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High resolution imaging systems for spin-stabilized Probe spacecraft

G. Edward Danielson
Division of Geological Planetary Sciences
California Institute of Technology, Pasadena, California 91109
Michael C. Malin
Department of Geology, Arizona State University, Tempe, Arizona 85281
W. Alan Delamere
Ball Aerospace Systems Division, Boulder, Colorado 80306

Abstract

A novel design for a high-resolution imaging system which includes on-board data editing and optical navigation, suggests high quality images can be acquired from spin-stabilized spacecraft oriented towards high velocity, short duration planetary missions ("Probes"). The approach to designing imaging systems requires that mission objectives be met within the physical and fiscal constraints imposed by the spacecraft and mission design. Severe constraints imposed on a Comet Halley probe (for example, 57km/sec encounter velocity with a small, 10km diameter, object coupled with a great uncertainty in encounter time and distance, were overcome by innovative use of existing technology. Such designs suggest that 3-axis stabilization or non-spinning platforms are not necessary to acquire high resolution, high quality planetary images.

Introduction

It is commonly perceived that high quality images of planetary bodies can only be acquired by framing cameras mounted on three-axis stabilized or non-spinning platforms. These perceptions do not acknowledge the excellent data provided by meterology and earth resources satellites, most of which do not depend on framing sensors nor on three-axis stabilization.

In order to meet severe design constraints for imaging systems for high velocity, short duration planetary encounters ("Probes"), most notably weight, data rates, cost, and simplicity, we have examined several alternative imaging techniques. Our principle motivation was in response to NASA-sponsored Announcements of Opportunity, first for the Jupiter Orbiter/Probe ("Galileo") and later the International Comet Mission; this work results from our response to the latter. However, the concepts can be applied to a variety of other missions including asteroid or satellite flybys, and atmospheric probes.

General considerations

Before designing an imaging system, one must answer several questions: (1) Is an imaging system necessary?; (2) If it is, what are its objectives? (i.e., why is it necessary?); (3) What are the minimum requirements necessary to meet these objectives?; (4) What are the mission-peculiar constraints that limit the type of imaging system? and (5) What implementation can allow the system to meet the objectives within the constraints? The first two questions are often reversed, as the objectives of a mission can usually be interpreted in terms of the objectives of the instrumentation aboard the spacecraft. In addition, common sense also dictates constraints on an instrument: its mass and volume should be as small as possible, its data rate and power consumption as low as possible, its moving parts few, its operation simple, and its cost modest. Imaging systems are often the gluttons on spacecraft--they monopolize power and data-rate, attention from spacecraft data command and processing systems, their optics are often heavy and voluminous, and with filter wheels, shutters and scan platforms, are among the more mechanically complex instruments. Thus, to address the general considerations outlined above for a highly physically and fiscally constrained mission is extremely challenging.

Probe imaging - an example

Perhaps the best way to show how the various elements of a "Probe" imaging experiment combine is to describe an example. In the following sections, we will use our recent work on a Comet flyby imaging system to illustrate the potential of simple, non-framing imaging systems on spin-stabilized spacecraft to return useful, indeed necessary, scientific information.

Mission objectives and imaging systems

Early objectives of the probe portion of the International Comet Mission (ICM) did not include studies of the physiography of the nucleus of Comet Halley (the intended probe target). Rather, objectives centered on the physical environment, particle and fields, and dust and molecular species surrounding the nucleus. Objectives for the ICM's second target, of the nucleus, and an imaging system for that portion of the spacecraft to encounter Temple II was planned. We will not address that system here, except to note its general similarity to past systems.

Our first task, then, was to determine the utility of an imaging system for the probe. After examining the scientific and engineering problems to be addressed, we found two overriding reasons for including an imaging system aboard the Comet Halley probe. First, owing to navigation errors associated with the high encounter velocity, low mass of the nucleus, and the mission requirement to release the probe from the main spacecraft many days prior to encounter, it was unlikely that the encounter geometry could be determined with any certainty. Second, the nuclear activity and physiography of the long period Comet Halley would likely be significantly different from that of the short period Comet Temple II. Thus, from a scientific perspective, observations of Halley's nucleus were deemed highly valuable. By working with the Imaging Sub-group of the Comet Working Group, we were able to demonstrate the need for imaging on-board the probe; the report of that Working Group properly communicates the importance of imaging to the probe's mission.

