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# Effects on Operations of Highly Adaptive Missions

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**A nonadaptive operations strategy was used by the Magellan mission to Venus, whereas an adaptive strategy was used for the Spaceborne Imaging Radar-C mission to Earth. The operational strategies employed by these missions are described, along with overviews of both missions and a summary of their systems and capabilities. The effects of adaptivity on the operations systems are discussed, and a summary of advantages of each strategy is given.**

## Introduction

SPACEBORNE remote sensing missions can be classified in many ways. From an operational standpoint, a useful class division is made according to the level of response required of the mission while it is in progress. Spacecraft such as weather satellites may be involved in long-term activities that are never changed. More complex missions may require their planned activities to be constantly updated. The number, complexity, and time criticality of such responses are major cost drivers of both the spacecraft and the ground system that operates it.[1]

There are at least two reasons for increased response requirements. Most obvious is the need to keep the spacecraft healthy. In the hostile environments that spacecraft inhabit, onboard anomalies occur with some frequency. Most traditional spacecraft are able to cope for a short time using various methods of autonomous fault protection,[2] but often ground interaction is required to avoid some curtailment of their mission function. The second reason for rapid response comes from the targets themselves. Adaptivity, the capability of a mission to respond to characteristics of its target by modifying future data acquisition plans, requires an effort similar to anomaly response except that the goal is to gain additional science return or other benefit to the user. Making a mission adaptable can impressively increase the return of many kinds of missions. However, adaptivity is a complicating and expensive addition to the design of the mission operations system, and the inevitable tradeoff between the two must be made advisedly.

Many missions inherently do not require adaptivity, or they may preclude adaptivity for cost reasons. An example is the Magellan mission to Venus,[3–5] where the primary objective was to map the planetary surface. In contrast, the Spaceborne Imaging Radar-C (SIR-C) mission,[6] flown on two flights of space shuttle Endeavour in 1994, required adaptivity to maximize science return during its short time in orbit. This paper describes the different operational strategies of a nonadaptive mission, Magellan, and an adaptive mission, SIR-C, and describes the effects on operations imposed by the level of adaptivity.

## Magellan Case Study

A mapping mission such as Magellan generally defines its nominal-mission goals prior to the operational period. Explicit within Magellan's goal was that regardless of discoveries, no change should be made to the mission objective of completing a global map of the surface of Venus. The addition of adaptivity can add significantly to the cost of a mission, and to some extent the Magellan decision was cost-driven. The Magellan design was preceded by a proposed mission called Venus Orbiting Imaging Radar (VOIR), also a mapping mission. But, without interrupting its mapping function, VOIR was to have the capability to take high-resolution images of features recognized in the mapping data. VOIR was canceled for cost reasons, partly due to the proposed inclusion of that capability.

### Mission Description

The Magellan spacecraft was launched May 4, 1989, and arrived at Venus on Aug. 10, 1990, as the spacecraft's solid rocket motor placed it into a near-polar elliptical orbit around the planet. During the first 8-month mapping cycle around Venus, Magellan collected radar images of 84% of the planet's surface, with resolution 10 times better than that of the earlier Soviet Venera 15 and 16 missions. During the extended mission, two further mapping cycles brought mapping converge to 98% of the planet, with a resolution of approximately 100 m. Late in the mission, an aerobraking maneuver circularized the orbit to improve gravity measurements. Finally, the spacecraft performed a controlled entry into the atmosphere in an experiment to study drag. The spacecraft ceased to operate, and portions of it may have survived entry and impacted the surface.

To collect its science data, Magellan used a single radar sensor, which collected synthetic-aperture radar (SAR) images (Fig. 1), microwave altimetry, and radiometry data. Another experiment used the mass of the spacecraft and accurate tracking of the spacecraft's position from Earth to refine knowledge of the Venusian gravity field. The mission's scientific objectives were 1) to provide a global characterization of observed land forms and tectonic features, 2) to distinguish and understand impact processes, 3) to define and explain erosional, depositional, and chemical processes, and 4) to model the interior density of Venus, especially to estimate the thickness of its lithosphere.[5]

To achieve its goal, Magellan mapped one thin image strip each time it passed the periapsis side of Venus and transmitted to receiving antennas on Earth. As Venus rotated below the spacecraft orbit, contiguous strips of its surface were imaged, and image-processing computers on Earth assembled the strips into global mosaics.

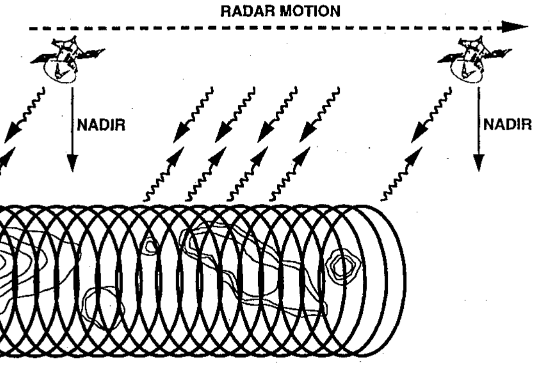


**Fig. 1 Radar data-collection geometry for a series of synthetic-aperture bursts. When the target and the radar are moving with respect to each other, a larger-than-life or synthetic aperture is created. If the phase and amplitude of the return signals are recorded, then an image may be generated having resolution equal to that of the synthetic aperture.**

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Simultaneously, altimetry and radiometry data were collected, transmitted, and mosaicked into other products.

