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Servicing mission of HST. One way to tell is the semi loaded space shuttle bay to deliver upgrades. (Rendering, NASA)

Contents

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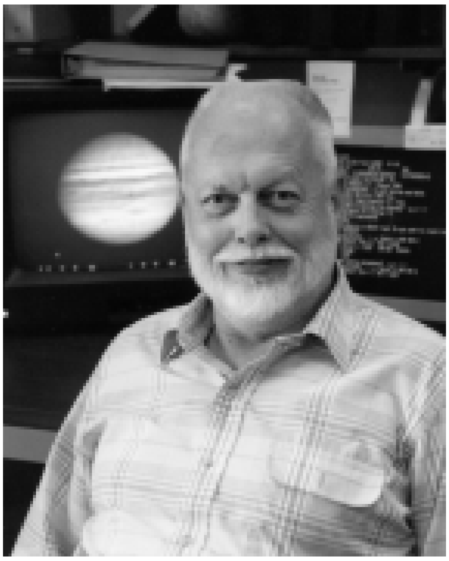

Image Courtesy, CALTECH

This issue Dedicated to:

Jim Westphal was the director of Caltech's Palomar Observatory from 1994 to 1997, and the first principal investigator of Hubble's Wide Field / Planetary camera WFPC I. He started his career at Caltech in 1961, and had a warehouse lab at caltech filled with optomechanical parts, and electronics components, and tools to make instruments. He was by all means a practical academic, an inventor, engineer, and astronomer.

Jim was a respecged man in astronomical community with his humble appearance. He was a professor of planetary science at Caltech, Pasadena. He had an interesting philosophy: 'There are always two ways to deal with a problem: You can get angry and upset and then try and fix it, or you can just fix it. Which way would you rather work on it?'

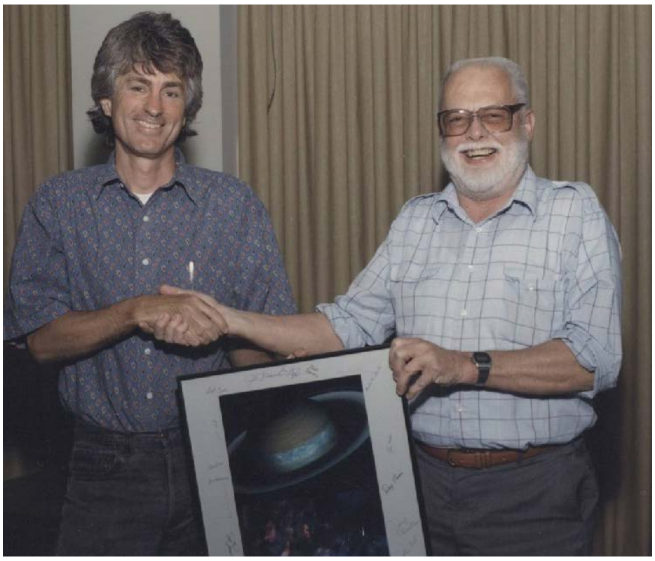

Image Courtesy, JPL

Left, Jim Westphal and Janesick shake hands, holding a photo of Saturn storm captured by Hubble Space Telescope. Jim Westphal gave most of the credit to amateur astronomers who had spotted the activity on Saturn, and notified the HST Science Institute to break from its normal schedule, and repoint the telescope to Saturn to record that historical activity.

Janesick was the research engineer behind the CCD device used in WF/PC. Jim Westphal first tested the CCD's performance at the focal plane of the 5 meter Hale telescope at mount Palomar before qualifying it to install on the WF/PC. During his career, Jim Westphal wrote 133 scientific papers.

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Optomechanix is a quarterly journal of Opto-Mechanical Institute of Design (OMiD), with technical articles for practical, hands-on opto-mechanical engineers. This magazine is privately founded.

Cover page photo: Hubble Space Telescope orbiting the earth, courtesy of NASA

Inside page photo: A rendering of Hubble's upgrade by Space Shuttle Discovery, new solar pannels

Remembering WF/PC II

This is a special issue that will go over one of the instruments inside HST. I worked at JPL during Hubble's servicing mission, and at the time, I was a contributor to Shutterbug magazine, and the current article was my assignment to write a descriptive article of the space telescope back in 1992. Hubble is the most famous space project around the world, second to the moon landing mission, and it's because of its beautiful images sent back to earth. With Hubble, scientists realized that the edge of universe they were looking for is expanding away from us at such speed (from Big Bang) that it would need a deep infra red instrument (James Webb) to observe it, and through a much larger aperture.

HST was first envisioned by Prof. Layman Spitzer (1914 – 1997), a theoretical physisist at Princeton. However, he never had imagined it would be at a cost of 4.7 billion dollars. It is now almost 29 years that the Hubble space telescope is in orbit, and scientists and engineers at Jet Propulsion Laboratory have delivered their second, and third Wide Field/Planetary instruments. NASA's space-walk mission to repair the Hubble was scheduled for late 1993. The WF /PC-II had two main missions: To upgrade the WF /PC-I instrument, and to fix Hubble's aberrated image with its new corrective optics.

I will explain how a picture was taken through the space telescope using WF/PC, and how it was sent down to the Space Telescope Science Institute (HSTSI). Things like how CCDs (Charge Coupled Devices) work, and the optical design of the telescope, will be presented with a non technical-illustrative approach. I will show you how to make a full size model of the WF /PC optics, and how the instrument's on board computer program can be changed while orbiting in space. In spite of the existing spherical aberration of Hubble, and the corrective optics that was later installed, scientists had reasonable success in using image processing techniques such as de convolution, which subtracted the known aberration from the images to create

Image Courtesy, Princeton

Prof. Layman Spitzer the visionary scientist behind HST

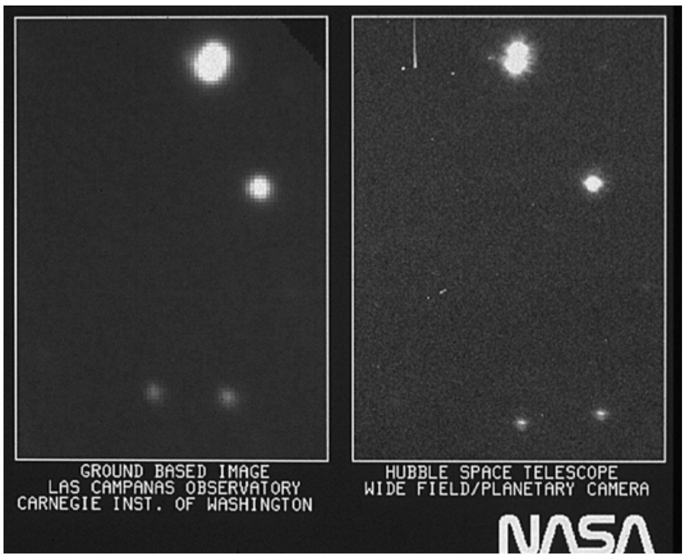
Image Courtesy, Caltech

Art Vaghn (1934 - 2015) was the chief optical designer of WFPC. He was strong supporter of historic Mount Wilson preservation.

Image Courtesy, Perkin & Elmer

HST's primary mirror made to the wrong shape by an error at Perkin & Elmer plant. The accuracy of the mirror shape was ground to reach 1/60 λ! (less than 1/120 microns)

Image Courtesy, NASA



The first image taken through HST revealed Hubble's flaw in its primary mirror. Its image (right) looked almost identical with ground based telescope image (left).

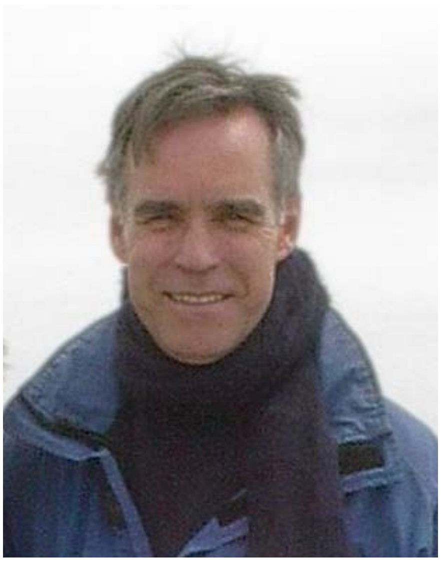
Above-left, an astronaut riding on the 15 meter canadian made robot arm to complete the installation of Hubble in space. Right, the solar pannels are shown in deployed position, fully extended out by Bistem tubes (see text for details).

good results.The de convolution method was useful in bringing out the shape of stellar or planetary objects, but it degraded the relative value of individual stars in the brightness scale. So while the perfect telescope was capable of resolving 0.07 arc seconds, it was still capable of resolving up to 0.12 arc seconds before WF/PC II upgrade. Opposite page, bottom, shows the first picture taken through the space telescope with the Wide Field Camera. The diagonal field of view of this image is 227.6 arc sec. In the telephoto mode, the field of view is switched to 97.3 arc sec. The Saturn image (page 37), was taken by using only a quadrant of HST's field of view in the telephoto (planetary) mode.

The Trouble with Hubble (The ryme that bothered NASA for over 3 years)

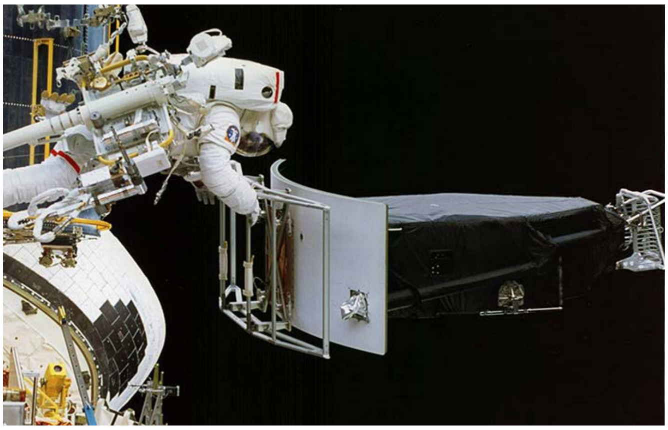
When Hubble was launched, everyone was excited about its results but after the discovery of Hubble's spherical aberration, most got discouraged, and thought it was hopeless. Only few had an idea how it could be fixed, and a plan to repair the space telescope was first presented to the public on June 27, 1990. I remember those days, and what a big toll it had on NASA's reputation. So people at JPL set about fixing the Hubble with the WFPC II upgrade. JPL team had sent up a perfect WF/PC I in space but now they had to let go of one of its useful original features (such as focus/magnification change) in order to guarantee its exact alignment with Hubble's opical axis to cancel out its spherical aberration.They worked with a small budget of $24 Million, while the costar upgrade cost $50 Million to turn a failure into success. As I will show later, a perfect idea (the pyramid mechanism) inside WF/PC I was abandoned so they could save the telescope. This is a great example for "A good design doesn't mean it's better, it's because it works."

John Trauger was PI (principal investigator) of WF/PC II



Bob Chave was the designer of Stimulus for testing WF/PC II instrument

Lloyd adams 1934-2009, was primary opto-mechanical designer of WF/PC



Astronaut Jeffrey Huffman pulled off the original WF/PC I from HST on December 1993, returned to earth onboard SSD.

Cored holes on WFPC II's white radiator were made to remove impact craters for engineering inspection. Courtesy, SNASM

Another great idea that they had to let go of was called the Bistem that deployed the solar arrays. The original idea worked similar to a carpenter's measuring tape, except there were two tapes facing each other, forming a rigid tube. When unrolled, the Bistems were fed out of a cassette simultaneously in opposite directions, forming tubular supports on both sides of the solar arrays, pulling out the blankets to a full deployed position. To stow the solar arrays, the bistems were rolled back into the bistem cassettes. The solar arrays generate a 34-volt output of up to 4000 watts.

In spite of their clever design, the space telescope had a few problems with changing temperature as it moved into, and out of sunlight. The solar arrays deflected back and fourth up to a meter at their tip. This was due to the individual semi tubular tapes of bistem supports, that expanded and contracted differently, depending on their angle with the sun. The sliding action of these supports also caused vibration, which affected the image stability of the telescope. If left alone, the bistem supports would have eventually collapsed, shutting off the power to the instruments. The replacement of solar arrays became another key tasks in late 1993 servicing mission. The reaction wheels also started failing in orbit, and had to be replaced. I'll explain the role of reactionn wheels in the next section.

When it comes to maintaining optical alignment in a spacecraft, temperature is the most talked about issue. The thermal radiation from the sun, for example, would drastically change the temperature of a spacecraft, and each supporting structure would tend to twist or bend the telescope in different directions. Many support components in space telescope are made of invar, due to its low coefficient of thermal expansion. I will talk about some of the methods which are being used for temperature compensation, later in this issue.

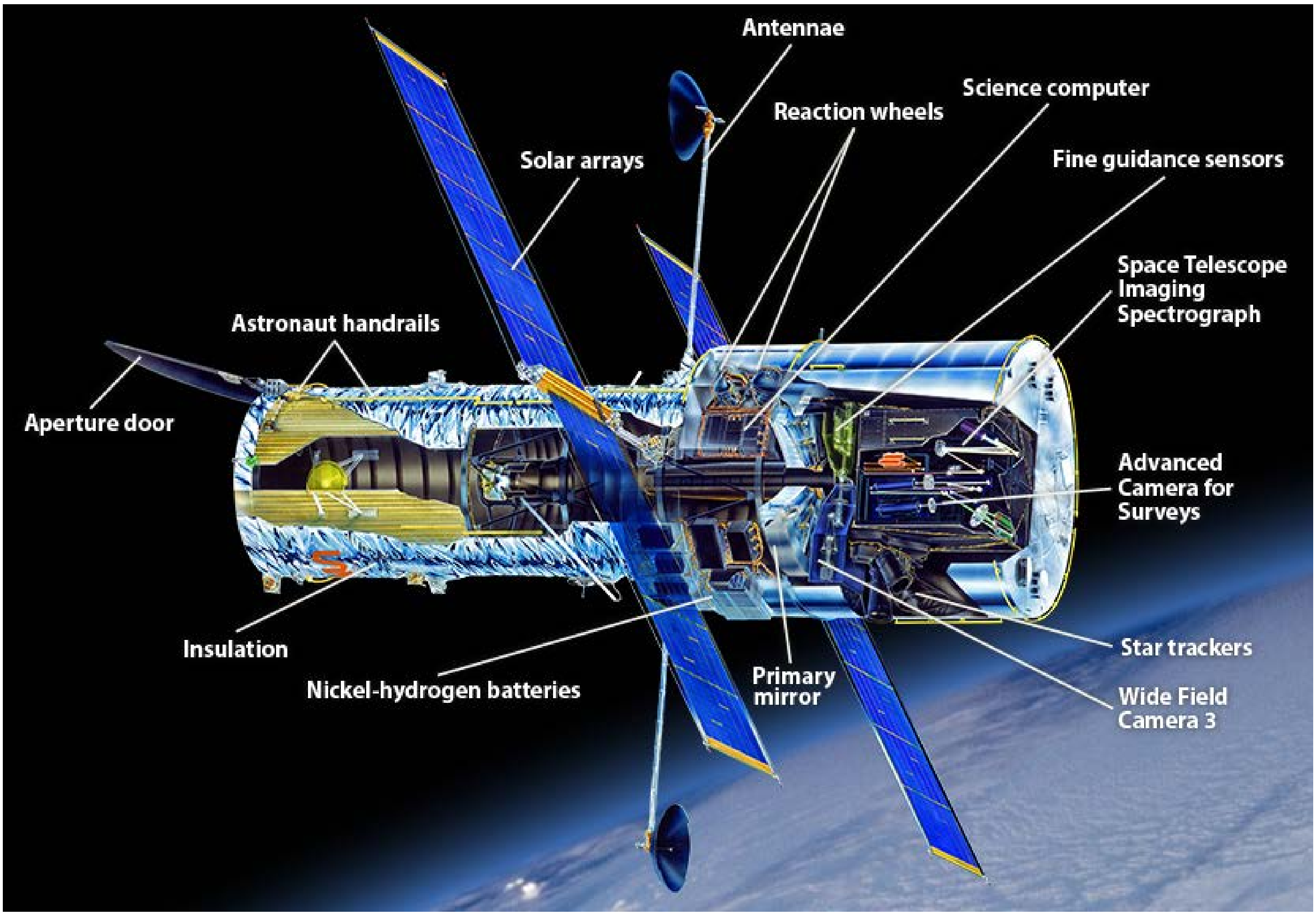
Ali Afshari

From a section of my book: "Marvels of SLR design and engineering, Vol2". It will be available from amazon.com

Astronaut taking a selfi next to HST

WFC III installed on HST is running till this day.
HST images, Courtesy NASA (see page 43 for more on WFC III)

Hubble Space Telescope



Rendering , Courtesy, NASA

The Hubble Space Telescope (HST) is a 2.4 meter f/24 telescope of Ritchy-Chretien design (Fig.4), where both the primary and secondary mirrors are aspherical (paraboloids). The effective focal length of the telescope is 57.6 meters, and its image is formed 1.5 meters behind the primary mirror. HST is a multiple instrument telescope, originally containing six major instruments:

Wide Field / Planetary Camera (WF/PC I, and II, subject of this article), currently WFC III
Faint Object Camera (FOC)
Faint Object Spectrograph (FOS)
High Resolution Spectrograph (HRS)
High Speed Photometer (HSP)
Fine Guidance System (FGS)

The space telescope orbits the earth once every 95 minutes, at 593 km altitude or 350 miles. Three reaction wheels (Fig. 4) keep the 25,500 pound telescope pointing to the right direction, and are used for maneuvering the spacecraft. It is solar powered when on the bright side of the earth, and uses a battery back up when on the dark side. The solar arrays were extraordinary in their design, allowing them to be extended, or rolled up. During the servicing missions they were replaced with a pair of fixed panels to withstand the extreme temperature variations in space.

The Fine Guidance System (FGS) is used for pointing the ST to a precise location in space. Using the outer most portion of the field of view of the telescope, 2 of the 3 FGS instruments find a star that is above 13th magnitude, and lock on the two stars interferometrically (Fig.5), achieving a pointing accuracy of +/-0.018 arcsec. This is equivalent to

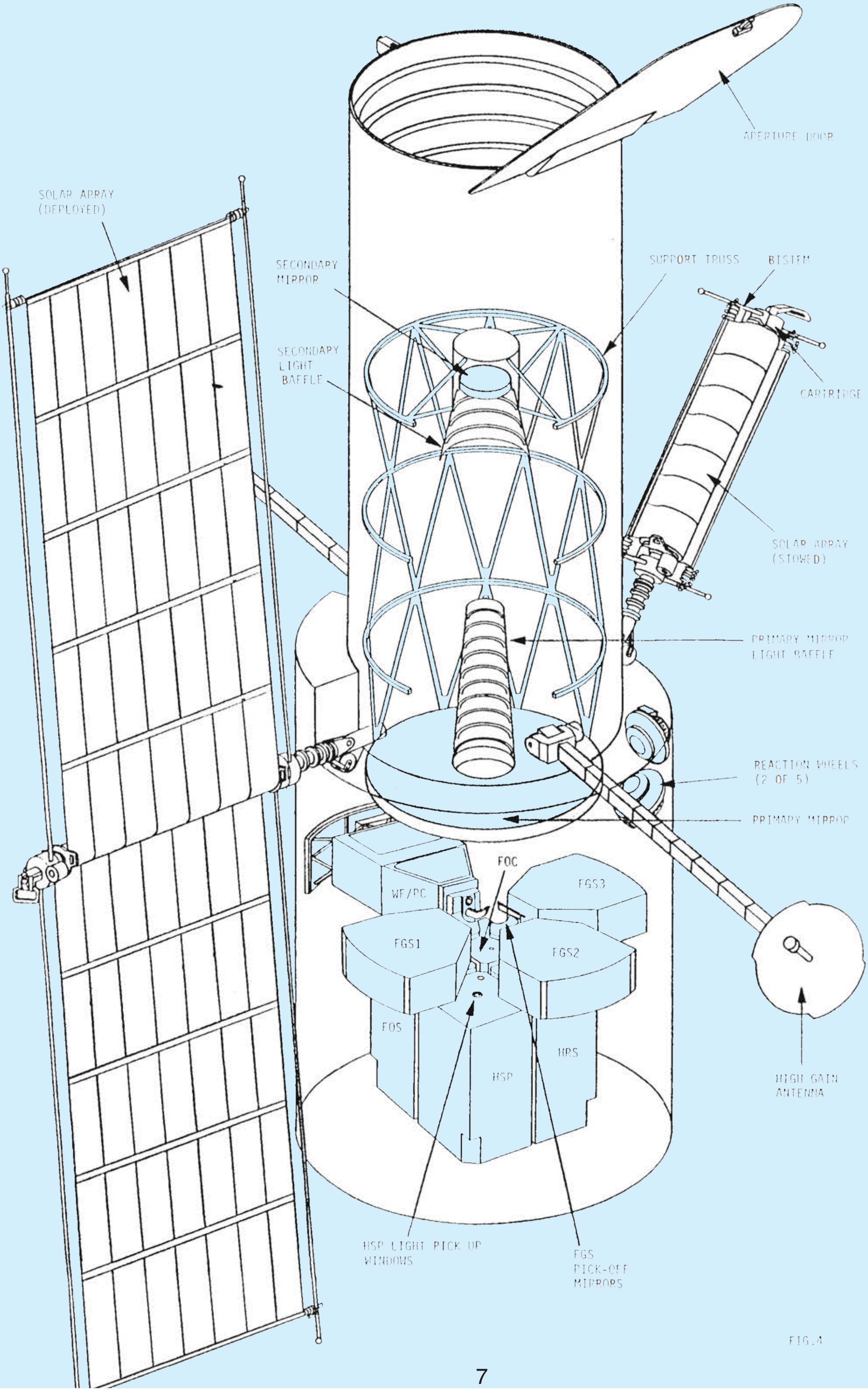

APERTURE DOOR
SOLAR ARRAY
(DEPLOYED)
SECONDARY
MIRROR
SECONDARY
LIGHT
BAFFLE
SUPPORT TRUSS
BISTEM
CARTRIDGE
SOLAR ARRAY
(STOWED)
PRIMARY MIRROR
LIGHT BAFFLE
REACTION WHEELS
(2 OF 5)
PRIMARY MIRROR
FOC
WF/PC
FGS3
FGS1
FGS2
FOS
HRS
HSP
HIGH GAIN
ANTENNA
HSP LIGHT PICK UP
WINDOWS
FGS
PICK-OFF
MIRRORS

FIG.4

sticking a long rod inside a wedding ring 381,972 feet away, and not allowing it to touch!