What, then, are the objectives of a probe imaging system for a Comet Halley fast flyby? They are:

1) determine the position, in space and time, of the spacecraft encounter with the cometary nucleus;
2) determine the size, shape, and volume of the nucleus;
3) study coma and nucleus dynamics and interactions;
4) search for color and albedo variations on the nucleus;
5) study surface morphology of the nucleus;
6) determine the nucleus spin axis and spin rate.

Instrument requirements and mission constraints

To meet the objectives outlined above requires several images of high quality and resolution. As the brightness of the nucleus, and its contrast with the surrounding coma, are not well known, the system must be able to span a large range in both brightness and contrast. Color filters are needed to search for color variations. High spatial resolution is needed to undertake size, shape and volume measurements, and to seek surface landforms.

The mission and spacecraft limitations affect great constraints: the flyby velocity of 57km/sec severely limits the time of encounter and could also produce smeared images; the spacecraft spin,one revolution every 5 seconds, limits the length of time any part of the sky can be visible; the probe size, power subsystem, and especially data rate place strict constraints on imaging system's volume, power consumption, and most importantly, data rate.

We combined many of the constraints and set targets for our potential system as follows:

mass - less than 10kg
power - less than 10 watts
data rate - less than 3 kilobits/second
color filters - at least 3 colors
spatial resolution - better than 100m at 1000km miss distance
encounter time prediction - better than + 10 seconds
encounter distance prediction - better than 10%

Implementation

We examined several possible sensors for our probe imaging system. A point-scan system, using a single-element detector and spacecraft rotation and a stepper mirror to scan the sky, could not adequately meet the objectives because of the long time needed to acquire an image. Two-dimensional arrays (vidicons or charge coupled devices) could work well when the target was along the spacecraft spin axis, but at closest approach would yield smeared images owing to high relative velocities and the inability to have microsecond shutter speeds (both because of mechanical and photometric limitations). One-dimensional arrays seemed a good possibility, again using spacecraft spin and a stepper mirror to scan the forward field-of-view, a technique we called line scan when proposed in 1975 for the Lunar Polar Orbiter. However, read-out rates were found to be high and too much power was needed to drive these rates. Similarly, read-in rates into data storage devices were too high and needed too much power. We finally settled on an innovative use of an array used in a "line" scan mode: a CCD array is masked such that most of its active surface is covered and can not receive stimulation from light. Information is then shifted from the active lines into the masked lines at high rates but at low power. In a sense, the device acts as its own data storage system. No mechanical shutter is needed; the system builds an image as the spacecraft rotates (Figure 1).

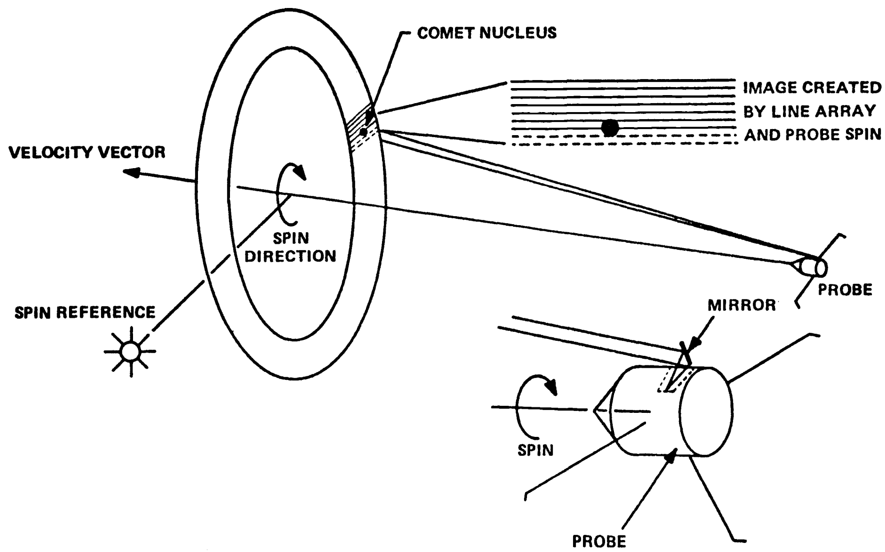

Figure 1 Two-dimensional image created by Probe spin andline array detector. Illustrated taking picture of comet nucleus.