**Spacecraft System and Operational Scenario**

The Magellan spacecraft (Fig. 2) used a 3.7-m-diam antenna both for radar mapping and for data transmission to the Earth. The spacecraft was three-axis stabilized, and attitude control was commanded from two redundant computers. Control was maintained through three orthogonal reaction wheels, and a star scanner was used to preserve attitude knowledge. Solar panels provided power, and two nickel–cadmium batteries acted as power storage. During mapping activities, four tape recorders collected radar data at 806 kbits/s and engineering data at 1200 bits/s, with an overall capacity of $1.8 \times 10^9$ bits.

Two redundant computers, distinct from the attitude control computers, handled command sequences transmitted from the ground.

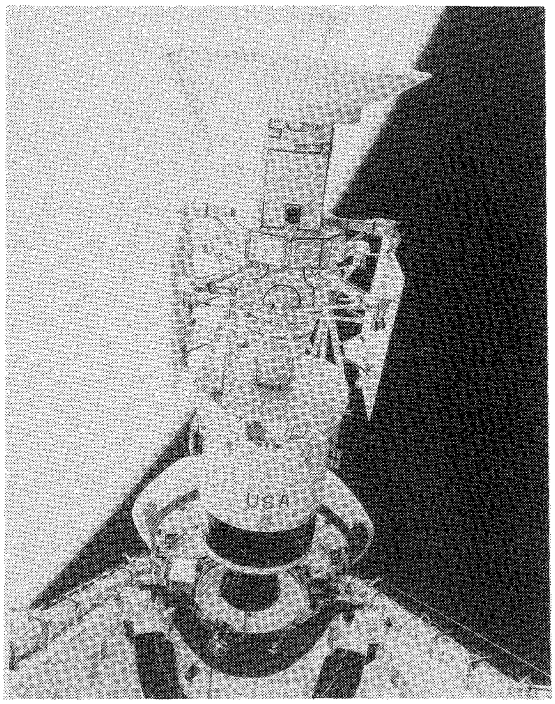


Fig. 2 Magellan spacecraft.

Command sequences were uplinked every two weeks and were constructed on an orbit-by-orbit basis. Magellan had a 3.25-h orbit period in its mapping phase, with apoapsis and periapsis altitudes of 8450 and 250 km, respectively. The spacecraft pointed the high-gain antenna toward the planet to collect data and turned its antenna toward Earth for data transmission.

The amount of data taken in each orbit was constrained by the amount of time needed for data playback (three minutes of playback for each minute of data taken). The amount of data taken was further constrained by several housekeeping functions, needed to keep the spacecraft healthy. A star calibration maneuver was performed each orbit to ensure pointing knowledge, and a reaction-wheel desaturation was performed every four orbits to ensure pointing control. These functions had little effect on functioning, but unexpected thermal anomalies constrained data collection more severely. When the orbits of Venus and Earth and the position of Magellan were such that the aft end of the spacecraft was pointed at the sun during playback, the sensitive bus components would heat to unacceptable levels. To combat this, Magellan used a strategy called hiding, where the spacecraft was maneuvered to an attitude where the bus was shadowed from the sun by the large antenna. While successful in reducing temperatures, this solution caused more time to be taken away from data collection periods, by reducing the amount of time in the orbit for data collection and playback.

Data and command flows for the Magellan operations system are shown in Fig. 3. The facility, distributed between the Jet Propulsion Laboratory in California and Martin Marietta Aerospace Group in Colorado, was operated 8 h per day, five days per week, for the duration of the radar collection period of the Magellan mission, approximately two years.

**Mission Results**

The high-resolution global images produced by Magellan have shown the surface of Venus to be covered mostly by volcanic materials. Volcanic surface features, such as vast lava plains, fields of small lava domes, and large shield volcanoes, are common. The scarcity of impact craters (Fig. 4) suggests that the surface is, in general, geologically young—less than 800 million years old. The typical signs of terrestrial plate tectonics (continental drift and basin floor spreading) are not in evidence on Venus. The planet's tectonics is dominated by a system of global rift zones and numerous broad, low domical structures called coronae, produced by the upwelling and subsidence of magma from the mantle. Thus, the mechanism that resurfaces the planet and keeps the visible surface young is different from that on Earth and is not well understood. The presence

