Reduced Cost and Increased Capability Through Technology in the New Millennium

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ABSTRACT

The National Aeronautics and Space Administration's (NASA's) New Millennium Program (NMP) is designed to reduce the cost of spacecraft in the 21st century while simultaneously increasing spacecraft capabilities, thereby increasing the return on our investment in space exploration. The NMP process is being enacted in the following manner: We are developing a science vision for the 21st century and identifying the attendant missions of this vision. These missions, in turn, will specify the capabilities that future spacecraft require. Technology-validation flights will be selected to demonstrate specific high pay-off technologies needed to provide these capabilities. These key technologies are categorized by certain areas — autonomy, microelectronics, communications, and so on — and will be flight validated prior to the 21st century in order to enable our vision for the next century. To that end, and keeping in mind our science vision, the technologies will primarily be those that allow us to reduce the size of spacecraft instruments, and in turn the size of the spacecraft itself, so that smaller launch vehicles can be employed. Also, these technologies will provide for autonomous spacecraft capability and shorter mission flight times so that the ground operations staff for future space missions can be reduced, thus bringing down costs in this area as well. This paper presents specific examples of these key technologies and their pay-offs.

TECHNOLOGY INVESTMENT

The National Aeronautics and Space Administration (NASA) has taken a hold and far-sighted step to seriously invest in revolutionary technology for the future with its New Millennium Program (NMP). In today's fiscal environment, where government funds arc so constrained and the political and public focus is on curbing government spending, it is difficult 10 convince the guardians of the treasury 10 invest in building a technological infrastructure for the country's space program that may not pay off for 1(1 to 15 years. ‘1 his situation is further complicated in [hat the societal benefits in terms of return on investment for a technology arc extremely difficult to evaluate. in general, one can estimate the relative value of one technology by comparing it to another, particularly in a very closely related discipline. nut comparing the value of, say, one computer technology to another is a much easier task than comparing it to the value of a welfare. program or a similar social investment.

The future well-being of the country lies in the strength of both its industrial and technological infrastructure and in its social programs, and there is a need to invest wisely in both. But the balance to be reached in deciding how much money to spend on each is always difficult. While both are to be considered investments in the future, we are more aware of and affected by the shortcomings of social programs in our everyday lives. The deficiencies in technological infrastructure, however, are only apparent on an international level, where the United States must compete with other countries in the global economic market.

The purpose of the NM}' is (o demonstrate and validate revolutionary technologies — in a series of flights that will be launched annually starling in 1998- to enable a new era in space flight. These technologies are expected to lay the groundwork and hc]p build the

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ACKNOWLEDGMENT

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technological infrastructure for NASA’S space exploration and Earth observation missions in the 21st century. The vision articulated by NMP is one of frequent launches of spacecraft that are considerably more capable and less expensive than those of today.

in addition to the fact that the value of a new technology is hard to measure, the value of demonstrating a space. technology through flight validation is a highly debated issue. While it maybe the most expensive way to test a technology to set that it works and is ready to be incorporated into science missions, flight validation is also the most comprehensive and thorough means of testing the technology’s state of development and level of readiness. On the other hand, many features of new technologies may be adequately demonstrated and tested on the.ground, both functionally and environmentally, so the cost value of spaceflight demonstration is often difficult 10 assess.

In other technology-validation programs, technologies are selected for flight validation by evaluating the technology’s state of development, and considering whether spaceflight validation is needed to further the technology along its development path. “1 he decision for selecting a technology is often made without a clear understanding of its relevance for mission application, and the process seems to be one of a solution looking for a problem. With NMP, this situation is avoided in the following manner: We have first articulated NASA’s vision for 21st-century missions then specified the capabilities needed to execute that vision, and finally, arc selecting technologies that will provide the capabilities and, in turn, enable the science vision (Figure 1). in this way, the technologies we select are a solution to the problem. In other words, they arc problem- driven technologies. So, while NMP is considered a technology program, it is in reality a science technology needs- driven program

SCIENCE VISION FOR THE 21 S-1 (“I NTURY

The science vision for the 21st century focuses on NASA’s Earth and space science program needs. In this context, these cardinal points are identified

- A fleet of individual spacecraft to extend our range of targets
- Constellations to study dynamic systems and provide global coverage
- New measurement techniques to extend our scientific horizons

‘1 he science vision includes networks of landers sent to Mars and Venus, clusters of probes mapping planetary ionospheres and magnetospheres, and spacecraft returning samples from asteroids and comets. We also envision fleets of spacecraft exploring diversity of targets such as Pluto and the heliopause, and beyond. Constellations and networks of spacecraft will address dynamic, complex systems. For example, a single lander can report on the weather at one spot on a planet, but a network of landers is needed to characterize the planet’s dynamic climate. Similarly, a single seismometer will indicate a planetquake, but a network of seismometers can use planetquakes to measure the size of a planetary core. Wc need multiple spacecraft to go beyond our initial reconnaissance, 10 completely characterize dynamic systems the way wc are able to on Earth’s surface.

