***** File GIOHMC.TXT

NOTE: This file was created by scanning the original hardcopy article
and only the Figure captions are included.

The Giotto Halley Multicolour Camera

W. K. H.Schmidt, H.U. Keller, K. Wilhelm
Max-Planck-Institut fur Aeronomie, Katlenburg-Lindau, Germany

C. Arpigny
Institut d’Astrophysique, Universite de Liege, Belgium

C. Barbieri
Instituto di Astronomia, Universita di Padova, Padova, Italy

L. Biermann
Max-Planck-Institut fur Physik und Astrophysik, Munchen, Germany

R.M. Bonnet
Institut d’Astrophysique, Universite de Liege, Belgium
and European Space Agency, Paris, France

S. Cazes
Laboratoire de Physique Stellaire et Planetaire, Verrieres-le-Buisson, France

C.B. Cosmovici
Deutsche Forschungs- und Versuchsanstalt fur Lufi- und Raumfahrt, Oberpfaffenhofen, Germany
and Istituto Fisica Spazio Interplanetario, Frascati, Italy

W.A. Delamere
Ball Aerospace Systems Division, Boulder, USA

W.F. Huebner
Los Alamos Scientific Laboratory, Los Alamos, New Mexico, USA

D.W. Hughes
University of Sheffield, Sheffield, UK

C. Jamar, D. Malaise
Institut d’Astrophysique, Universite de Liege, Belgium

H. Reitsema
Ball Aerospace Systems Division, Boulder, USA

P. Seige
Deutsche Forschungs- und Versuchsanstalt fur Lufi- und Raumfahrt, Oberpfaffenhofen, Germany

F.L. Whipple
Harvard College Observatory, Cambridge, Mass., USA

Abstract

The Halley Multicolour Camera (HMC) is a Ritchey-Chretien type Cassegrain telescope (1000 mm focal length) with CCD imagers in the focal plane. It is mounted

on the experiment platform of the Giotto spacecraft and looks out via a 45deg turret mirror. It is suspended in a revolving mount so that the centre of its field of view can be moved freely in a half plane that contains the spin axis of the spacecraft. Together with the spinning motion of the spacecraft, this mobility enables the HMC to image any part of the whole 4 pi solid angle of the sky.

The line-scan imaging technique uses the spacecraft’s spin for one dimension and the length of the line for the other dimension of the image. Four line sensors with filters of different colour bands take images almost simultaneously. Onboard electronics controlled by three microprocessors operate the camera almost autonomously. The image of the comet will be searched for at the beginning of encounter operations. Having found it, the camera will switch to the imaging mode.

The contents of the images are to be telemetered to ground in sections and at the same time used onboard to update the parameters that describe the spacecraft’s trajectory relative to the cometary nucleus. With this information, the HMC’s field of view will be able to track the centre of the comet’s image.

1 Introduction

In recent decades, Whipple’s ’dirty snowball’ picture of the cometary nucleus has become widely, but not universally accepted. Proof of the nucleus’ existence and study of its properties require pictures in various colour bands, preferably together with other information. Acquisition of these pictures is the task of Halley Multicolour Camera (HMC), which has been designed and built by an international collaboration of scientists and engineers.

2. Scientific Objectives

The aim of the HMC is to provide high-quality images of the comet’s nucleus in four colours with two polarizations, and of the coma in several filter bands. The generally accepted Whipple model predicts an icy conglomerate nucleus composed of frozen molecules mixed with dust. Because of the lack of resolution of ground-based instruments, a cometary nucleus has never been observed. Multicolour high-resolution imaging of the nucleus will contribute to the investigation of its:

- size, shape, and volume
- surface properties (structure, morphology, and inhomogeneities due to possible active regions)
- photometric properties (albedo as a function of wavelength and phase angle, for a better understanding of the chemical composition of the nucleus)
- large-scale asymmetries in the sublimation process related to the rotation of the nucleus, and the solar phase angle (thermal lag, jets, envelopes, etc.)
- rotation period and spin-axis direction
- mechanism of mass loss
- energy balance on the surface (insolation/sublimation).

In addition to studying the cometary nucleus, multicolour imaging of the coma will permit investigation of:

- the production and evolution of gas molecules and dust grains
- the characteristic scale length of the interaction of the coma with the nucleus, the acceleration of the dust by the gas, and the dust density distribution from the nuclear surface outwards
- dust-grain size distribution and physical properties from scattering and albedo measurements
- chemistry of inner gas coma
- time-dependent properties of the dust-gas outflow (streamers)
- the possible presence of an icy grain halo.

Simultaneous observations from the Earth will permit stereo views and determinations of the three-dimensional geometry of the coma.

3. Overview

3.1 The Camera

The scientific objectives are to be pursued with a 1000 cm focal length telescope. designed to operate on a spin-stabilized platform. The shortest exposure times for off-spin-axis observations near closest approach to the nucleus will be less than 20 micro s, determined by the pixel crossing time of the rapidly moving image in the focal plane, so that a mechanical shutter cannot be used. The field of view (FOV) of a telescope with high resolving power/magnification is necessarily quite small, and as the aspect angle of the cometary centre will change during the flyby from near 0deg to 180 deg the telescope has to be articulated so that its FOV can follow it.

The above considerations led to the basic design illustrated in Figures 1 to 5 (details to be described in the following sections). A line-scanning imaging technique is employed whereby the spacecraft’s rotation provides one spatial dimension and the linear dimension of the line detector provides the orthogonal dimension. A set of five linescanning detectors - one for timing control and four for imaging in different colours - is used to provide colour images of the comet. Figure 4 illustrates how a line-scan image of the target is taken at the proper angle and time, and Figure 5 shows the arrangement of the line detectors in the focal plane.

In order to be able to follow the target to large offset angles, the telescope is mounted with its optical axis perpendicular to the spin axis of the spacecraft, and its FOV is deflected by 90deg via a 45deg turret mirror. Rotating the telescope around its optical axis by 180deg changes the centre direction of the FOV from alignment with the spin axis (at the beginning of encounter operations) to the antiparallel direction. This rotational motion, together with the spacecraft’s spinning motion, allows the HMC to image a target anywhere within the complete 4 pi solid angle of the sky. A possible small ’blind spot’ near the spin axis due to misalignment is avoided by the possibility to tilt the deflecting mirror by about 1deg in either direction from the 45deg centre position. This tilt capability can also be used if the target should be found to be aligned exactly with the spin axis. In that event there will be no linear motion of the image, which is needed to employ the line-scanning technique; the scene will then be swept smoothly across the line detector by tilting the deflecting mirror, thereby introducing an artificial linear movement of the image (’on-axis-imaging’ in HMC terminology).

Figure 1. Cross-section through the Halley Multicolour Camera. The spacecraft experiment platform is at the lower edge. X, Z and X’, Z’, are HMC internal coordinate systems. In the position shown Z’ is (within alignment errors) parallel to the +Z axis of the Giotto spacecraft

Three of the four line detectors are covered by permanent colour filters, while the fourth (line C in Fig. 5) has an 11-position filter wheel in front of it (see Section 4). This filter wheel contains narrow and wideband filters and polarizers, so that the dust as well as the gas coma can be investigated, in addition to the cometary nucleus.

The search for the cometary nucleus here will be conducted by looking for the brightest spot in the FOV. This is the least model-dependent principle compared, for instance, with the search for a contrast pattern or even negative contrast (dark nucleus on light background). If the nucleus is visible at all, the dust cloud must be optically thin, and chances are then high that the surface of the nucleus will be the brightest part in the FOV. Should the reflectivities of the surface and the dust be so drastically different that the dust is brighter than the surface of the nucleus, then in the optically thin case the brightest spot must still be very close to the nucleus, because the dust density is highest there.