The fact that the Hubble instruments are so massive and bulky, and yet so modular, is mind boggling. The WF/PC is the size of a baby grand piano, and weights around 800 pounds. Now consider designing a mount that would secure this piano at three points (like its three legs), in the cargo bay of space shuttle, with hundreds of smaller pieces inside it, and they ask you to keep all this in precise alignment until it reaches the Earth's orbit, within a thousandth of an inch. One more thing - it should be easily removable with the turn of a latch by a servicing astronaut! The result is a remarkable engineering accomplishment. It is hard to believe things worked out as well as they did, and more things didn't go wrong. Hubble is made by a city of people, each coming up with clever ideas to solve engineering problems. To avoid a lengthy article, I will skip the other instruments, and only show their location (Fig.4), and field of view through the telescope (Fig.5).

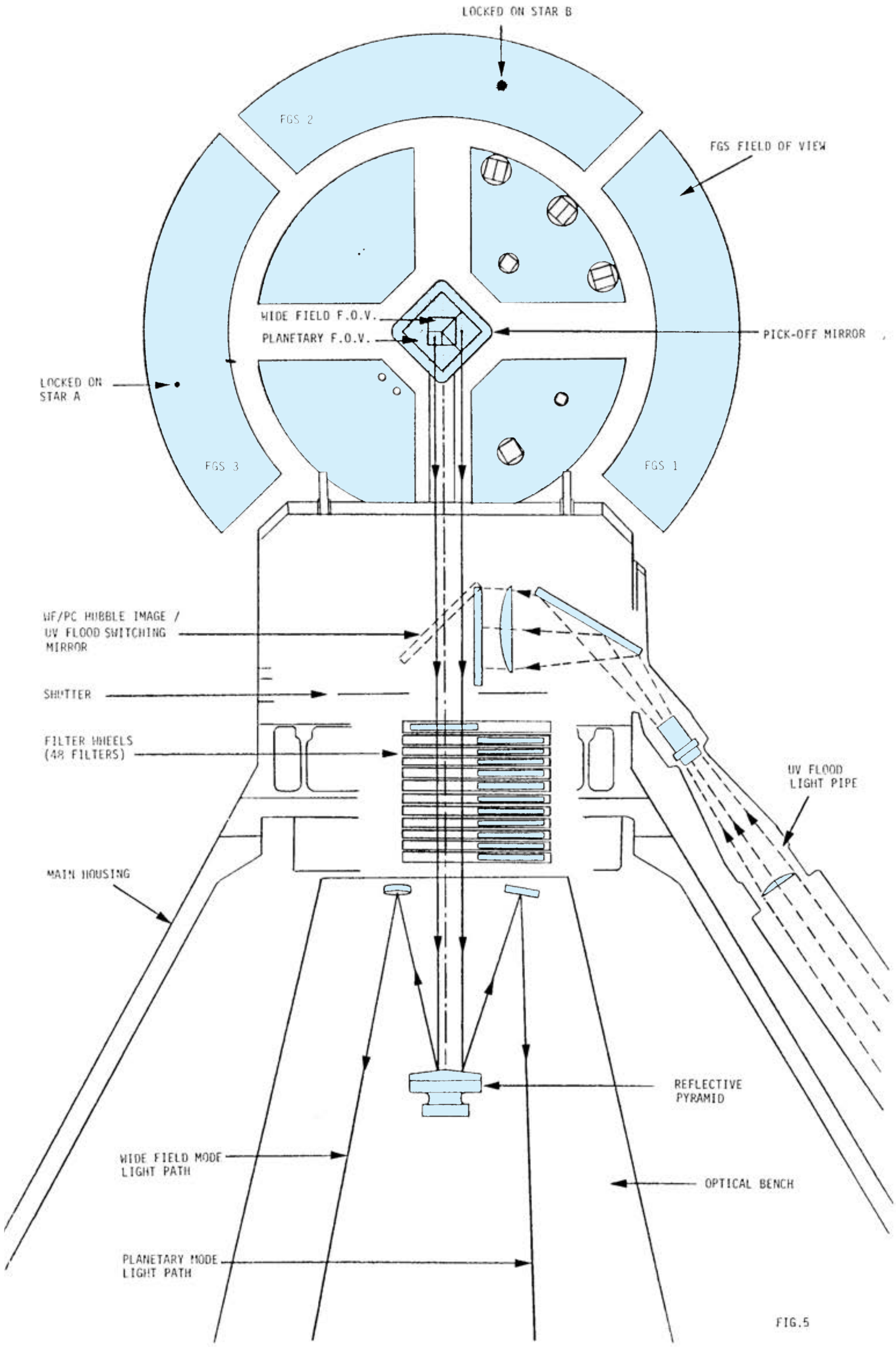
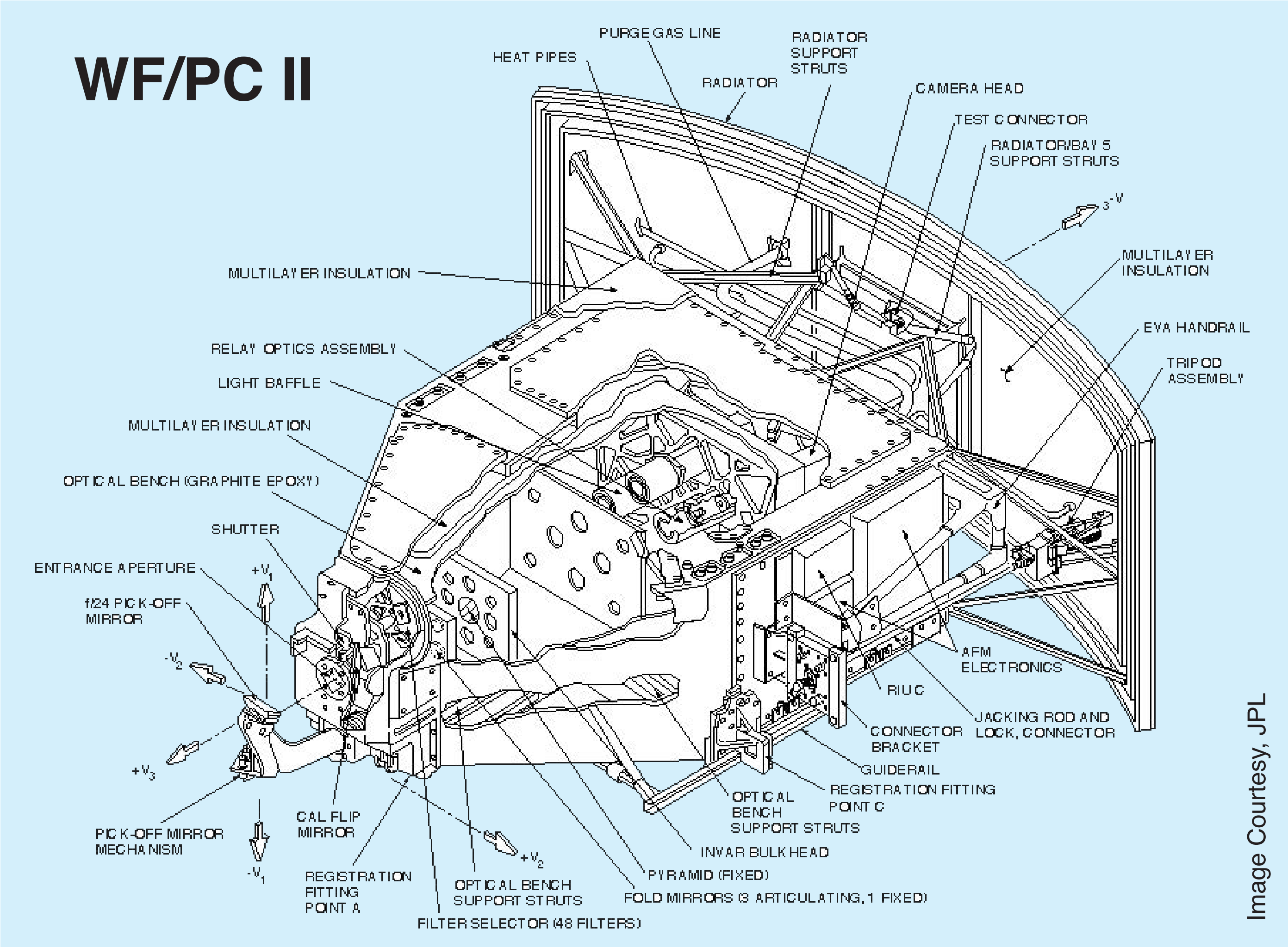


FIG.5

THE WIDE FIELD / PLANETARY CAMERA:

The WFPC or "WIFPIC" as people at JPL called it, was a radial instrument (Fig.4, 5), and like many other on board instruments in HST, it was upgradable. This instrument interfaced with HST like the electrical interface in a removable car stereo, but consuming up to 290 watts of power. Taking apart this camera, we find the major sub-assemblies shown in figure 6. The 16- layer blankets are designed to keep the instrument's temperature within -10 to + 20 degrees C. The housing shell encloses the instrument against possible contamination, and serves as a radiation shield. The radiator is where the temperature is radiated into space from the instrument. It is painted with a special coating to minimize heat absorption from the sun. During the repair missions, the WF/PC cameras were carried inside the bay of the space shuttle, where they experienced much colder temperatures down to -60 degrees C. The electronic bays contained a micro-computer, logic boards, temperature control circuitry, mechanism driver board, digital sampling and video

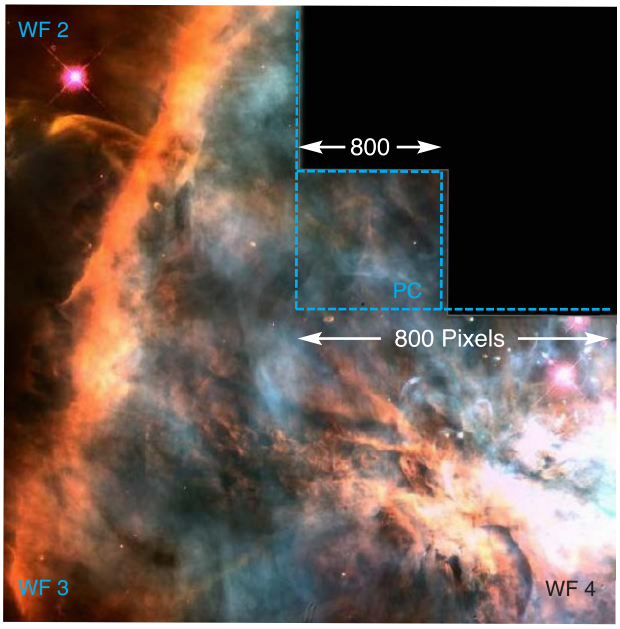


The Widefield / Planetary Camera II (WF/PC II)

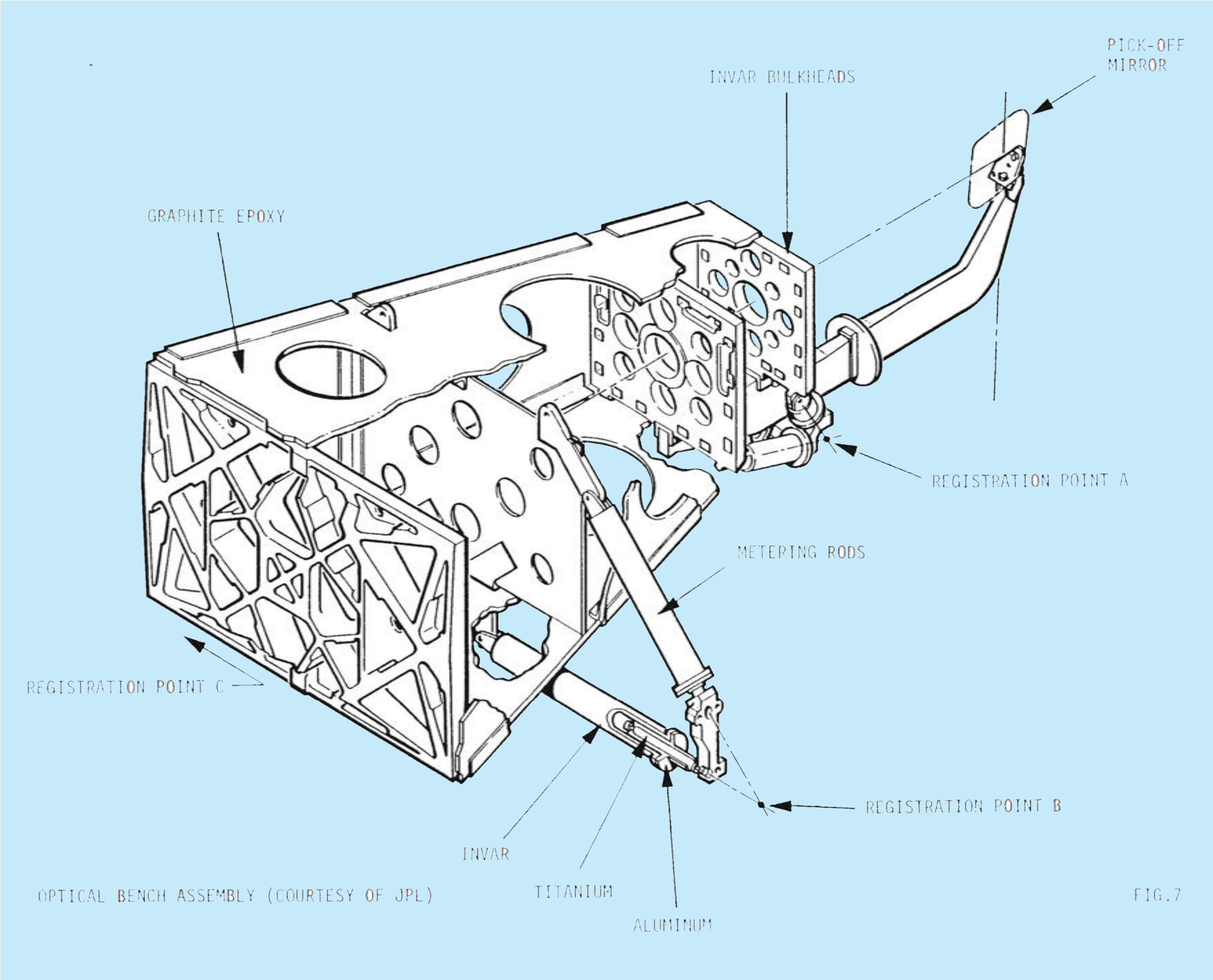
Wide Field / Planetary Camera was designed at JPL, and some Caltech students to have a wide spectral imaging range by using an all-reflective optical design. The image was brought into the instrument through a diamond shaped pick-off mirror, just like a SLR camera, and divided to four by a pyramid mirror, and then focused to four separate camera heads, each having an 800 x 800 CCD.

As for learning optomechanics in this issue, I am in favor of WFPC I, and II. I wasn't part of the WFC III project so I can't explain it as good as what I worked on, but I have been remotely following its progress. The second WFPC was interesting because it had steering mirrors to center the corrective optics. The first WFPC I was also very interesting because it had a full set of eight cameras, and a fully operational pyramid mechanism. So what I will discuss next is a combination of the two instruments. The original WFPC II (page. 5) is now displayed at Smithsonian National Air and Space Museum in Washington, DC.

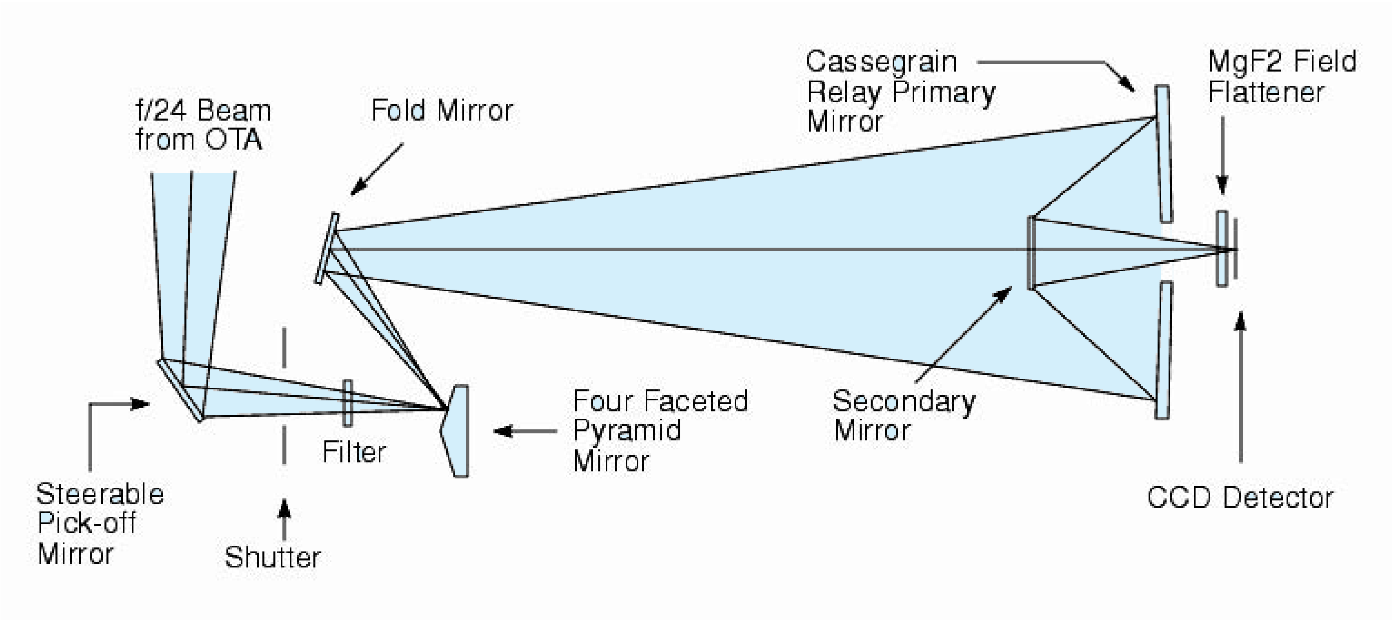
Image Courtesy, NASA



Mosaic Signature of WFPC II images had one planetary image (upper right), and three wide field images in each shot. To cancel out Hubble's Spherical Aberration, the fold mirrors of relay optics in WF 3, and 4 had to be tiltable, while it was fixed for WF2. This way, the pick off mirror could center the corrective optics to WF2, while other tiltable fold mirrors would center HST's aberrated wave-front to relay's corrective secondary mirrors (See P 40).