One example of a high-priority mission to explore the univer sc is a free flying interferometer constellation that is capable of imaging extrasolar planets (Figure 2). Such a constellation could detect ljarth-like planets and provide information (hat would clarify the origin and evolution of planetary systems in general. Based on a widely spaced constellation of three or more spacecraft with precision formation control, this mission would require precision pointing and control of a constellation, rlatlomclcr-scale interspacecraft metrology, and accurate stationkeeping. Quiet spacecraft structures, low-thrust propulsion, and low-mass, high-quality optics arc also needed capabilities to implement a free-flyitlg interferometer.

Comet sample-return missions form another category of high-priority missions focused on our solar system, grouped within the unifying theme of “Our Planetary Neighbors.” Characterization of the primitive materials of which comets are composed will shed light on the origin and evolution of the solar system. The envisioned mission implementation includes the selection of an appropriate landing si(c following an orbital survey, in situ study, selection and collection of local samples, and return of samples to Earth through a direct atmospheric entry. “1’0 carry out such a mission, advances in autonomous operations, low-mass structural materials, and high specific-irnpulse propulsion will be required. 1 ligh-capability, low-mass onboard computers and ncw approaches to sample handling and preservation arc also needed capabilities.

FROM THE VISION TO THE CAPABILITY TO THE TECHNOLOGIES

Increased capability, reduced cost, and increased flight rate will be achieved by using small launch vehicles that are enabled by microspacecraft and microinstruments. It will also be necessary to have shorter flight times and to decrease the size of missions operations staff through the use of intelligent flight systems.

A Roadmap For Microspacecraft Development

We could reduce spacecraft mass and reduce costs by miniaturizing spacecraft components. However, miniaturization alone would reduce our capabilities to obtain the science data required to fulfill the vision for the 21st century. Through the infusion of new technologies, such as innovative architectures and highly capable microdevices, we can develop new concepts that will actually increase our capabilities beyond what is currently possible, while simultaneously reducing mission costs.

Spacecraft Mass Decrease

Because of the importance of bringing down spacecraft weight through the NMP, a chart illustrating how spacecraft mass has evolved over time was developed. The chart (Figure 3) shows the historical increase of spacecraft mass during the 1960s, 1970s, and 1980s, and the start of decreasing spacecraft mass in the late 1980s and early 1990s. Projections for the future clearly show a rapid decrease in mass, made possible by a dramatic reduction in the size of digital electronics, and a concurrent increase in their capability.

Capable Microspacecraft Flight Avionics

New chip technologies allowing three-dimensional stacking of microelectronics are examples of emerging technologies that can significantly reduce the mass and size of spacecraft subsystems. This new approach reduces multiple cards of electronics to single chip stacks and can be applied to some of the massive spacecraft subsystems, including onboard computing, power, and telecommunications. The novel stacking and interconnected technologies enable new integrated computing architectures and automated design methodologies, promising reduced design costs. In comparison to the Mars Pathfinder flight computer, this technology reduces the mass and volume by a factor of 100, with a 20-fold reduction in power, while enhancing the onboard capability.

Instrument Miniaturization

Small spacecraft require smaller instruments. Orders of magnitude reductions in instrument mass and volume are anticipated through the infusion of new miniaturization technologies. A typical instrument deployed during the "flagship" era is the Microwave Limb Sounder carried by the Upper Atmosphere Research Satellite, launched in 1991 (Figure 4). At 250 kilograms, it towers over the human in the picture. In contrast, the Planetary Integrated Camera Spectrometer, incorporating multiplexed foreoptics, low-mass composite structures, and advanced focal-plane technologies, has a mass of only 5 kilograms.

Emerging microelectromechanical systems (MEMS) technology promises orders of magnitude reduction in size of a variety of instruments for space exploration and Earth observation. Following in the footsteps of the microelectronics revolution, this technology extends on-chip capability beyond electronics to include mechanical and optical capabilities. MEMS technology enables new classes of microinstruments that make in situ measurements a practical alternative to costly sample return for a variety of analytic measurements of planetary surfaces and atmospheres, as well as small-body investigations.

Future instruments incorporating MEMS, permitting on-chip integration of sensors and electronics, will reduce some instruments to mere grams in weight, A concept for a complete free-flying magnetometer, with onboard power, data processing, and telecommunications, envisions a mass of only a 100 grams. The realization of such "spacecraft-on-a-chip" concepts will enable swarms of free-flyers capable of mapping complex and dynamic systems in space.