Only in the optically thick case, where the nucleus will be invisible anyway, is it likely that the brightest spot will be far from the nucleus, and it is then still likely that

Figure 2. The HMC with its electronics box on a laboratory support. The rotational position is the same as in Figure 1, i.e. looking towards

the +Z axis of the spacecraft

Figure 3. Schematic of the HMC and spacecraft interfaces

the vicinity of the brightest spot will be the most interesting part of the whole scene.

The data rate allotted to the HMC is 20058 bit/s. At 8 bit/pixel, this is sufficient to transmit the content of an image section of 98X98 pixels, plus appropriate housekeeping information, to ground during each 4s spin period. The picture format will be changed at times so that smaller and larger picture sections can be transmitted alternately or interleaved.

In order to transmit a maximum of information within the given data-rate constraints, the analogue signal data are compressed by taking the square root of the signal. In this way the digitization error or step width is proportional to the standard deviation of the fluctuation distribution, with the actual signal as the assumed mean value. Data compression is therefore naturally fitted to the inherent uncertainties of the data to be gathered.

3.2 operations

The HMC operates in four basic modes, called Acquisition, Coma, Nucleus and Observatory Modes.

3.2.1 Acquisition

At the beginning of encounter operations, the image of the comet has to be found and identified. A line detector 1.6deg wide in the focal plane of the HMC will be used for this purpose. By tilting the deflecting mirror and rotating the barrel (telescope) appropriately, a 4.4deg X 4.6deg field in front of the spacecraft centred on its nominal spin axis will be searched. The image of an object in front of the spacecraft will move in circles in the focal plane with the spin angular velocity. By sweeping the FOV across the line detector, the moving image must cross the detector, and the time and place of the detector crossing will be recorded. A sufficiently large search field has been chosen that the full circle of the worst-case misaligned cometary image will be covered. After having recorded a sufficient number of crossings, the Digital Processing Unit (DPU) will calculate the parameters of the image’s movement: spin and nutation period, radius, and phase. It uses this information in the next operational mode (Coma) to take pictures around the brightest spot in the FOV at the proper time.

At this time in the mission, the cometary nucleus is expected to be much smaller than a pixel of the line detector (30 micrometer X 375 micrometer, l micrometer is equivalent to 1 microradian). The signal on one of the large pixels is therefore expected to be dominated by the coma of the comet, because it will project an extended image into the focal plane. The algorithm will therefore search for an extended object in the scene.

Figure 4. Principle of line-scan imaging from a spin-stabilized spacecraft

3.2.2 Coma Mode

For most of the mission, the circle that the image describes in the focal plane will be so small that it is expected to cross only one line detector safely. For circle radii rho <0.8deg, the on-axis-imaging technique (see Section 3.1) will be used. The geometry for data acquisition has been chosen such that the cometary image crosses one detector line (line C, Fig. 5) at right angles. Only this detector line will be used for picture taking during Coma Mode.

There will be >= 3 h between completion of the acquisition and closest approach. During this period a large number of pictures will be taken in various formats and using all of the filters. This will yield data on the innermost coma with varying FOV and resolution; the largest picture transmitted will be the full CCD area of 292 pixels (height) by 390 pixels (width).

3.2.3 Nucleus Mode

Depending on the final flyby distance, some 9 min or less before closest approach, the radius of the cometary image’s track in the focal plane will exceed 1.6 deg. The circle will then be so large that all four imaging line detectors will be crossed by the image nearly perpendicularly. This is therefore the threshold for switching to Nucleus Mode. Image sections of 76 X 76 pixels from all four detectors will be transmitted to ground once during each spin period. The resolution on the surface of the nucleus will be better than 800 m per pixel from this distance.

The line detectors have different filters in front of them (Fig. 5 and Table 1). Line B has a red filter, line C an orange or polarizing filter, line D a blue filter, and line E is the clear channel integrating over the whole spectrum (see spectral responsivity of the CCDs, Fig. 9). The clear channel will be read out at full resolution, the coloured channels at half resolution, i.e. 38 X 38 pixels of double linear size each. With this information, a colour picture of 76 X 76 pixels of the highest obtainable resolution can be constructed just before loss of tracking or loss of the mission.

3.2.4 Observatory Mode

In order to take pictures anywhere in the sky at will, an operational mode has been included that permits imaging at arbitrary separation angles (i.e. telescope rotation angles) and spin phases without the need for tracking (see below).

Figure 5. Image plane (virtual focal plane, see text) showing the arrangement of the four CCD imager lines and the double-line diode array (top). The complete circle shows the outer boundary of the unvignetted field of view. The circular arc indicates the track of of the target’s image through the image plane when the target’s aspect w.r.t. the spin axis is 1.6deg

3.2.5 Tracking of the comet

As pointed out above, the movement of the cometary image in the focal plane of the telescope will initially be determined during Acquisition Mode. Later, in Coma Mode these parameters will be used to rotate the telescope and time the detector clocking properly, so that the predicted location of the image will be in the centre the active CCD area. In addition to being telemetered to ground, the actual location of the centroid of brightness compared with the predicted one will be used to update

Table 1. Filter configurations for the four imaging line detectors

Filter no.	Filter		Characteristic	Cut-on wavelength	Cutoff wavelength
1	C1	shutter	shutter	N/A	N/A
2	C2	clear	wide band, full CCD response	<300 nm	>1100 nm
2	E	clear			
3	C3	red	wide band	700+/-5 nm	>1100 nm
3	B	red			
4	C4	orange	wide band	580+/-5 nm	700+/-5 nm
5	C5	blue	wide band	< 360 nm	490+/-5 nm
5	D	blue			
6	C6	P(par)(polarizer, clear)	wide band-polarizer	<300 nm	> 1100 nm
7	C7	P(perpen)	wide band-polarizer	<300 nm	> 1100 nm
8	C8	cont. 1	dust, narrow band	440+/-2 nm	456+/-2 nm
9	C9	cont. 2	dust, narrow band	716+/-2 nm	742+/-2 nm
10	c10	OH	gas, narrow band	302+/-2 nm	320+/-2 nm
11	C11	C3	gas, narrow band	398+/-2 nm	416+/-2 nm

12	c12	C2	gas, narrow band	500+/-2 nm	520+/-2 nm

* Wavelengths with tolerances refer to 50% of peak transmission points; other wavelengths refer to

knowledge of the image's movement as seen from the HMC. These 'tracking calculations' will predict the flyby geometry all the way through closest approach. At the beginning of the encounter operations, the tracking algorithm makes use of the estimated time to closest approach as transmitted from the ground; when the separation angle has changed noticeably, the onboard software will determine all parameters, including the time to closest approach, autonomously, so that the FOV of the telescope can follow the position of the cometary nucleus accurately on the sky. As a byproduct, the high-accuracy flyby parameters will be available at the ground station in near-real-time.

3.2.6 In-flight performance

As the Giotto spacecraft is now well on its way to Halley's Comet, the HMC system has already been tested in space and found to be working with only minor deviations from its expected behaviour.

The camera's imaging capability and quality was demonstrated when, for test purposes, it was turned last October to look back towards the Earth. Pictures taken on 18 and 23 October 1985 from a distance of 2.1 X 10**7 km have been published in ESA Bulletin No. 44 (cover and pp. 96 and 97). The distance was too great to pick out details of the Earth's surface (ground resolution ~= 500 km per resolution element), but the large-scale bright cloud pattern could be clearly recognized, demonstrating satisfactory imaging performance.