The Optical Design



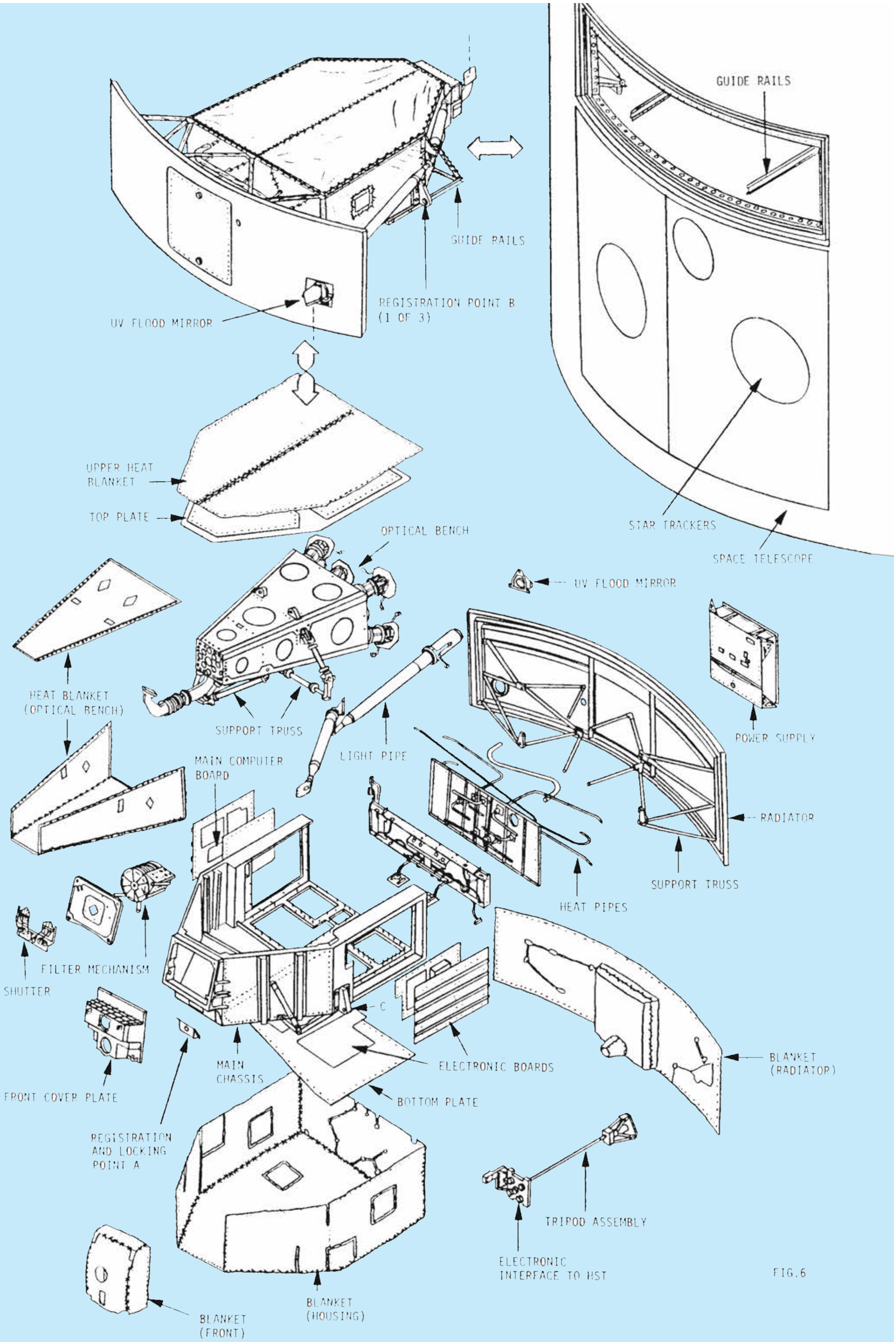

GUIDE RAILS
GUIDE RAILS
UV FLOOD MIRROR
REGISTRATION POINT B
(1 OF 3)
UPPER HEAT
BLANKET
TOP PLATE
OPTICAL BENCH
STAR TRACKERS
SPACE TELESCOPE
UV FLOOD MIRROR
HEAT BLANKET
(OPTICAL BENCH)
SUPPORT TRUSS
LIGHT PIPE
POWER SUPPLY
MAIN COMPUTER
BOARD
RADIATOR
SUPPORT TRUSS
HEAT PIPES
FILTER MECHANISM
SHUTTER
C
ELECTRONIC BOARDS
BLANKET
(RADIATOR)
FRONT COVER PLATE
MAIN
CHASSIS
BOTTOM PLATE
REGISTRATION
AND LOCKING
POINT A
TRIPOD ASSEMBLY
ELECTRONIC
INTERFACE TO HST
BLANKET
(HOUSING)
BLANKET
(FRONT)

FIG.6

boards, etc. These boards are powered by the power supply, which converts the 28 volt input power to the required voltages. The power supply is mounted on the coolest part of the instrument, the radiator.

The on-board computer and interface unit, hand shakes with telescope's main computer. The commands received by the telescope, are instrument specific, and WFC has its own unique code (like having a different phone number to receive commands). These commands can be like: What shutter speed to use, what filter to select, which magnification is needed, etc. These are known as prepare commands, which are sent before making an exposure. Executable commands include making an exposure, and transmitting down the image. The optical bench is at the heart of the camera. It is mounted by invar support rods with special geometry to avoid the housing weight, or other loads to affect its accurate position. Going back to how to install a baby grand piano on the space telescope, WF/PC does it with registration points A, B, and C on the main chassis (Fig.6, point B being on the other side, symmetrical to C). Point A holds the two front bulkheads, each at two points. This is also the locking point of the instrument, when it is inserted into the telescope. Points B, and C hold the intermediate bulkhead at three points. The four bulkheads are then bonded together by four outer sheets of graphite epoxy. The electronic interface connector, also locks to its mate by a tripod assembly (Fig.6).

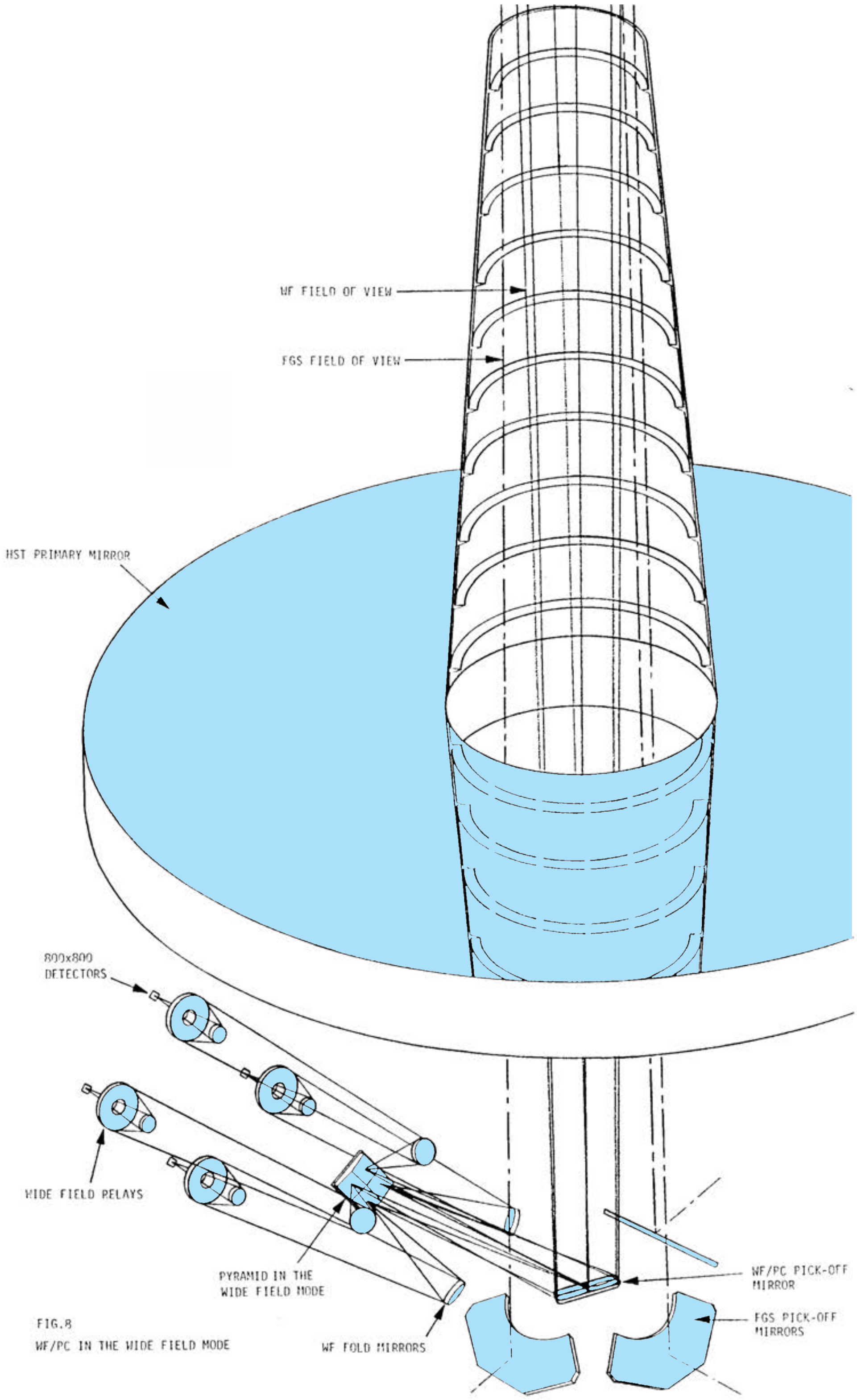


FIG.8
WF/PC IN THE WIDE FIELD MODE

To cancel out temperature variation effects, each metering truss is designed to internally compensate for expansion, and contraction. The key player in the design of the metering truss is an aluminum tube that connects the inner titanium shaft on one end, to the outer invar tube on the other end. In simpler terms, if an ant decides to travel from point B towards C, she has to walk the length of the titanium shaft, then walk back on the aluminum tube towards B, and then walk across the invar tube towards C (Fig.7).

Let's say the temperature increases, and the invar expands slightly towards B (1.6 microns per degree C), and the titanium bar expands a little more towards C (12 microns per degree C). CTE is coefficient of thermal expansion. If the length of aluminum (22 microns per degree C) tube is properly chosen, it would expand precisely as much as the invar and the titanium bar combined, canceling out the overall expansion. The reason these specific metals are picked, is that the non-linear coefficients of expansion of these metals behave in a reasonably linear fashion when combined! The entire instrument is designed for a 52 degree temperature range (-12 to +40 degree C). The other support legs are designed differently. Since each bulk-head expands or contracts differently (depending on its area and geometry), its supporting truss is purposely designed to back off in opposite directions, keeping the optical axis of the instrument in precise alignment with the telescope. I will later explain how this technique is used inside the optical bench itself, to compensate for focus shift inside the optical assembly.

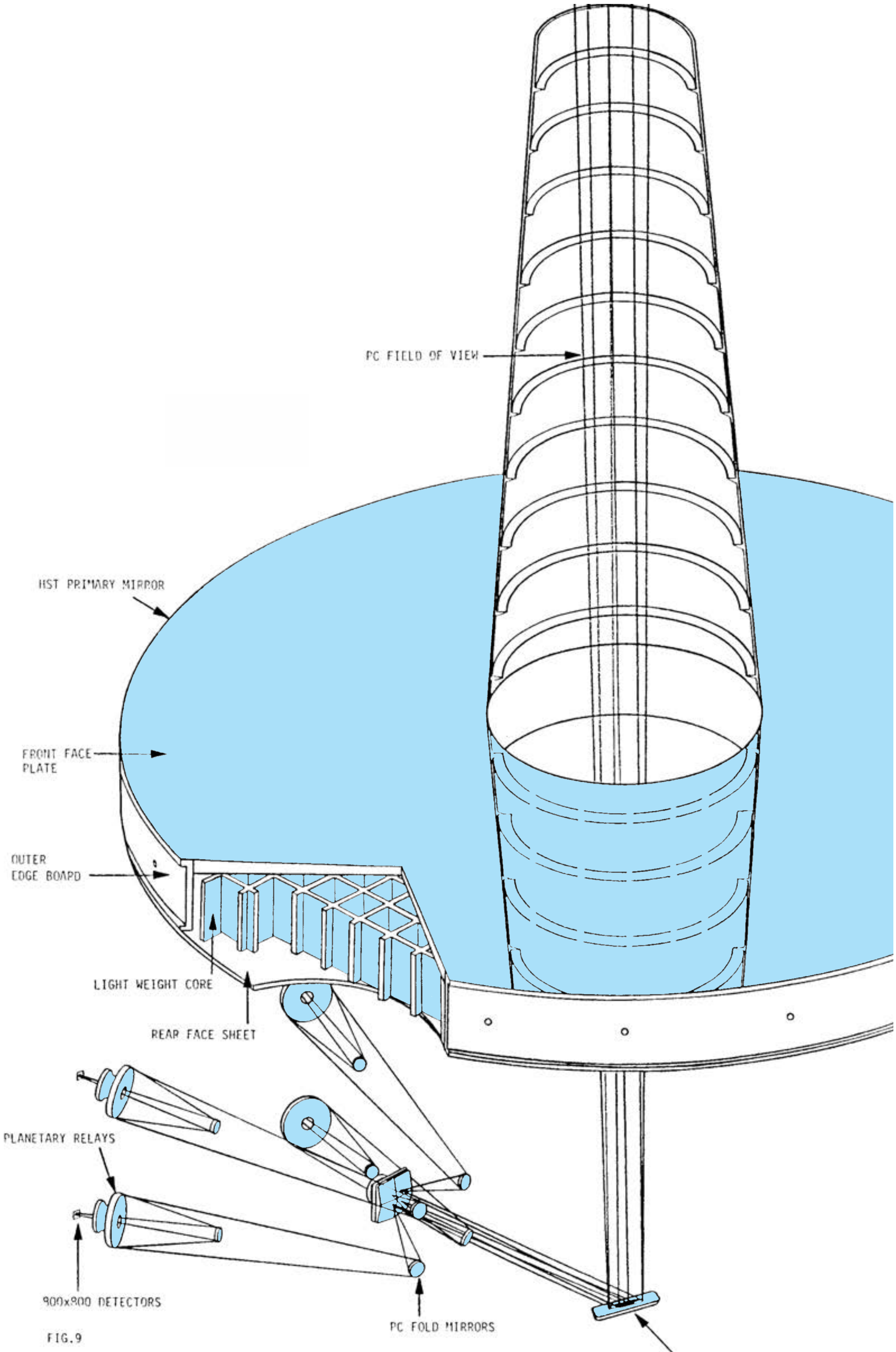
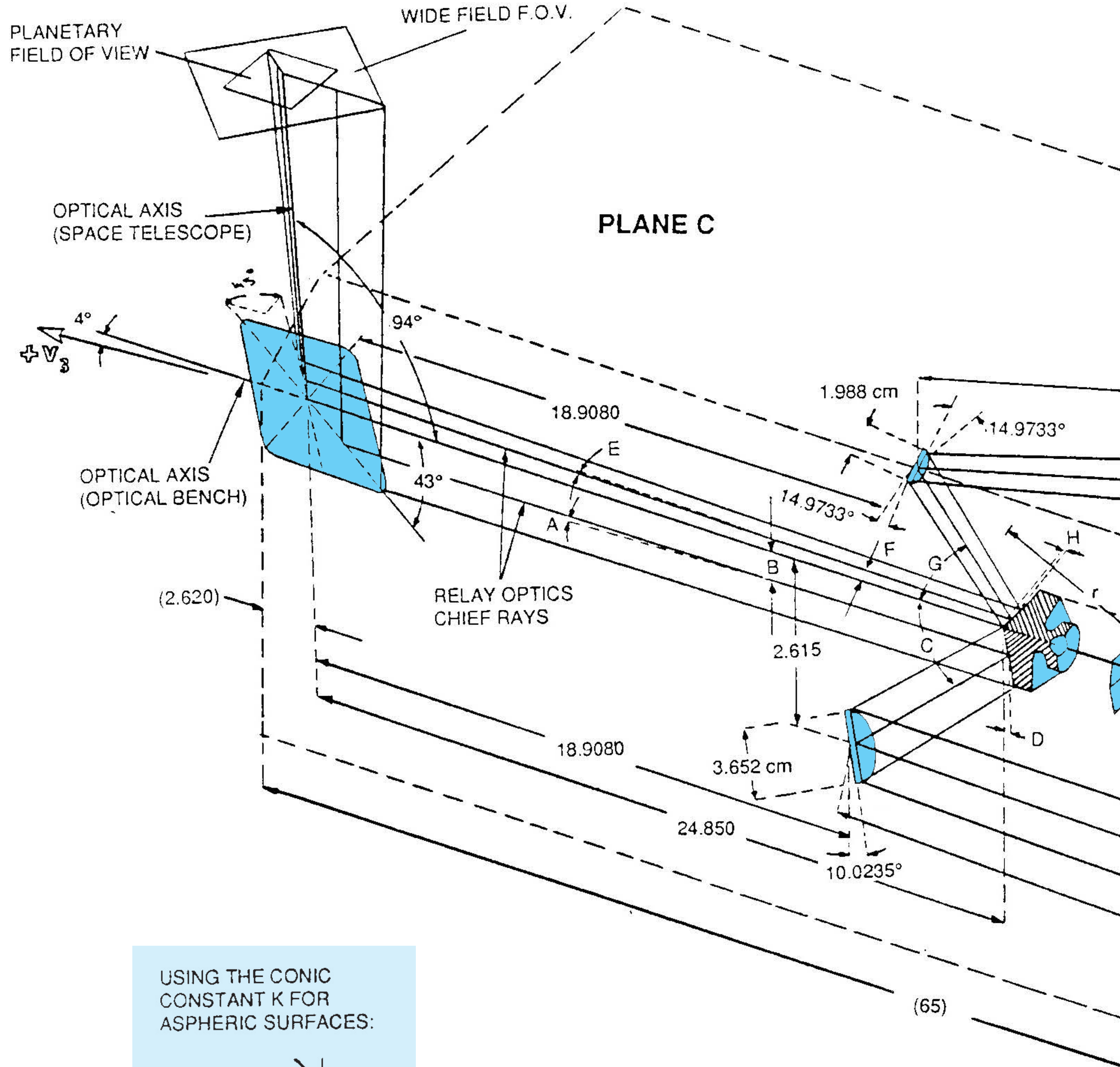


FIG.9

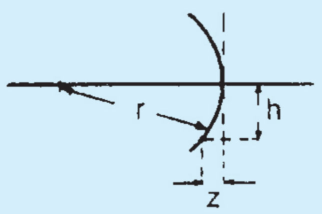
WF/PC IN THE PLANETARY MODE

A CLEVER CONCEPT:

The WFPC uses a 2.7x2.7 inch area of HST's central field of view (Fig.5). Like FGS, the image is reflected off of a pick off mirror, but is focused inside the instrument (Fig.8) at a four-faced reflective pyramid. The optical design of the WFPC I and II were credited to be the work of Dr. Art Vaughn, an astronomer and physicist, who had been involved with the instrument from its early days. Since the original specifications of the telescope's field of view and resolution exceeded the capability of a single CCD detector (800 x 800 pixels), the idea of the four-faced reflective pyramid was suggested by Bob O'Dell, HST's chief scientist. The pyramid breaks the image into four, redirecting each quadrant of the image to a separate detector (1600 x 1600 overall pixels) (Fig.8). Bill Baum, another Hubble scientist, suggested that by rotating the pyramid, it can act as an optical switch, to direct the light to four additional detectors with a different magnification (Fig.9). So the WF /PC optical design was born.



