp}.

How can micromachining techniques enable the building of propellant tanks, propellant lines, and valves? One solution is to bond several micromachined layers so that shallow surface cavities become tubes and deep cavities become propellant tanks. Figure 2.16 shows the basic concept in which three layers are bonded to form a propellant tank, associated plumbing, and two simple expansion nozzles. Multiple thrusters and propellant feed systems can be produced on the same substrate.

Micromachining offers new thruster design possibilities, which are presented in Chapter 17. As shown in Fig. 2.16, complete thruster systems need more than just thrusters; they also require propellant storage, propellant distribution, flow rate control, and health and status monitoring (temperature and pressure). MEMS nozzles and thrusters have already been demonstrated; yet to

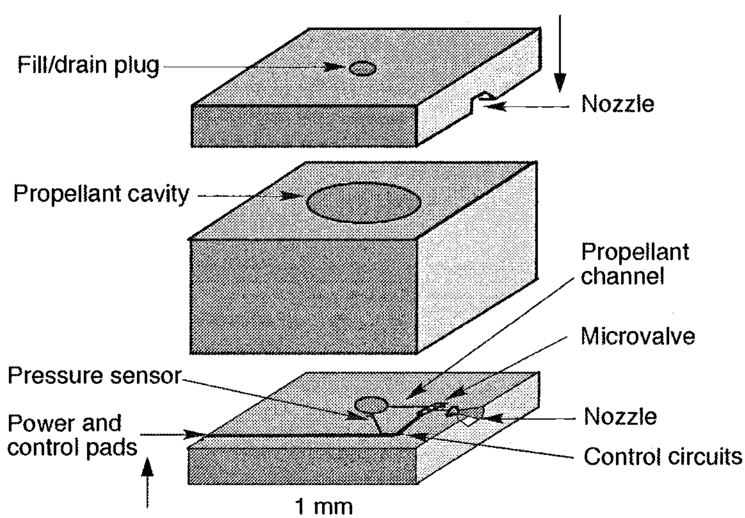

Fig. 2.16. Schematic assembly of a dual thruster micropropulsion system based on microfabrication techniques. The top and bottom wafers contain etched propellant channels with 100 to 1000 μm widths, multiple microfabricated valves, sensors and control electronics, and thrusters. The center wafer contains the propellant cavity (1mm to 1 cm diam) and may support additional microfabricated components.

be addressed are the leak rates of MEMS valves, the relatively slow response time of thermally actuated valves (typically 0.1–1 s), the operating pressure ranges of currently available valves (up to 100 psig), and the need for filtration of micron-scale particles within a propellant feed system.

MEMS valves typically use silicon-silicon or silicon-glass valve seats that do not have adequate seals for space applications; the leak rates can be 0.02 sccm or larger. At this rate, about 40 mg of propellant will be lost per day through each valve, or about 0.5 g per day through a 12-valve attitude control system. While this loss rate may be tolerable for spacecraft with mass greater than 50 kg, it would be intolerable for a 1 to 10-kg-class spacecraft that had to function for 5 years or longer. Elastomeric or "soft goods" seals, which are standard in macroscopic spacecraft valves, have just recently appeared in a MEMS valve produced by Redwood Microsystems.[88] There are other approaches to circumvent the traditional MEMS "leaky valve" problem. The JPL approach is to use resistive heaters to sublimate an otherwise low-vapor-pressure solid or liquid on demand.[89] Another approach, funded by DARPA and executed by TRW, Inc., Aerospace, and the California Institute of Technology, is to construct an array of single-shot microthrusters.[90,91] In its simplest form, this "digital" propulsion concept uses individually addressable sealed microcavities containing propellant, an internal heating resistor, and a micromachined silicon or silicon nitride burst disk as shown in Fig. 2.17. Each microcavity provides an impulse when the contained propellant is ignited and the gases exhausted. The diaphragm is designed to burst at a preset pressure, and for additional thrust the exhaust gases are made to flow through a converging/diverging nozzle. Preliminary "burst tests" have shown that a 0.5-μm-thick, roughly 500-μm-sq silicon-nitride diaphragm can be made to burst cleanly without clogging the flow channel. Polysilicon resistors can be placed directly on a thin oxide layer without regard to thermal loss because the firing time is so fast, on the order of 25 μs, that heat penetration into the oxide layer and substrate is minor. Micromachining enables the fabrication of thousands of similar microthrusters so that hundreds of complex propulsion maneuvers can be accomplished. Chapter 17 gives additional details of the digital propulsion system.

Micromachined pressure sensors can be integrated into conventional or micromachined propulsion systems once the materials compatibility issues have been addressed. Hydrazine (N_2H_4) is widely used as a space-storable propellant, but becomes an anisotropic etchant for silicon if water is present. The basic process involves formation of hydrated silica, which gets dissolved in the hydrazine/water mixture.[92,93] Water acts as a catalyst to generate OH^- ions, which can oxidize silicon. Monopropellant grade (MIL-P-2653C Amendment 2) hydrazine can contain up to 1% (by

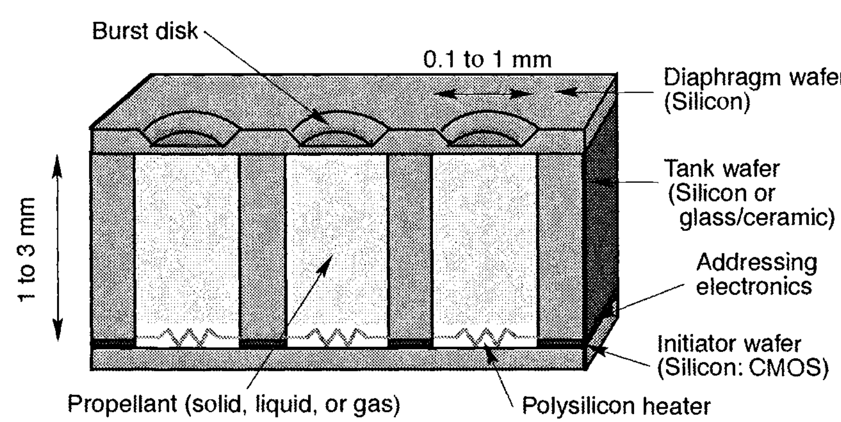

Fig. 2.17. Schematic cut-away view of a "digital" propulsion thrust system.

weight) water, which can be reduced to ~0.07% by passing it through an activated alumina column.[94] Our experience is that dry hydrazine will not etch bulk silicon with a native oxide layer. Materials compatibility testing of propellant-grade hydrazine with doped silicon, undoped silicon, and polysilicon at spacecraft temperatures is still needed.

2.2.4 Optical Systems

In current spacecraft, optical components are primarily used for imaging systems. These systems include Earth-imaging sensors and optical attitude determination sensors. MEMS and MOEMS will not replace macroscopic lenses and mirrors, but they could be used in controlling the image focal plane and to direct light beams for inter/intra satellite optical communications.

Near-term applications should include fiber-optic data buses, FOGs, and laser communication systems. MEMS and MOEMS can be used in all these applications. For example, light output from diode lasers and VCSELs (vertical cavity surface emitting laser) could be used more efficiently with "on-chip" optics for focusing (i.e., Fresnel lens) into a fiber or with micromachined scanning mirrors for beam steering (e.g., laser to fiber coupling module [95]). MEMS technology has successfully fabricated such components.[96] The devices are initially fabricated planar to the surface, but can be rotated out of the surface plane under microactuator control and locked into position.[97] Figure 2.18 shows an example of a micromachined beam steering system produced by the University of California, Berkeley.[98] The polysilicon reflector or mirror is near the bottom right of the photo and has been popped out of the plane of the silicon substrate. MEMS vibromotors, visible as flat structures with comblike features, control mirror orientation about a single axis (in plane of substrate) and mirror translation along a perpendicular axis (also in plane of substrate). The roughly 200-μm-sq mirror has an angular travel range of 90 deg, a translation range of 60 μm, and a maximum angular scan rate of 10.2 radians/s.