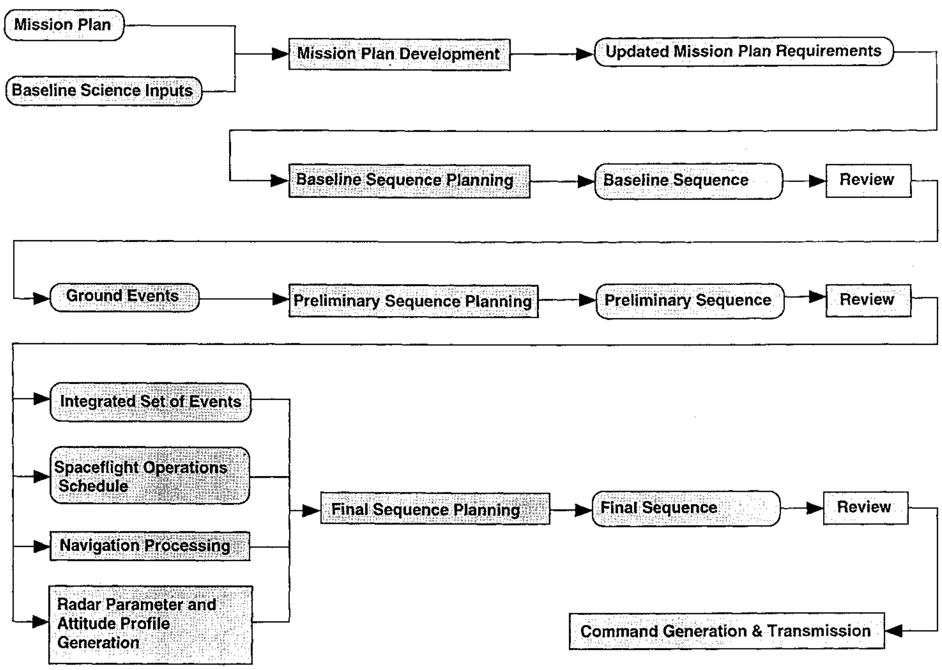



Fig. 3 Magellan mission operations flow. Tasks are shown as boxes with squared corners, products, with rounded corners.

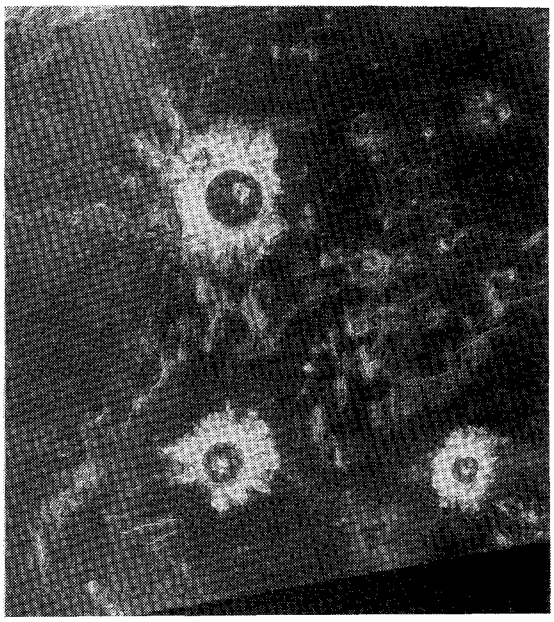


Fig. 4 Magellan radar image of the "crater farm," showing the craters (clockwise from top left) Danilova, Aglaonice, and Saskia centered at 27°S, 339°E. Aglaonice is 65 km in diameter.

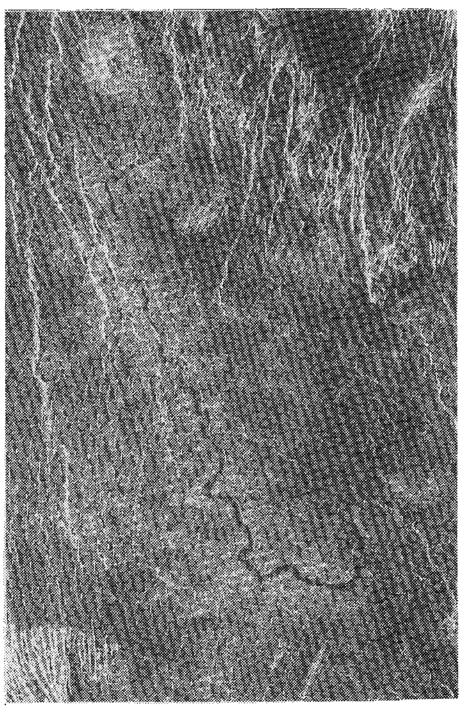


Fig. 5 Magellan radar image of a portion of a lava flow. This segment is over 200 km long. These channel-like features are common on the plains of Venus.

of lava channels (Fig. 5) over 6000 km long suggests riverlike flows of extremely low-viscosity lava that probably erupted at a high rate.

Venus has a dense atmosphere, composed of carbon dioxide (96%), nitrogen (3%), and trace amounts of sulfur dioxide, water vapor, carbon monoxide, argon, helium, neon, hydrogen chloride, and hydrogen fluoride. However, the surface reveals no evidence of substantial wind erosion, and evidence of only limited wind transport of dust and sand.

Magellan data have been made available to the scientific community and the public for research. This massive data set is providing evidence to understand the role of meteor impacts, volcanism, and tectonism in the formation of Venusian surface structures. The later data will also be used to infer the interior structure of the planet and to reveal details about its atmospheric structure.