Integrated microsensor packages are also small enough to be deployed as networks of microlanders and orbiters offering global planetary coverage. For example, a network of microseismometers can provide information on global seismometry and could map the interior structure of planets. Similarly, networks of micrometeorological sensors such as pressure sensors and hygrometers can be used to investigate planetary climate and complex atmospheric dynamics,

CAPABILITIES

Once having identified in the broadest sense the technologies needed to carry out 21st-century space missions, it becomes necessary to group them into certain key areas and begin their focused development. To this end, NMP integrated product development teams (IPDTs) have been formed. The IPDT concept has been highly successful in private industry, and revolves around formation of a team with cross-departmental representation within a company. For example, automotive companies have brought together members from their design, sales, manufacturing, and strategic planning departments to work together making concurrent decisions to define and manufacture a final product.

Though such cross-sectional representation has not traditionally been used to develop a product — design and sales departments, for instance, have widely differing views of what a customer wants and how much he's willing to pay -- each department's individual input is vital for the success of the product in the marketplace. IPDTs provide the mechanism for getting the best input and expertise simultaneously to influence how a product is developed. Those companies that have used IPDTs to manufacture low-cost, reliable, and thus highly desirable products, find that their competitive edge in the market is increased and they are able to operate very effectively.

One NMP objective has been to improve the working relationships among government, industry, and academia in the development and application of technology. NMP is using the concept of IPDTs in a similar manner to that used in private industry, but to bring together representatives from different sectors of the country. Just as industry uses IPDTs to increase its competitive edge in its particular area of the market, the nation can use NASA's NMP IPDTs to increase its competitive edge in global space exploration.

In implementing this concept, NMP IPDTs were formed around six key areas of technology:

- Autonomy
- Microelectronics
- Telecommunications
- Instrument Technologies and Architectures
- In Situ Instruments and Microelectromechanical Systems (MEMS)
- Modular and Multifunctional Systems (MAMS)

These teams were then tasked to identify a broad suite of revolutionary technologies and select certain high priority candidates in an initial phase of the technology-selection process; develop a roadmap for each of those technologies; bring members from industry, government, and academia together within the teams; spawn further partnerships with industry; ; and finally, deliver the technologies for flight validation.

The IPDTs were formed in August- September 1995 and have been working with great success ever since. Initial startup issues such as membership, frequency of meetings, and so on were worked out by the teams themselves with little direction from the Program Office. The teams are self-governing and have proved highly effective in carrying out their charge. Each IPDT has a representative within each of NMP's mission flight teams for those technologies that are selected for validation) on a given flight.

Unlike IPDTs in private industry, where there is no contact among different teams, a working rule of the NMP IPDTs is that there must be interaction among the teams. Though the IPDTs focus primarily on their own scope of technologies, they also interact with each other where their technologies are interdependent. For example, the software concepts that are developed by the autonomy team must be implemented and executed on the hardware that comes from the microelectronics team. Cross-fertilization among teams is facilitated through workshops and roadmapping

There are two annual workshops at the program level. The NMP Annual Technology Workshop is conducted each spring for all interested individuals from government, industry, and academia. At the workshop, the overall program plan, validation flights, flight results, and plans for the future direction of the program are discussed. Each IPDT presents the latest version of its roadmap, as well as its flight plans and flight results to date. This workshop has a large attendance, with participants from the Program Office, the IPDTs, industry, government, and academia. The IPDT Forum is the other annual workshop, conducted in autumn. Participation in this workshop is limited to IPDT members and some Program Office personnel. At this workshop, the emphasis is on the IPDTs' roadmaps and on cross-fertilization of ideas among the teams.

MICROELECTRONICS

The technological advances being made in the area of microelectronics will especially enable revolutionary advances in making future spacecraft less expensive hut mm-c reliable. and capable. At the beginning of deep space planetary exploration in the early 1960s, spacecraft design was implemented with mostly analog electronics technology and discrete components, resistors, **capacitors,** and transistors. Transistor counting networks and magnetic coils were the beginning of bulky but flexible digital electronics technology. The first programmable memory of 128 words, implemented wilh discrete magnetic coils, was flown on the 1969 Mariner mission to Mars.

As time progressed, spacecraft design implemented more and more digital electronics technology, as shown in Figure 5. At the same time, the functionality of the system architecture was becoming fixed around specific disciplines, such as communications, power, sequencing, data handling, telemetry, and so on. As system capability was enhanced to meet the challenges of a particular mission, the subsystems grew in complexity, but the basic spacecraft design architecture remained essentially unchanged, except for an occasional introduction of a new subsystem. The kinds of new subsystems being introduced, however, were dictated more by management and personnel needs than by the tlvm-current stale of implementation technology. in the 1970s, a strong correlation developed **between** the technology department that existed in an organization and the subsystems required on a spacecraft; that is, if there were personnel for a particular discipline within an organization this necessitated a corresponding subsystem on the spacecraft. This cultural interlocking of spacecraft design with an organization's staffing considerations impeded the assimilation of new technology and system restructuring.