Variable gratings such as the vertical-motion "Grating Light Valve" phase grating by Silicon Light Machines[99] (vertical-motion phase grating) and the horizontal-motion grating device designed at AFIT, presented in Chapter 12, can be used to construct miniature programmable spectrometers for visible and infrared radiation. Simple versions could be used in Earth horizon sensors; while more complex imaging versions could be used for Earth observation, that is, cloud

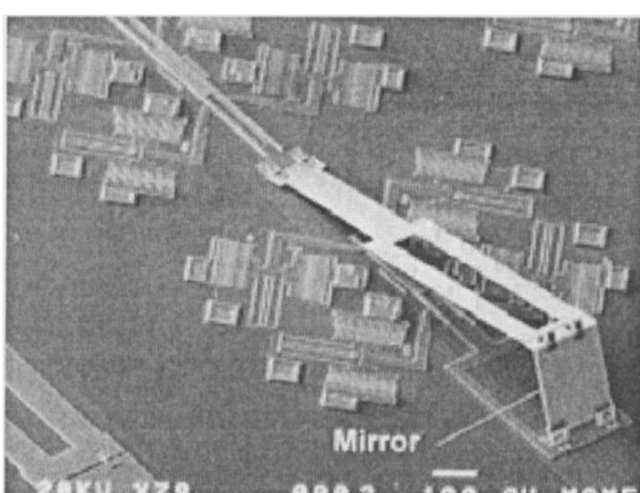

Fig. 2.18. Scanning electron micrograph of a microreflector with two degrees of freedom. (Photo courtesy R. S. Muller.[98])

cover, vegetation, and surface-temperature monitoring. Remote sensing from space-based platforms is becoming commercially viable.[100]

The growing demand for high-speed and high-density communication networks, both within and between spacecraft, and the potential impact that photonics technology may have in realizing that demand, will force both MEMS and MOEMS technology to be utilized on orbit. Examples of potentially useful devices include corner-cube microreflectors,[101] tunable optical filters,[102] and deformable mirrors for aberration control.[103] Figure 2.19 shows a hexagonal array of electrostatic-driven micromirrors, designed at AFIT, which is intended for aberration control in optical systems. The nonsegmented continuous-membrane array design of Boston University is also of great interest.[104]

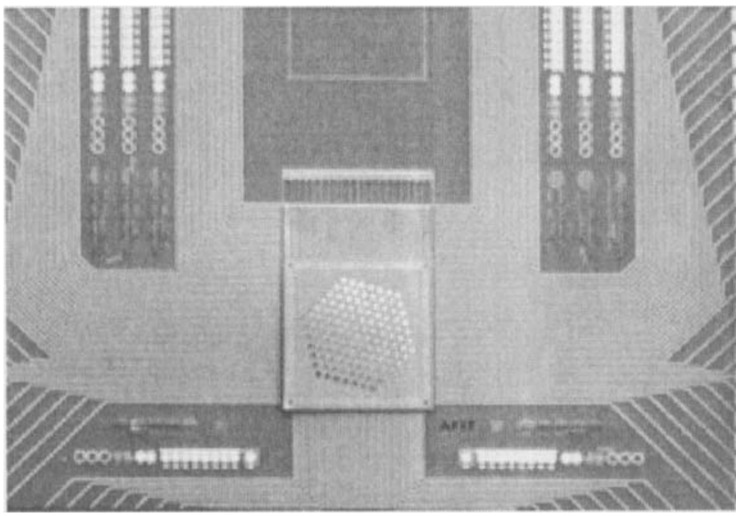

Fig. 2.19. Array of segmented micromirror piston-actuators designed at AFIT and fabricated at the North Carolina's MCNC MUMPs (Multi-User MEMS Processes). (Photo courtesy V. M. Bright.[103])

2.2.5 Thermal Control

The effective absorptivity/emissivity ratio, which determines the temperature of exposed spacecraft surfaces, can be modified using thermal louvers.[105] Many current spacecraft control heat rejection within a ~6:1 range by employing rectangular blade (venetian blind) and pinwheel designs driven by bimetallic springs. Figure 2.20 shows a conceptual micromachined implementation of the thermal louver concept based on the Texas Instruments Digital Micromirror Device.[106] The vanes and exposed silicon surfaces are coated with vapor-deposited aluminum to give a solar absorptivity of ~0.1 and an emissivity of ~0.05. When a vane is rotated out of the surface plane, a high-emissivity surface of either high or low absorptivity is exposed to the outside environment. Since silicon is transparent to infrared radiation between ~1.2 and 6.5 μm, elimination of the high emissivity coating would allow a warm object located below the silicon substrate to radiate to space while the vane was open. The hinge line is offset from the center-of-surface area to allow wide opening angles without requiring a large-gap height separation. The advantages of micromachined louvers are rapid response time and the ability to tailor the emitted thermal spectrum; the cavity can act as a high-pass (in frequency) filter if suitably designed.

Another approach to spacecraft thermal control is to use mechanical "thermal switches" that open or close a thermal conduction path between a heat source and a heat sink. An international

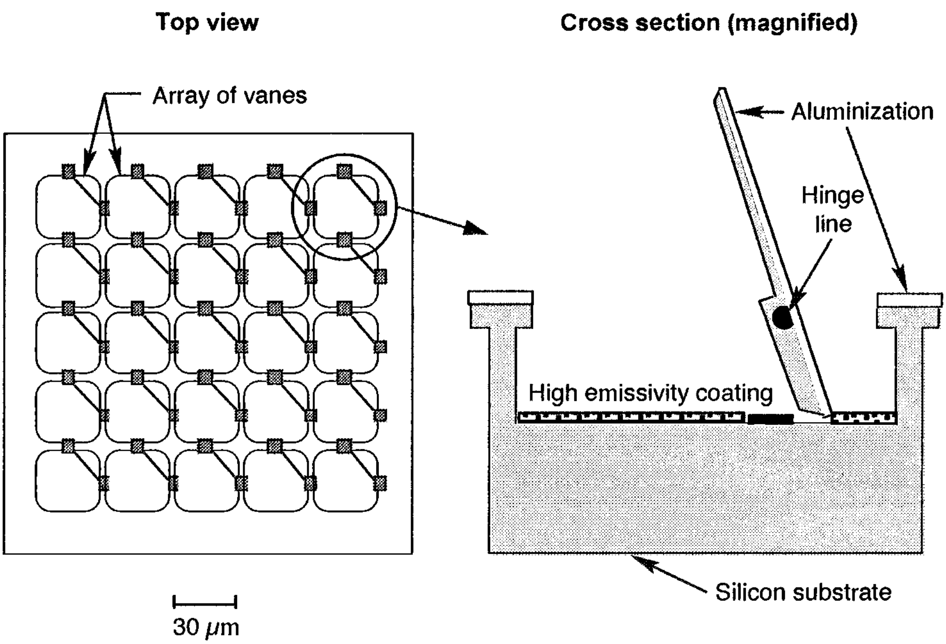

Fig. 2.20. Conceptual design of a micromachined thermal louver array for control of surface heat rejection capability.

team has demonstrated a micromachined active radiator tile (ART).[107] These 1-in.-sq (2.5 cm × 2.5 cm) prototypes are composed of two bulk-etched silicon wafers and use electrostatic attraction to pull a flexible upper diaphragm into thermal contact with the base wafer. The thermal gap between the diaphragm and base plate is 10–20 μm thick, and about 40 V is required to pull the diaphragm across that gap. A new design is under development that should withstand launch vibrations and accelerations.

Within the spacecraft, heat pipes are normally used to provide high thermal conductivity paths. Heat pipes are sealed tubes that transfer heat from one location to another, using vaporization of a working liquid at the "hot" end followed by convective transport of the vapor and condensation at the "cold" end. The condensed liquid returns to the hot end via a wicking or surface tension process. Miniature heat pipes have hydraulic diameters on the order of 1 mm; while micro heat pipes have diameters on the order of 10 μm. Additional information on miniature and micro heat pipes can be found in Cao *et al.*[108] and Khrustalev and Faghri.[109] The miniaturization of heat pipe technology using MEMS fabrication techniques allows heat dissipation to be enhanced over small distances for individual integrated circuits, detectors, or actuators. Micromachined heat pipes have been investigated by a number of researchers with some promising results.[110,111] Fabrication is relatively straightforward using a (100) silicon wafer. A long, thin exposed region of silicon can be anisotropically etched to produce a "V" groove, which becomes a sealed tube when bonded against a flat surface. Methanol has been used as the working fluid. Figure 2.21 gives the dimensions and geometry used.[110,111] The results show an increase in effective thermal conductivity of up to 81%, compared with a standard silicon wafer, and a significantly improved transient thermal response. Micromachined heat pumps may provide an effective way of removing heat from integrated circuits without using metallic heat radiator elements.

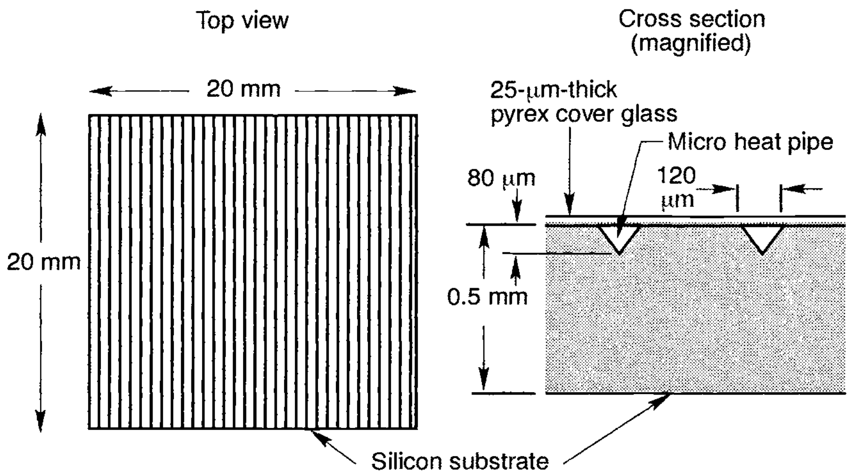

Fig. 2.21. Micro heat pipe construction.