4. The Instrument

4.1 Overall Design

4.1.1 Mission and instrument constraints

The spacecraft for the Giotto mission was designed to be a spinning body, and the flyby geometry calls for the spin axis to be parallel to the spacecraft-comet relative velocity vector. The intended very close encounter with the comet immediately imposed a number of constraints on the basic camera design:

(a) The cometary image is always moving (on circles); this would cause a smearing of the image if the exposure time were longer than that needed for a point image to cross a basic resolution element (smearing time). The smearing time depends on the separation angle rho between the spin vector and the direction towards the target, and is obviously shortest for rho=90deg.
(b) The separation angle rho changes during the mission. This necessitated some kind of articulation for the FOV between small and large rho.
(c) Dust will be encountered near the comet, so that the most sensitive parts of an instrument had to be protected by the dust shield against high-velocity (69 km/s) dust impacts
(d) CCDs were selected as image sensors, which need a cooled environment to avoid excessive dark-signal integration.

4.1.2 Basic design

To comply with the above constraints, the basic HMC design was developed as follows. The main body of the telescope, including optics, image detectors, and electronics, has been mounted on the experiment platform of the spacecraft, behind the dust shield. Viewing directions other than 90deg w.r.t. the spin axis are obtained by means of a rotating turret mirror. Cooling is achieved by radiating heat to space, and the short exposure times which would not be possible with mechanical shutters (shortest smearing time for this particular design is 14.2 micro s) are achieved by line-scan imaging.

Line-scan imaging leads to undistorted imaging only for a 90deg separation angle; at other angles the image is not only moving linearly in the focal plane of the telescope, but also rotating. This causes a particular distortion when scanning it by a line detector, but the data can be deconvolved. The limiting case in which the target appears to be exactly on the spin axis would cause some deconvolution problems, because here the image only rotates and has no linear movement. In this case (for separation angles smaller than 0.8 deg) ’on-axis-imaging’ will be achieved by tilting the deflecting mirror (see Section 3.1). A particular problem with a line-scan camera on a spinning platform is the potential ’blind spot’ if the target is on the spin axis, and the spin axis and the optical axis (after deflection by the mirror) are not perfectly parallel; this problem is overcome when the image is moved artificially by tilting the mirror.

The basic design of the HMC is illustrated by Figures 1 to 4. In Figure 1, which is a cross-sectional schematic of the camera, the optics of the telescope and the focal plane, as well as the detectors, are situated behind the dust shield. The 45deg deflecting turret mirror allows the FOV to be parallel to the spacecraft’s spin axis (rho=0deg) The turret mirror allows the HMC to reach rho= 180deg (i.e. the position shown in Fig. 1) by rotation about the optical axis and this together with the spinning motion of the spacecraft, makes it possible to cover the whole sky.

With the turret-mirror design, the detector line has always to be parallel to the deflecting mirror plane, which implies that the detector line has to be turned in the same way as the turret mirror. As a result, the whole camera - telescope, focal-plane detectors, deflecting mirror and baffle - has been designed to rotate as a unit. The detectors need cooling and so it was decided to use the ’knee’ that houses the deflecting mirror as a radiator, and to use the ’barrel’ that houses the telescope as a heat conductor between the Focal Plane Unit (FPU) and the radiator.

The mechanical connections between the moving camera and the experiment platform (bearing, rotation drive mechanism and cabling) were all designed so as to minimize heat conduction from the spacecraft into the camera. The original design goal was to achieve -30degC in the FPU; the final construction yielded >= -20degC, which the detectors can readily cope with.

Figure 3 is a schematic of the telescope system and associated electronics.

In order to help visualize the operation of the HMC, Figure 4 is an attempt to illustrate the taking of a picture. Because of the spinning motion of the spacecraft, the FOV of the HMC covers an annulus on the sky with radius rho during the course of one spin period. If the target (comet) happens to be within this strip as seen from the spacecraft, proper triggering and timing allows the HMC to take image data of just that part of the strip that is centred on the comet.

4.2 Structure and thermal system

4.2.1 Mechanical design

As mentioned in the last section, the optical telescope, with FPU, deflecting mirror (except for its small tilt capability) and baffle, is a mechanically rigid unit. Two support structures, each containing three bearings, and attached to the experiment platform, hold the barrel and allow it to rotate about its axis, which is also the optical axis of the telescope. Two additional bearings control the axial position of the barrel.

The cabling posed a particular problem. From the detectors, the filter wheel, the mirror motor and the position encoders, there are a total of ~ 100 connections between the rotating camera unit and the static part of the system, with all the mechanical and thermal constraints. The solution employed is shown in Figure 6. The wires are the thinnest allowed by ESA specifications, in order to keep the heat input to the rotating unit at 200 mW.

In order to avoid the camera’s rotation having any influence on the spacecraft’s spin period, its nonsymmetric rotating parts (deflecting mirror plus drive and baffle) had to be balanced so that the moments of inertia w.r.t. two axes perpendicular to the rotating axis are equal, to better than 10**-5. This required two protrusions at 120deg to the baffle, which can be clearly seen in Figure 2.

During Giotto’s Ariane-l launch the moving portion of the HMC had to be clamped with two metal strings so that it could not rotate erratically. A pyroelectric cutter was used to release the HMC 39 days after launch.

Figure 6. Cabling between the fixed structure

and the rotating part of the HMC, viewing towards the back of the telescope (FPU = Focal Plane Unit)

4.2.2 Thermal design

The thermal design called for a cooled telescope focal plane, which is achieved by radiating heat to space from a surface covered with second-surface-mirror material (alpha/epsilon ~0.3). The surface radiating to space is approximately 600 cm**2. The attached baffle is painted with white Astral PCBZ paint, and it is sufficiently cold for a negligible amount of heat to be conducted to the knee. The barrel is made from 0.8 mm thick aluminium and conducts the heat from the focal plane to the radiator. The whole rotating unit is coupled conductively to the spacecraft only by the 8 titanium bearings, the worm gear drive and the wiring to the FPU. Radiative coupling to the spacecraft has been minimized by covering the barrel with multi-layer insulation. All aluminium parts have an iridite surface finish. Having thermally insulated the rotating unit, it is obviously of paramount importance to keep the latter’s electrical power dissipation to a minimum. As a result, most of the detector circuitry - except for preamplifiers - is in the electronics box, well separated from the focal plane.

With this thermal design it is possible to cool the camera by passive means despite the fact that (because of the spinning spacecraft) the radiator is periodically exposed to sunlight.

A 26-node thermal model of the HMC was developed to verify first estimates and help in the design. This model clearly demonstrated the feasibility of our design. The FPU temperature is expected to vary between -38degC and -18degC during the mission, as the solar aspect angle varies. The predicted FPU temperature at encounter is -25degC and it will rise during the 4 h of operation by ~ 4degC, due to the electrical power dissipation.

4.3 Mechanisms

As indicated earlier, the HMC has three separate moving subsystems: the telescope assembly as a whole, the deflecting mirror, and the filter wheel. Stepper motors are used to drive the different mechanisms and the overall operation of the HMC is based on counting the step drive pulses transmitted to the motors with the proper sign. Angular position encoders (two potentiometers and one optical/digital) are used on all mechanisms for housekeeping information, so that the user can assess the performance of the mechanisms.