USING THE CONIC CONSTANT K FOR ASPHERIC SURFACES:



$$Z = \frac{h^2 / r}{1 + \sqrt{1 - (1+k)h^2 / r^2}}$$

PYRAMID FACE:
a = 9.1056°
b = 0.915
r = 120.8

- ALL DIMENSIONS ARE IN INCHES EXCEPT OTHERWISE NOTED
- DIMENSIONS INSIDE PARENTHESIS ARE FOR WF / PC FULL SIZE

CHIEF RAY'S POINT OF INCIDENCE AT PYRAMID FACE:

A = .1201°	B = .6260	C = 18.3411°	D = .1052
E = .0556°	F = .2673	G = 18.6114°	H = .0510

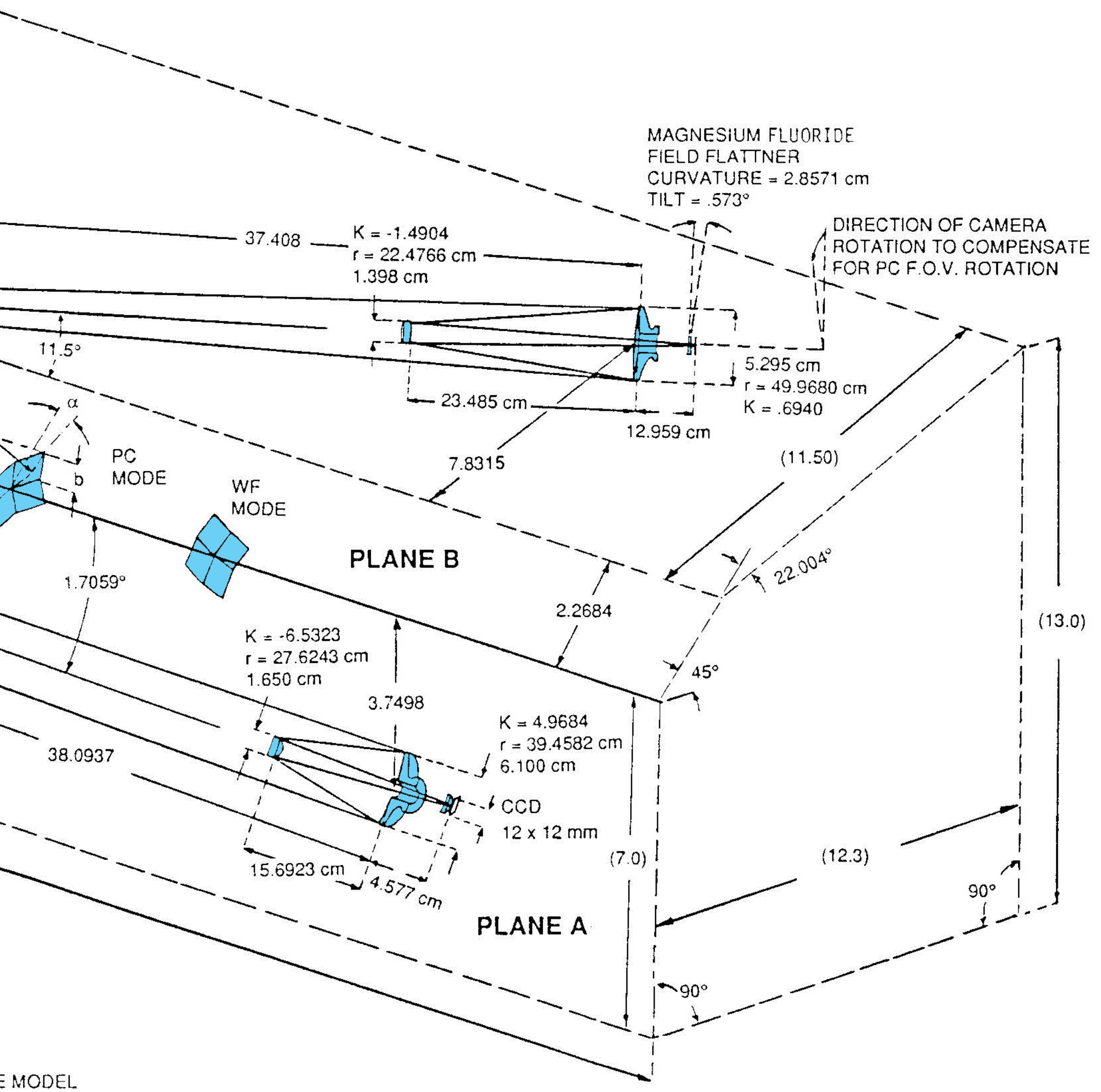


FIG.10

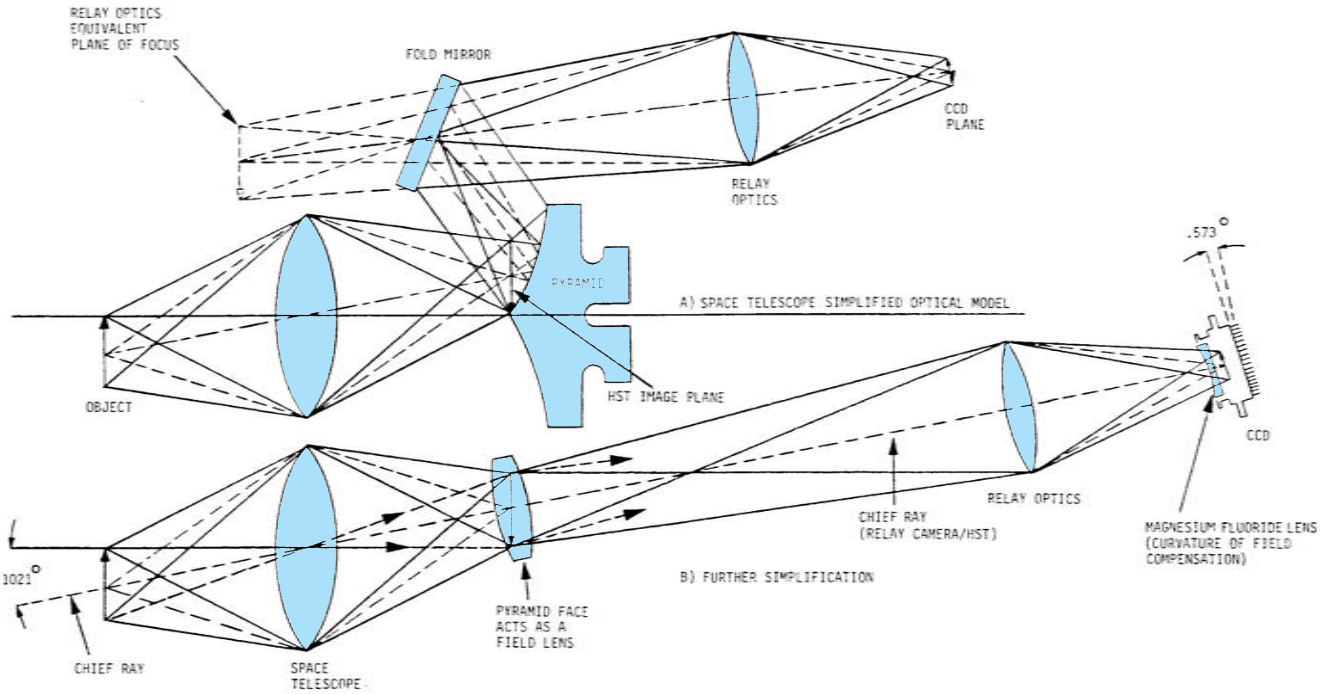


Fig. 11 The simplification of beam path through relay optics

Figure 5 on Page 8 shows a top view of the WF/PC, the location of the shutter, filter wheels, and the pyramid, which is at the focal plane of HST. The UV light pipe, is designed to flood the camera with sunlight (a rich UV source). It receives sunlight through a hole in the radiator (Fig. 6), where an angled mirror reflects the sunlight into the instrument. The UV food control mirror (Fig. 5) works like a backwards SLR camera, switching the light coming from the telescope to the light pipe. The UV flooding enhances, and stabilizes the quantum efficiency of a back illuminated CCD device, or its ability to collect electrons, released by the incoming image photons. The WF /PG-II CCD's are front illuminated, and don't require UV flooding. I will explain how the CCD works later in this issue.To understand the optical geometry of the instrument, one can imagine the optical axis of the space telescope in a vertical plane A (Fig.10). The incoming image from ST is reflected off of the pick off mirror, and focused on the pyramid. In the wide field mode, the image is reflected to four perpendicular planes (Fig. 8), one of which is shown in figure 10 as the A plane (the other three planes are oriented 90, 180, and 270 degrees from A). You can think of the fold mirror as dentist's mirror, used to see behind your teeth!

The relay optics functions like a 35mm camera fitted with a mirror lens, and focused on the pyramid face about 1.1 meters away. It is the focal length of this lens that determines the magnification of the instrument, and its f-ratio. The wide field cameras actually demagnify the HST image, by projecting each pyramid face (0.915 inch square) to the CCD imaging area (0.472 inch square). This in turn, increases the image intensity, and switches the total f-ratio of the telescope from f/24 to f/12.8. To change magnification, the pyramid rotates 45 degrees, to the planetary mode (Fig. 9, 10). The incoming light from ST is now brought to four new planes, one of which is shown as plane B. The planetary relay cameras have a longer focal length, and project a much smaller area of the pyramid's face (close to its tip) on the CCD. This increases the magnification, but also increases the f-ratio to f/30. Before you get used to the idea, the original designers made an additional twist to this!

In the wide field mode, the four relay cameras are positioned at the four corners of a square (Fig. 8). To save space, the planetary relay cameras are placed at the corners of a rectangle (Fig.9). To accomplish this, each planetary plane B (Fig. 10), is bent an additional 22 degrees (plane C), on the axis of the fold mirror. This has no effect on the focus, but rotates

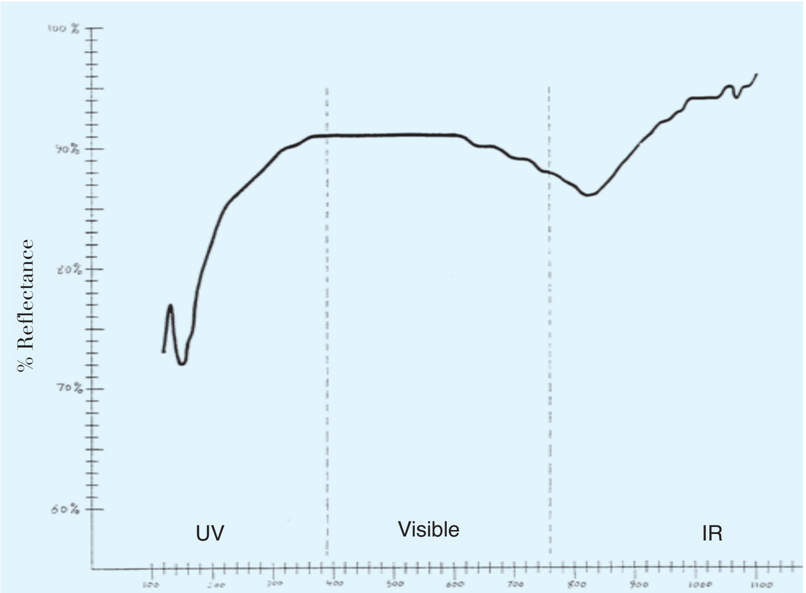
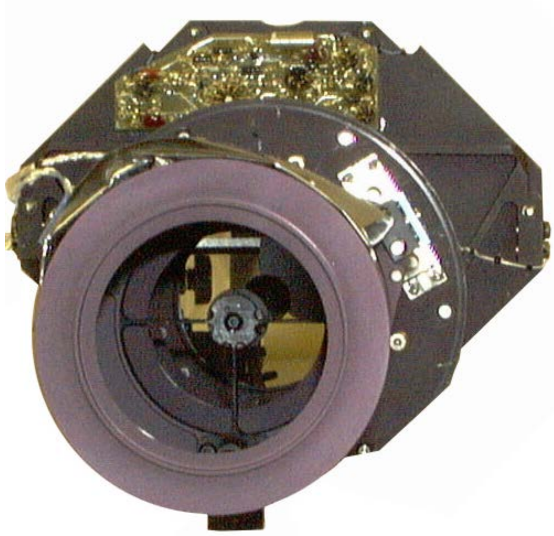


Fig. 12 Reflectance measurement made on relay optics primary mirror



Wide Field Relay Optics Image, Courtesy JPL

the field of view of the relay camera by fraction of a degree. To compensate for this, each planetary relay camera is slightly rotated about its axis.

The best way to study-the WF /PC's optical design is to do what I did, and that's to build one! Figure 10 gives enough information to help you build this model. You can then cut out the optical components on a reflective sheet of material, and insert them onto the model, to get a more realistic look. For me, sharing the WF/PC design, is with a great level of excitement. The more you know about it, the more you wish to know, and if you fully understand it, you can design anything! I will briefly answer some of the immediate questions that may easily come up, like why it is all done with mirrors, why is the pyramid's face spherical, how can you keep things in focus with de-centered optics, and how can you keep all this in exact alignment while the temperature changes? Figure 11-A shows a simplified version of the ray tracing of the wide field camera (A plane) using lenses. There are, in fact, no lenses used in the WF /PC with the exception of one field flattener, and there is a good reason for it. An all mirror system is less sensitive to wavelength variations of light than a refractive system, because as the wavelength changes, so does the plane of focus of a glass lens.

Photographic systems are chromatically corrected for this, only for the visible spectrum, and have to be refocused for infrared films. But when designing for a much wider wavelength range, from 150 nm (wave length of ultra-violet lamps used in E-PROM erasers) to 1100 nm (beyond the sensitive wave length of many hand held infra-red viewers), mirror systems are a far better alternative. There is still, one remaining problem: The light transmission efficiency of a lens changes at different wave lengths. For example, in the ultraviolet wave lengths, ordinary glass becomes opaque. Similarly, in reflective systems, the reflectivity is wavelength dependent Figure 12 shows the reflectivity plot of relay optics mirror versus the wave length. A pure aluminum coating would not be as reflective in the UV region (left of the curve). Without a protective overcoat, the aluminum would suffer from oxidization, causing an overall decrease in reflectivity, and much faster roll off in the ultraviolet region, shortly after the mirror is removed from the coating chamber. WF /PC mirrors are coated with magnesium fluoride to enhance reflectivity, and prevent oxidization. At a precise thickness, the MGF2 acts as a quarter-wave coating, enhancing reflection, and linearizing the reflectivity curve (Fig. 12). In a quarter-wave coating, the reflected light from the aluminum surface combines with the light reflected off of the coating itself. This occurs near a specific wavelength in the UV region. The sharp jump on the left of the curve is due to the phase shift of the two reflected rays in the coating, as the wave length changes.

In figure 11-A, the Space Telescope is shown as a single lens, and there is also no pick- off mirror. The image is focused slightly beyond the tip of the pyramid, and is relayed to the CCD device by a single lens, representing the relay optics. The spherical pyramid surface acts as a field lens. similar to the one shown in figure 11-B. It's function is to bend the light rays on the corners of the field (at the pyramid face), towards the center of the relay lens, and minimize vignetting. In simpler terms, it acts like the condenser lens in slide projectors. In such systems, the condensing lens, projects the image of the filament on the center of the projection lens. In the WF/PC, the pyramid face projects the pupil of the telescope on the primary mirror of the relay optics.

The field flattener window is the only refractive element in the optical system, and is used for correcting the field curvature of the telescope. It is made of Magnesium Fluoride (MgF2), whose index of refraction is much less dependent on the wavelength than most other glasses (Fig. 10, 11). In simpler words, if you project sunlight through an equilateral glass prism (usually made of crown glass BK7), you'll see a much wider spread of the rainbow colors, than through an identical size prism made of magnesium fluoride. By the same principle, a magnesium fluoride lens would have a much less focus shift as the wavelength changes.

The magnesium fluoride lens is packaged with the CCD device, and acts as its protective window. Prior to the assembly, the MgF2 window is pressed on a ring with a layer of Indium seal (soft metal), and the ring is laser welded to the package. The back side of the CCD is finally sealed with 1 atmosphere pressure of Argon.

The last but very important point to observe in the optical design is the 0.573 degree tilt angle of the CCD detector (the entire camera head is tilted). This has to do with how the relay cameras are oriented with respect to the telescope's focal plane (Fig.11-B). In order to avoid vignetting in each quadrant, the chief ray of the relay optics has to be in line with the chief ray of the telescope. In figure 11-B, the central dotted line represents the chief ray for a quadrant of the field of view of the telescope. This means that each relay camera is actually looking down at the image plane with an angle. To actually experiment with this, point a SLR camera at a slight angle to a flat wall, and try to keep all of it in focus without closing down the aperture. View cameras allow tilting of the film holder to make this possible.

How much the relay cameras are tilted down, depends on where their chief rays arrive at the pyramid. This is not the same for both wide field, and planetary cameras, since the reflective surface angle of the pyramid is not equal for both cases (reflection angles C and G are not equal in Fig.10). This is also why the planetary cameras are more spread out than the wide field cameras. As a result, the required CCD tilt should be different for each case. But to avoid the complexity of building two separate sets of cameras, the optical designers decided to use an optimum tilt angle that would work for both.

THE PYRAMID MECHANISM

The pyramid was the heart of the optical bench in original WF/PC I, and had four major functions: It focused the relay optics to the incoming image from the telescope. It switched the field of view between planetary, and wide field cameras. It provided registration points for aligning the four CCO images (K-spots). It also provided a fail safe-operation that switched the camera to the wide field mode. The first thing that comes to mind is that if the camera has focusing capability, why couldn't it focus the Hubble's image? The answer is that the Hubble's image is not at a single given point, it is rather spread out in a two-inch depth. By moving back and fourth, one can only obtain a sharp focus coming from a circular stripe of the telescope's primary mirror, combined with all other rays focused to a different plane. One more thing: Where would be the best plane to focus to? If the primary mirror was strictly spherical, the maximum energy would be coming from the edges of the mirror, and be concentrated behind the other rays. But because the mirror is aspherical, the outer rays correspond to a narrower area on the mirror's surface, than in the case of a spherical mirror. The prime answer, however, is that the pyramid could have only moved a fraction of a millimeter. It was designed to compensate for the focus shifts of the telescope due to temperature changes.

The prime player in the focusing accuracy of the pyramid is a double acme thread design (Fig. 13), which is separated by a spring washer, eliminating the slightest backlash. The pyramid is mounted to a central shaft, which is held by two titanium flexures. The focus motor rotates the inner acme shaft, causing the outer nut to move the pyramid back and forth. The rotation motor rotates the pyramid itself, which is rotationally isolated from the focusing shaft by a duplex

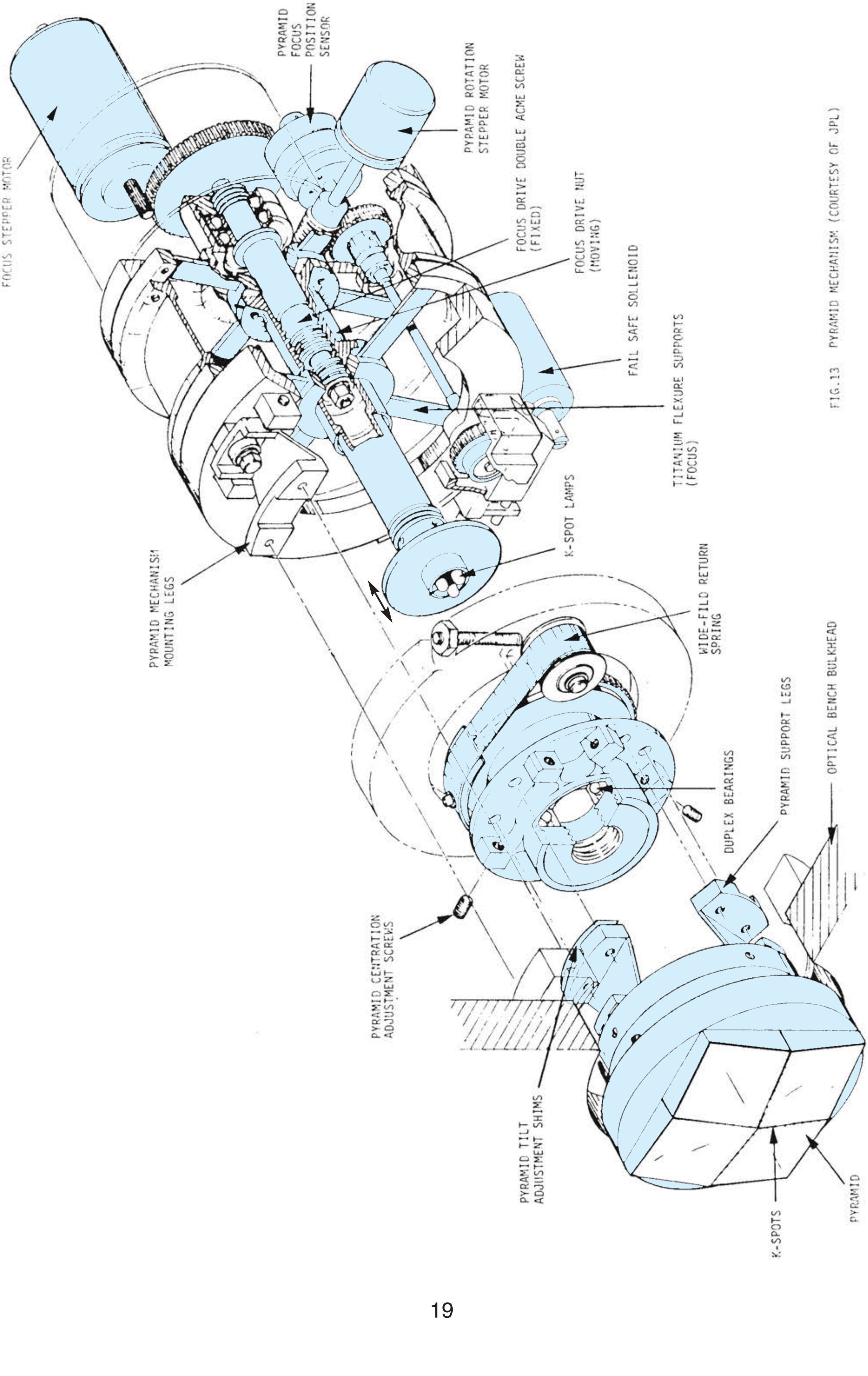


FIG.13 PYRAMID MECHANISM (COURTESY OF JPL)

bearing assembly. This rotation is limited by two stop pins, 45 degrees apart. The registration accuracy of the pyramid's rotation at both ends is + /-30 degree seconds. The backlash is minimized by the WF return spring (behind the pyramid). The tension of this spring is very small (about twenty times lighter than the tension spring in an old telephone dial). In case there is a failure in the pyramid's rotation, there is a fail-safe solenoid (Fig. 13) that can be energized to disengage the rotational drive gear, allowing the return spring to permanently rotate the pyramid to the WF mode.