2.3 Silicon Satellites

2.3.1 Basic Concept

Figure 2.22 shows a rendering of an Earth-observation, silicon satellite (also known as the nanosatellite) to be used in LEO. Introduced in Janson, Helvajian, and Robinson,[112] this concept presents a new paradigm for space system design, construction, testing, architecture, and deployment. Integrated spacecraft that are capable of attitude and orbit control for complex space missions can be designed for mass-production using adaptations of semiconductor batch-fabrication techniques. Integrated circuits for command and data handling (C&DH), communications, power conversion and control, on-board sensors, attitude sensors, and attitude control devices can be manufactured on 1 to 4-mm-thick silicon substrates that simultaneously provide structure, radiation shielding, and thermal control. Silicon compares favorably with aluminum in terms of thermal conductivity, radiation-shielding ability, and mass density, yet it is stronger than steel (~7 GPa maximum stress vs ~1 GPa for steel) and transparent to IR radiation between 1.2- and 6.5-μm and also between 25- and 100-μm wavelengths. Diamond is better on almost all counts, but silicon is readily available and easily processed. Silicon's main weakness is its brittleness; impact and shock loading must be controlled during fabrication, assembly, testing, and launch. Batteries and solar cells for the nanosatellite will still need to be fabricated using conventional materials. The spacecraft shown in Fig. 2.22 is essentially a stacked multiwafer package. A multichip module approach combined with partial wafer-scale integration would be used to fabricate the wafers. Useful silicon satellites will have dimensions of 10 to 30 cm; while more complex configurations using additional nonsilicon mechanical structure (i.e., truss beams, honeycomb panels, and inflatable structures) will be much larger. The benefits of batch-fabricated silicon satellites are:

- Radically increased functionality per unit mass
- Ability to produce 10,000 or more units for "throw-away" and dispersed satellite missions
- Decreased material variability and increased reliability because of rigid process control
- Rapid prototype production capability using electronic circuit, sensor, and MEMS design libraries with existing (and future) computer-assisted design (CAD)/CAM tools and semiconductor foundries
- Reduced number of piece-parts
- Ability to tailor designs in CAD/CAM to fabricate mission-specific units

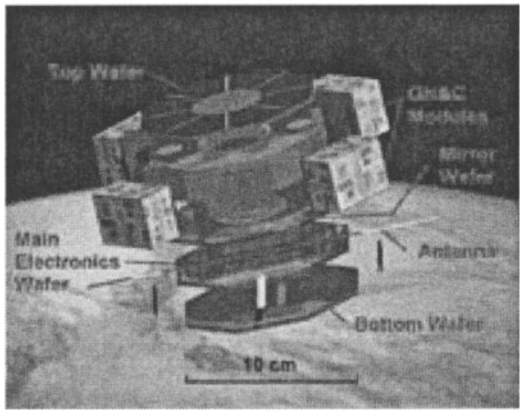

Fig. 2.22. Rendering of a hypothetical Earth observation silicon satellite.

Initial nanosatellite designs use two types of processed wafers: wafers that incorporate a sparse number of electronic devices (i.e., low interconnect density, as opposed to memory or microprocessor fabrication wafers), numerous micro channels, plus MEMS and MOEMS; and wafers that are essentially multichip modules (MCMs) that contain most of the centralized signal processing, command, and control electronics and the RF communications. These MCM wafers will need a high density of interconnects and the capability for mixed-signal processing. In the near-term nanosatellite designs, communication between wafers will be via metal and polysilicon lines routed to the wafer edges with a perimeter connection system that constitutes the satellite bus. In long-term nanosatellite designs, communication between wafers is more likely to be via local RF or free-space, optoelectronic switching technology, for example, use of heterojunction phototransistors (HPTs) integrated with vertical cavity surface-emitting lasers (VCSELs).[113]

2.3.2 Size Impacts: Feasibility of a Pico-Femto Satellite

Silicon satellites can be classified as microsatellites (1–100 kg mass), nanosatellites (1 g–1 kg mass), picosatellites (1 mg–1 g mass), or femtosatellites (1 μg–1 mg mass). While picosatellites and femtosatellites would have seemed absurd 10 years ago, they are now conceptually feasible because of continuing decreases in electronic gate size and the emergence of MEMS and MOEMS. These technologies permit the integration of the C&DH and communication systems, low-resolution attitude sensors, inertial navigation sensors, and a propulsion system into a 1-cm-cube or smaller size satellite. On the other hand, by removing propulsion, for example, picosatellites and femtosatellites would be ideal as simple space environment sensors. Using only solar radiation and depending on the overall configuration, picosatellites through microsatellites can produce power levels in the 1–100 W range. On the other hand, femtosatellites can only generate microwatts to milliwatts. This directly affects how much power is available for power-hungry communication and data-processing systems. Thermal control is also an issue for these lilliputian satellites. Simple lumped-parameter models of silicon satellite temperature swings between fully lit and Earth-eclipsed conditions have shown that passive thermal control is possible for nearly spherical nanosatellites and microsatellites.[114] When dimensions drop below 2 cm, the temperature extremes exceed typical electronics and battery limits. Femtosatellites, with their extremely low mass, can reach the equilibrium sunlight (or eclipse) temperature within minutes. As a consequence, picosatellites and femtosatellites will require some form of thermal control.

Small size also affects radiation shielding ability and orbit lifetimes. For constant altitude and spacecraft density, the ratio of air drag to spacecraft mass is inversely proportional to scale length.

As spacecraft shrink in size, the deceleration due to the air-drag becomes stronger, resulting in more rapid orbital decay. At altitudes below 500 km where radiation shielding (0.38 mm maximum length for a 1-mg mass cubic femtosatellite) may be adequate for radiation-tolerant electronics (about 10^4 rads total dose with error detection and correction), the orbit lifetime is only a few days. At higher altitudes, rapidly increasing radiation levels limit the lifetime to a few days unless special radiation-hard (e.g., silicon-on-sapphire) electronics are used. Femtosatellites should be nearly spherical in shape to minimize air drag and maximize radiation shielding. Maximum power generation levels will therefore be in the submilliwatt range. Femtosatellites are an extremely difficult challenge because of their low thermal mass and wild temperature swings as they enter and exit Earth's shadow.

Picosatellites are the smallest useful satellites, but active thermal control will be required. A thermally passive picosatellite will have temperature swings of 90 K between sunlight and eclipse in low Earth orbit. Cubic picosatellites made of silicon can have as much as 0.18 cm radiation shielding and orbit lifetimes of several years at 700-km altitude under solar-maximum conditions. Nearly spherical satellites are needed again to provide radiation shielding, and if low-inclination orbits are used (below 700-km altitude), use of radiation-soft CMOS electronics may even be feasible. Available power will be in the tens of milliwatts range. Picosatellites may be good for disposable or short-duration (i.e., 1-week) missions (i.e., as space probes).

2.3.3 Missions

Silicon nanosatellites and microsatellites with 10 cm and larger dimensions, micromachined attitude sensors, and micropropulsion for attitude and orbit control could perform useful missions with on-orbit lifetimes of 1 to 5 years. Possible mission applications are communication relay, cloud cover monitoring, geolocation, and space environment monitoring. Mission applications can be grouped into three broad categories:

- Disposable missions that use silicon satellites for a short period of time followed by deorbit
- Global coverage missions that use hundreds of silicon satellites in LEO to provide continuous Earth coverage for communications or Earth observation
- Local cluster missions that utilize hundreds of silicon satellites in a sparse array configuration to provide a large effective aperture

An example of a "disposable" mission is the untethered flying observer (UFO) that was analyzed during the workshop portion of the First International Conference on Integrated Micro/Nanotechnology for Space Applications.[115] A UFO, shown in Fig. 2.23, could be deployed on command and flown about the host vehicle to provide a visual assessment of the larger spacecraft health and physical attributes, for example, after an operational anomaly is detected. The UFO would be mounted on the surface of a LEO spacecraft in a "cocoon" and would lie dormant until activation. The workshop effort produced a conceptual design with a mass less than 1 kg, a maximum power level of 1.6 W, and an operational lifetime of 48 h. A lithium primary battery supplies power, a 2000 × 2000 pixel CCD imager provides images and high-resolution attitude information, and ammonia cold gas microthrusters provide maneuvering and attitude control. Image and telemetry data would be transmitted at S-band using omnidirectional antennas (the stubs protruding from the UFO in Fig. 2.23) to Space Ground Link Subsystem (SGLS) stations in the Air Force Satellite Control Network (AFSCN) using 0.5 W of RF power. Following the mission, the UFO does not return to the mother ship but is deorbited.