4.3.1 Rotation drive

The rotation mechanism is a worm-gear drive with the wheel mounted directly on the barrel and the worm pushed against it by a spring-loaded lever to prevent backlash. Power is transmitted from the stepper-motor assembly to the worm shaft via a toothed belt. To monitor the rotation movements of the barrel, a high-precision potentiometer strip encoder (read out by a 12-bit ADC) is included in the design. The resistive strip is bonded to the outer surface of the barrel, and the wiper, with associated electronics, is integrated into the foot structure.

Each full step rotates the barrel by 1/100 deg, which is then the basic resolution of the rotation drive. A fixed drive frequency of 1000 full steps per second results in a consant rotational speed of 10deg per second. This frequency was chosen to allow the HMC to follow the apparent cometary motion for flyby distances of 500 km and larger. For closer flybys, there is a point some time before closest approach at which the cometary image will be lost and only regained some time after flyby at rho>90deg, i.e. looking backwards w.r.t. the relative-velocity vector.

A reference position indicator and safety end switches complete the rotation drive mechanism. The reference indicator is an LVDT with voltage zero detection; its moving core is actuated by the rotating barrel. The resolution of this device is better than 0.01deg, which is adequate. The safety end-of-range switches are Reed relays, which cause the electrical driver circuitry to reverse the polarity of the pulses fed to the motor windings; this action is not controlled by the Motor-Control Processor, but rather by the Reed switches only.

4.3.2 Deflecting mirror mechanism

The mirror drive consists of a stepper motor and a worm drive gear that drives a high-precision cam made from a titanium alloy. A lever rigidly connected to the mounting flange of the mirror rides on the polished surface of this cam. The mirror in turn is suspended by two flexural pivots, their centre line being the tilting axis. As the cam turns, the lever follows its outer edge surface and thereby tilts the mirror slowly, the allowed tilt range being 2.2deg around the 45deg position w.r.t. the optical axis. Software limits watched over by the DPU ensure that the lever cannot slide across the steep part of the cam.

Speeds of 11.2 and 5.6 mrad/s, selectable via software by the DPU, are available corresponding to stepper-motor frequencies of 1000 Hz and 500 Hz, respectively. One step has been chosen to correspond to a distance of 22.4 microradians (~= 4.8") in the focal plane of the telescope, which is the size of a pixel for the CCD image detectors used. This was done so that images can be obtained without smearing. The faster mirror speed is to be used for on-axis imaging, while the slow speed will be used for acquiring the target (comet) at the beginning of the encounter operations (Acquisition Mode). A zero-position reference indicator completes the design of this mechanism. It is an LVDT device similar to the one used in the barrel rotation mechanism.

The angular-position encoder for housekeeping purposes is again a high-precision conductive plastic potentiometer; its wiper is rigidly fixed to the rotating cam. The potentiometer is again read out by a 12-bit ADC.

4.3.3 Filter-wheel mechanism

The filter wheel, with its 12 positions, is moved via a spur gear drive by a stepper motor. Four steps are necessary to change from one filter position to the next. A four-channel optical encoder (holes in the filter wheel) reads the correct filter-wheel positions, with a fifth channel (data valid) to indicate erroneous positions between filters.

4.3.4 Motor drive circuitry

As motor currents are high and the stepper pulse shapes can cause a lot of ripple on the supply voltage, the HMC has been allotted two lines from the main power bus, one for the analogue and digital electronics and a separate one for the motors. The motor power line feeds the drive circuits for the motors directly. A filter and a current limiter on the motor line are used to keep inrush current and ripple feedback onto the main bus to acceptable levels. Coupling between the motor control electronics, powered by the converter line, and the motor drive electronics is achieved with optocouplers. Only one set of control and drive electronics is used, as only one motor is allowed to operate at any one time.

4.4 Optics and baffle

The optics consist of two pans, namely the telescope itself and the deflecting mirror. As we have to expect small dust particles to hit the deflecting mirror long before closest approach to the comet, it is necessary to avoid direct sunlight or that reflected from parts of the spacecraft striking the mirror. This would cause a significant stray-light background to the images and a baffle had therefore to be added.

4.4.1 Telescope

The telescope is mounted as a unit to the backplate of the barrel (Fig. 1). It is a modified Ritchey-Chretien design with a correcting field lens and a focal length of 1000 mm. The active diameter of the primary mirror is 166 mm, the maximum compatible wth the HMC’s basic design and the spacecraft constraints. The nonspherical primary and secondary mirrors are 246 mm apart. The secondary mirror is supported by a mu-metal tube and four struts and has no mechanical interface with the barrel (Fig. 1). The geometric focal ratio is F/6.25, and the effective ratio is F/7.7, taking into account the obscuration by the secondary mirror, the support struts and reflection losses at the lens. Taking into account all components, together with alignment errors and the diameter of the Airy disc, we arrived at an estimated width of about two pixels for a point-source image, which has essentially been confirmed since launch.

4.4.2 Deflecting mirror

As the 160 mm diameter telescope’s entrance pupil is situated near the deflecting mirror, the latter has to be elliptical, with minimum dimensions of 160 X226 mm**2. A polygonical figure slightly larger than the minimum ellipse was therefore chosen. The conflicting needs of achieving a good optical figure and keeping the weight quite small (<=650 g) led to a highly unusual design. Starting from a solid slab of aluminium (alloy 7075), material was removed by means of two series of mutually perpendicular holes drilled in parallel to and between the two flat faces of the slab. Structural analysis of this shape was carried out, including the simulation of particle bombardment (Angrilli et al., 1984). The final product has outside dimensions of 244X l90X 17.5 mm**3 and weighs only 658 g.

Particle bombardment studies were also carried out on a number of candidate substrate materials, using explosive charges at the premises of Difesa e Spazio at Colleferro in Rome, and dust particles at the linear accelerator of the University of Kent (Coradini et al., 1982; 1984). One result of these studies was that the usual technique of covering the aluminium surface with a hard layer of nickel-chromium (Kanigen) could not be employed, as the bombardment tests showed that large pieces of Kanigen could be removed by a particle impact. The pure aluminium surface had therefore to be used, with only a thin protective layer of MgF2.

The final quality of the mirror surface was measured in the optical workshops of the European Southern Observatory, with the following results: at 632 nm, 100% of the active surface has a planarity of better than Lambda/5, 94% of better than Lambda/6; 80% of the reflected energy is enclosed in a cone of 20 microradian diameter, closely matching the pixel size of the detector.

The reflectivity was measured at both normal and 45deg incidence in the spectral range from 300 to 1000 nm; the results are shown in Figure 7 for both polarization states.

Figure 7. Reflectivity of the deflecting mirror:
The surface is polished aluminium, with a thin
layer of MgF2

4.4.3 Baffle

The entire baffle system was designed using adapted versions of both the APART and GUERAP software programs, the latter kindly being made available by ESA/ESTEC. Details of this design have been reported by Brunello (1983).

The external cylinder is made from kevlar fibre and the attenuating rings from aluminium. The internal finish is ASTRAL/S2 paint, and the flight model is coated externally with a conductive white paint. The attenuation of the cylinder, whose main limitation is the unfavourable length-to-width ratio as dictated by spacecraft constraints, exceeds the specifications (Fig. 8).

4.5 Focal-Plane Unit

The Focal-Plane Unit (FPU) is made up of the image detectors and associated optical, mechanical and electronic support components, and the filter-wheel assembly. The filter-wheel mechanism has been described in Section 4.3; a description of the filters and their arrangement is more appropriately included here.

4.5.1 The detectors and their readout principle

Two types of photon detectors are used in the HMC: CCD imagers and a double-line photodiode array (reticon). The tasks of the two different detector types and their readout principles are quite different.