To meet the color requirements, we selected an 800 x 800 CCD array, developed by Texas Instruments, that is internally divided into four sections, each 200 x 800 elements. By masking each section separately, we had, in effect, four separate line scan systems each with its maximum of 199 x 800 elements of storage. In practice, there would be 4 active lines in each section (to account for possible smear or low light levels by time delay integration) and 196 lines of storage. Three sets of active lines would be covered by a different color filter, with bandpasses centered at .45, .55, and .75um. The fourth would have a clear filter, limited only by the CCD's spectral sensitivity (Figure 2). Thus, in one sweep of the sensor, three color images and one broadband image would be acquired. This solution eliminated the need for a filter wheel (a mechanical device to rotate various filters in front of the detector) or for multiple detectors (each with a separate filter), at a savings of mass, power, complexity and cost.

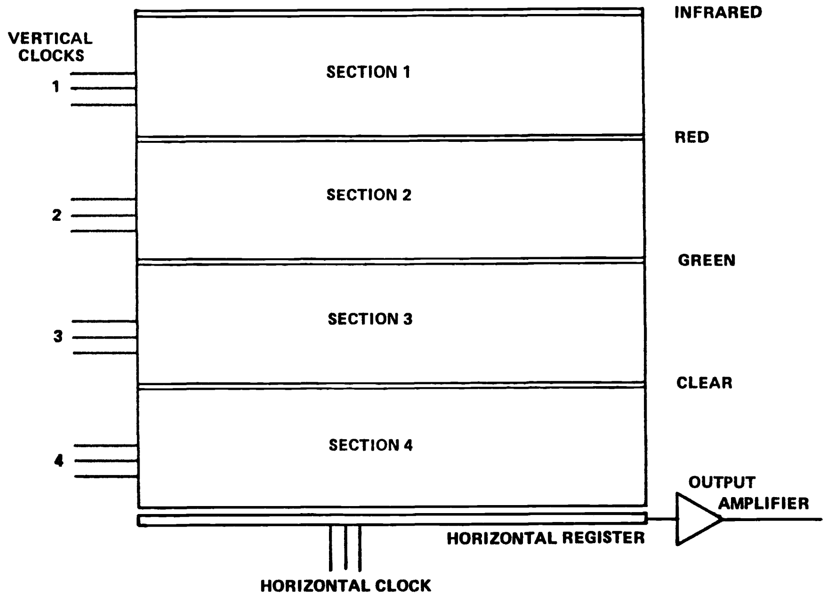

Figure 2 800 X 800 CCD is segmented into four independent sections.

Perhaps the most challenging part of the probe's mission derived from a limitation in its communication and on-board data control systems--the probe could only transmit signals after separation from the main spacecraft, it could not receive. This meant that all functions of the imaging system (e.g., pointing, framing the comet in the "center" of its image, navigation calculations, etc.) had to be either preprogrammed months prior to encounter, or completely autonomous and self-controlled. The lack of 'a priori' knowledge of the trajectory led to including an imaging system in the first place, so a completely autonomous system was the only choice. We thus designed a system to make full use of microelectronics and to carry out pointing calculations. Operationally, this meant the instrument needed three modes of data acquisition, which we called "Search and Acquire", "Track and Data Transmission", and "Final Image Transmission".

The Search and Acquire mode would begin immediately after the instrument received its turn-on signal at -3 hours. A low resolution initial readout rate would allow it to construct an image of the field-of-view in front of the spacecraft. This image would be processed in realtime. Figures 3 and 4 show schematically how these data would be acquired and processed.

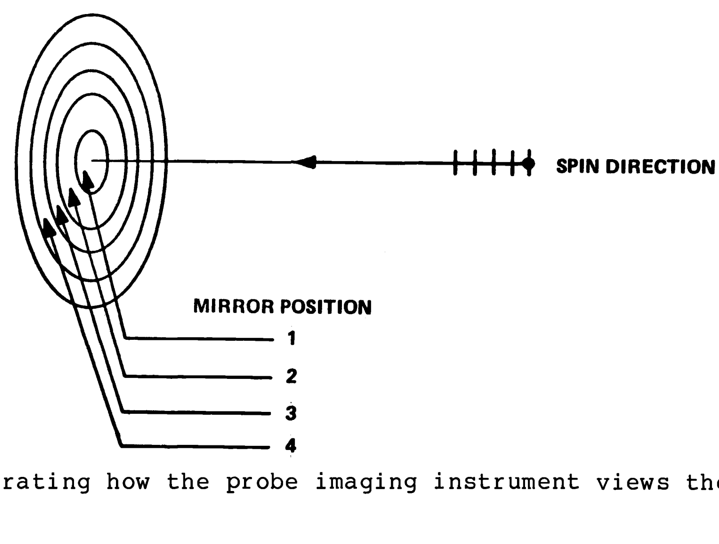

Figure 3 Illustrating how the probe imaging instrument views the forward direction.