Silicon satellites can also be dispersed as local clusters. One approach, analyzed by researchers at MIT, is to use random clusters in which individual nanosatellites move with respect to each other. The Aerospace approach is to utilize orbital mechanics to create configurations that

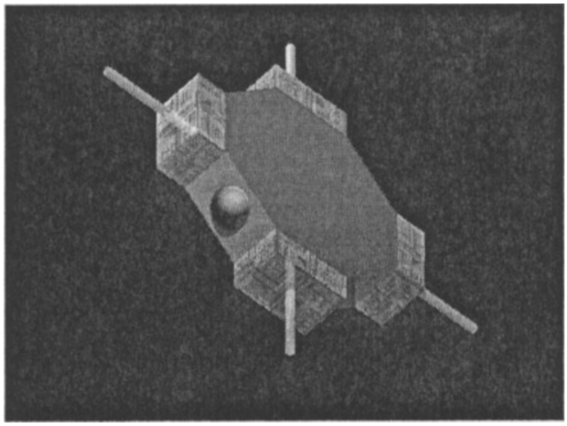

Fig. 2.23. Artist's concept of an untethered flying observer. The main body is 10 cm in diameter.

maintain a fixed geometry without requiring continuous thrusting.[116] A circular ring of physically unconnected satellites will maintain its geometric configuration, to first order, if the ring diameter is orders of magnitude smaller than the orbit radius, the ring itself is in a circular orbit, and the surface-normal vector of the ring points 30 deg away from the nadir (toward the Earth's center) in the orbit-normal direction. The major orbit perturbations to these clusters result from so-called "J2" effects (the Earth's mass distribution cannot be adequately represented by a point mass because the Earth is slightly flattened because of rotation and "J2" represents the gravitational perturbation that results from this flattening), which decrease rapidly with altitude. Once established, this ring of satellites will rotate once per orbit period as seen in the reference frame of the orbiting cluster; for example, the ring rotates about its center while the whole cluster rotates about the Earth. Since the ring rotation rate is independent of radius, multiple concentric rings of different diameters will rotate together, thus producing a rotating disk of fixed geometry. These local clusters, composed of hundreds to thousands of individual silicon spacecraft, can operate in a concerted fashion as a single large phased array at radio frequencies. Each cluster would operate as a local area network with short-range optical or RF communication links between the nanosatellites and a central mother ship.

Silicon satellites have not yet been built, but they offer radically new ways to perform space missions. MEMS and MOEMS advanced microelectronic processing and packaging make them possible. More development effort is required for miniaturizing space systems, in particular micromachined gyros, micropropulsion, and micromachined laser communications. MEMS sensors for on-board health and status monitoring are also needed, fulfilling similar tasks as that required in larger satellites.

2.4 Manufacturing Future Space Systems

2.4.1 Manufacturing Challenges and Limits of MEMS/MOEMS Technology Insertion

MEMS and MOEMS technology will inevitably be used in future space systems. Investigations are already under way to reduce spacecraft size and weight and to modularize the subsystems to enable new technology insertion in future block changes of existing satellite programs. Studies that look further into the future than the next block change already know that space is a strategically lucrative platform for conducting business–both civilian and military. Pragmatically, some of these missions can only be accomplished by orbiting a large constellation of satellites. The nanosatellite concept is one solution to meet this challenge. The infrastructure necessary to assemble a mass producible nanosatellite does not yet exist within the space community; however, elements of this required infrastructure do exist in the commercial world, for example, in the manufacturing of laptop computers, personal information systems, cellular phones, and hand-held video cameras. Regardless of how the necessary manufacturing infrastructure is mobilized, future satellite systems will be designed to process more data on board, to operate more autonomously, and to be manufactured by automated assembly-line processes as opposed to the current piecemeal building approaches used. In addition, to reduce the cost of building satellites, statistical quality-control methods must be implemented as a requirement for achieving overall high-quality systems.[117] These criteria alone provide an avenue for technologies like MEMS and MOEMS to be inserted into space systems, either as monitoring instruments (e.g., satellite manufacturing process line, onboard satellite health and welfare systems management) or to provide new and enhanced capabilities. The extent to which MEMS and MOEMS can be inserted into future satellite designs will depend on how rapidly microengineering prototyping centers can be established and how rapidly microdevices can be fabricated on materials not within the conventional microelectronics industry repertoire. The latter requirement arises because besides semiconductors, materials such as ceramics, glasses, diamond, polymers, and composite materials are typically used in space systems. The fabrication of microdevices and complete ASIMs on these materials is crucial to satellite design approaches for a fully integrated system. The alternative is to implement a macro-scale package for each individual micro device, which negates the desire to reduce excessive packaging. In reality, if new satellite design paradigms are implemented, the most likely path space system engineers will follow is to design for full integration but incorporate nonintegrated components as add-on systems and only if there are compelling benefits to satellite operations.

2.4.2 Need for Rapid Prototyping Centers

The success of micro/nanotechnology to revolutionize our world will, in general, depend on the development of effective rapid prototyping centers and the networking of these prototyping centers to enable users to draft process sequences that can be cycled through physically separated sites. For example in the United States, the Multi-User MEMS Processing Service (MUMPS), the Metal Oxide Semiconductor Implementation Service (MOSIS), other "virtual" foundries, and most university and industry research centers offer an excellent path to accelerated component prototyping, and the recent DARPA-initiated MEMS-Exchange program[118] could establish the environment for distributed MEMS fabrication and manufacturing. In most fabrication centers the tools and fabrication processes are geared for semiconductor materials processing. This fact will certainly influence the design of many terrestrial and space instruments such that wherever feasible, components, devices, and complete subsystems will be designed to leverage the use of existing microelectronics technologies.

For space applications, however, the use of materials other than semiconductors can be advantageous. Combustion chambers must withstand high temperatures and possible chemical attack. Silicon may work for hydrazine monopropellant microthrusters, but bipropellant thrusters have combustion temperatures far in excess of silicon's melting temperature. High thermal conductivity and electrically insulating materials (e.g., diamond) should be used around high-power circuits while polymers or other ductile materials are preferred in valve seats to limit leakage. As a result, processing tools and techniques that can efficiently micromachine/process nonsemiconductor materials may become necessary. The laser is one example of such a processing tool.[119] Laser material-processing technology has experienced a robust growth in the past decade. This is mostly because the reliability of laser systems has increased, higher repetition rate lasers are now commercially available (e.g., kilohertz to megahertz), and a variety of wavelength (e.g., vacuum UV—far IR) and pulse-width (e.g., femtoseconds to continuous wave) choices are on the market. As a material-processing tool, the laser is a nonintrusive, in-situ material-processing tool, which in principle can remove material, deposit material, and anneal the surface. It can serve as a diagnostic of the surface quality, morphology, surface adsorbates, and gas phase reactant; and it can "micromachine" structures on the surface or imbedded in the bulk. Lasers can process not only silicon but also other semiconductors, ceramics, metals, glasses and composite materials. However, unlike semiconductor processing in which the processing tools are automated and the process recipes refined over the past three decades, laser-based tools are just becoming commercially available with comparable automation capability and process control.[120]

2.4.3 Need for Mixed Technology Integration and CAD

Rapid-prototyping centers alone will not advance MEMS technology. To adequately capitalize on investments in the manufacture, design, and test of semiconductor integrated circuits toward future terrestrial and aerospace applications, computer-assisted manufacturing programs for mixed technology systems must be developed. Mixed-technology systems are defined to include mixed-energy domains (electronic, kinematic, optical, fluidic, and electromagnetic domains, etc.) and mixed-signal integrated microsystems. Mixed-technology systems may incorporate hundreds to thousands of integrated microdevices that create new system capabilities unachievable through more traditional hybrid integration. Their design represents unique challenges and opportunities. The tight integration of microdevices in mixed-technology systems, however, requires more than just an electronic domain analysis to understand and optimize the functionality of the design. Issues such as coupled energy domain simulation, three-dimensional shape analysis before and possibly after integration, and mixed-technology-interconnect design and analysis need to be addressed as part of the design process. Key to enabling mixed-technology systems is the development of a design environment that supports both design and manufacture based upon many available mixed-technology and electronic building blocks. In addition, design trade-offs, optimizations, and synthesis need to be explored from an overall systems perspective in a mixed-domain design and layout environment. The DARPA-funded Composite CAD[121] program is an attempt to create a design environment that encompasses these challenges. Figure 2.24 shows the paradigm shift in CAD, which is enabled by Composite CAD. In effect, the approach to a system design changes from the current bottom-up process to a top-down process. In the top-down process the overall system requirements are first defined and then reduced to the component level specifications. This is visualized in the spiral model shown in Fig. 2.25. Starting from the center

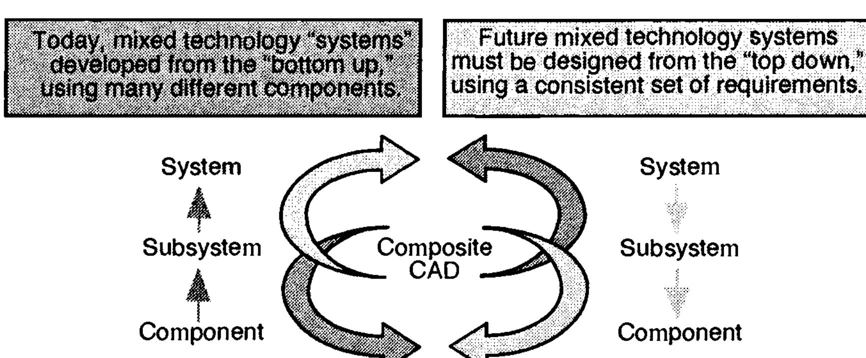

Fig. 2.24. Comparison of today's and future mixed technology design. (Drawing courtesy H. Dussault.[121])