4.5.1.1 CCD detectors

The CCDs are virtual phase devices made by Texas Instruments Inc. for portable television cameras. Our special devices were made without the normal anti-blooming drain in the image section. The total sensitive area is organized in 584 lines, made up of 390 pixels, each 22.35 micrometer square.

The operating principle is as follows. An area detector is covered with an opaque mask containing a window that leaves a few lines of pixels uncovered. The slit is located near the ’top’ of the area, i.e. the edge parallel to but furthest from the readout register. If an image moves perpendicularly across the slit, the CCD is clocked synchronously, which means that the charge packets are physically moved at the same average speed as the image. The charge pattern under the mask is representative of the image simultaneously displayed on the top surface of the mask. It is essentially the principle of a slit-shutter camera, the difference being that here the image and the 'detector' (charge pattern) are moving in synchronism while the slit is stationary w.r.t. the optics; in the slit shutter camera, the slit moves across the detector plane while it is illuminated by a 'still' picture.

Electronically speaking, the masked area CCD is a line detector with an analogue storage area attached to it. Once clocking has been stopped, other parts of the image may move across the slit without contaminating the part of the picture under the mask.

Figure 8. Stray light propagated through the baffle as a function of incident-light-beam angle theta. A = transmitted stray light/incident light

The reason for using this intermediate data storage is that lower noise readout is possible at slower than real-time readout rates. Real-time readout in our case would require a maximum of 2.7 X 10**7 pixels per second. By contrast, in the system flown the total area is read out in 3.2 s, leaving some time for overhead within the 4 s spin period. The data rate is 73 pixels/s (or 13.75 micro s per pixel), allowing low-noise readout and easier data handling even with a 12-bit ADC. On the other hand, the long residence time of the pixel charges allows dark current to accumulate and therefore the device has to be cooled mildly, in our case to less than -20 deg C.

An additional advantage of using masked-area detectors as line detectors is the potential use of a TDI (Time Delay and Integrate) technique for fine tuning or optimizing exposure times. If several lines of pixels are exposed under a slit, and the image and the charge pattern move on average in synchronism along the columns, then the smearing time is governed by the individual pixel height (because of the incremental movement of the charge packets), but the exposure time is governed by the total height of the exposed column of pixels and therefore can be longer than the smearing time. If lateral movements of the image are included, however, as in our case of the rotating image for rho << 90deg, then another smearing time across the columns has to be taken into account.

In the actual flight detectors, two groups of 292 lines each can be clocked independently and both read out through the same readout register. In television applications, the upper area is used for imaging, and the lower area for intermediate analogue data storage and readout whilst the next picture is being integrated in the upper area. Our specially fabricated detectors have a uniform layout and gate structure so that both areas can be used for line imaging and storage in the same way. The only difference between the two areas is that the image stored in the upper one has to wait at rest until the lower one has been read out. Only then is the upper charge pattern shifted into the lower section before read out. The upper area will therefore accumulate somewhat more dark signal than the lower one.

The virtual phase CCDs have the advantage that the thermal dark charge generation rate is greatly reduced - as much as an order of magnitude compared with conventional multiphase devices - so that testing with several seconds of integration/readout time can conveniently be conducted at room temperature. As a side effect, however, another type of dark signal that has been termed 'spurious charge' is generated which depends on clocking amplitudes and wave forms rather than integration time. In addition, noise in these devices is somewhat larger than in other CCD devices, because the output amplifier has been optimized for high gain and speed (for easy TV applications) rather than for low noise.

Figure 9 shows the spectral response of the virtual-phase CCD. A special characteristic of this device is that its gate structure covers only half of each pixel, the other half being covered by a 0.1 micrometer SiO2 protective layer only. Therefore, in contrast to other CCDs, some sensitivity at Lambda<400 nm is preserved. The multiple peak structure in the response is caused by interference in the uniformly very thin gate structure.

4.5.1.2 Line detector diode array

An additional line detector placed in ’front’ of the CCDs, in the sense of the moving image in the focal plane, performs two functions: it will be used for finding the cometary image at the beginning of encounter operations, and for timing the picture-taking correctly even in the presence of spacecraft attitude disturbances near the cometary nucleus. In both cases near-real-time readout and fast data processing will be required. This detector line has to be longer than the CCD lines, and as high a sensitivity as possible is required.

The detector chosen is a CP 1001 reticon diode array, which consists of two rows each of 936 pixels, without dead area between. The pixel size along the row is 30 micrometers, and the pixel height across the row is 375 micrometers. The total sensitive area is therefore 28.08 mm X 0.75 mm. The double row was chosen to guard against the cometary coma being rather faint at the beginning of encounter operations. This needs a large detector, which in turn will be hit frequently by cosmic rays, causing spurious events.

Figure 9. Spectral response of a CCD. Points for Lambda>400 nm are from the supplier and those for Lambda<400 nm from our own measurements (line E, clear channel)

As the image of a celestial object moves across the double line, it will cause a response of at least two opposite pixels, one in each row. Almost point-like cosmic-ray events, however, can cause coincident signals in opposite pixels only if they impact very close to the dividing borderline, and therefore the requirement of coincident signals keeps the sensitive area for cosmic-ray-induced events small while offering the full height of the pixels for a moving image.

The detector can be read out in either of two modes, ’slow’ or ’fast’. The need to drive this detector at vastly different pixel readout rates caused some headaches. Normally, the fixed pattern of offsets can be minimized by lowering the clock amplitude. However, since safe fast (MHz) operation can only be achieved with high amplitudes (>= 11 V), this feature could not be used to our advantage. Fortunately, it turned out (for our method of clocking and driving the clock lines) that a relative minimum in fixed-pattern amplitude could be achieved for both clocking speeds at the same clock amplitude. With onboard fixed-pattern determination and subtraction, this finally did not cause a major problem.

4.5.2 Mechanical arrangement

4.5.2.1 Detector arrangement - virtual focal plane

As has been pointed out, the image data are gathered by a line-scanning technique. In order to obtain several colours almost simultaneously for pictures, four CCD detector lines with different colour filters superposed are placed in parallel in the focal plane so that the image crosses all four of them in succession. The path of the image in the focal plane will generally be a circular arc due to the spinning motion of the spacecraft, the radius being the tangent of the separation angle rho. The virtual focal plane is illustrated in Figure 5.

If rho is sufficiently large, all four detector lines are crossed and, once the data have been properly deconvolved and matched, a colour picture can be constructed. As there is some uncertainty in the movement of the image due to spacecraft nutation and, in the late phase of the encounter, dust impacts on the spacecraft, another wider line detector has been added in front of the four colour lines so that the image crosses the wide detector first. Very fast readout and real-time analysis of this detector’s signals will be used for ’triggering’ the instrument. Rho and the spin period define the speed of the image, and when the image’s crossing has been recognized by the wide line, the timing of the data acquisition of the colour lines is adjusted so that image data around the centroid of brightness are gathered and stored for subsequent transmission to the ground station. The width perpendicular to the direction of motion of the image of the triggering detector is larger than for the other detector lines, so that triggering will not be lost if the cometary image ’jumps’ occasionally due to dust impacts. In addition, the wide line will be used during the ’Acquisition’ phase of encounter operations to search for the cometary image in a 4.4deg X 4.6deg field, and compute the parameters of its movement in the focal plane. Thereafter, data acquisition can be placed accurately in space and time centred on the cometary image.