The purpose of K-spots (illuminated by small lamps behind the pyramid) is to ease the alignment of CCD images. When a picture is taken using all four CCDs, the K-spots would appear on the corners of each image, simplifying reconstruction of the four image mosaic. Since the K-spots fall on specific CCD pixels, slight deformations in the optical bench are detected by comparing their location between different images.

THE RELAY OPTICS

The relay optics is a Ritchy-Chretian design, similar to the space telescope itself (Fig. 14). The function of each relay is to project each face of the pyramid on the CCDs. It is thermally compensated by three metering rods. Each metering rod consists of an invar rod and a tubular aluminum front piece. As temperature changes there is nearly a cancellation between the thermal expansion of the two metals. As a result, the distance between the primary and secondary mirrors varies slightly. This slight variation is intentional, and is used to compensate for the shifts in the optical bench. The secondary mirror is mounted on a spider, which has three support legs oriented 90 degrees apart. I remember asking Lloyd Adams why he didn't add the fourth leg, and he calmly responded: "Three is sufficient"! The primary and secondary mirrors for WFPC-I camera are hand matched to produce the best performance. The WFPC-II mirrors are so perfect that they are interchangeable between different relays. The hexagonal fixture in figure 14, supports the CCD mounting fixture on its back side, and is mounted to the relay optics by three support legs and vibration damping assemblies. The back side of the CCD mounting fixture is wedged, causing the CCD assembly to be tilted 0.573 degrees. As I explained earlier, this is necessary to keep the image in focus at the focal plane of relays.

The vibration dampers are intended to absorb the 30 Hertz frequency, where the CCD surface resonates during the vibration testing. They consist of two L-shaped brackets bonded to a block of Viton (a type of rubber). The O-rings on the metering rods also provide vibration isolation between the rods and the relay housing.

RELAY OPTICS ALIGNMENT ANO THE CAMERA HEAD INSTALLATION

Each relay assembly went through separate alignment steps. The primary mirror was first centered with the relay barrel. The secondary was then aligned to the exact optical axis of the secondary, and the relay focus was also adjusted by this mirror. During the optical bench assembly, the relays were mounted with precise alignment to the already aligned pyramid mirror. Each relay camera was individually aligned to the field of view of the telescope within- + / - 10 pixels. After all the eight relays were optically aligned, the CCD and camera head assemblies were installed to the hexagonal mounting fixtures (Fig.14). The heat pipes were then clamped to each camera (Fig. 15). At the end of assembly, the thin-wall titanium supports and thermoelectric cooler temporary supports were disengaged to mechanically isolate the camera heads and relays from the heat pipes (Fig.15). Those tiny secondary mirrors were figured to cancel out the HST mirror's spherical aberration. I'll show you how this small alteration changed the entire design of the WF/PC II.

THE CAMERA HEAD ASSEMBLY

This assembly is built with extreme complexity (Fig.15). It has a built in thermoelectric cooler, which can cool the CCD to a temperature as low as -115 degrees C. Each camera head contained a thermally isolated, 800X800 CCD device. The CCD temperature was monitored, and maintained at a precise level. The heat from the camera heads would radiate into space by a heat pipe, which was filled with ammonium, and held up a temperature difference of less than 3 degrees at its two ends. The heat pipe saddle was clamped to the thermoelectric cooler assembly base plate (Fig.15).

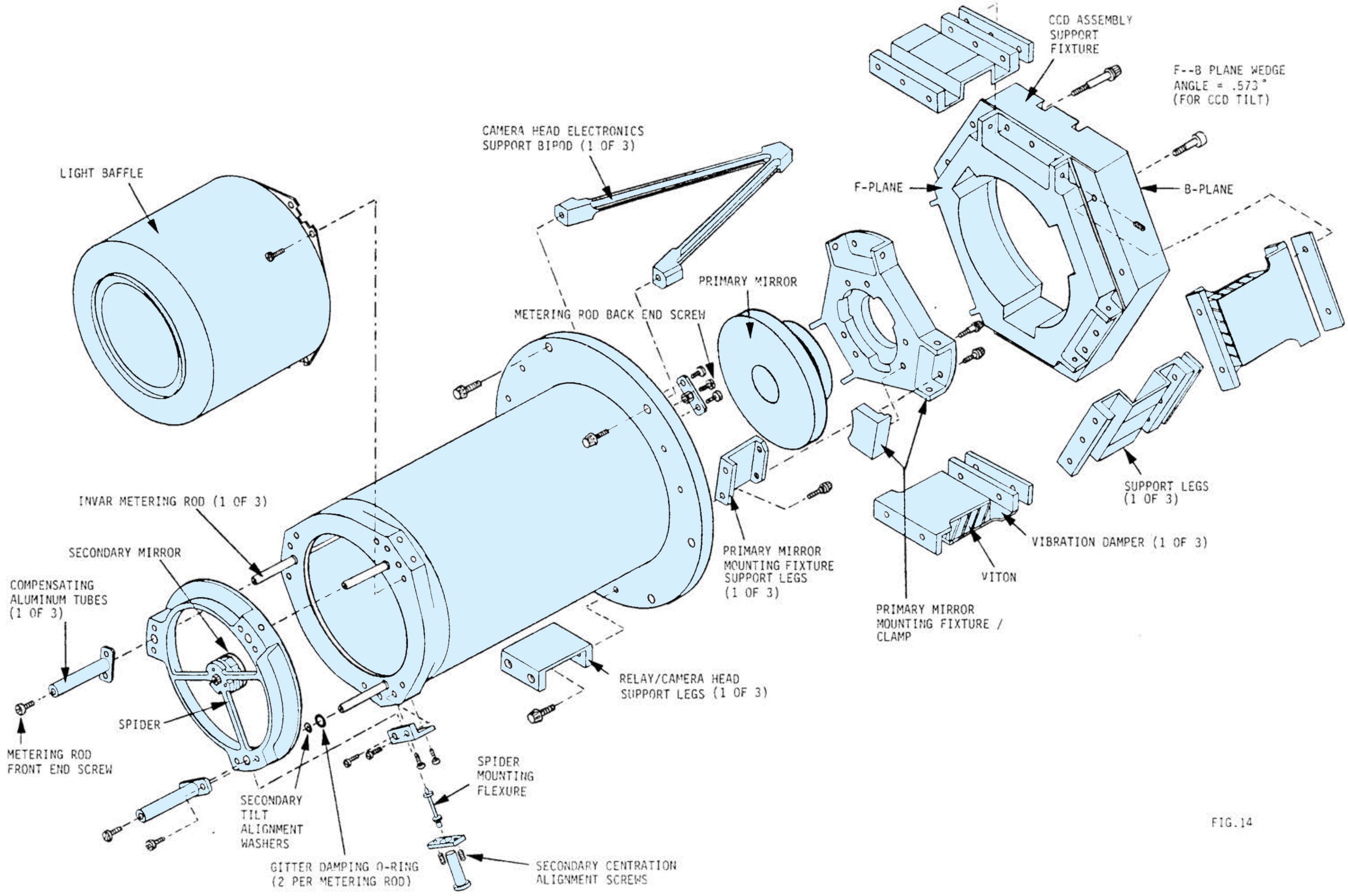

CCD ASSEMBLY SUPPORT FIXTURE
F--B PLANE WEDGE ANGLE = .573° (FOR CCD TILT)
CAMERA HEAD ELECTRONICS SUPPORT BIPOD (1 OF 3)
LIGHT BAFFLE
F-PLANE
B-PLANE
PRIMARY MIRROR
METERING ROD BACK END SCREW
INVAR METERING ROD (1 OF 3)
SECONDARY MIRROR
COMPENSATING ALUMINUM TUBES (1 OF 3)
SUPPORT LEGS (1 OF 3)
VIBRATION DAMPER (1 OF 3)
VITON
PRIMARY MIRROR MOUNTING FIXTURE SUPPORT LEGS (1 OF 3)
PRIMARY MIRROR MOUNTING FIXTURE / CLAMP
RELAY/CAMERA HEAD SUPPORT LEGS (1 OF 3)
SPIDER
METERING ROD FRONT END SCREW
SPIDER MOUNTING FLEXURE
SECONDARY TILT ALIGNMENT WASHERS
GITTER DAMPING O-RING (2 PER METERING ROD)
SECONDARY CENTRATION ALIGNMENT SCREWS

FIG.14

The thermoelectric cooler was a stack of six sandwiches of two semiconductor metals (Bismuth-Tellurate, and Borrelia), that when a current of 1 amp (7 volts) was applied to the device, it generated a temperature drop from its back end (connected to the heat pipe) to its front end, which was thermally connected to the CCD. The thermal connection was made by 1/1000 inch thick, multi-layer gold coated silver straps (Fig.15) which connected the last stage of the TEC to the CCD, and its third stage to the thermal shield for minimizing the ambient thermal radiation. The purpose of the TEC was to maintain the CCD temperature much bellow the ambient level, which in many ways improved its performance. At room temperature, the CCD device is saturated by thermally generated electrons in the Silicon substrate. This phenomenon is known as the dark current, which means generation of electrons without exposure to light. The thermal excitation of these electrons is minimized at lower temperatures. The CCD performance in the infrared wavelength was also improved at lower temperatures.

The dark current is not a big concern in home video cameras, since the CCD image is read out at a rate of 60 frames per second (interlaced, back in analog TV days). But in the space telescope, a single CCD image may get up to 50 minutes of exposure, and without cooling, the entire CCD array would become saturated by dark current in the first few seconds, as if you took a picture of the sun! The WF IPC-II utilized MPP devices, which allowed room temperature imaging. This technology minimized the dark current generation in the CCD, and required less cooling.

While the CCD device itself was thermally isolated from the camera head assembly, its exact alignment was to be maintained with the focal plane of the relay optics. The way this was accomplished was by three fiber glass bands that pull the CCD support ring in three radially symmetrical directions, 120 degrees apart (Fig.15). As the temperature changed, the three fiber glass bands expanded or contracted symmetrically, maintaining the central alignment of the CCD support pins. The tension of these bands were accurately measured, and adjusted by a strain gauge mounted against one of the pulleys. After completion of the adjustment, the strain gauge wires were clipped off.

The camera head assembly supported a total of three major electronic boards. The main board contained amplifiers that increased the level of the CCD video output, at the closest possible location to the device (below). This served as a noise reduction technique in the system, boosting the amplitude of signal before it traveled through cables to other boards farther away. It is like the effect of a small rock on top of a smooth curve 1 foot high or 24 feet high: The taller the curve, the less noticeable is the small rock. Electronic noise is the same as the small rock, the bigger the signal compared to the noise, the better it would appear at the end. The bipolar driver boards were added to improve the CCD performance. These boards swing the timing signals of the CCD to both positive, and negative levels. The CCD operation is later explained in the CCD section.

Camera Head Electronics Board

This board contains pre-amp circuitry to amplify the voltage from each pixel 21 times (see Fig. 29) before sendig the video signal to post-amp Sample and Hold electronics. Electronics components in aerospace are each tested, and qualified before their installation. Space components are radiation hardened (Rad Hard) to survive the harsh environment of outer space. Resistors are wire wound. No Carbon resistors in avionics or space!

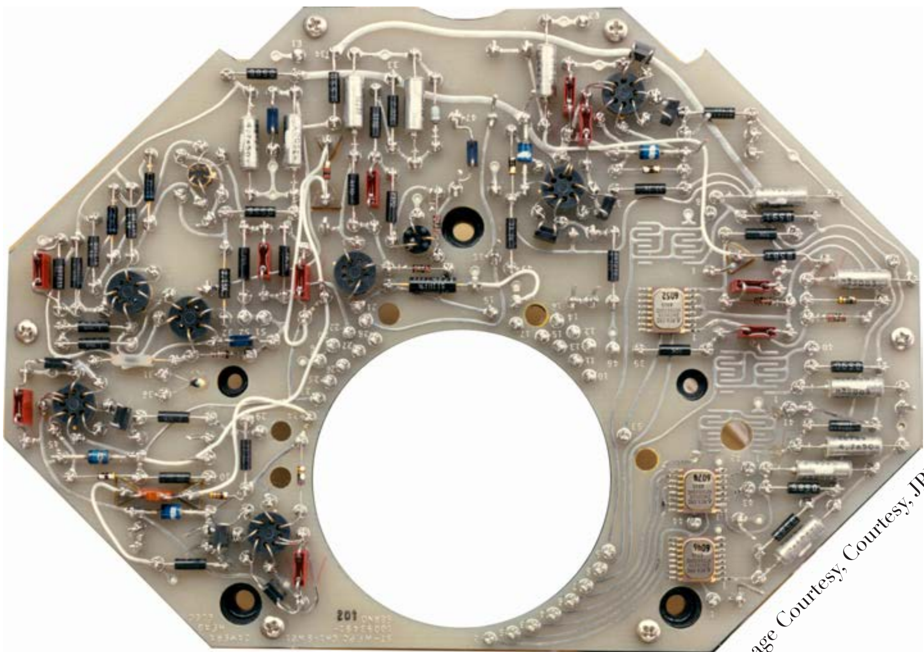
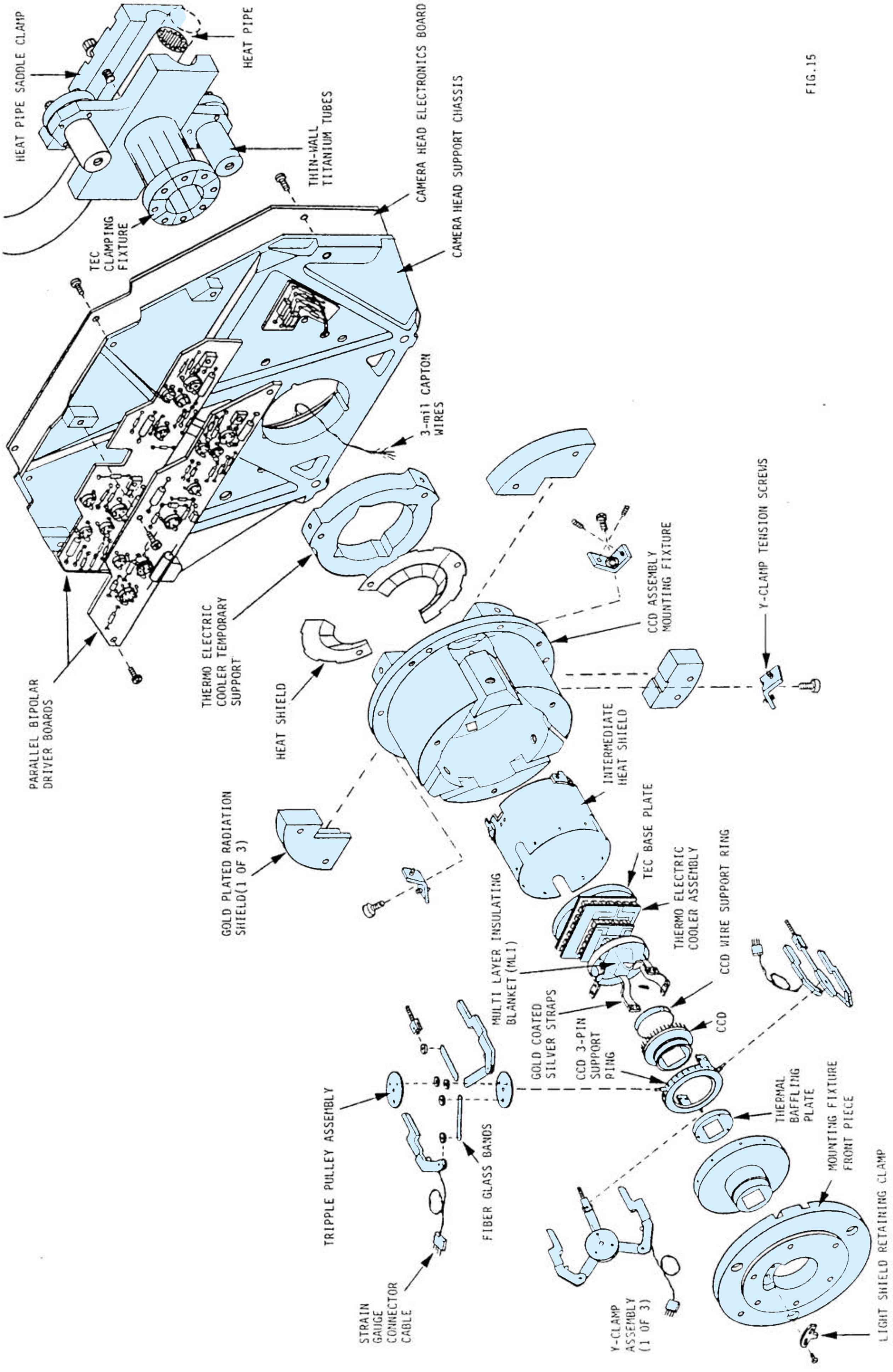


Image Courtesy, Courtesy, JPL


HEAT PIPE SADDLE CLAMP
HEAT PIPE
THIN-WALL TITANIUM TUBES
CAMERA HEAD ELECTRONICS BOARD
CAMERA HEAD SUPPORT CHASSIS
TEC CLAMPING FIXTURE
3-mil CAPTON WIRES
PARALLEL BIPOLAR DRIVER BOARDS
THERMO ELECTRIC COOLER TEMPORARY SUPPORT
HEAT SHIELD
CCD ASSEMBLY MOUNTING FIXTURE
Y-CLAMP TENSION SCREWS
INTERMEDIATE HEAT SHIELD
TEC BASE PLATE
THERMO ELECTRIC COOLER ASSEMBLY
CCD WIRE SUPPORT RING
GOLD PLATED RADIATION SHIELD(1 OF 3)
MULTI LAYER INSULATING BLANKET(MLI)
GOLD COATED SILVER STRAPS
CCD
CCD 3-PIN SUPPORT RING
THERMAL BAFFLING PLATE
MOUNTING FIXTURE FRONT PIECE
TRIPPLE PULLEY ASSEMBLY
FIBER GLASS BANDS
LIGHT SHIELD RETAINING CLAMP
STRAIN GAUGE CONNECTOR CABLE
Y-CLAMP ASSEMBLY (1 OF 3)
FIG.15

THE FILTER WHEEL ASSEMBLY

The filter assembly (still part of WFC III) carries a total of 48 filters in 12 filter wheels (Fig .16). It is made by Schaeffer Magnetics. The filter mechanism operates similar to a large six-phase stepper motor. Each filter wheel has an outer fused magnetic layer of 240 poles, which you can see, and feel as you move the tip of a screw driver across its edges. The filter wheels rotate with a tight tolerance, inside a rotor, which has 215 coils. By using some magnetic tricks, the filters are strongly held in position in a magnetic detent, which is precisely selectable in half a degree increments. To rotate a given filter wheel to its next filter position (1/5 of a turn), 144 steps are generated by the drive electronics. The total of coils used for all 12 wheels are 2,580. The fact that these filter wheels maintain their alignment with the rotors, is not trivial. The central shaft plays the role of keeping all the filters in line. The outer rotors are sandwiched together with tight radial registration grooves. The front and back face plates are the only bridges between the wheels and the rotors. The optical path length of the filters (determined by their index, and thickness) are kept the same to eliminate refocusing when changing filters. Filters that are designed to be used in conjunction with others, have curved surfaces for focus compensation. There are three diffraction grating filters with a wedge angle to redirect one of the diffracted beams to the center of the CCD. By knowing a star's original position in the field of view, and selecting one of the grating filters, the CCD pixels could be used to detect specific wavelengths of the star's spectrum. Other filter slots contain polarization, and interference filters that transmit a narrow band of wavelength (Fig.16).