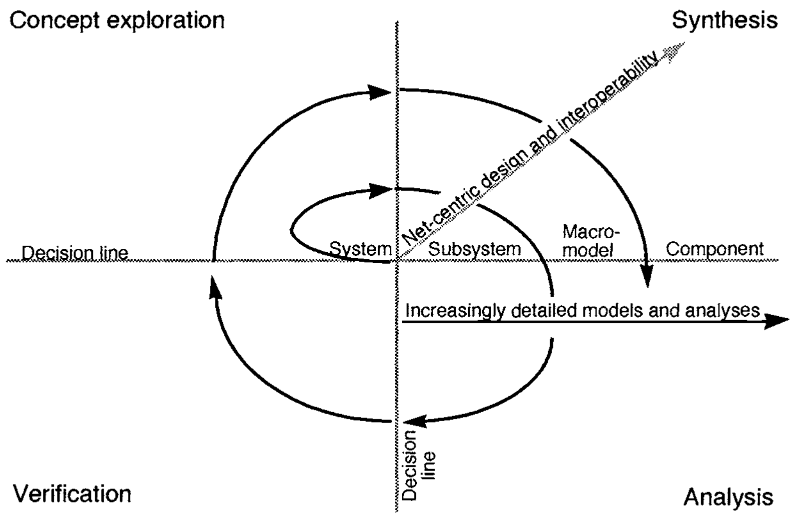

Fig. 2.25. Adapted from the spiral development model for software development and applied to CAD. (First proposed by B. Boehm in 1988 and the Software Productivity Consortium's Evolutionary Spiral Process [ESP] Model in 1991. Drawing courtesy H. Dussault.[121])

and a high-level definition of the required system, there is a sequential process of concept exploration, synthesis, analysis, and verification with decision points at every boundary. With every full cycle the models and analysis become progressively more detailed. Much as CAD has helped to foster new generations of highly complex digital VLSI systems, the Composite CAD program will enable designers to create complex, highly integrated, mixed technology "systems on a chip" by rapidly exploring multiple design alternatives. Efforts similar to the DARPA program are also being explored in Europe and are presented in Chapter 7.

2.4.4 Need for Flight Demonstrations

New technology is fundamentally risky. It must be tested and verified under relevant conditions before being accepted by the aerospace community. "I don't want to be the first to fly that device, but I'll be the second," is commonly heard by technologists trying to get new systems and subsystems used on-orbit. Experimental test flights are required, and Aerospace is trying to shorten the laboratory-to-operational-use time lag for MEMS by inserting emerging devices onto space platforms. The NASA Johnson Space Center, in collaboration with Aerospace, has developed a MEMS testbed that can be flown on the U.S. Space Shuttle.[123] The testbed, shown in Fig. 2.26, is due for flight in 1999 (STS-93) inside a middeck locker. It incorporates multiple MEMS accelerometers, several rate gyros, chemical sensors, nanoelectronics, and a variable surface emissivity device into an industrial PC card frame. Rate gyros and accelerometers are mounted on the rear wall of the middeck locker (top left in Fig. 2.26) to measure Shuttle angular accelerations, vibrations, and linear accelerations. Additional accelerometers and rate gyros are mounted on ISA bus cards within the PC card cage (middle and lower right in the figure) to characterize the experiment environment. The card cage is wrapped in foam and inserted into the middeck locker to provide acoustic and vibration damping. Data are obtained and logged during launch, on-orbit operations, reentry, and landing. The intent is to provide a standard and easy-to-use experiment infrastructure for MEMS researchers; integration of devices into the testbed and integration of the testbed onto the Shuttle are performed by Aerospace, NASA, and Air Force personnel. The middeck

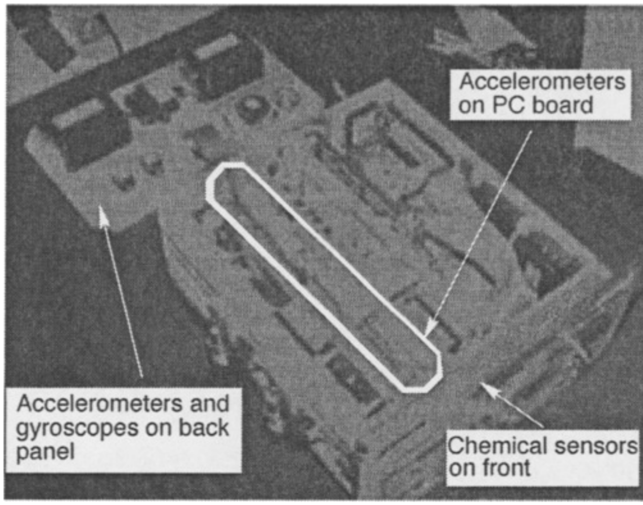

Fig. 2.26. Photograph of the NASA-Aerospace MEMS testbed. The card cage measures 50 × 50 × 25 cm. (Photo courtesy of The Aerospace Corporation.)

implementation provides exposure to launch and reentry loads, microgravity conditions on orbit, and on-board atmosphere (composition and pressure).

2.5 Conclusions

In the United States, both NASA and the DOD have recognized the potential of using microengineered systems in space applications. A similar conclusion has been reached by technology pundits at the ESA[122] and by independent space-system contractors. Major programmatic funding for space applications, outside of that from NASA's New Millennium Program (NMP), still remains in the realm of systems analysis and reliability studies. For example, the U.S. Air Force Research Laboratory in Albuquerque, New Mexico, is performing radiation effects testing of MEMS, and technology demonstration experiments are under way at NASA JPL and Aerospace. Many universities, including those not traditionally involved in MEMS research, are entering the "MEMS for space" arena. Many spacecraft designs will continue to shrink in mass and size, given the resounding success of the Mars Pathfinder mission. Experimental spacecraft currently on the docket will increase the confidence of the space community that small can be good. Additional confidence in "small and capable" spacecraft will be attained as the NMP spacecraft complete their missions to Mars, Pluto, and the asteroids. Finally, there have been numerous workshops hosted by JPL, Round Table discussions hosted by ESA, and a focused conference sponsored by NASA and Aerospace at the Johnson Space Center, Houston, Texas (1995).[122] In April 1999 The Aerospace Corporation, DARPA, JPL, and the Air Force Research Laboratory Vehicle Systems Directorate will host the Second International Conference on Integrated Micro/Nanotechnology for Space Applications, in Pasadena, California. Interest and momentum are increasing steadily.

This chapter has focused on technologies, which if applied to space systems, can result in revolutionary changes in current and future space systems. The specific technologies presented are primarily in the microengineering realm and show clear evidence for worldwide terrestrial use. The underlying assumptions are three: the best means for attracting the space community attention to these new technologies is to identify examples that present distinct advantages when incorporated into space systems; the identified technologies can be incorporated in both a revolutionary and evolutionary manner; and there exists a significant terrestrial application base from which to draw upon. Other technology areas currently less mature in development will also have revolutionary impact on space systems. Two deserve brief mention: nanotechnology and micro-robotics.

Nanotechnology deals with the development of processes whereby a strong level of atomic or molecular control is exercised in the device fabrication. Micro-robotics is an interdisciplinary technology area whose objective is to assemble a class of limited-"intelligence," autonomous robots of sizes ranging from millimeters to centimeters. Both technologies have identified terrestrial applications. For nanotechnology the industrial drivers are pharmaceuticals, bioengineering, advanced lithography, nanoelectronics (e.g., resonant tunneling devices), and functionalized surfaces. For micro-robotics, the industrial applications appear to be in toys, micro inspection systems (e.g., pipelines), microsurgery, and miniature information devices. Both areas have experienced rapid growth in interest, and both have benefited from MEMS/microsystems technology. Nanotechnology benefits because microsystems used in large arrays permit the nanofabrication/processing over practical areas; Microrobotics, because of the implementation of micro-actuation and the resulting capability to interact with the physical world. For space applications, manned and unmanned, both technologies can potentially revolutionize the deployment, assembly, and governance of space systems. In the near term, nanotechnology will be useful in space as nanoelectronics (multivalued logic circuits); basic components (e.g., resonant tunneling diodes, transistors) and some circuits have already been fabricated. Multilevel logic nanoelectronic circuits can provide the same function as binary circuits but with reduced component count, and they offer distinct advantages in computation-intensive tasks (e.g., image processing). The applications of micro-robotics to space systems will strongly depend on the level of capability endowed. Based on the developments for terrestrial applications (i.e., providing local diagnostics in pipelines), similar applications could be used in the ISS and other satellites, for example, in monitoring the integrity of the ISS hull, fuel tanks, and other critical surfaces that could develop stress, fracture, or sustain a micrometeorite impact. Longer term applications of nanotechnology and micro-robotics lead to speculative answers and deserve the benefit of observation for a few more years.

Microengineered devices will inevitably reduce the size of spacecraft or increase its functionality manifold. The path of size reduction will in turn address the use of a smaller launch vehicle, and this combination will undoubtedly reduce the total cost of launching to orbit. Another expected outcome is that the incorporation of these devices will also increase the autonomy in operations and increase availability through the use of condition-based maintenance protocols. Perhaps the most profound result from this revolution will be that satellites will become truly mass-producible commodities much like dynamic RAM chips are today.

2.6 Acknowledgments

The authors gratefully acknowledge the MEMS and MOEMS communities for providing information, The Aerospace Corporation Corporate Research Initiative Program for supporting much of our research efforts, and The Aerospace Institute for making this publication possible. We also gratefully acknowledge the DARPA MEMS program for supporting the digital microthruster effort at TRW, Aerospace, and California Institute of Technology.