4.5.2.2 Detector arrangement - actual focal plane

As the housing of a detector (CCD and diode array) usually takes up significantly more space than the detector chip itself, it proved impossible to get two CCDs and the line array sufficiently close together to make an image plane of practical size without a special CCD development programme. Two plane mirrors were therefore introduced in front of the focus so that the two CCDs could be physically well separated, with their sensitive lines nevertheless close together in the virtual focal plane. A schematic cross-section through the FPU (Fig. 10) shows the arrangement of the individual detectors and the filter wheel, and how a converging beam of a moving star-like image successively crosses detector lines A to E.

4.5.2.3 Filters

The CCDs are covered by different filters, as already mentioned. Care has been taken to compensate for the different filter-glass refractive indices and light wavelengths by choosing the thicknesses such that the focus through all filters lies on the CCD surface, and the heights of the windows in the CCD masks differ in order to compensate somewhat for the differences in expected signals.

Figure 10. Schematic of detector arrangement in the Focal Plane Unit. The path of a converging beam from a pointlike image through the field of view is also shown

In addition to the wideband filters for acquiring near-simultaneous pictures in different colours on different detectors, in front of one of the detectors there is a filter wheel with 10 different narrowband and polarization filters, a clear filter, and a shutter which can be changed from one spin period to the next. These filters are intended mainly for the observation of gas and dust in the cometary coma when the spacecraft is still far from the nucleus. All available filters, fixed and exchangeable, are listed in Table 1.

4.5.3 Detector electronics

The detector electronics are mainly housed in the electronics box, which also contains all the electronics for the digital processing unit, motor-drive circuitry and DC-DC converter. The preamplifiers for the detectors are housed within the FPU. The FPU housing is electrically insulated from the structure and the telescope barrel, and connected to the signal ground of the most interference sensitive detector, the diode array. The CCD circuitry return lines are connected to signal ground inside the electronics box. This has resulted in acceptable performance for all detectors. The detector electronics have been described elsewhere (Kramm & Keller, 1985; Meyer et al., 1985) and a short description should therefore suffice here.

4.5.3.1 CCD electronics

The CCDs are read out by Correlated Double Sampling (CDS), a method widely used for low-noise readout, and the signals are digitized in a 12-bit ADC. In order to improve on dynamic range, a factor 4 gain switch has been included, so that the total dynamic range is equivalent to a 14-bit word length. Each step in the low-gain range contains 150 electrons, so that the full range of signals (up to 5 X 10**5 electrons full well capacity of the CCDs) is covered. The clamping time of the CDS circuitry is 1.25 micro s, and the clamp-to-sample time is 3.25 micro s. The total cycle time per pixel is 13.75 micro s, and as both CCDs are read out in parallel (staggered so that a digitized signal is transferred to the DPU every ~ 7 micro s), the total readout time for twice 584 lines each with 390 pixels is 3.2 s. If only half of a CCD is read out, or ’super pixel’ readout is used (one of which is generally the case), this total time is even shorter leaving sufficient time for calculations and repositioning of the telescope within one spin period of the spacecraft. The term ’super pixel’ applies when charge packets of several pixels are summed physically on the charge sensing node of the output gate of the CCD, thereby effectively increasing the size of the resolution element on the CCD. As signal noise is dominated by the noise of the first stage of the output amplifier, the super-pixel readout results in higher sensitivity (and at the same time a larger field of view) at the expense of spatial resolution. Readout noise levels of 25 electrons equivalent r.m.s. on the laboratory bench and 75 electrons equivalent r.m.s. within the full working HMC electronics system have been achieved. The latter value was confirmed during post-launch spacecraft operations but there appears to be some interference from other experiments on board Giotto.

The clocking of the CCDs has to be rather versatile. The typical sequence of clocking during one spin period consists of: (a) dumping of dark or other parasite charges, (b) acquisition of data, and (c) readout.

(a) The charge dumping is achieved by clocking the lines at 13.75 micro s per line and the serial readout register at 0.625 micro s per pixel, the highest available clocking frequency. Square waves with somewhat ’softened’ edges between about -17 V and +1 V are used.

(b) Data-taking speed has to be synchronized with the speed at which the image crosses the window in the mask. Periods of 1 ms per line (for ’on-axis-imaging’), and 14.23 micro s per line when the comet’s aspect angle is 90deg, have to be accommodated. This clocking is done by ’tri-level-clocking’ , in which the positive- (+1 V) and negative-going parts (-17 V) of a bipolar pulse for shifting the charge packets are about 7 micro s each, and in the variable interval between two successive bipolar pulses the ’mid level’ of approximately -6 V is maintained. With this type of clocking, the virtual-phase CCD generates increased dark current (like other ’regular’ CCDs), but little spurious charge, provided the interval between the negative-going pulse followed by the positive-going pulse is 50 micro s or longer. For shorter intervals, increased spurious charge cannot be avoided.

(c) During readout, the potential of the gates in the imaging area is held negative during most of the period in which the serial register is being read out. During this 5.4 ms, the rate of dark charge generation is low. About 50 micro s prior to the next shifting of a line of charge packets into the serial register, the gate voltage is raised to the mid level of -6 V, followed by a 7 micro s positive pulse, the trailing edge of which goes to the negative level of -17 V again. During the 50 micro s at mid-level the dark charge generation is normal, which is not a problem due to the low duty cycle. The spurious-charge generation during line shifting is held to a minimum because the time between negative and positive levels is sufficiently long. With this type of ’mixed mode’ clocking, the spurious-charge generation during readout is restricted to less than 500 electrons per pixel, while with bi-level clocking (without the 50 micro s mid level pedestal) the same devices generate up to 10**4 electrons of spurious charge, per pixel.

4.5.3.2 Diode-array electronics

The two lines of the diode array are each connected to two video lines. During comet acquisition, the whole array will be used, and the readout order is cyclical w.r.t. all four video lines (slow readout). During nucleus imaging, only one array is to be used (fast readout). A particular complication is that the analogue circuitry’s frequency response had to be sufficiently wide to accommodate the two switchable frequencies of about 10.9 k pixels/s and 2 M pixels/s (both per video line). This has been achieved by actually switching the preamplifier bandwidth, and using two separate signal chains thereafter.

Slow readout is the high-sensitivity, low-noise readout mode. All four video lines are read out cyclically, each with a 92 micro s repetition period. The video line is connected to the virtual ground input of the preamplifier. There the charge pulse is converted to a voltage pulse, decaying with a time constant of about 20 micro s via a 39 Mohm feedback resistor and its associated parasitic capacitance. Any influence of a not fully decayed pulse on the next one is removed by Correlated Double Sampling (CDS). The CDS integrator takes a dark sample just prior to the arrival of a pulse and stores it in a capacitor on one input of an operational amplifier; thereafter, part of the pulse is integrated on the other input of the operational amplifier. The output of the integrator is fed via a four-channel analogue multiplexer into a 12-bit ADC. The ’fixed pattern’ of offsets inherent in the diode array’s operation is subtracted after digitization in the DPU. The offset pattern is recorded onboard just prior to any operation of the HMC, so that long-term changes do not play a role.

Noise levels of 1300 electrons equivalent r.m.s. on the laboratory bench and 3000 electrons r.m.s. within the fully operating HMC system have been achieved. The noise on the bench was dominated by the particular switchable fast pulse preamplifier that we have to use. A quick check with a slow, low-noise preamplifier in its place showed that the system is capable of as low as 600 electron equivalent r.m.s.

Fast readout is used during Nucleus Mode. The object is to read out the array so fast that its output can be assessed before the part of the image that is being evaluated has reached the end of the uppermost CCD area, which is the storage area of line B. This time interval can be as short as 6 ms.