Thus, two important changes that were occurring simultaneously in technology were not being capitalized upon. First, functional implementation was moving from analog electronics to digital electronics. Second, digital electronics were becoming exponentially denser in terms of devices per chip; specifically, the. number of devices per chip was increasing by a factor of a thousand every 10 years, as shown in Figure 6. For example, the Galileo spacecraft uses 10,000 chips (integrated circuits [ICs]) to perform all its digital functionality. With today's technology, this functionality can be accomplished on a single chip, and by the 21st century, a hundred times the Galileo's functionality could be carried out on a single chip. In order to take advantage of this explosion in digital capability, the spacecraft hardware configuration of many discrete subsystems has to be collapsed into a monolithic design in order to achieve a "spacecraft on a chip."

While the functional capability of spacecraft is dramatically increasing, however, the cost is surprisingly decreasing. This is simply because the cost per chip to the first order is independent of the devices per chip, or density of the chip. There is a larger initial cost investment to set up a new family of ICs, but after reliable yield is achieved and the set-up costs amortized, the. unit production cost of the. new family is similar to the last generation unit cost. In summary, then, as the number of device.s per chip increases exponentially and the cost per chip rises slightly (see Figure 7), the cost per device (functionality) decreases exponentially, as shown in Figure 8. In a comparative rate sense these trends are not identical, since the cost reduction is less than the capability increase when design complexity and verification are included,

This phenomenon of more devices pcr chip has been taking place in planetary missions over the past two decades in keeping with the continual pressure to decrease weight and cost - though functionality has still grown, as shown in Figure 3. Here we see that while the spacecraft weight grew to a maximum in the Galileo and Cassini era and then began to decline from other pressures, such as bringing down launch vehicle costs, spacecraft capability continued to increase. Figures 9, 10, and 11 show how the capability per kilogram of spacecraft weight ant] digital hardware weight changed over the same period of time. 'l'he bits per kilogram decreased to a minimum until serious steps were taken to restructure the spacecraft design and reduce the number of digital subsystems.

Fifty years ago today, the first electronic computer - the Electronic Numerical Integrator and Computer (ENIAC) -- was unveiled at the University of Pennsylvania. It weighed 30 tons, occupied the space of a small house, and dimmed the lights of Philadelphia when it was operating. Today's handheld calculators are more powerful, one and a half million times cheaper, twenty thousand times smal and use. ten thousand times less power. By the 21st century, one desk-top computer will have the capability of all those in Silicon V-alley today. A spacecraft on a chip is not a concept, it isa reality asking to be implemented.