## SIR-C Case Study

### Mission Description

The SIR-C/X-SAR imaging radar is the latest in a series of Earth-observing, spaceborne imaging radars that began with the Seasat satellite in 1978 and continued with the SIR-A in 1981, Germany's Microwave Remote Sensing Experiment in 1983, and the SIR-B in 1984. SIR-C/X-SAR is an international effort, with the United States providing L- and C-band SARs (SIR-C) and the European Space Agency providing an X-band SAR (X-SAR). Because of technological advances incorporated in the SIR-C/X-SAR radar antenna, each SIR-C/X radar image contains more detailed information than a corresponding image from the previous experiments. Images resulting from this mission are providing terrestrial scientists with an unprecedented view of our planet and how it is changing.

As the Shuttle orbited Earth, the SIR-C/X-SAR radar antenna collected SAR data in a fashion similar to Magellan. Because of the larger number of data acquired in each orbit, and because of the larger power requirement of these radars, images were acquired over selected areas of scientific interest. These data are now being used to derive information about the Earth on a global scale, including the distribution and amount of vegetation cover, extent of snow packs, wetland areas, rock type and distribution, geological features (such as volcanic activity), ocean wave height, and wind speed and direction.

### Payload System and Operational Scenario

The antenna of the SIR-C mission (Fig. 6) measured $4 \times 12$ m and at 10,500 kg was the most massive hardware ever assembled by the Jet Propulsion Laboratory. The antenna was able to transmit and receive both in horizontal and vertical polarizations in both the C and L microwave bands. During mapping activities, radar data were collected at a rate of up to 150 Mbits/s and recorded on special cassette recorders housed inside Endeavour. Tape cassettes were swapped by the Endeavour crew as they were filled. Endeavour's orbit was approximately circular with an altitude that was adjusted between 210 and 230 km to meet targeting requirements and a period of approximately 89 min.

The SIR-C payload operations control center (POCC) consisted of 17 functions, each represented by a console and operator. The process of command generation (Fig. 7) began with the arrival of a state vector, containing the recently reconstructed orbital elements of the shuttle. This information was then propagated into an ephemeris covering the next 12 h of flight time. From this ephemeris, a set of target opportunities was generated, based on targets preselected by the science community. A subset of targets was selected, and radar parameters computed for each target, taking account of the newest trajectory information. The information for this 12-h set of targets was then converted into commands and uplinked to the shuttle.

Concurrent with this process, another short-term process was executed by the POCC staff. Three hours before a command was to begin execution, a one-hour slice of the long-term plan beginning three hours prior to execution time was updated again by the latest Shuttle state-vector information. The one-hour period was updated for new trajectory information as necessary, and a revised set of target opportunities was selected and updated with new radar parameter information. This one-hour block of commands was then uplinked, nominally one hour before the first command was to begin execution.

The facility was co-located with Mission Control in Houston and operated 24 h per day for the duration of the shuttle flight.

### Mission Results

Preliminary results from SIR-C/X-SAR have been used to validate and to develop numerical models of how electromagnetic radiation interacts with the Earth's various types of surfaces. For example, vegetation characteristics affecting the global carbon cycle were monitored during and between the two flights, including mapping of the extent of clearcutting, flooding under forest canopies, and regrowth after fires or deforestation. Using models that relate backscatter and phase information from SAR images to geophysical characteristics, maps of biomass (Fig. 8) and vegetation type

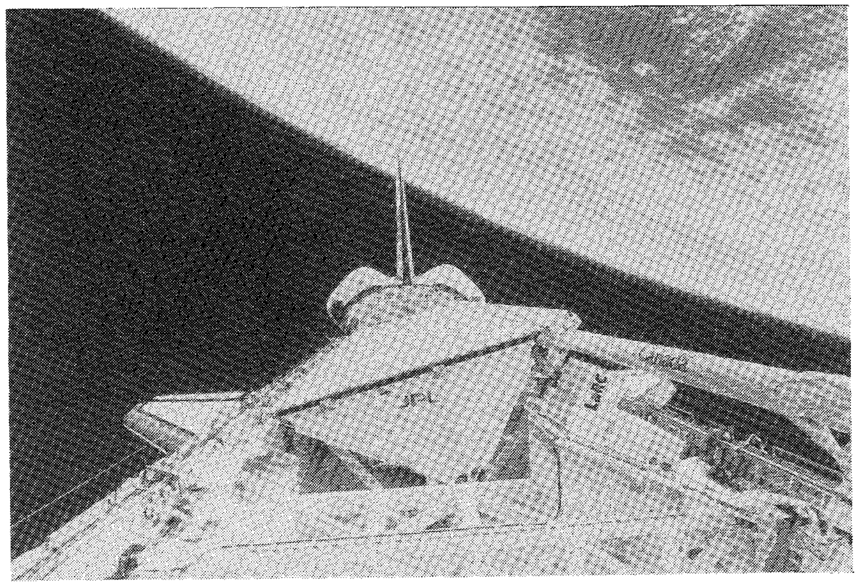


Fig. 6 SIR-C/X-SAR antenna.