To speed up the readout, only one of the two lines is used, the other one being available for backup on command. Furthermore, pixels are grouped in pairs by summing the signals of the two video lines for simultaneous readout. This results in 468 double pixels per single array, which is read out at 2 M pixels/s. For this fast operation, the bandwidth of the preamplifier on each video line has been increased by shunting the 39 Mohm feedback resistor by a network of 1.5 kohm and 4.7 pF in parallel. The charge pulses on the video lines are thus converted into fast voltage pulses, summed in pairs, further amplified and fed to a 7-bit flash ADC with a response time of a few nanoseconds (made from two 6-bit interated-circuit flash type AD 3000 ADCs from RCA). Fixed-pattern offset correction is again effected by the DPU, after having recorded the pattern just prior to any operation. Noise levels less than 15000 electrons equivalent r.m.s. within the fully operational HMC system are achieved in this way.

4.6 Digital Processing Unit

The Digital Processing Unit (DPU) can be divided into four ’levels’:

(i) interface to sensor electronics
(ii) the fast-event-driven preprocessing of sensor data by special hardware processors, which are supported by one of the microprocessors (signal processor)
(iii) two universal microprocessors (Experiment Control Processor and Motor Control Processor) for
  - evaluation and formatting of measured data
  - servicing of Spacecraft interfaces
  - servicing of status and command interfaces to sensor electronics and drives
(iv) the interfaces to the Spacecraft.

The requirements of levels (ii) and (iii) differ basically in their response time to critical requests (microseconds as opposed to milliseconds).

Figure 11 shows the structure of the DPU. In level (ii), the sensor data first pass the preprocessors (PP) to reduce the data rate for subsequent processing by the signal processor (SP). Special features of the SP are the support of the NSC 800 microprocessor by a hardware multiply/divide unit and the special interrupt service routines with their five hierarchical levels.

In parallel with the extraction of some specific parameters from the sensor data in the block acquisition preprocessor (ACQ PP), tracking preprocessor (TRACK PP) and signal processor (SP), the original CCD data are stored in their entirety in the mass memory after word-length shortening by a square-root function (SQR COMP, basically a 12-bit to 8-bit lookup table). It is possible to store part of the image in the empty half of the telemetry buffer. The size and allocation of this small image (max. 16 k pixels) can be selected by the SP.

The level (iii) tasks are assigned to two NSC 800 microprocessor systems. The Experiment Control Processor (ECP) controls the data transfer to telemetry, receives the telecommands and is responsible for the image sequences. In some particular spin phases, control data have to be sent to the diode array electronics and the CCD electronics, as well as to the drives for telescope rotation, mirror tilting and filter-wheel positioning. The pulse generation for the stepper motors and control of the movements

Figure 11. Schematic of the Digital Processing

Unit

performed are the responsibility of the second NCS 800 system (Motor Control Processor = MCP).

The three microprocessor systems communicate with each other via mailboxes between the SPU bus and the ECP bus, and the ECP bus and MCP bus.

4.6.1 Acquisition Preprocessor

Figure 12 shows the structure of the Acquisition Preprocessory During the acquisition phase, a 4.4deg X 4.6deg field of view is searched completely by the diode-array line detector. Each extended object produces a stripe of bright pixels. The ACQ PP generates five characteristics parameters for each hit:

- the address of the last pixel
- the stripe length in pixels
- the number of the line in that scan (= mirror position)
- the number of the scan
- the hit time.

The task of the ’Fixed Pattern Correction’, ’Threshold’ and ’Single Spot Rejection’ blocks is to clean the real diode-array signal of noise and offsets and to compress it into single-bit information (dark/bright). The resulting hit is only accepted for further calculations if its extent is at least 2 pixels in the horizontal and vertical directions.

The ’CCD Trigger Delay’ is used to stop the clocking of the CCD a well-defined time after the comet’s image has crossed the diode array (used in Nucleus and Observatory Modes). This delay time depends on the transit speed of the cometary image.

The Acquisition Preprocessor reduces the data rate from l pixel per 23 micro s to about 1 byte per 2 ms, because the readout of hits is limited to five hits per line, equal to 25 bytes per 50 ms. The data rate is therefore reduced by a factor of about 100.

Figure 12. Schematic of the Preprocessing unit
for diode array data (Acquisition Unit)

Figure 13. Schematic of the preprocessing unit
for imager data (Tracking Unit)

4.6.2 Tracking Preprocessor

The task of the Tracking Preprocessor (Fig. 13) is to determine the intensity centre of the CCD image. This point is the input variable to the tracking program and also the centre of the small image section that is transmitted to ground. The telemetry rate of 20 kbit/s = 10 kbyte/spin allows transmission of only 98 X 98 pixels.

To determine the brightest area of the picture, the full image is divided into 24 X 20 elements (’bins’) of 16 X 14 pixels each, and the intensity of these 224 pixels is accumulated for each bin. The sum is stored in the ’Bin Intensity RAM’. The SP searches for the brightest bin in this memory and requests the ECP to transfer an image area of 32 X 28 pixels around this central element from the mass memory to the SPU. This area is used to calculate the centroid of brightness. Its coordinates and the hit time constitute input parameters for the tracking program.

The three anterior blocks are intended for the correction of defective columns of the CCD, by replacing them by their respective adjacent column, as well as the noise suppression. At the time of writing, no badly defective columns requiring this correction have been found.

4.6.3 Mass Memory

The Mass Memory is able to store a full four colour image of the four CCD sections. After compression of the CCD data into 1 byte, there is a net capacity of 4 X 391 X 292 X 8 = 3.65 Mbit necessary, which increases to a total of about 6 Mbit due to the use of Hamming correction. This has been implemented by using 96 X 64 k DMOS devices. The minimum cycle time is 4 micro s, which is associated with a maximum power dissipation of 4.6 W. This relatively low consumption can be achieved by

’power strobing’ of the peripheral electronics.

4.6.4 Structure of the SPU sofware

Figure 14 shows the SPU software’s structure. All routines that communicate directly with the hardware are included in the ’operating software’ block.

The hardware-oriented ’operating software’ surrounds the software kernel that contains the mathematical algorithms for calculating the acquisition and tracking parameters like a shell. These programs are exclusively software interfaced to the outer shell and could be written and tested without knowledge of the hardware. The ’acquisition’ and ’tracking’ programs, which are activated in sequence, contain a set of common subroutines for floating-point operations, coordinate transformations, averaging, trigonometrical functions, their inverse functions, etc.

The program request service is controlled by the ’interrupt service routine’, whilst the ’abbreviated functional test’ program automatically checks the hardware function after switch-on. The result is transmitted to ground via telemetry. This test provides quick information about the status of the instrument.

Figure 14. Overall structure of the Signal Processing Unit’s software

5. Ground-Support Equipment

The role of the ground-support equipment was to simulate the various subsystems and the HMC as a whole as an aid in their development. Part of the Electrical Ground-Support Equipment (EGSE) has also been used at the European Space Operations Centre (ESOC) in Darmstadt for quick-look and preliminary-data-evaluation purposes.

5.1 Electrical Ground-Support Equipment

The various functions of the EGSE during the development of the HMC are shown schematically in Figure 15:

(a) First of all, the EGSE provided correct spacecraft interface simulation to the Digital Processing Unit (DPU).

(b) Wherever the HMC had to be operated without the help of the DPU, the EGSE provided a correct simulation of the interface between the sensor electronics and the DPU, so that the HMC could be actuated, and data could be retrieved for evaluation.

(c) To test the DPU in the absence of individual detector or analogue electronics idiosyncrasies, the EGSE provided a simulated sensor electronics interface. Here the EGSE calculated ’images’ of the comet, simulating their apparent movement during a complete encounter scenario so that both the DPU functions and the acquisition and tracking algorithms could be tested.