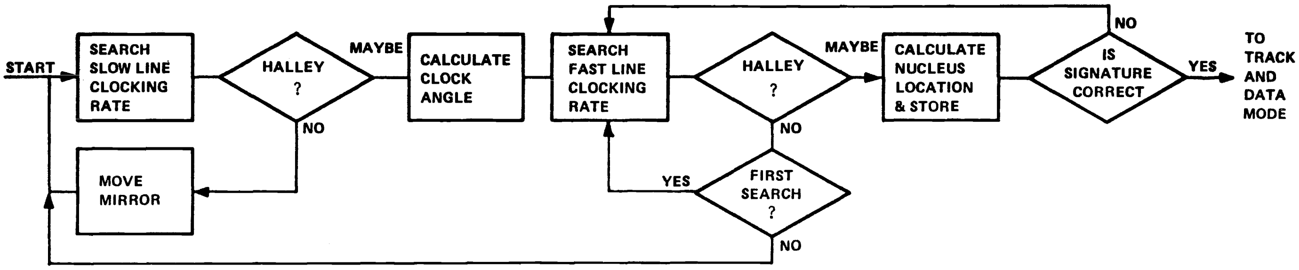

Figure 4 Search and Acquire mode logic

During each rotation, the lines and pixels that contain the brightest features would be noted. If a feature had the proper brightness, the nucleus would have been acquired and its line number and the rotation rate could be used to predict the next passage across the sensor. The line readout rate would then be adjusted for high resolution scan. The resulting pictures would be analyzed perpendicular to the line direction to determine the precise position angle, and along the lines to determine the cone angle elongation of the image of the nucleus. If no feature with the proper brightness was found within one field-of-view of the spin axis, the mirror would be activated and the next annulus out from the axis searched in analogous fashion. This procedure would continue until either the nucleus was acquired or the entire field-of-view had been searched. In the latter case, the brightest object found would be assumed to be the nucleus. Once identified, the nucleus location would be examined in subsequent images for variations due to spacecraft nutation. If these variations occurred, their periodicity would be measured and a calculation performed to adjust for these angular offsets.

In the Track and Data Transmission mode, the optical navigation calculations would be made on-board in realtime and made available to other instruments on the probe. If the feature identified as nucleus or coma had either not increased in size after a certain period of time, or begun to move off axis, the intrument would return to the Search and Acquire mode and again search the forward hemisphere, this time also looking for features multiple elements in size. There is a possibility that the probe trajectory would lead to a very close encounter. In this case the nucleus would continue to grow but not to move off axis. The angular rate of growth (derived from pixel number growth) and the velocity of the spacecraft (known from pre-mission trajectory analysis) would be used to predict the encounter time and range. Eventually, even for a 10km miss distance, the nucleus would begin to move off axis. On each successive probe rotation, the position of the nucleus would be determined and its positional rate of change calculated (Figure 5). As the nucleus neared the edge of the field-of-view, the instrument would command its mirror to offset the field-of-view to keep the nucleus in sight. By precisely measuring the location within the field-of-view and combining this with mirror pointing information, the angular offset could be determined.

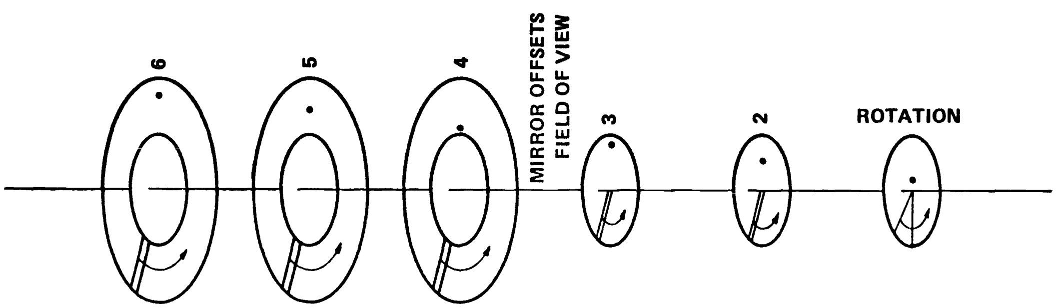

Figure 5 Tracking of nucleus image as it moves off axis.