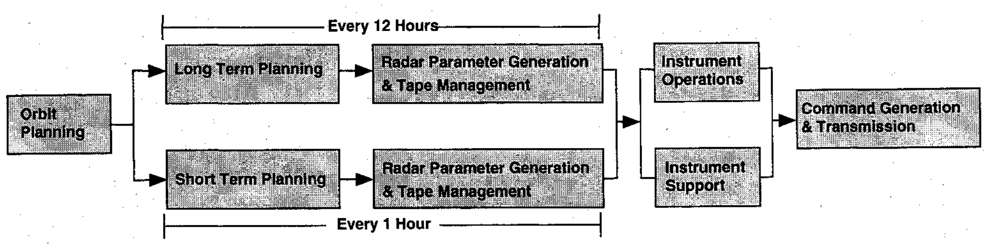



Fig. 7 SIR-C/X-SAR mission operations flow.

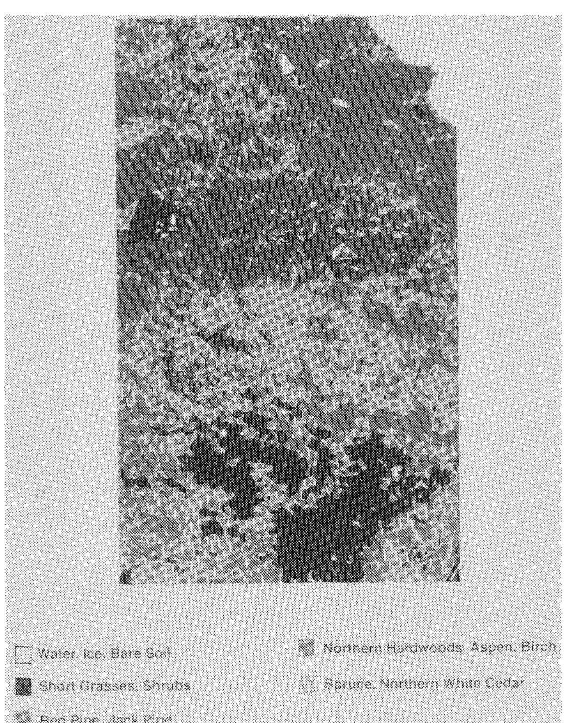



Fig. 8 SIR-C/X-SAR image of a test site near Raco, Michigan, where a team of researchers from the University of Michigan monitored a forestry test site and used radar data to infer above-ground biomass.

have been produced and verified from ground truth data. Changes were detected at most of the ecology sites: thaw-cycle effects were seen in Canada, growth of crops and foliage dramatically changed in Germany and the northern United States, and the presence of subcanopy flooding was detected in the central Amazon.

Radar's ability to monitor the global hydrologic cycle was studied at test sites in Brazil, Italy, Austria, and the central and western United States. Soil moisture can be derived from radar using models, and quantitative measurement of soil drydown following rainstorms was confirmed. Another algorithm allowed SIR-C/X-SAR to measure snow wetness. From this measurement the snow water equivalent, important for predicting water runoff, can be derived. Understanding the water cycle through measurement of both soil moisture and snow cover is also of use in global climate modeling. Similarly, wave fields can be examined in SAR images, revealing features such as swell, internal waves, thermal fronts, and rain cells, and new information about wave directions in the southern oceans have been derived from SIR-C/X-SAR ocean images.

A practical application of spaceborne remote sensing was demonstrated as several natural hazards presented themselves to both flights. Of the 15 decade volcanoes, 13 were imaged, including 5 recently active sites. Current activity was monitored at Kilauea, Kliuchevskoi, and Pinatubo (Fig. 9), where new lava deposits were detected by comparison of data from the two flights. Identification of areas threatened by future deposition of this mobilized ash may be possible using these same images. In a controlled experiment held in the North Sea, oil slicks were identified and classified. Because radar is responsive to different surface textures, it is an especially useful tool for discerning different surface units. For the same reason, SAR data are a valuable contributor to geological investigations. A study of the effects of windblown sand and dust in desert areas will enable researchers to identify areas likely to be subject to future desertification. Climatic changes in the recent past produce surface texture changes that enable radar to identify such areas.

## Mission Similarities and Differences

The level of adaptivity required of a space mission depends largely on two conditions. The first condition is whether or not the mission is encounter-class. Encounter-class missions have relatively short time periods in which to observe their intended targets. SIR-C was an encounter-class mission, having only 10 days on each of its two flights to meet its objectives. Other encounter-class missions include the Voyager and the upcoming Pluto Express missions, each of which gathers planetary data for a total of only a few weeks, even