THE SHUTTER UNIT

The WF/PC shutter is similar in design to the shutters used in Voyager I, and II, but about four times bigger in size. Canon 14 fps high speed 35mm camera designed for photographing Olympic games, utilized a similar concept. The shutter unit consists of two horizontal running blades, that are activated by two solenoids. Each solenoid has two coils, which are wound in two opposite directions. Energizing the first coil would cause blade A to move to the right (Fig.17) or close it. Energizing the second coil would cause blade A to move to the left, and re-open the blade. This design uses a magnetic detent which attracts the solenoid armature at the end of its clockwise, or counter-clockwise position to eliminate blade bounce.

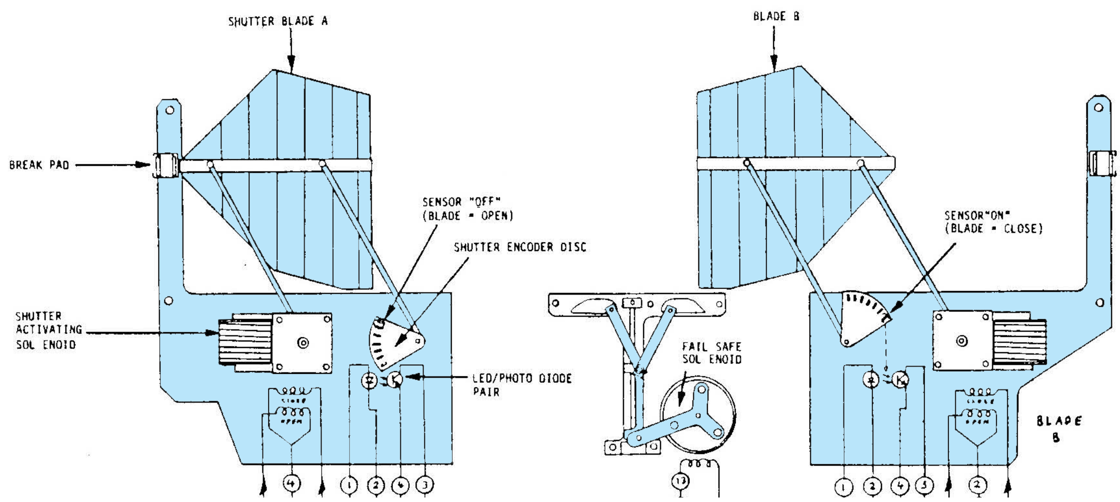


Fig. 17

Shutter blades are made of Aluminum painted with dull black paint on their front side, and are supported by two arms that pivot at four points. At the end of one arm is attached an encoder disc, which runs between two detectors and two infrared diodes (for redundancy). As the-shutter blades move, the square wave output of the detector sequentially starts and stops six independent counters (inside the logic board). Thus, time-tagging the motion of each blade at specific points of its travel. This data is included in each image to give exact velocity of the blades during the exposure.

The fail-safe solenoid is attached to a Y-shaped arm, which opens both blades with a clockwise motion of its armature. Since the shutter is an essential part of the camera, it can not afford to fail, and this mechanism minimizes this possi-

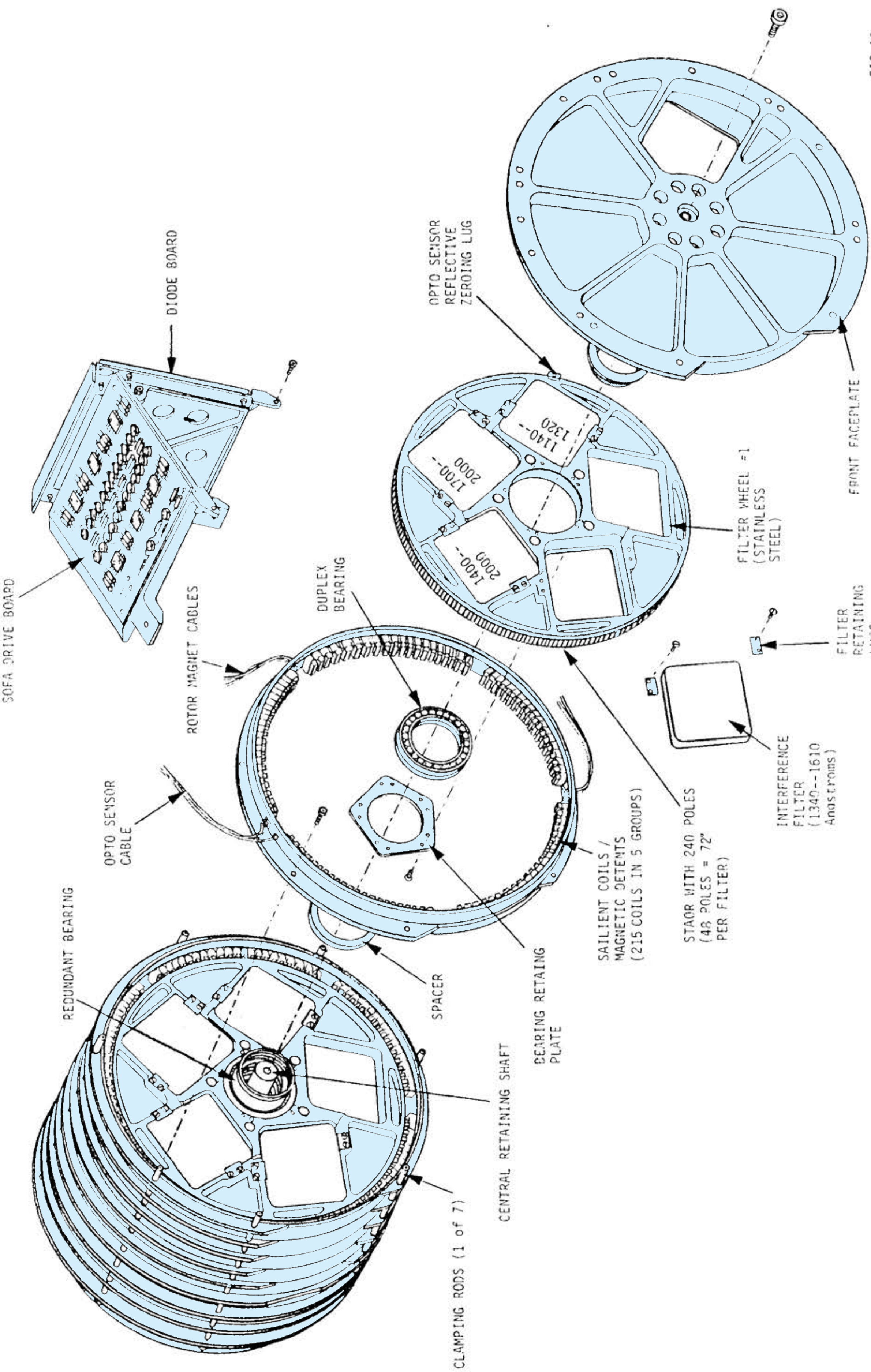

SOFA DRIVE BOARD
DIODE BOARD
ROTOR MAGNET CABLES
OPTO SENSOR CABLE
REDUNDANT BEARING
DUPLEX BEARING
OPTO SENSOR REFLECTIVE ZEROING LUG
1140--1320
1700--2000
1400--2000
FILTER WHEEL #1 (STAINLESS STEEL)
FRONT FACEPLATE
FILTER RETAINING LUGS
INTERFERENCE FILTER (1340--1610 Angstroms)
STAOR WITH 240 POLES (48 POLES = 72° PER FILTER)
SAILIENT COILS / MAGNETIC DETENTS (215 COILS IN 5 GROUPS)
BEARING RETAING PLATE
SPACER
CENTRAL RETAINING SHAFT
OUTER CLAMPING RODS (1 of 7)

FIG.16

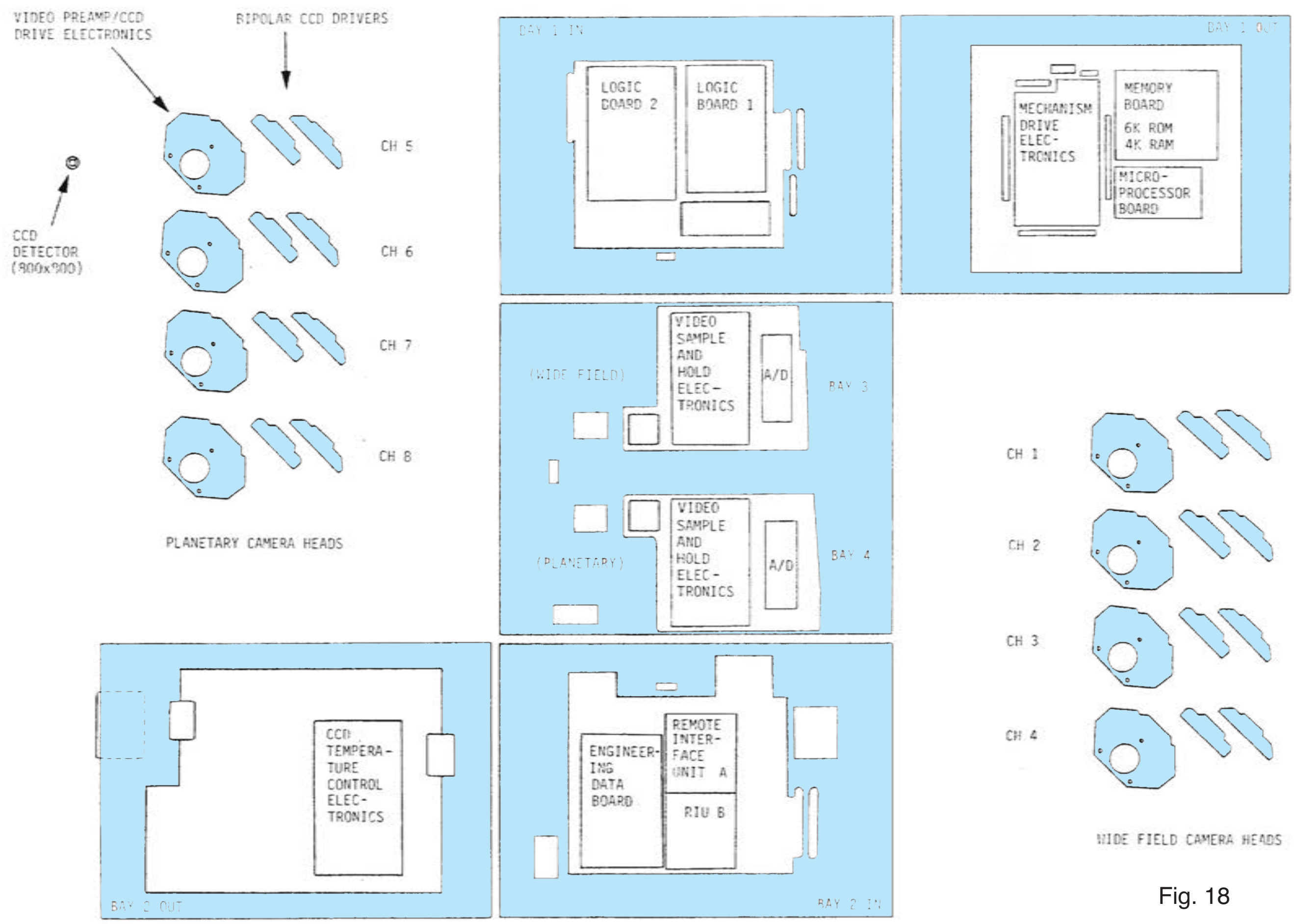


Fig. 18

bility. In case one of the blades should fail, the shutter can still operate with only one blade. When sending commands to the telescope, the operator has to know which blade is open, and which one is closed. When a shutter blade is in the open position, the encoder disc blocks the IR diode, and allows the light to go through when in the closed position (Fig.17). This status is displayed as telemetry information on the user's monitor. The shutter encoder circuitry is an integrated part of the shutter mechanism, while the shutter drive circuitry resides in the mechanism driver board, described next.

THE ELECTRONIC BAYS

The Wide Field and Planetary Camera has 5 electronic bays, which provide power and control signals, and monitor many parameters throughout the camera. The electronic layout is given in figure 18. If you cut this layout, and fold it as shown in figure 19, you'll get the exact configuration of the system.

1) BAY 1 OUT, MECHANISM DRIVER BOARD - Provides the drive signals to activate different mechanisms inside the camera, such as moving the shutter blades, turning the pyramid, filter wheels, etc.

2) BAY 2 IN, REMOTE INTERFACE UNIT - Receives commands from the radio signals received and processed by the telescope, such as making an exposure, reading the image, etc., and relays it to the logic board. The RIU also monitors many parameters in the camera such as the shutter blade position, filter position, etc, and sends these down through the telescope as engineering telemetry.

3) BAY 2 IN, ENGINEERING MEASUREMENT BOARD - Receives signals from different sensors and switches in the camera, such as sensing the temperature in the camera heads, and converts them to a digital number that can be read by the logic board, and sent down with the image (see page 28 for a picturial view of this board).

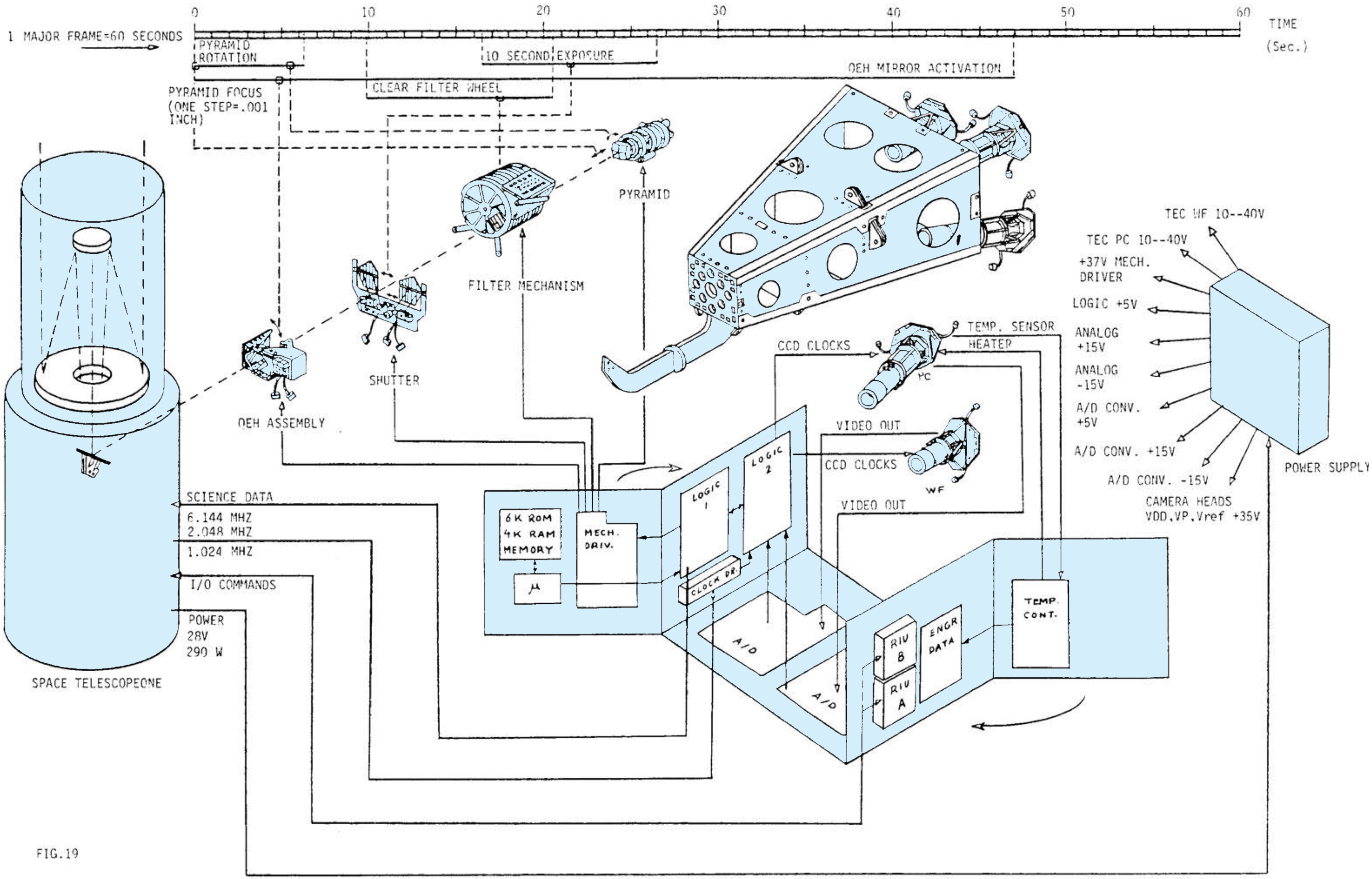

1 MAJOR FRAME=60 SECONDS
0
10
20
30
40
50
60
TIME (Sec.)
PYRAMID ROTATION
10 SECOND EXPOSURE
OEH MIRROR ACTIVATION
PYRAMID FOCUS (ONE STEP=.001 INCH)
CLEAR FILTER WHEEL
PYRAMID
FILTER MECHANISM
SHUTTER
OEH ASSEMBLY
SPACE TELESCOPEONE
SCIENCE DATA
6.144 MHZ
2.048 MHZ
1.024 MHZ
I/O COMMANDS
POWER
28V
290 W
6K ROM
4K RAM
MEMORY
μ
MECH. DRIV.
LOGIC 1
LOGIC 2
CLOCK DR.
A/D
A/D
RIU B
RIU A
ENGR DATA
TEMP. CONT.
CCD CLOCKS
VIDEO OUT
CCD CLOCKS
VIDEO OUT
TEMP. SENSOR
HEATER
PC
WF
TEC WF 10--40V
TEC PC 10--40V
+37V MECH. DRIVER
LOGIC +5V
ANALOG +15V
ANALOG -15V
A/D CONV. +5V
A/D CONV. +15V
A/D CONV. -15V
CAMERA HEADS VDD,VP,Vref +35V
POWER SUPPLY

FIG.19

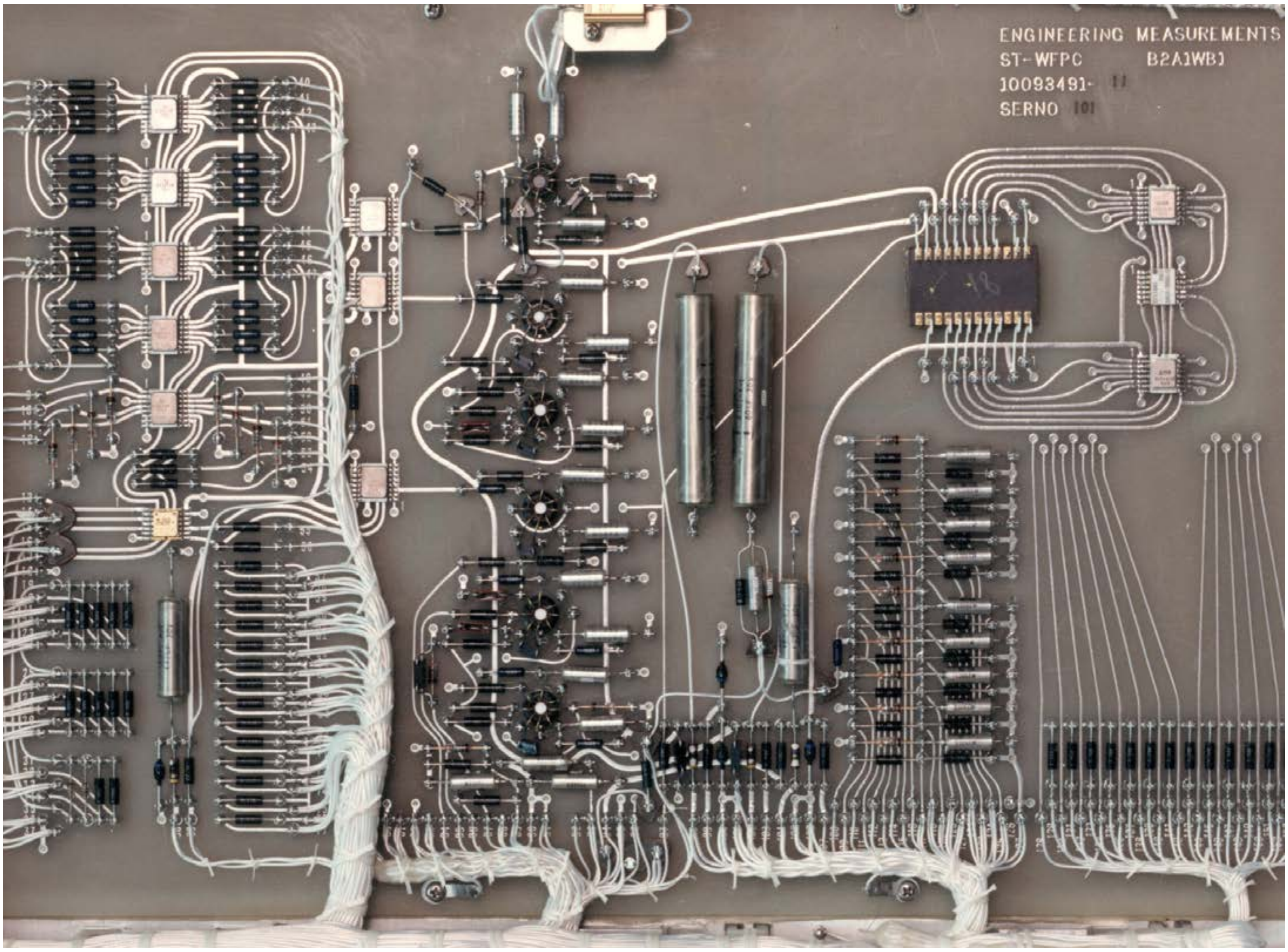
4) BAY 2 OUT, CAMERA HEAD TEMPERATURE CONTROL BOARD - Measures the CCD temperature in the camera heads, by a temperature sensing device (a thermo-couple), and controls the temperature with a heating element (a carbon resistor). For example, if one of the camera heads gets too cold, the resistance of the-thermo-couple decreases. This turns on a circuit inside the temperature control board which increases the voltage across a carbon resistor mounted close to the CCD, and raises the temperature. When the correct temperature is reached, the drive circuit automatically shuts off.