(d) The EGSE was also used as a spacecraft simulator and quick-look facility for testing the whole system realistically with the opto-mechanical ground support equipment, which simulated an encounter scenario by projecting optical images into the HMC.

(e) The EGSE is still being used as a quick-look instrument during flight.

The EGSE hardware consists of two computers, each with specific characteristics which determined its choice. The central or host computer is an LSI 11/23 mini computer with hard-disk and tape storage and various peripheral interfaces. It provides the user interface to the EGSE, because of its programming comfort and flexibility. It has been used to develop software, execute test routines, store data, manage the operation of the EGSE and communicate with the spacecraft checkout equipment.

Figure 15. The Electrical Ground Support Equipment (EGSE) and its uses in different configurations with the HMC system

The software is written in Pascal and all programs requiring user modification during development of the camera, such as monitoring of telemetry data, generation of test routines and calculation of spacecraft motion and images for the dynamic simulation, are resident in this computer. Uncorrected quick-look image display and the generation of synthetic images for simulation are provided by this computer. Communication between the host computer and the variety of asynchronous ’real-time’ camera interfaces is performed by the interface computer, which is connected to the host by means of a bi-directional Direct Memory Access (DMA).

The interface computer contains all of the ’real-time’ interfaces, which closely simulate the electrical characteristics of the spacecraft, as seen by the HMC, such as voltages, impedances, timing and logic. It also provides preprocessing of telemetry data before transmission to the host for subsequent display and storage. All interfaces are serviced by the MC 68000 microprocessor-based interface computer under the control of the host machine (Fig. 16).

Dynamic closed-loop simulation is provided by combining motion control output from the HMC microprocessors in the form of demanded telescope rotation and mirror tilt angles with simulated spacecraft body motion to generate the focal-plane dynamics in free space. The fact that the HMC focal-plane interface involves high-resolution images of several hundred thousand pixels of motion-corrected images for a single 4 s revolution of the spacecraft limited the practical simulation to small-area comet shapes with a constant background. Even so, the large amount of computation necessary for the geometrical distortion, motion and image generation, permits only quasi-real-time dynamic simulation. This is achieved with the use of halt states for the flight computer, while the EGSE calculates new images. Simulation is controlled by the host computer, which calculates the relative trajectory of the comet, the spacecraft body motion and the attitude of the Sun. Considerable effort was expended on the acceleration of simulation and reduction of halt time, by simplification of the motion algorithm and elimination of redundant image generation. This has resulted in a run-time factor of approximately 4 X real time for the most complex Nucleus-Mode simulation.

The development of the HMC EGSE has served to demonstrate the feasibility of quasi-real-time closed-loop dynamic simulation of complex image-input systems by the appropriate combination of fast microcomputer-controlled hardware interfaces and a general-purpose minicomputer.

5.2 Opto-Mechanical Ground Support Equipment

An opto-mechanical simulator facility was built at the IAL in Liege, Belgium to simulate the encounter scenario by actually projecting a moving cometary image into the HMC. The movements of the image (spin motion, nutation, change of aspect and spin phase) were simulated by using a turntable and articulated mirror. Large aspect angles were achieved by having the HMC itself mounted on a turntable, so that large camera rotational movements were compensated by counter-rotating the turntable. The whole simulator was set up in a vacuum chamber, and a liquid-nitrogen-cooled heat-sink plate was installed opposite the radiator plate of the HMC for realistic simulation of its radiative cooling.

Figure 16. Simplified block diagram of the
Electrical Ground Support Equipment (EGSE)

For extended room-temperature testing in air during the development of the software, a small opto-mechanical simulator was constructed at MPAe in Katlenburg-Lindau, which also used a turntable to compensate for large HMC rotation angles, and a moving spot on an oscilloscope as a cometary object.

6. Data Evaluation

The specific nature of the images to be taken by the Halley Multicolour Camera during the Giotto mission called for the design and installation of a dedicated image-processing system by DFVLR. The cometary images are taken by CCD sensors with non-uniform pixel response. The motion of the rotating and nutating spacecraft results in geometrical distortion and the image-processing system had therefore to be designed to correct for sensor and motion effects, as well as to enhance and analyze images of as yet unknown content.

The HMC image-processing system has been designed as a flexible configuration based on:

- reliable standard hardware (32-bit processor)
- proven multi-user operating system
- independent multi-workstation concept
- image database and powerful image engineering tools
- a high-level image interpreter language as the principal user interface.

A user can run existing software or develop his own algorithms. This is especially useful if different image processing methods have to be compared, such as time-delay-integration effects, readout noise or blurring caused by motion.

The internal hierarchy of the image processing system is depicted in Figure 17.

The resulting structure is characterized by an image database with uniform storage and access conventions and an image-processing library which provides routines for the database access, device I/0 support and a toolbox of image-processing subroutines.

Figure 17. Internal hierarchy of the HMC’s image-processing system

The application package contain programs for:

- telemetry and calibration data input
- validation of images
- radiometric correction of images
- restoration of pixels
- geometric rectification
- enhancement
- image registration
- scientific-evaluation support

The extensive resources at the disposal of users of the image-processing system include colour-slide production and various hardcopy facilities.

Acknowledgements

Very many people have collaborated in putting the HMC together and thereby contributed to the success of this experiment. Aside from their hardware and software contributions, J. Turner, G. Scwarz and E. Krahn contributed to the writing of this paper. For their numerous contributions to instrument hardware and software, we would also like to thank F. Angrilli, C. Becker, G.A. Bianchini, P. Bouyries, P.F. Brunello, W. Curdt, M. Coradini, A. Cucchiaro, W. Degenhardt, J. Degewij, W. Engelhardt, F. Gliem, M. Gull, H. Hartwig, J. Koyro, R. Kramm, A. Loidl, J.P. Macau, D. Macau-Hercot, H.J. Meyer, H. Michalik, E. Mikush, E. Prager, E. Ress, H. Reffel, P. Rober, P. Ruffer, E. Schmidt, H.P. Schmidt, H.U. Schmidt, K. Schmidt, R. Schmidt, R. Seifert, P. Stelter, K. Vo1k, B. Wand and U. Zahoransky.

Last but not least, we wish to thank all the technical and administrative personnel at the various contributing institutes and companies without whose active support it would have been impossible to complete this novel project.

References

Angrilli F, Bianchini G & Fanti G 1984, Dynamic analysis of a pierced plate under impulsive loading. In: Numerical Methods for Transient and Coupled Problems, 2nd Int. Conference on Numerical Methods, Venice, July 1984.

Brunello P F 1983, Conceptual Design and Stray Radiation Analysis of Baffling Systems for Space Applications, Istituto Fisica Tecnica Report 114, Univ.

Padova, Italy.
Coradini M, Flamini E, Hurren P, Martelli G & Smith P N 1982, The effects of microparticle hypervelocity impacts on various surfaces etc. In: Comparative Studies of the Planets, D. Reidel Publ. Co., Dordrecht & Boston, 367-387.
Coradini M, Etenardi A, Flamini, Hurren P, Martelli G, Smith G N 1984, Modification of the optical properties of several materials following microbombardment, Anna l. Geophysica 2, 1,47-52.
Kramm l R & Keller H U 1985, Getting more by taking less: A method of summing up pixels on a CCD Imager, Adv. Electr. Electron Physics 64, 193.
Meyer H l, Schmidt W K H & Rosenbauer H 1985, Reticon Detector Electronics for the Halley Multicolour Camera, Adv. Electr. Electron Physics, 64, 223.