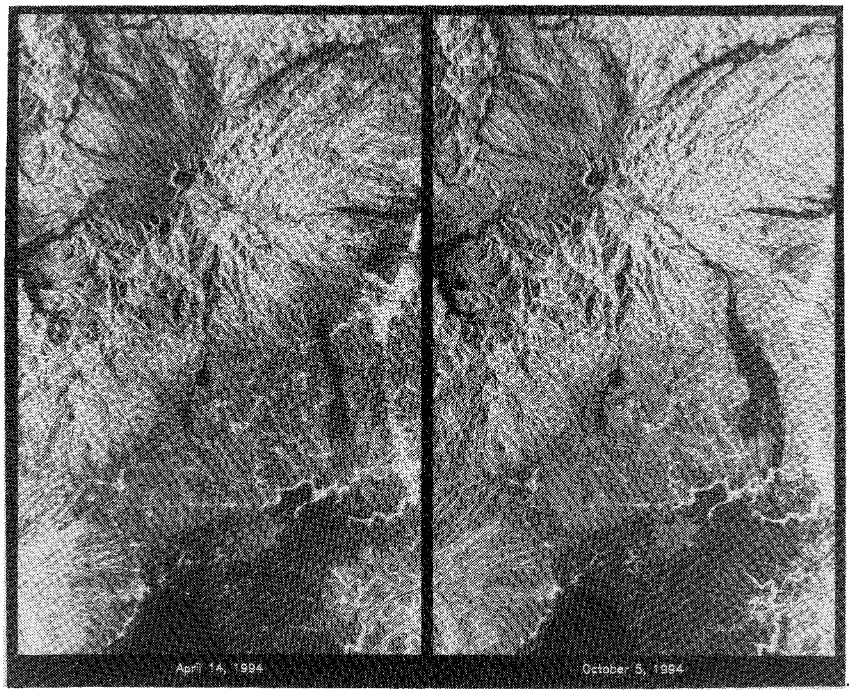
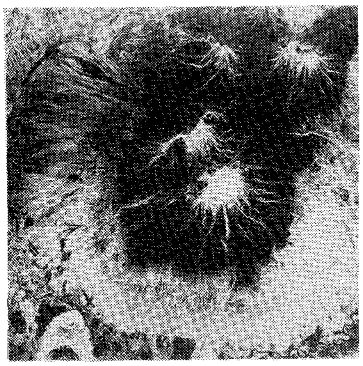



**Fig. 9 SIR-C/X-SAR image of Mt. Pinatubo, Philippines. To the lower right of this image, lava flows in the Pasig-Potrero river area are identified by the dark areas.**

**a) Shuttle photograph**



**b) SIR-C/X-SAR radar image**

**Fig. 10 Volcano Kliuchevskoi, on the Kamchatka peninsula, as acquired by SIR-C/X-SAR, Oct. 5, 1994.**

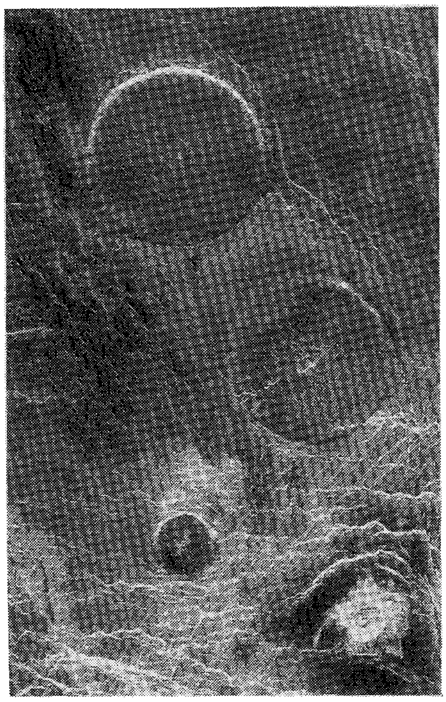


**Fig. 11 Volcanic domes in Alpha Regio in Venus's southern hemisphere.**

though their missions last many years. By contrast, Magellan was in orbit for two years of continuous radar data collection and afforded several opportunities to recapture missing data. Other nonencounter missions include the Galileo mission to Jupiter and the upcoming Cassini mission to Saturn. These flights will tour their respective planetary systems for several years.

The second condition is how dynamic is the phenomenon that is being measured. The following examples illustrate this point. SIR-C/X-SAR was able to respond to an eruption at Kliuchevskoi, a volcano on the Kamchatka peninsula, and thus provides in its archive a valuable record of an ongoing volcanic process. Figure 10 shows the eruption site in both optical and radar images. Paths of lava flows can be seen as thin lines in various shades of blue and green on the north flank in the middle of the image. The Kamchatka volcanoes are currently active, and the ability to characterize eruptions is important to geological study of the region. The current state of vulcanology does not allow prediction of such events, and only through either adaptive operations or continuous monitoring can such data be acquired.

Magellan's routine mapping revealed a distinct form of volcanism that later became known as the pancake domes (Fig. 11). Though these domes are roughly similar in appearance to terrestrial examples of silicic volcanism,[7] more detailed analysis of the structure and radar backscatter shows that there are also distinct differences.[8] Eight months later, this area was imaged again, with a different set of characteristics that allowed a stereo observation of these domes to be produced. The morphological details derived from the stereo data were made possible by both the nonencounter-class nature of Magellan and the nondynamic nature of the phenomenon under observation.