5) BAY 1 IN, CLOCK DRIVER - This package takes the incoming clocks of the spacecraft (Fig.19), which are sine waves, and outputs them as square waves. The logic board then takes this square output, and divides it down to generate slower clock rates. The idea is to fine-tune (synchronize) the clocks inside the WF /PC with the running clocks of the telescope.

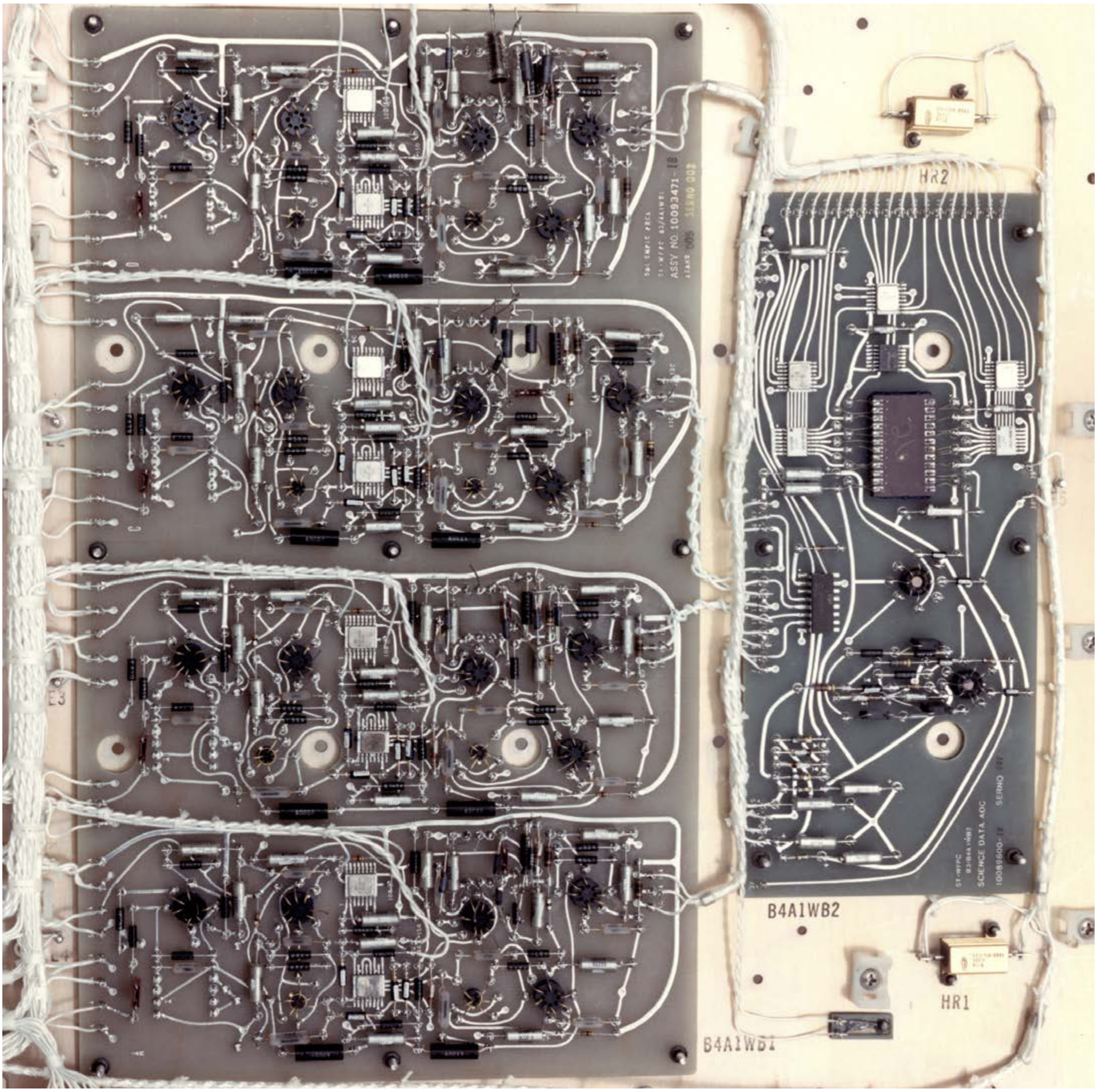
6) BAY 3, VIDEO AMPLIFIER AND DOUBLE SAMPLING ANALOG TO DIGITAL CONVERTER - Further amplifies the video signal coming from any of the planetary camera heads, and converts it to a digital number (opposite page).

7) BAY 4 - Same as BAY 3, but for wide field cameras.

8) BAY 1 IN, LOGIC BOARD 1, 2 - The logic board was initially one large board, but was divided to two, because of the size limitations in manufacturing. The logic board is the interface between the microprocessor and the mechanism driver board. It also converts the image readout from the camera, and other readings from the instrument into a format which can be sent down through the telescope. Time tagging of the shutter blade movement is also done by this board.



BAY 2 IN (Refer to Fig. 18), Engineering Data Board, Image Courtesy, JPL

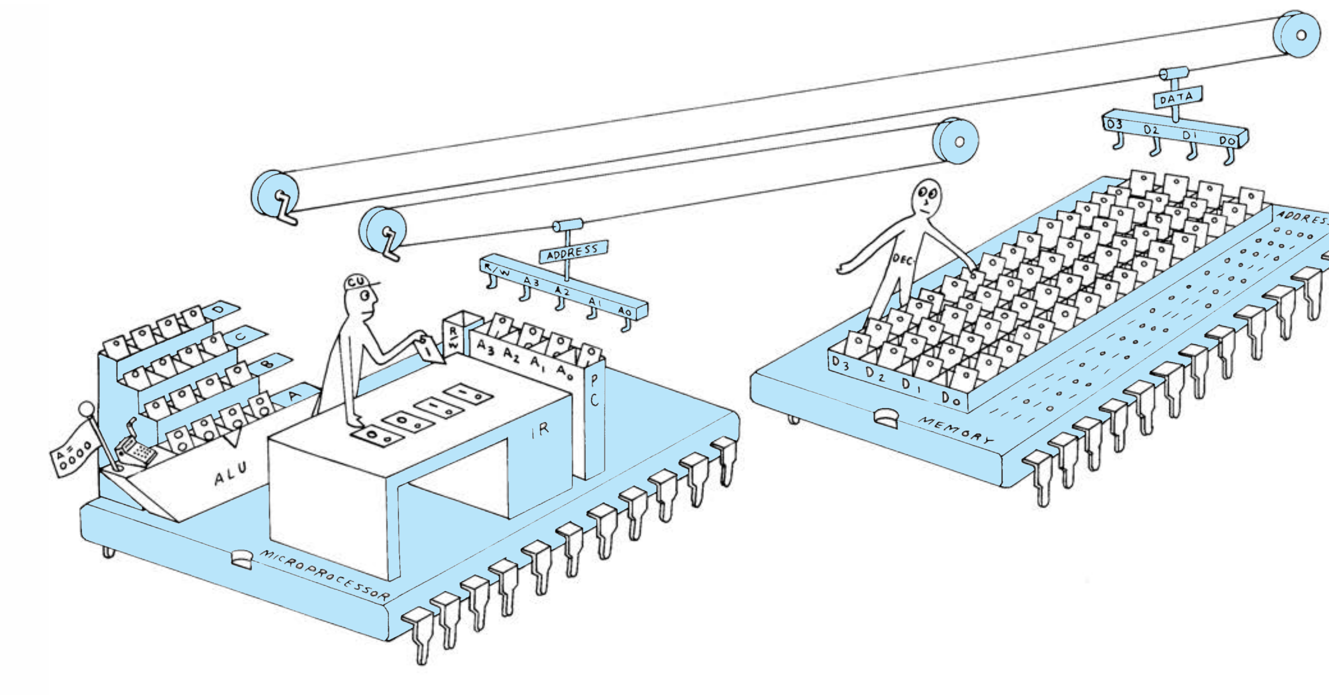


Bay 3 (also refer to Fig. 18) Video Sample and Hold Electronics (above left), and A/D converter (above right) Image Courtesy, JPL

9) BAY 5, POWER SUPPLY - Converts the power line coming from the telescope (28 volts) to the required voltages used by the instrument. The thermoelectric cooler power supply monitors the voltage across the cooling device in the camera heads, and adjusts the applied power, so that the cold side of the cooler remains at a constant temperature. This is necessary, because depending on the position of the telescope with respect to the sun, the temperature at the radiator would change, and so would the temperature at the CCD. You can think of the thermoelectric cooler as a heat pump, or a fan. If the environment behind the fan gets cooler, the fan has to slow down to keep the temperature constant in front of it, and vice versa.

THE MICROPROCESSOR

The WF /PC uses an 8-bit, REA 1801 microprocessor (above), which is so slow compared to today's micro processing speeds. Before I got involved with space instruments, I always asked myself what would people do if some part of the memory fails, or what if they decided to change the program while the space craft was way up there in space? As I will



A detailed model of a 4-Bit Microprocessor, and how it reads/writes to memory, and its internal registers.

explain shortly, the way WF/PC did this was by setting break points at different parts of the program. The way a microprocessor works is like someone following your instructions, written on pages of a book called memory. In the WF /PC processor as well as in your home computer, these instructions are written as an eight-digit binary number (or one byte, such as 1100,0000, or 0111,0001, etc. These numbers can be easily represented in the form "CO", or "71", known as a hexadecimal representation (Binary numeral system is base 2, while Hexadecimal numeral system is base 16).

The book that memorizes all this even when the computer is off, is called ROM or read only memory. The 6K ROM in WF/PC is like a book with 6144 pages. There is also a 4k RAM or random access memory, which is like a diary book with 4096 pages (only half of the available RAM is normally used). The diary book can be erased by either writing over it or by shutting off the computer.

The so called computer brain refers to the fellow reading the cards (Fig.20), and doing exactly what they say. For example, "CO" means to jump to some other page in the book, and do what it says in that page, "F8" means to read from some location of memory. When the computer is turned on, it starts reading location 0000 (Fig.20, inside ROM), and executes the program one by one. To do this, he uses a chalk board (Registers), a hand calculator (Arithmetic and Logic Unit), and a place on the board where the results from ALU are displayed (D register).In home computers, programs are loaded into RAM, and changed if necessary. But in spacecraft applications, the programs are usually executed from ROM, and no new page can be added to the book, or taken out. A way out of this is to divide the book into chapters (Fig.20) and at the end of each chapter (break point), we'd tell the processor to jump to a page inside the RAM book (the first break point is at ROM location 010B). This page of RAM (for the first break point, this would be RAM location 4100) would simply tell the processor to go back to the beginning of next chapter in ROM, and continue with the program until the next break point (ROM location 012D; etc.). The advantage of this is that if you decide to Change the program within any of the chapters, you can change the page in RAM to tell the processor to skip any chapter, and continue with a new program loaded in RAM. For example, if we decide to do some changes in the program that resides within ROM locations 012E and 017 A, a substitute program can be transmitted to the spacecraft, and written to any RAM location between 4800, and 4FFF (spare RAM).

When the processor reaches the second break point, it jumps to RAM location 4103, and then jumps to the beginning of the new program in RAM, and continues the rest of the program in ROM (locations 4104 and 4105 in RAM have a new jump address). So instead of having to transmit an entire new program, we have the convenience of changing

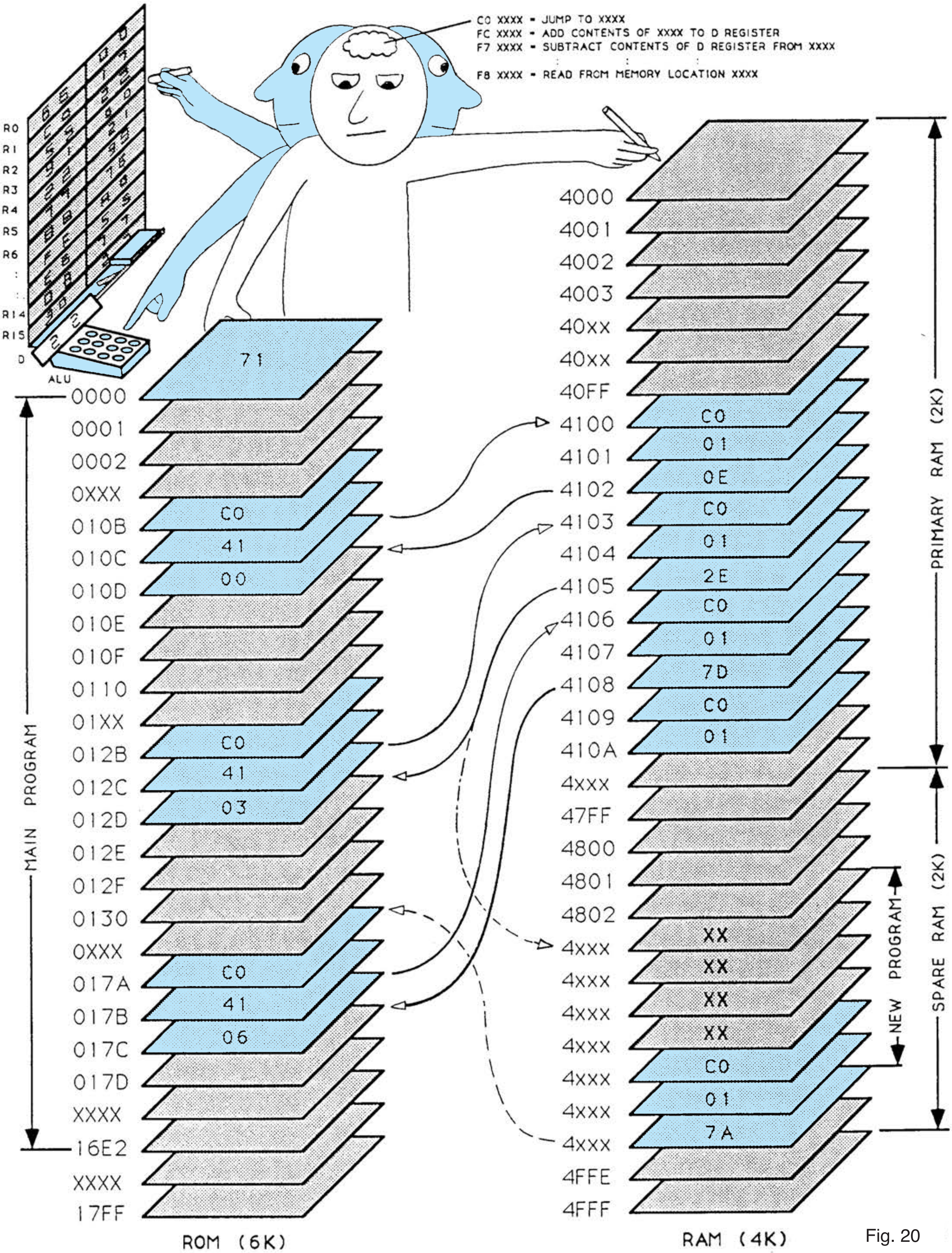


Fig. 20

How the Microprocessor, and RAM / ROM memories are layed out in a spacecraft to work in space, see text for details.

only a portion of it. Of course, if there is a short power failure in the space craft, the RAM contents are destroyed, and the computer starts running the same old program stored in ROM, and we'll have to upload the RAM once again. In the real world, a single memory chip is not big enough to contain all the program. Each pair of WF IPC's ROM chips (books) contains 256 pages, making an array of 48 chips. If any of the memory chips would fail, break points are useful to go around bad ROM locations. In case of primary RAM failure, the microcomputer uses the spare RAM.

EXECUTING COMMANDS

During the program execution, one of the tasks of the microcomputer is to check if any new commands have been sent to the camera. If a new command has been received, the microcomputer checks to see what it is, and then schedules them to be executed in the next major frame. Every mechanism operation inside WIFPIC is activated at a specific time during the major frame. Figure 19 shows when some of the mechanisms are activated during a major frame, and how long it takes them to complete their operation.

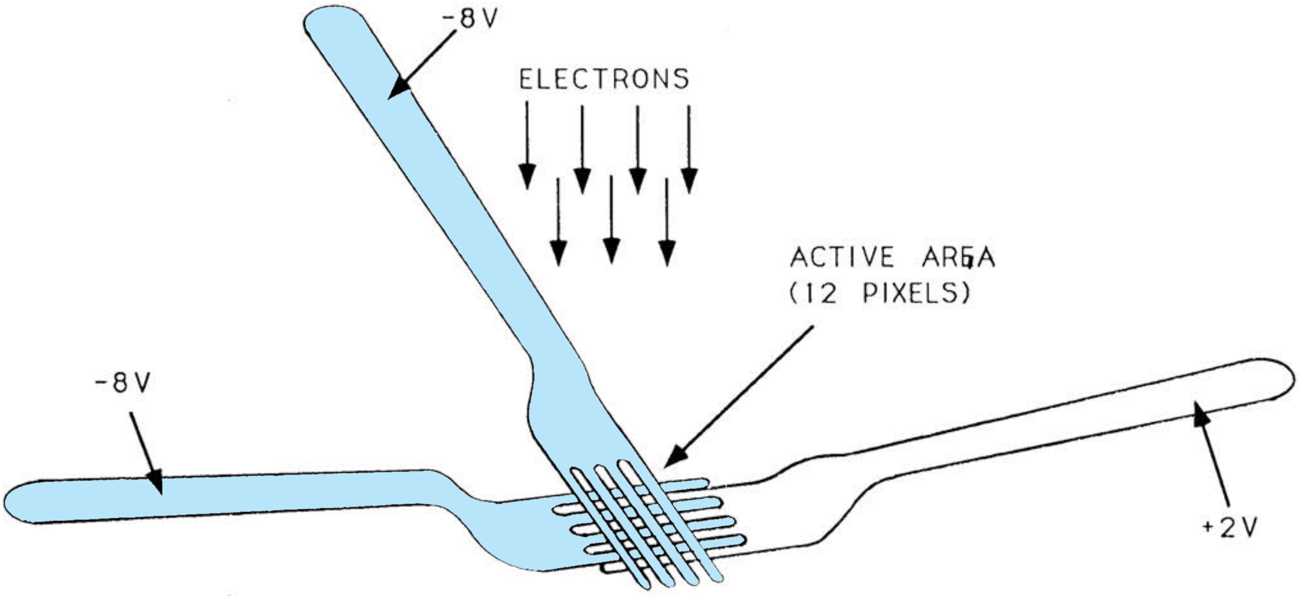
THE CHARGE COUPLED DEVICE (CCD)

Next time you have dinner, pick up three forks, and orient them at 90 degree angles on the table. Now slide the. two forks that are facing each other so that their teeth interlace together, then place the third one on top of the next two (Fig.21). Imagine connecting any of the two perpendicular forks to a negative potential (let's say -8 volts), and the third one to a positive (or less negative) potential (let's say + 2 volts). You have just constructed a model for a two phase CCD device with 12 pixels!

The way a CCD works, is by trapping tiny elements of an image in a matrix array of storing elements called pixels. In simple electronic terms, projecting an image on a CCD is like pouring a hand full of electrons on the square area interlaced by the three forks: The electrons will be collected only on nine different locations, with the + 2V potential. The idea is that each pixel encloses electrons in both vertical and horizontal directions by the two perpendicular forks connected to -8 volts. The electrons, having a negative charge, would only be attracted to the teeth of the fork connected to + 2 volts, or in electronics terms, they would migrate to a higher potential, and remain there.