Figure 1 NMP Program Process

Figure 2. Extrasolar Planetary Imaging

Figure 3. Spacecraft Dry Mass vs. Time

Figure 4. Instrument Miniaturization

Figure 5. **Digital Electronics Technology**
Used **in** Spacecraft

Figure 6. **Growth in**
Chip Complexity

Figure 7. Cost per **Chip**
Over Time

Figure 8. **Cost** per **Bit**
Over Time

Figure 9. Spacecraft Capability
vs. Digital Hardware Mass Over Time

Figure *10.* Spacecraft Capability
vs. Spacecraft Mass Over Time

Figure 11. Spacecraft Capability vs.
Digital Hardware Mass Over Time

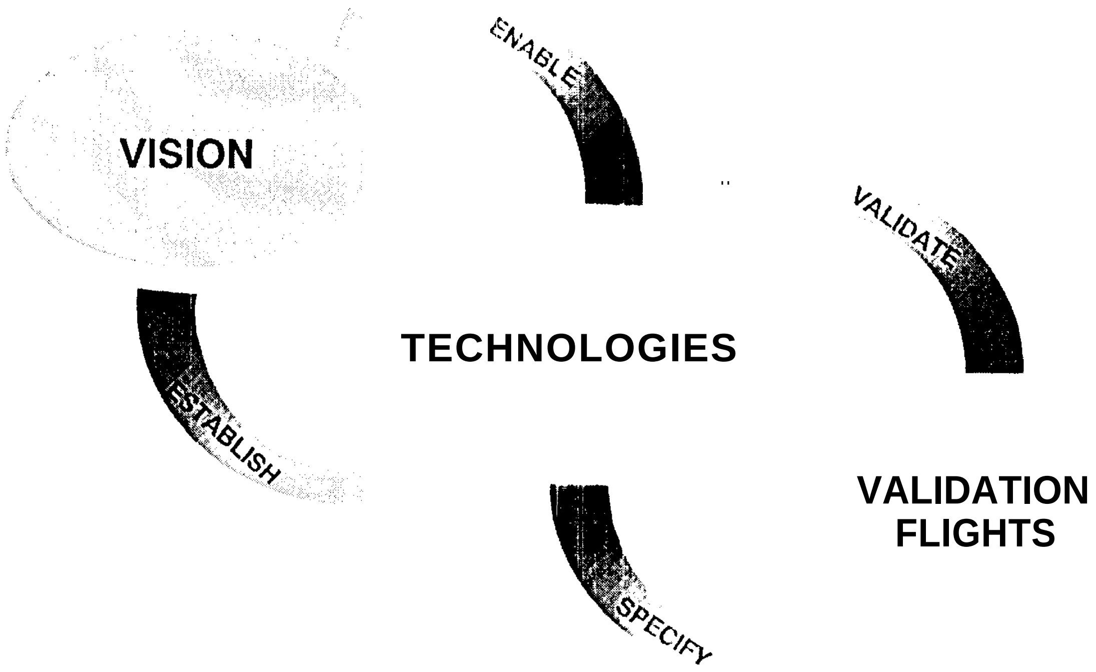
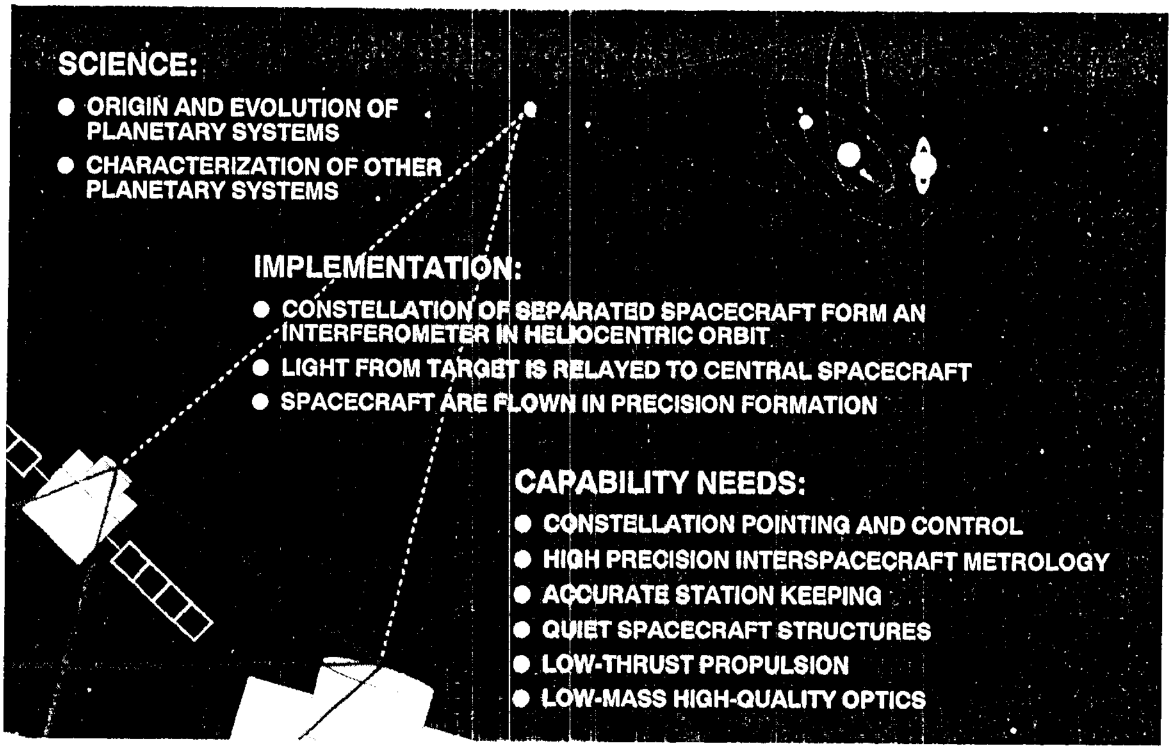


Figure 1. NMP Program Process



SCIENCE:

- ORIGIN AND EVOLUTION OF PLANETARY SYSTEMS
- CHARACTERIZATION OF OTHER PLANETARY SYSTEMS

IMPLEMENTATION:

- CONSTELLATION OF SEPARATED SPACECRAFT FORM AN INTERFEROMETER IN HELIOCENTRIC ORBIT
- LIGHT FROM TARGET IS RELAYED TO CENTRAL SPACECRAFT
- SPACECRAFT ARE FLOWN IN PRECISION FORMATION