At a broad scale there are many distinctions between Magellan and SIR-C, other than the level of required adaptivity. Magellan operated a complete spacecraft, consisting of a platform (bus) and payload. SIR-C was a payload that used Shuttle Endeavour as a platform. Also, Magellan imaged Venus, whereas SIR-C imaged the Earth. Thus, light-time transmission periods were as long as 20 min for Magellan, and SIR-C was not constrained by such effects. Importantly, Magellan was a NASA class A (low-risk) planetary mission, whereas SIR-C/X-SAR was classed as C and was expected to take higher risks to achieve lower overall cost.

Both the Magellan and SIR-C missions used SAR as the primary data collection instrument.[9] Magellan was a mapping mission and was charged with producing continuous, global coverage maps. SIR-C, on the other hand, was a targeting mission. On any given orbit, targets were selected according to what was deemed scientifically important.

## Operational Effects

This section addresses the differences in operational requirements between Magellan and SIR-C resulting from differences in the level of adaptivity. Since these are real missions, each with its own set of driving requirements, there are distinguishing features between the two in addition to their adaptivity level, as previously discussed.

### Closer-to-Execution Command Development

The first feature to stand out in this comparison is how much more quickly a sequence must be developed and uplinked in an adaptive mission. Table 1 illustrates the time until execution at which various milestones in the uplink process were required to be completed. Note that the comparisons are approximate because of different operational styles, and in both missions exceptions were made to these schedules when deemed appropriate by their management to meet mission goals.

Earth-targeted missions like SIR-C have a fundamental advantage over their planetary companions. Planetary missions suffer from significant delays in command and data transmission time, an average 20 min in Magellan's case. However, if the later elements of comparison are adjusted for this difference by padding the SIR-C schedule up to a day for each hour listed, one can still see a significant command generation speedup.

### Acceptance of Late-Breaking Observation Requests

The reduction in command generation time provided by an adaptive mission operations system directly leads to a second effect, the potential to accept late-breaking observation requests. Table 2 illustrates the differences in flexibility of the emerging plan as the time to execution decreased, and lists some typically allowed changes as sequence (or command) execution approached. In this table, the term baseline refers to a general plan for what objectives were to be satisfied during various time periods and how large-scale resources were to be deployed towards meeting those objectives. Preliminary refers to a more complete set of instructions with regard to parameters such as start times, incidence angles, etc., and final indicates that, at least in normal situations, the command requests were considered ready to be passed on for final implementation.

**Table 1 Sequence generation comparison**

| Milestone | Time relative to command execution: Magellan (nonadaptive) | SIR-C (adaptive) |
|---|---|---|
| Baseline version of sequence complete | −6 weeks | −1 week |
| Preliminary version of sequence complete (O.K. to uplink) | −4 weeks | −12 h |
| Final version of sequence complete (O.K. to uplink) | −2 weeks | −3 h |
| Sequence uplinked | −1 day | −1 h |

**Table 2 Comparison of observation input ports**

| Port | Time relative to command execution: Magellan | SIR-C/X-SAR |
|---|---|---|
| Baseline inputs collection | −16 weeks | −2 weeks |
| Preliminary inputs collection | −12 weeks | −12 h |
| Final input collection | −8 weeks | −3 h |
| Emergency inputs | −1 week | −1 h |

**Table 3 Peak staffing levels according to function**

| | Magellan staff | SIR-C/X-SAR staff | Staff ratio |
|---|---|---|---|
| Science team | 43 | 52 | 1.2 |
| Science interface | 5 | 10 | 2.0 |
| Mission planning[a] | 11 | 15 | 1.4 |
| Instrument engineering | 22 | 43 | 2.0 |
| Commanding | 8 | 6 | 0.8 |
| | 89 | 126 | 7.4 |

[a]Includes conflict negotiation, sequence design and tape management.

Emergency inputs were infrequent and discouraged by project management. The one-hour turnaround was made possible on SIR-C, not because of real-time analysis of the returned data, but because of the requests of ground-based observers who saw conditions change at their locations. Though it is technically possible to do such data analysis (the X-SAR team in fact did this real-time analysis) the characteristics of the orbit were such that a repeated pass in an hour was not possible. Such a one-hour turnaround would not make sense for a mission like Magellan, as there are no such observers on Venus. However, the capability to react as little as one hour before execution was supported.

### Streamlined Decision Making

The deliberation and decision-making process must be streamlined in an adaptive system. The paper trail left by SIR-C is much smaller than by Magellan, because of an interactive database system. This database integrated an electronic paper-handling capability with several basic operational software functions and provided the command approval structure that has normally been realized on paper in previous missions. This implementation resulted in a speedier overall integration time.

### Shortened Cycle for Design and Verification of Experiments

A side effect is an integration of analysis software, which allows for an integrated experiment design. Each mission enabled investigators to add special flight experiments to image specific regions or to test physical hypotheses. In the second mapping cycle of Magellan, an experiment was executed to determine the dielectric constant of a set of surface features by flying the spacecraft in such a way as to enable oppositely polarized returns.[10] This experiment was designed over a two-month period and consumed approximately 80 h of analysis. In contrast, an experiment on SIR-C was requested to capture data over a thunderstorm in the southern Pacific ocean several hours before the experiment needed to begin. The design was handled as part of the controlling process already in place and consumed approximately 8 h.