To meet our objective of on-board optical navigation, simple calculation would be programmed into the control of the imaging system, to combine the measured angular offsets and diameter of the nucleus or coma with the velocity (v) of the spacecraft to calculate the probe-comet miss distance (b), the distance to the nucleus (d), the radius of the nucleus (R), and the time to encounter (T).

The simple equations are:

$$b = \nu(\Delta t)(\cot\theta_1 - \cot\theta_2)^{-1}$$

$d_1 = b/\sin\theta_1$	Where: $t_2 - t_1 = \Delta t$, the time
$d_2 = b/\sin\theta_2$	(in seconds) between observations
$R_1 = d_1 \tan\phi 1/2$	usually rotations),
$R_2 = d_2 \tan\phi 2/2$	θ is the angle from the spin axis
$T_1 = b/\nu \tan\theta_1$	ϕ is the angular size of the nucleus,
$T_2 = b/\nu \tan\theta_2$	1, 2 represent sequential observation

Our design required that the instrument continually compare and update these values and model their variation to reduce errors due to pointing uncertainties. These values were to be used to update the mirror pointing commands and the scientific image sequence to assure the highest possible resolution last frame.

At the same time that the optical navigation calculations were made, data would be continuously transmitted to the main S/C. These would be digitized charges of the CCD elements of different sections and fractions of sections. The basic mode would consist of transmitting 50 x 50 pixels at 5 bits per pixel around the position of the identified nucleus during one rotation of the spacecraft. This fraction of the data best fit our goal of keeping our bit rate as low as possible. Color bands would be read sequencially from rotation to rotation so that every four rotations (20 seconds) all four color bands would be transmitted. Representative plans for picture transmission are shown in Table 1.

TABLE 1 TYPICAL OBSERVATION SEQUENCE
Data Rate - 2.5 kbps

Observation Phase	Time From Encounter	Revolutions From Encounter	Transmission Format pixels/lines/bits pixel	Activity
Search and Acquire	10800 sec	2160	50x50x5	Search forward 90 cone for comet nucleus position.
Acquisition	---	----	50x50x5	Nucleus located. Begin tracking nucleus.
Track and Data Transmission	Nominal Start	----	50x50x5	Nucleus tracked centered. Navigation parametersupdated each revolution. 1 each of 4 colors on sequential revolutions. Transmissions of centroid.
	7200 sec	1440	50x50x5	
	3600	720	50x50x5	
	1800	360	50x50x5	
	900	180	50x50x5	
	450	90	50x50x5	
	225	45	50x50x5	
	60	12	50x50x5	
Final Image Acquisition	30 sec	6	50x50x5	Acquire 800x200x8 through each filter. Transmit cen trol 50x50x5 in each color.
	E to E+34min		40x40x8	Transmit 400 blocks 40x40x8 entire final image, full frame in four colors.

The highest resolution observation and Final Image Transmission would occur just prior to encounter. Three color and one broadband image at 800 x 200 pixels would be acquired at a range of about 2000km, providing an image of the comet nucleus with resolution better than 100m/pixel pair. To match the bandwidth available, this picture would be read out in 50 x 50 pixel segments digitized to 8 bits/pixel. The entire final picture will take 34 minutes to transmit; the center portion of the image would be transmitted first, in case the spacecraft did not survive encounter.

Performance

After a detailed design and costing exercise, a proposal for a probe imaging experiment was submitted. The final parameters met or exceeded our early requirements:

Mass	5 kg
Power	7 watts
Volume	30 x 32 x 35 cc.
Data Rate	2.5 kbits/second
Spatial Resolution	100 m/pixel pair at 2000 km
Navigation Forecasts:	
Time to Closest Approach	< 1 second or ±0.1%
Miss Distance	±1.2 km for 1000 km miss
Spectral Coverage	0.35-1 um (clear)
	0.42-0.58 um (green)
	0.58-0.70 um (red)
	0.70-1 um (infra-red)

Conclusion

In the preceding sections, we have discussed one example of a probe imaging system--designed to fit the objective and constraints of a specific mission. For other missions, different designs might be better suited. We are convinced, however, from our study, that high resolution, high quality images do not require 3-axis stabilized or non-spinning platforms, nor do they a priori require framing systems. With the difficulty in establishing new large initiatives in planetary exploration experienced by NASA in the past five years, it may be that future missions will need to be simpler and of lower cost. Our work suggests that imaging systems need not be excluded from such missions.

The European Space Agency Giotto mission to Comet Halley will have an imaging instrument of this type. It is based on our initial work and has been designed to provide coma data early in the flyby as well as high resolution imaging of the nucleus.