CAPABILITY NEEDS:

- CONSTELLATION POINTING AND CONTROL
- HIGH PRECISION INTERSPACECRAFT METROLOGY
- ACCURATE STATION KEEPING
- QUIET SPACECRAFT STRUCTURES
- LOW-THRUST PROPULSION
- LOW-MASS HIGH-QUALITY OPTICS

Figure 2. Extrasolar Planetary Imaging

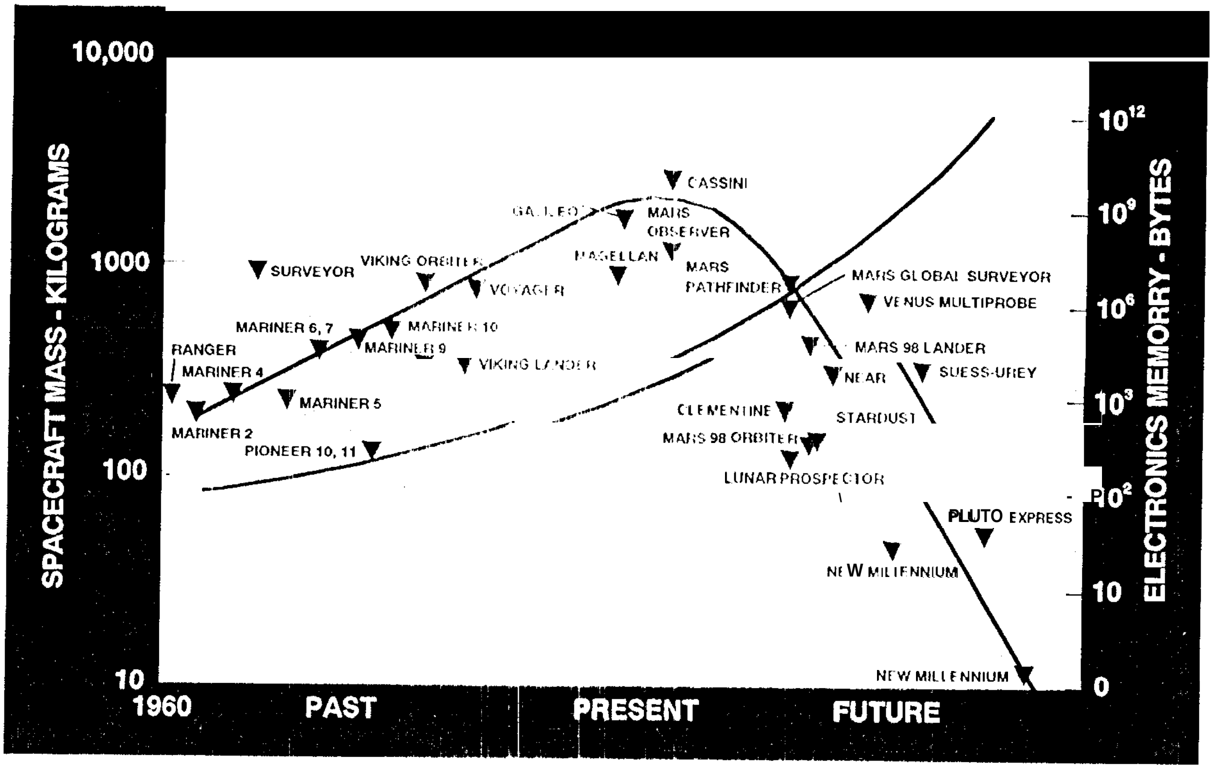


Figure 3. Spacecraft Dry Mass vs. Time

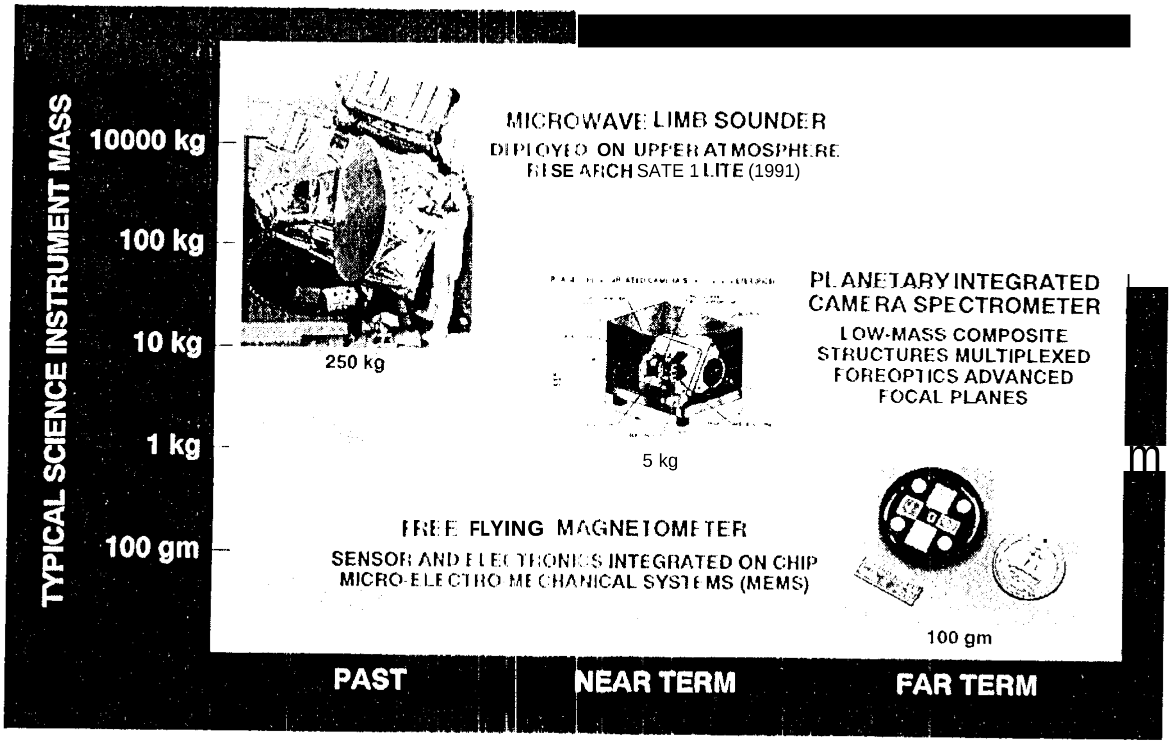