2.7 References

1. H. Helvajian, ed., *Microengineering Technology for Space Systems*, Monograph 97-02 (The Aerospace Press. El Segundo, CA, 1997), p. 1. First published as The Aerospace Corp. Report no. ATR-95(8168)-2 (1995).

2. J. P. Aguttes, J. Sombrin, and E. Conde, "Charting the Course for Radar Sail," *Aerospace America*, **35** (9), 30–33 (September 1997).
3. W. C. Tang, "Micromechanical Devices at JPL for Space Exploration," *1998 IEEE Aerospace Conference* (Snowmass, CO, March 1998).
4. D. Collins, C. Kukkonen, and S. Venneri, "Miniature, Low-Cost, Highly Autonomous Spacecraft—A Focus for the New Millenium," IAF paper 95-U.2.06, *46th International Astronautical Congress* (Oslo, Norway, October 1995).
5. H. W. Price, K.B. Clark, C. N. Guiar, J. M. Ludwinski, and D. E. Smyth, "X2000 Flight Missions Utilizing Common Modular Components," *1998 IEEE Aerospace Conference* (Snowmass, CO, March 1998).
6. *Proceedings 2nd Round Table on Micro/Nanotechnologies for Space* (ESTEC, The Netherlands, 15–17 October 1997), ESA WPP-132; See also A. Martinez de Aragón, "Future Applications of Micro/Nanotechnologies in Space Systems," *ESA Bull.*, No. 85, 65 (February 1996).
7. Brite/Euram II Project, "MAGNIFIT," Reference no. BRE20536.
8. Brite/Euram III Project, "Thick Film Ferroelectric Actuators for New Design Industrial Applications," Reference no. BRPR960318.
9. Brite/Euram III Project, "Basic Research on the Use of Magnetic Fluids in Microsystems," Reference no. BRPR970598.
10. Brite/Euram III Project, "A Novel Method for the Synthesis of Microsize Permanent Magnets," Reference no. BRPR970488.
11. Brite/Euram III Project, "Thick Oxide Films for Passive And Active Optical Components," Reference no. BRPR970434.
12. Esprit-4 Project, "Field Programmable System on Chip," Reference no. 21625.
13. T. Diehl, W. Ehrfeld, M. Lacher, and T. Zetterer, "Electrostatically Operated Micromirrors for a Hadamard Transform Spectrometer," *1998 IEEE/LEOS Summer Topical Meetings on Optical MEMS* MOEMS '98 (Monterey, CA); See also R. Riesenberg, T. Seifert, and J. Schöneich, "Slit Array Made by Microsystem Technology for Performance Improvement of CCD-Detector Arrays and Mini-Spectrometer-Instruments," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, ESA Report WPP-132, p. 145.
14. Fine Sun Sensor Literature, Daimler-Benz Aerospace: Jena-Optronik GmbH, Prüssingstraße 41, D-07745 Jena, Germany.
15. J. P. Krebs, O. Brunel, C. Guerin, D. Guillon, and J. M. Niot, "A New IR Static Earth Sensor for Micro and Nanosatellites," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 187.
16. C. Cavadore, P. Magna, Y. Degerli, A. Gautrand, F. Lavernhe, J. Farre, F. Solhusvik, and R. Davencens, "Active Pixel Image Sensors for Space Applications," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 115; See also W. Ogiers, B. Dierickx, D. Scheffer, D. Uwaerts, G. Meynants, and C. Truzzi, "Compact CMOS Vision Systems for Space Use," *Ibid.*, p. 123; and J. Josset, P. Plancke, G. Boucharlat, and C. Val, "Digital 1k x 1k Microimager for Planetary Surface Exploration," *Ibid.*, p. 143.
17. J. P. Pekola, M. M. Leivo, M. J. Peltomäki, and A. J. Manninen, "NIS Microrefrigerators and Microcalorimeters on Silicon and Silicon Nitride Membranes," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 61.
18. L. Stenmark, J. Köhler, M. Lang, and U. Simu, "Micro Machined Propulsion Components," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 69.
19. R. Linnemann, M. Richter, and P. Woias, *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 83.
20. F. Eckhard, B. H. va der Schoot, K. Fluri, Ch. A. Paulus, R. H. Huijser, P. Reijneker, D. Va den Assem, A. J. Kramer, H. Leeuwis, and A. Prak, "CAELIS, Capillary Electrophoresis in Space," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 37.

21. R. Born, Ph. Arquint, B. va der Schoot, F. van Steenkiste, V. Spiering, J. Cefai, and K. Schumann, "Sensor and Integration Technologies for a Multisensor Array," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 45.
22. P. Woias, M. Richter, K. Hauser, E. Yacoub-George, H. Wolf, T. Abel and S. Koch, "Silicon Microreactors for Space-Bound Chemical Microanalysis," *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 49.
23. A. Prak, M. Richter, J. Naundorf, M.Eberl, H. Leeuwis, P. Woias, and A. Stechenborn, *Proceedings of 2nd Round Table on Micro/Nano Technologies for Space*, p. 55.
24. "Sensors 2000! Sensor Technology for the Next Millenium," NASA Program at Ames Research Center, http://s2k.arc.nasa.gov/welcome.html (August 1997).
25. S. Santoli, "Nanobiotechnology: An Emerging Source of Innovation for Competitive Space Strategies," *ESA-ESTEC International Workshop on Innovations for Competitiveness* (Noordwjik, The Netherlands, 19–21 March 1997).
26. A. Hansson, "From Microsystems to Nanosystems," Special issue: "From Microsystems to Nanotechnology for Space Missions," *J. of the British Interplanetary Soc.* **51** (4), 123 (1998).
27. A. Teshigahara, M. Watanabe, N. Kawahara, Y. Ohtsuka, and T. Hattori, "Performance of a 7 mm Microfabricated Car," *J. MEMS* **4**, 76 (1995).
28. Asian Technology Information Program, http://www.atip.org/MEMS.
29. S. Konishi and H. Fujita, "A Conveyance System Using Air Flow Based on the Concept of Distributed Micro Motion Systems" *J. MEMS* **3**, 54 (1994).
30. S. W. Janson, "Spacecraft as an Assembly of ASIMS," in *Microengineering Technology for Space Systems*, edited by H. Helvajian, Monograph 97-02 (The Aerospace Press, El Segundo, CA, 1997), pp. 143–201.
31. E. Y. Robinson, "ASIM Applications in Current and Future Space Systems," in *Microengineering Technology for Space Systems*, edited by H. Helvajian, Monograph 97-02 (The Aerospace Press, El Segundo, CA, 1997), p. 21.
32. "Smart Structures and Materials: Implications for Military Aircraft of New Generation," Advisory Group for Aerospace Research & Development (AGARD), AGARD-LS-205 (NATO/AGARD) 1996.
33. W. R. Davis Jr., B. B. Kosicki, D. M. Boroson, and D. F. Kostishack "Micro Air Vehicles for Optical Surveillance," *Lincoln Laboratory J.* **9** (2), 197 (1996).
34. D. A. Lorenzini and C. Tubis "Vehicle Tracking System Using Nanotechnology Satellites and Tags," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
35. P. W. Siglin and G. F. Senn, "The Courier Satellite," in *Communication Satellites. Proceedings of a Symposium Held in London*, edited by L. J. Carter, 1962.
36. R. Steele, C. McCormick, K. Brandt, W. Fornwalt, and R. J. Bonometti, "Utilization of the Multiple Access Communications Satellite (MACSAT) in Support of Tactical Communications," *Proceedings 5th Annual AIAA/USU Conference on Small Satellites* (Utah State University, Logan, Utah, 26–29 August 1991).
37. N. P. Bean, "A Modular Small Satellite Bus for Low Earth Orbit Missions," *Proceedings 2nd Annual AIAA/USU Conference on Small Satellites* (Logan, Utah, September 1988).
38. J.A. King, R. McGwier, H. Price, and J. White, "The In-orbit Performance of Four Microsat Spacecraft," *Proceedings 4th Annual AIAA/USU Conference on Small Satellites*, Vol. 1 (Logan, Utah, 27–30 August 1990).
39. S. Handler, "Birth of a Satellite," *Satellite Times* **1** (4), 10–14 (March/April 1995).
40. P. R. K. Chetty, *Satellite Technology and its Applications* (TAB Professional and Reference Books, Blue Ridge Summit, PA, 1991), pp. 457–468.
41. J. Wallach, "Automatic Pictures via NOAA 14," *Satellite Times*, **1** (4), 66–68 (March/April 1995).
42. R. Tessier, "The Meteosat Programme," *ESA Bull.*, No. 58, 44–57 (May 1989).
43. S. Bruzzi and M. Wooding, "ERS-1: A Contribution to Global Environmental Monitoring in the 1990s," *ESA Bull.*, No. 62, 11–21 (May 1990).