### Increased Staff Size

Table 3 is a comparison of the staffing levels required for MOS functions related to the payloads for the two missions. The staffing listed in Table 3 is in full-time equivalents and does not imply numbers of individuals. No effort in development, maintenance, or spacecraft (platform) is included. Scientists were represented, both before the mission and during data collection, by resident individuals acting as science interfaces. The third function, mission planning, includes all effort dedicated to interpreting and coordinating science requirements with available resources, negotiating and resolving conflicts between objectives, designing commands or sequences of commands to accomplish the objectives, managing onboard storage of data, coordinating data downlink, and similar tasks.

**Increased Risk**

By their very nature, NASA class A missions have concentrated on the avoidance of risk. The combination of class A risk avoidance and adaptivity leads to the highest of operations costs, driven by all of the requirements listed here. In the current economic environment, where total expense and operations expense are constrained, the assumption of adaptivity is more likely to lead to a policy where risk is allowed and even encouraged as a means of saving costs. In this case risk must be managed, in some ways similarly to the management of funding or schedule, rather than be avoided. Accordingly, the risk manager identifies and ranks goals, procedures, commands, and contingencies that might require the expending of risk. Risk is permitted where it is most productive, and in some way the total risk is kept below some allowable maximum.

For example, for some missions risk of losing telemetered data might be highly tolerable if the same data could be replayed from onboard storage or reacquired at a later time. However, risk of loss of a valued nonredundant component such as a command receiver or central processor might be unacceptable. This evaluation could lead a project to allow the former risk by accepting higher bit errors in telemetry and spending more resources on protection of the valued component. Similarly, in adaptive missions projects must be willing to allow sufficient latitude to command in an adaptive fashion and be prepared to accept losses for the potential of greater data gains.

**More Up-Front Design**

Capabilities that support adaptivity require up-front design. The complications are threefold. The uplink subsystems must be designed to carry the extra load of adaptivity, involving additional interfaces, additional software testing, and increased complexity. An adaptive mission requires a flexible and reactive uplink process, the changing nature of which provides increased opportunity for commanding errors, unavoidably adding risk to the program.

Second, in nonadaptive missions that portion of the ground operations dedicated to the handling and production of data products can be essentially removed from the pressures of real-time operations. This statement does not mean that there is no driver for the production of data products—such pressures come from the user as well as from financial considerations. But it does imply that those downlink functions can be spared the inevitable pressures and resulting resource requirements that time pressures produce. In the adaptive mission, data products are as time-driven as the engineering telemetry, and expedient operation of the data production function is as crucial as it is for the planning and uplink functions.

Third, the data analysis process must also be carried out under a tightly controlled operations schedule. Data analysis, which generally is able to forsake expedience in favor of exactness, is not well suited to such an environment. For example, imaging sensors generally require some form of computer-intensive image processing in the data-processing stream to analyze the full resolution content of the data. When there is no schedule constraint, these processes can be carried out with ample operator interaction and on relatively inexpensive computer systems. It is not uncommon for some such operations to require hours of computer time to complete. However, when a tight timeline requirement is imposed, significant changes to both hardware and software results.

**Potential for Creeping Requirements**

Projects that decide to support high levels of adaptivity should do so in a carefully bounded fashion. Response capability is never unlimited. A personnel-extensive mission operations system is generally limited by human capability, and in more automated designs it might be limited by command channel capacity, sequencing capability, or other resources. Since adaptive response often utilizes the same resources as anomaly response, overuse can mean that the capacity for anomaly response will be unavailable if and when required.

## Conclusions

The advantages of a nonadaptive mission are lower cost, lower risk, and smaller operations staff size. Magellan was an extremely successful mission, and employed little in the way of adaptive control. SIR-C, also very successful, paid the higher costs and enjoyed the capability to accept late-breaking observation requests, streamlined decision making, and a faster turnaround of experiment design. The level of required adaptivity was shown to be a function of the length of time available for observations and the dynamic nature of the phenomenon being observed.

In their conceptual phase, missions should consciously decide whether or not to include the option of allowing adaptivity, with due consideration of the resources that will be required. The operational difficulties of implementing such a function are not to be underestimated when the mission operations system designers accept the job. Retrofitting a system designed without sufficient adaptivity provisions is expensive and painful.

Parameters that can be set and held to include the following:

1) Set and enforce minimum allowable times to command. Several such time limits might be set—for example, a 12-h limit on advance notice of a changed or newly discovered target characteristic, a 1-h limit on input to the planning process of the required change, and a 30-min limit on the completion of the command upload prior to its execution.

2) Limit adaptivity classes. For example, an adaptive mission could choose to support a single class of adaptivity during a given mission phase, such as targets of opportunity defined by real-time weather phenomenon. During this phase, other classes of adaptivity, such as sample site selection to increase observations of a certain static phenomenon, would not be supported concurrently.

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