Figure 4. Instrument Miniaturization

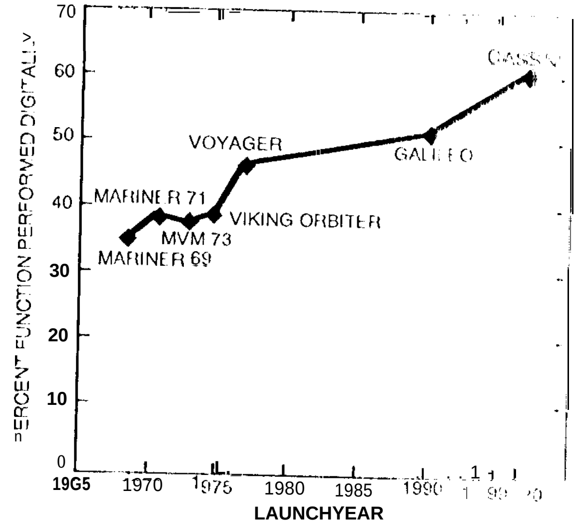


Figure S. Digits] Electronics 'J ec 1lll010{;%
Used in Spacecraft

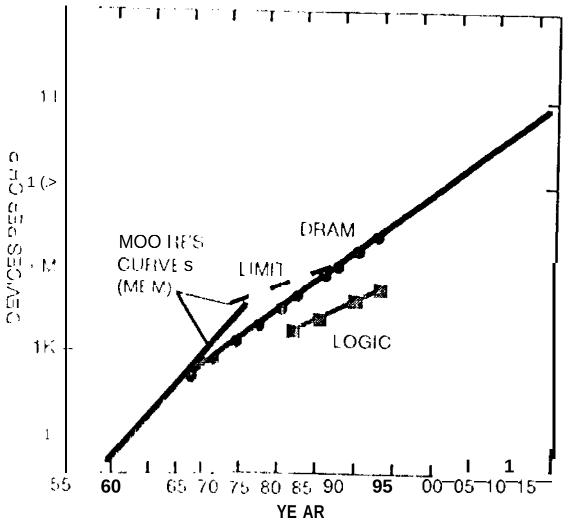


Figure 6. Growth in
Chip Complexity

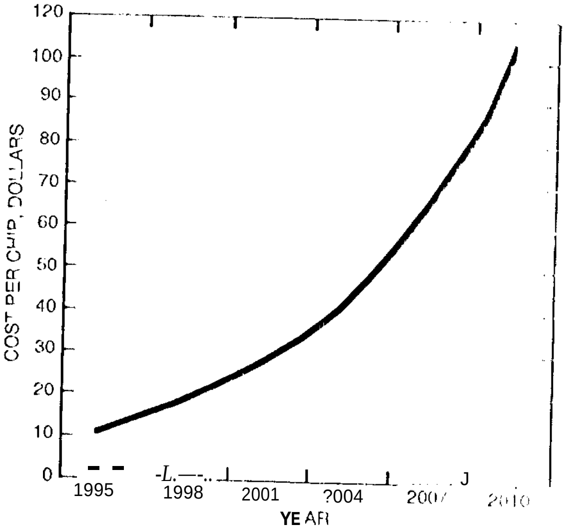


Figure 7. Cost per Chip
Over Time

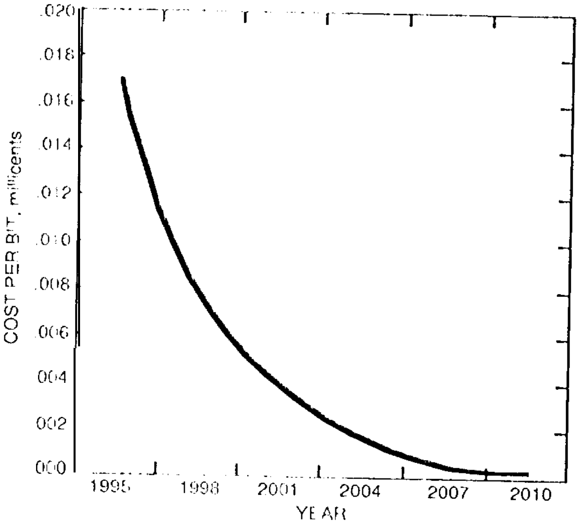