44. E.W. Mowle, "Landsat-D and D'—The Operational Phase of Land Remote Sensing from Space," in "Monitoring Earth's Ocean, Land, and Atmosphere from Space—Sensors, Systems, and Applications Progress," edited by Abraham Schnapf, *Astronautics and Aeronautics* **97**, 349–370 (1985).
45. M. Courtois and G. Weill, "The SPOT Satellite System," in "Monitoring Earth's Ocean, Land, and Atmosphere from Space—Sensors, Systems, and Applications Progress," edited by Abraham Schnapf, *Astronautics and Aeronautics* **97**, 493–523 (1985).
46. S. J. Isakowitz, *International Reference Guide to Space Launch Systems*, 2nd ed. (American Institute of Aeronautics and Astronautics, Washington, D.C., 1991).
47. B. A. Banks and C. LaMoreaux, "Performance and Properties of Atomic Oxygen Protective Coatings for Polymeric Materials," *24th International SAMPE Technical Conference*, T165-T173 (Toronto, Canada, 20–22 October 1992).
48. R. D. Rasmussen, "Spacecraft Electronics Design for Radiation Tolerance," *Proceedings of the IEEE*, Vol. 76 (November 1988), pp. 1527–1537.
49. M. D. Griffin and J. R. French, *Space Vehicle Design* (American Institute of Aeronautics and Astronautics, Washington, D. C., 1991), p. 70.
50. J. V. Osborn, D. C. Mayer, R. L. Lacoe, S. C. Moss, S. D. Lalumondier, and G. Yabiku, "Total Ionizing Dose and Single Event Latchup Characteristics of Three Commercial CMOS Processes," *Sixth NASA VLSI Design Symposium* (5 March 1997).
51. M. Alles and S. Wilson, "Thin Film Silicon on Insulator: An Enabling Technology," *Semiconductor International*, 67–74 (April 1997).
52. M. M. Gates, M. J. Lewis, and W. Atwell, "Rapid Method of Calculating the Orbital Radiation Environment," *J. Spacecraft and Rockets* **29**(5), 646–652 (September–October 1992).
53. L. Muller, M. H. Hecht, L. M. Mitler, H. K. Rockstad, and J. C. Lyke, "Packaging and Qualification of MEMS-Based Space Systems," *Proceedings IEEE 9th Annual Workshop on Micro Electro Mechanical Systems* (San Diego, CA, February 1996), pp. 503–508.
54. C. Barnes, A. Johnston, and G. Swift, "The Impact of Space Radiation Requirements and Effects on ASIMS," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
55. W. Stuckey, "Environmental Effects Guidelines for Materials Selection," in *Microengineering Technology for Space Systems*, edited by H. Helvajian, Monograph 97-02 (The Aerospace Press, El Segundo, CA, 1997), pp. 51–57.
56. B. Boser and D. Young, "Monolithic Tunable RF Oscillators based on Micromachined Variable Capacitors," http://kowloon.EECS.Berkeley.edu/~boser/vco.html (1997). D. J. Young and B. E. Boser, "A Micromachined Variable Capacitor for Monolithic Low Noise VCOs," *Proceedings of the 7th IEEE Solid State Sensor and Actuator Workshop* (Hilton Head Island, SC, 3–6 June 1996), pp. 86–89.
57. J. Y. Chang, A. A. Abidi and M. Gaitan, "Large Suspended Inductors on Silicon and Their Use in a 2-m CMOS RF Amplifier," *IEEE Electron Devices Letters* **14**, 246–248 (May 1993).
58. D. P. Morgan, *Surface-Wave Devices for Signal Processing* (Elsevier Publishing, NY, 1985), pp. 1–14.
59. J. R. Norton and J.M. Cloeren, "Precision Quartz Oscillators and Their Use in Small Satellites," *Proceedings of the 6th Annual AIAA/UTAH State University Conference on Small Satellites* (Logan, Utah, 21–24 September 1992).
60. J. Marshall, M. Gaitan, M. Zaghloul, D. Novotny, V. Tyree, J.-I. Pi, C. Piñà, and W. Hansford, "Realizing Suspended Structures on Chips Fabricated by CMOS Foundry Processes Through the MOSIS Service," Report no. NISTR 5402 (National Institute of Standards and Technology, Gaithersburg, MD, June 1994).
61. R. A. Buser and N.F. deRooij, "Capacitively Activated Torsional High-Q Resonator," *Proceedings of the IEEE Micro Electro Mechanical Systems Conference* (Napa Valley, CA, 11–14 February 1990), pp. 132–135.

62. "Microelectromechanical Systems," R & D Programs, Electronics Technology Office, DARPA, http://web-ext2.darpa.mil/ETO/MEMS/.
63. S. J. Wineland. "Trapped Ions, Laser Cooling and Better Clocks," *Science* **226** (4673), 395 (1984).
64. H. An, B. K. J. C. Nauwelaers, G. A. E. Vandenbosch, and A. R. Van De Capelle, "Active Antenna Uses Semi-Balanced Amplifier Structure," *Microwaves and RF* **33** (13), 153–156 (December 1994).
65. T. Razban, M. Nannini and A. Papiernik, "Integration of Oscillators With Patch Antennas," *Microwave J.* **1993**, 104–11 (January 1993).
66. J. Lin, "Active Integrated Antennas," *IEEE Transactions on Microwave Theory and Techniques* **42** (12), 2186–2194 (December 1994).
67. A. Yarbrough, "Applying Micro-/Nanotechnology to Satellite Communications Systems," in *Micro- and Nanotechnology for Space Systems: An Initial Evaluation*, edited by H. Helvajian and E. Y. Robinson, Monograph 97-01 (The Aerospace Press, El Segundo, CA, 1997), pp. 17–30. First published as The Aerospace Corp. Report no. ATR-93(8349)-1 (1993).
68. C. C. Ling, "A 94 GHz Planar Monopulse Tracking Receiver," *IEEE Transactions on Microwave Theory and Techniques* **42** (10), 1863–1871 (October 1994).
69. G. L. Lan *et al.*, "Millimeter-Wave Pseudomorphic HEMT MMIC Phased Array Components for Space Communications," *Proceedings of the SPIE: Monolithic Microwave Integrated Circuits for Sensors, Radar, and Communications Systems* (Orlando, FL, 2–4 April 1991), pp. 184–192.
70. K. A. Shalkhauser and C. A. Raquet, "System-Level Integrated Circuit (SLIC) Development for Phased Array Antenna Applications," *Proceedings of the SPIE: Monolithic Microwave Integrated Circuits for Sensors, Radar, and Communications Systems*, pp. 204–209.
71. H. J. De Los Santos, R. A. Brunner, J. F. Lam, L. H. Hackett, R. F. Lohr Jr., L. E. Larson, R. Y. Loo, M. Matloubian, and G. L. Tangonan, "MEMS-Based Communications Systems for Space-Based Applications," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
72. T-H. Lin, P. Congdon, G. Magel, L. Pang, C. Goldsmith, J. Randall, and N. Ho, "Silicon Micromachining in RF and Photonic Applications," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
73. M. W. Phipps, "Design and Development of Microswitches for Microelectromechanical Relay Matrices," Master's thesis, Air Force Institute of Technology (AFIT/GE/ENG/95J-02), 1995.
74. P. M. Zavracky, S. Majumder, and N.E. McGruer, "Micromechanical Switches Fabricated Using Nickel Surface Micromachining," *J. Microelectromechanical Systems* **6** (1), 3–9 (March 1997).
75. P. M. Zavracky, "Electrostatically Actuated Micromechanical Switches Using Surface Micromachining," http://www.ece.neu.edu/edsnu/zavracky/mfl/programs/relay/relay.html, 1997.
76. J. S. Eterno, R. O. Zermuehlen and H. F. Zimbelman, "Attitude Determination and Control," in *Space Mission Analysis and Design*, 2nd ed., edited by J. R. Wertz and W. J. Larson (Kluwer Academic Publishers, Boston, 1992), pp. 616–629.
77. W. L. Pritchard and J. A. Sciulli, *Satellite Communication Systems Engineering* (Prentice-Hall, Englewood Cliffs, NJ, 1986), p. 114.
78. W. Johnson, "Attitude Adjustment; GPS Innovation Keeps Satellites Oriented," *Satellite Commun.* **1995**, 19–21 (June 1995).
79. Honeywell HMC2003 Three-Axis Magnetic Sensor Hybrid data sheet, Solid State Electronic Center, Honeywell Inc., Plymouth, MN, 1995.
80. "Rapid Prototype Integrated GMR Magnetic Sensors," "GMR Magnetic Bridge Sensor—NVSB," and "Integrated GMR Magnetic Sensors—NVSI," Nonvolatile Electronics, Inc., Eden Praire, MN, 1995.
81. D. K. Wickenden, R. B. Givens, R. Osiander, J. L. Champion, D. A. Oursler, and T. J. Kistenmacher, "MEMS-based Resonating Xylophone Bar Magnetometer," *Proceedings SPIE Micromachining* (1998).
82. ASEM02-S and ASEM02-T/6 data sheets, *Centre Suisse d'Electronique et de Microtechnique SA*, P.O. Box 41, CH-2007, Neuchatel, Switzerland, 1994.

83. C. A. Kukkonen, presentation at the *Micro/Nano-Technologies for Space Workshop* (European Space Agency ESTEC, Nordwijk, The Netherlands, 27–28 March 1995).
84. M. Schuyer, P. Silvestrin, and M. Aguirre, "Probing the Earth from Space—The Aristoteles Mission," *ESA Bull.*, No. 72, 67–75 (1991).
85. G. N. Smit, "Performance Thresholds for Application of MEMS Inertial Sensors in Space," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications*, (Houston, TX, 30 October–3 November 1995).
86. J. H. Connelly, J. P. Galmore, and M. S. Weinberg, "Micro-Electromechanical Instrument and Systems Development at the Charles Stark Draper Laboratory," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
87. 1K/80 High Accuracy FOG data sheet, Fibersense Technology Corporation, Canton, MA, 1996.
88. A. K. Henning, "Microfluidic MEMS for Semiconductor Processing," in *Proceedings, Second Annual International Conference on Innovative Systems in Silicon* (IEEE Press, Piscataway, NJ, 1997), pp. 340–349.
89. J. Mueller, *Proceedings of the JPL Micropropulsion Workshop* (Pasadena, CA, 7–9 April 1997).
90. S. W. Janson, R. B. Cohen, H. Helvajian, W. W. Hansen, E. J. Beiting III, B. B. Brady, P. Fuqua, R. Robertson, and M. Abraham, "Digital Micropropulsion Program Status, January 1998." The Aerospace Corp. Report no. ATR-99(7527)-1 (November 1998).
91. S. W. Janson, R. B. Cohen, H. Helvajian, W. W. Hansen, E. J. Beiting III, B. B. Brady, P. Fuqua, R. Robertson, and M. Abraham, "Digital Micropropulsion Program Status, July 1998," The Aerospace Corp. Report no. ATR-99(7527)-2 (November 1998).
92. M. J. Declercq, L. Gerzberg, and J. D. Meindl, "Optimization of the Hydrazine-Water Solution for Anisotropic Etching of Silicon in Integrated Circuit Technology," *J. Electrochem Soc.* **122** (4), 545–552 (April 1975).
93. D. B. Lee, "Anisotropic Etching of Silicon," *J. of Appl. Phys.* **40** (11), 4569–4574 (October 1969).
94. E. W. Schmidt, *Hydrazine and Its Derivatives* (John Wiley & Sons, NY, 1984), pp. 84, 452.
95. M. J. Daneman, O. Solgaard, N. C. Tien, K. Y. Lau, and R. S. Muller, "Laser-to-Fiber Coupling Module Using a Micromachined Alignment Mirror," *IEEE Photonics Technol. Lett.* **8** (3), 396 (1996).
96. M. C. Wu, L. Y. Lin, and S. S. Lee, "Micromachined Free-Space Integrated Optics," *SPIE* **2291**, 40 (1994).
97. V. M. Bright, J. H. Comtois, J. R. Reid, and D. E. Sene, "Surface Micromachined Micro-Opto-Electro-Mechanical Systems," *IEICE Trans. on Electron. Micromachine Technol.* **E80** 206–213 (February 1997).
98. M. J. Daneman, N. C. Tien, O. Solgaard, K. Y. Lau, and R. S. Muller, "Linear Vibromotor-actuated Micromachined Microreflector for Integrated Optical Systems," *Proceedings of the 1996 Workshop on Solid State Sensors and Actuators* (Hilton Head, SC, 1996).
99. D. M. Bloom, "The Grating Light Valve: Revolutionizing Display Technology," *Proceedings of the SPIE—The International Society For Optical Engineering*, Vol. 3013 (San Jose, CA, 10–12 February 1997), pp. 165–171.
100. D. L. Glackin, "Future Space Systems," Invited paper, *2nd International Symposium on The Expansion of the Remote Sensing Market* (Paris, March 1997).
101. L.Y. Lin, S.S. Lee, K. S. J. Pister, and M.C. Wu, "Three-Dimensional Micro-Fresnel Optical Elements Fabricated by Micromachining Technique," *Electron. Lett.* **30** (5), 448–449 (March 1994).
102. J. Klemic, J. M. Sirota, and M. Mehregany, "Fabrication Issues in Micromachined Tunable Optical Filters," *Proceedings SPIE Micromachining and Microfabrication 1995*, p. 89.
103. M. C. Roggemann, V. M. Bright, B. M. Welsh, S. R. Hick, P. C. Roberts, W. D. Cowan, and J. H. Comtois, "User of Micro-Electro Mechanical Deformable Mirrors to Control Aberrations in Optical Systems: Theoretical and Experimental Results," *Opt. Engin.* (May 1997).

104. T. G. Bifano, R. Krishnamoorthy Mali, J. K. Dorton, J. A. Perriault, N. Vandelli, M. N. Horenstein, and D. A. Castanon, "Continuous Membrane, Surface Micromachined, Silicon Deformable Mirror," *Opt. Engin.* (May 1997).
105. B. E. Hardt, R.D. Karam, and R. J. Eby, "Louvers," in *Satellite Thermal Control Handbook*, edited by D. G. Gilmore (The Aerospace Press, El Segundo, CA, 1994), pp. 4-97–4-121.
106. M. A. Mignardi, "Digital Micromirror Array for Projection TV," *Solid State Technol.*, July 1994, 63–68.
107. H. Zaid, P. Van Gerwen, K. Baert, T. Slater, E. Masure, and F. Preud'homme, "Thermal Switch for Satellite Temperature Control," *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
108. Y. Cao, A. Faghri, and E. T. Mahefkey, "Micro/Miniature Heat Pipes and Operating Limitations," *HTD 29th National Heat Transfer Conference, Heat Pipes and Capillary Pumped Loops American* (Society of Mechanical Engineers, Atlanta, GA, 1993), pp. 236, 328–335.
109. D. K. Khrustalev and A. Faghri, "Thermal Analysis of a Micro Heat Pipe," *J. of Heat Transfer* **116** (1), 189–198 (1994).
110. G. P Peterson, A. B. Duncan, and M. H. Weichold, "Experimental Investigation of Micro Heat Pipes Fabricated in Silicon Wafers," *J. of Heat Transfer* **115**, 751–756 (August 1993).
111. A. B. Duncan and G. P. Peterson, "Charge Optimization for a Triangular-Shaped Etched Micro Heat Pipe," *J. of Thermophys. and Heat Transfer* **9** (2), 365–368 (April–June 1995).
112. S. W. Janson, H. Helvajian, and E. Y. Robinson, "The Concept of Nanosatellite for Revolutionary Low-Cost Space Systems," Paper IAF-93-U.5.573 presented at *44th Congress of the International Astronautics Federation* (Graz, Austria, October 1993).
113. J. Cheng, P. Zhou, S. Z. Sun, S. Hersee, D. R. Myers, J. Zolper, and G. A. Vawter, "Surface Emitting Laser-Based Smart Pixels for Two-Dimensional Optical Logic and Reconfigurable Optical Interconnections" *IEEE J. Quantum Electron.* **29**, 741 (1993).
114. S. W. Janson, "Silicon Satellites: Picosats, Nanosats, and Microsats," *Proceedings of International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
115. *Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications* (Houston, TX, 30 October–3 November 1995).
116. J. G. Walker, "The Geometry of Satellite Clusters," *J. British Interplanetary Soc. 35*, 345–354 (1982).
117. Presidential Blue Ribbon Commission on Acquisition (known as the Packard Commission), 1986.
118. MEMS-Exchange http://www.mems-exchange.org.
119. M. J. Kelley, H. F, Dylla, G. R. Neil, L. J. Brillson, D. P. Henkel, and H. Helvajian, "UV Free Electron Laser Light Source for Industrial Processing" *SPIE* **2703**, 15 (1996); See also H. Helvajian, "Laser Material Processing: A Multifunctional in Situ Processing Tool for Microinstrument Development," *Microengineering Technology for Space Systems*, edited by H. Helvajian, Monograph 97-02 (The Aerospace Press, El Segundo, CA, 1997), p. 67.
120. C. P. Christensen, "Laser Processing Works on a Micro Scale," Industrial Laser Review, Application Report, June 1994; See also R. R. Kunz, M. W. Horn, T. M. Bloomstein, and D. J. Ehrlich, "Application of Lasers in Microelectronics and Micromechanics," *Appl. Surf. Sci.* **79/80**, 12–24 (1994); R. V. Belfatto, F. Sansone, and E. Young, "Laser Based Machines for Hybrid and Semiconductor Manufacturers," *Proceedings SouthCon*, Vol. 90 (1990), p. 90; Revise Corporation literature, Revise Inc., 79 Second Ave., Northwest Park, Burlington. MA, 01803; Potomac Corporation literature, Potomac Photonics Inc., 4445 Nicole Dr., Lanham, MD, 20706.
121. *Proceedings, Design for Mixed Technology Integration (Composite CAD) Program, Semi-Annual Principal Investigator's Meeting* (1–3 December 1997). See also H. Dussault, Program Manager; DARPA Composite CAD home page, http://web-ext2.darpa.mil/eto/CompCad/; R. Goering, "Funding for Advanced Tools to Push Envelope in Sensing, Measurement, Optical Devices—DARPA program Seeds Mixed-Technology CAD," *EE Times*, No. 937, 4 (20 January 1997).

122. A. Martínez de Aragón, "Future Applications of Micro/Nanotechnologies in Space Systems," *ESA Bull.*. No. 85, 65 (February 1996).
123. D. G. Sutton and R. S. Smith, "MEMS Spaceflight Testbed," The Aerospace Corp. Report no. ATR-99(2101)-1 (to be published).