Figure 8. Cost per Bit
Over Time

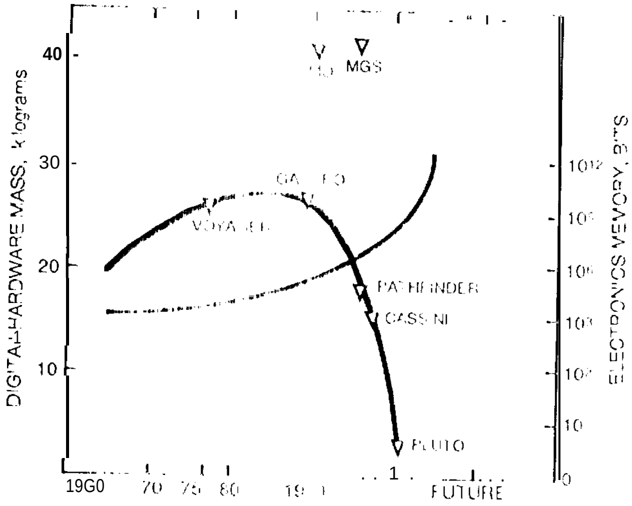


Figure 9. Spacecraft Capability vs. Digital Hardware Mass Over Time

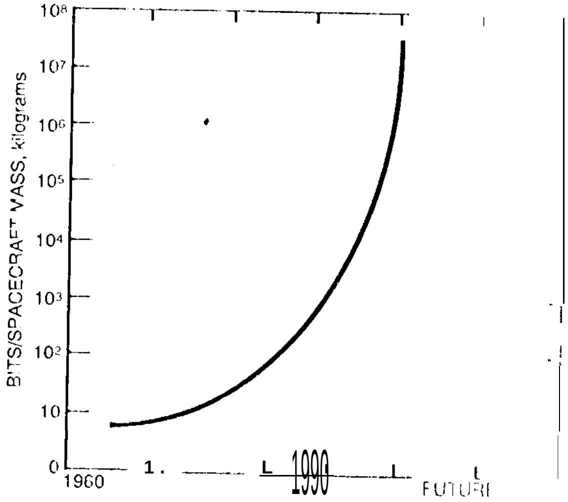


Figure 10. Spacecraft Capability vs. Spacecraft Mass Over Time

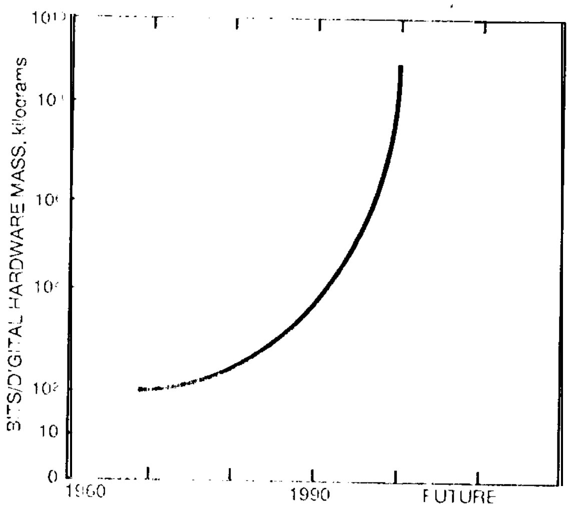


Figure 11. Spacecraft Capability vs. Digital Hardware Mass Over Time