The number of electrons in each pixel would record the brightness level in that area of the image: The more the number of electrons, the brighter the image, and vice versa. CCD's then, behave similar to photographic film, and would require a shutter, and should get the right amount of exposure. If over exposed, the electron capacity of the pixels is exceeded, and the electrons would overflow to the neighboring pixels. But the light itself consists of photons, and how is a "photon image" converted to an "electron image"? The way this works is like how photo transistors convert light into an electronic signal. Inside a photo transistor is a layer of silicon, and when a photon enters this layer, it generates one or more electrons if it is powerful enough to release those electrons from the outer layer of Silicon atoms. The energy of this photon is determined by its wavelength. In the ultra-violet region, photons have a much higher energy, and interact immediately after entering the Silicon layer. In the infrared region, photons have less energy, and penetrate deeper into the Silicon to release an electron.

Figure 22 shows the schematic of a WF IPC-II CCD, with simplified array of 3 (vertical) by 9 (horizontal) pixels. The actual CCD in WF/PC II contained an 800 x 800 pixel array, produced by four interlacing structures that resemble forks with 800 teeth! These CCD's come in a 40-pin package. You can think of pins 10, 11, and 12 as the arms of the forks sticking out of the chip (this is a 3-phase CCD device). The teeth of these three forks run horizontally across the active area of the device, and are labeled 1, 2, and 3. For example, if you trace the wire from pin 10 under a microscope, you'll reach a vertical bar, which is connected to every other three horizontal running traces (labeled "2" in Fig.22). All the horizontal traces 1, 2, and 3 are separated by running over a series of vertical barriers, labeled "B". In CCD terminology, forks are called phases (i.e. P1, P2, and P3), and the charge Barriers (labeled "B") are equivalent to the vertical fork shown in Fig.21.


-8V
ELECTRONS
ACTIVE AREA
(12 PIXELS)
-8V
+2V

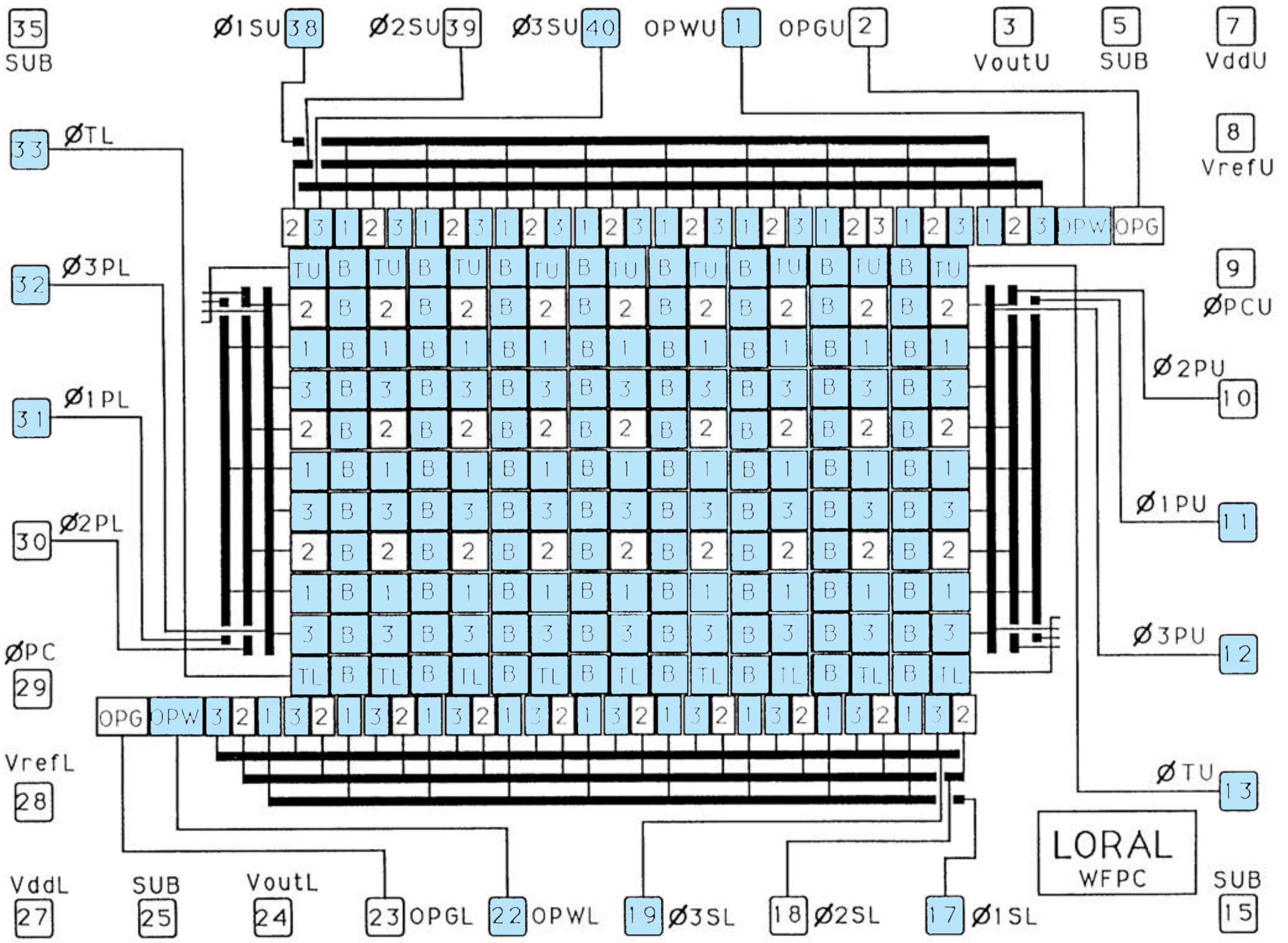

35 SUB
Ø1SU 38
Ø2SU 39
Ø3SU 40
OPWU 1
OPGU 2
3 VoutU
5 SUB
7 VddU
8 VrefU
9 ØPCU
Ø2PU 10
Ø1PU 11
Ø3PU 12
ØTU 13
33 ØTL
32 Ø3PL
31 Ø1PL
30 Ø2PL
ØPC 29
VrefL 28
VddL 27
SUB 25
VoutL 24
23 OPGL
22 OPWL
19 Ø3SL
18 Ø2SL
17 Ø1SL
SUB 15
LORAL
WFPC
OPW
OPG
ALI AFSHARI 6, 21, 91

FIG.22

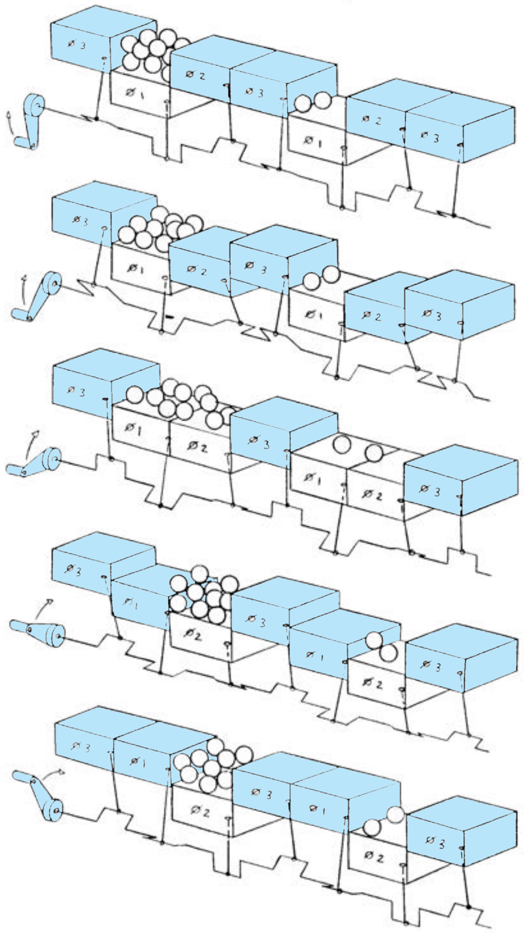
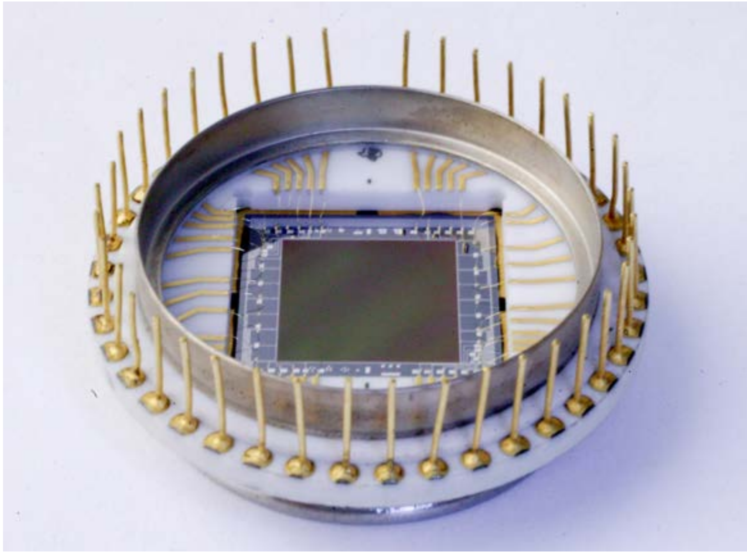
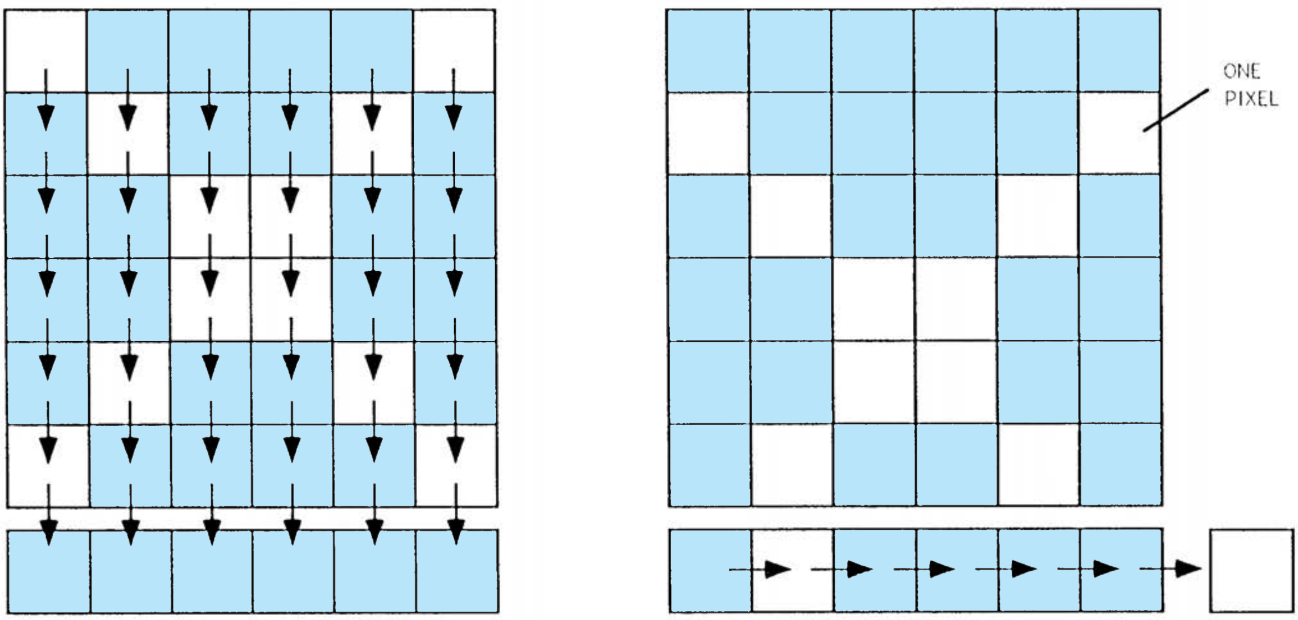


Fig. 24 Transfer of Electrons from Phase 1 to phase 2



WF/PC's CCD back illuminated 800 x 800 sensor made by Texas Instruments. A back illuminated CCD is produced by etching the substrate by acid to make it an extremely thin, and then projecting the image on its back instead of its front. When you look CCDs through a microscope, you'll see the actual forks ovrlapping each other to form pixels. Back then, the layout was designed using AUTOCAD, and then manufactured on a 100 mm substrate. The substrate was then cut into 32 pieces to make 32 CCDs. Each CCD chip was then cemented onto the housing which was made of ceramic. A welding robot would then connect each contact to the CCD chip to its Gold plated legs. See Fig. 22 for a simplified schematic diagram of this CCD. WF/PC II utilized a similar but front illuminated CCD. Each device had to be qualified, and matched to each camera head.



VERTICAL OR PARALLEL SHIFT. Fig. 23 HORIZONTAL OR SERIAL SHIFT.

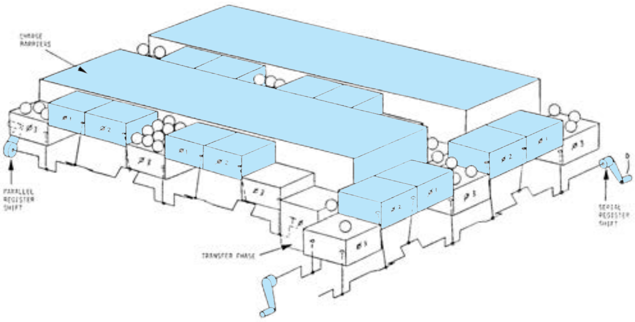


Fig. 25 Transfer of electrons from vertical channels to horizontal readout channel

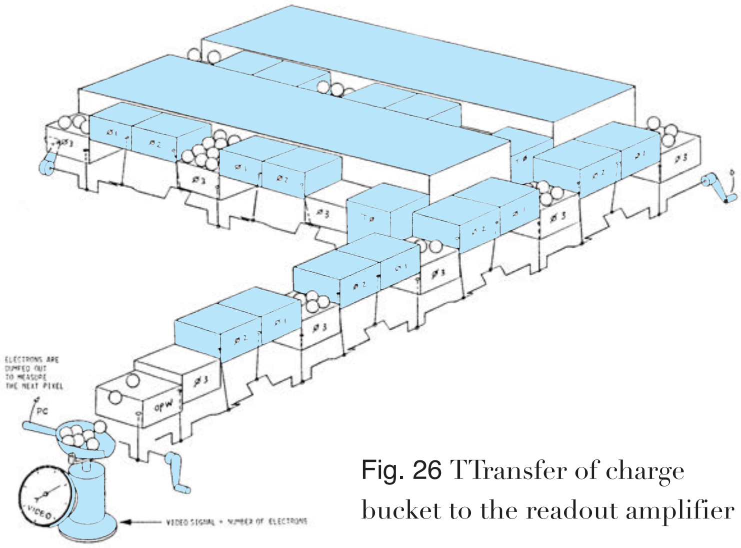


Fig. 26 TTransfer of charge bucket to the readout amplifier

In reality, these fork structures are thin implants on the surface of a substrate, which is a stack of several Silicon layers. When the light strikes the Silicon layer, it releases electrons, which are then collected in pixels. During the exposure, phases 1 and 3 are held low by applying -9 volts to pins 12 and 13, and Phase 2 is held high by applying +3.5 volts to pin 14. This makes phase 2 to be the electron collecting phase of the CCD, creating a total of 27 "charge buckets" (640,000 pixels in the real device). Let's say a star image falls on any given area of the CCD, and forms an image the size of a pixel. The light photons would penetrate into the silicon substrate, and releases a number of electrons. Depending on the brightness of the star (and its wave length). The generated electrons would be gathered at the closest phase with the highest potential, or the closest phase 2. Each pixel in WF IPC CCD has an area of 15X15 microns (each micron = 1 millionth of a meter), and can collect up to 50,000 electrons. The exposure time must be chosen such that the brightest area of interest would not generate over 50,000 electrons.

READING OUT THE CCD IMAGE

Figure 23 shows the basic readout scheme of a CCD, using parallel and serial shifting of the pixels. A single parallel shift, dumps every row of the CCD to its lower row, and dumps the very bottom row to a horizontal shift register. The horizontal array is then read out one by one, and the number of electrons in each pixel is measured (six horizontal shifts for every one vertical shift). To understand the shifting operation,' consider switching the voltages between phases 2 and 3 in figure 22. For the same reason the charges were collected under phase 1, they will now migrate to phase 3. Now switch the voltages between phases 3 and 1: The charges would be collected under phase 1. Finally, by switching the voltages between 1 and 2, the charges end up on a new phase 2, at a higher row.

To visualize this, consider a series of mechanical pistons that go up and down by a common crank shaft (Fig.24), which moves each two neighboring pistons 120 degrees out of phase. Similar to the CCD, phase 1 is lower than the rest of the pistons, so all the electrons end up in phase 1. Transfering the Electrons be-

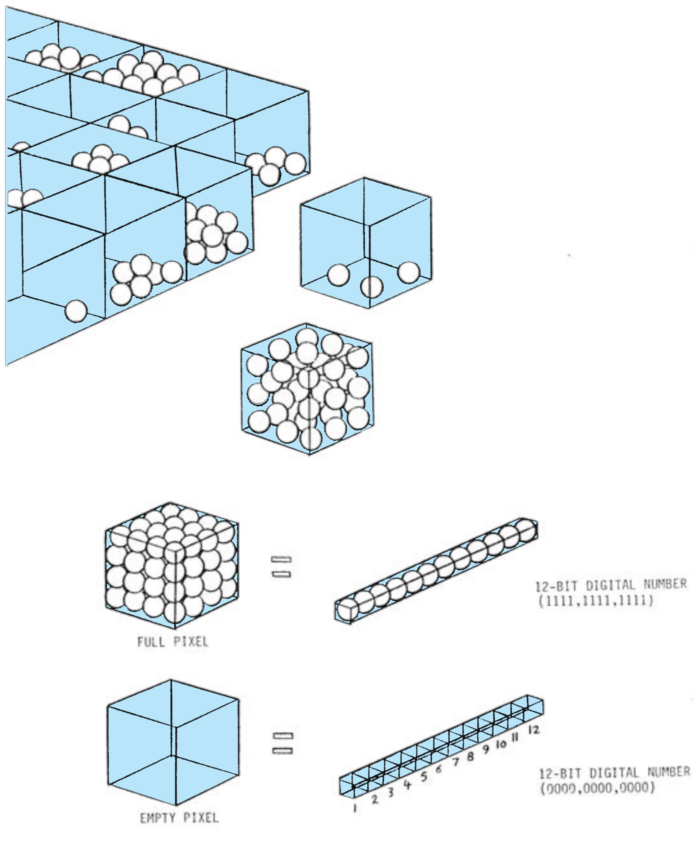


Fig. 27 Full electron capacity of a 15 micron pixel in HST was 50,000 electrons, converted to 12-Bit digital number

tween phases 1 and 2, is like turning the crank shaft 120 degrees (Fig.24). The barrier columns separate the vertical pixels in the horizontal direction (Fig.25). With a complete rotation of the crank shaft, the electrons from the bottom pixels are fed to a serial register (the electrons from the parallel registers can either go to phase 2 or 3 of the serial register). Before the serial register can start shifting out the electrons, it has to be first isolated from the parallel (or vertical) registers. This is the job of the transfer register (Fig.25-26). The serial shifting operation is the same as the parallel register, but it is made longer to provide more information about the exposure. I will explain this later in more detail. The job of the output well is similar to the role of the transfer phase (Fig.26). The contents of each pixel are dumped into a measuring system, which measures the voltage generated by the number of electrons. The PC (pre charge) is synchronized with the serial shifting register, so that it dumps out the previous content of the measuring device, while the serial register is shifting the contents of the next pixel (Fig.26, 28). The output of the measuring device is the video signal (a single voltage value between 0.003 to 12.228 millivolts).

If you now go back to the CCD schematic (Fig.22), you know the job of every pin in the device. There are in fact two ways to read this CCD, from the top, or from the button. This is similar to rotating the crank shaft in the opposite direction. The pin names followed by letter "L" correspond to control pins for the Lower register, and those followed by "U" correspond to the upper register.

CONVERTING THE NUMBER OF ELECTRONS TO A DIGITAL NUMBER

Considering the possible number of electrons in a given pixel, we could have any number of electrons ranging from zero to 50,000 (Fig.27). In order to transmit this information to a ground station through a radio antenna, it first has to be converted to a digital number. The WF/PC analog to digital converter did this conversion with 12 bits of resolution. This translates to 7.5 electrons per digital number, or 4094 different shades of gray. In simpler terms, if a pixel is empty, the A/D converter would assign the value 0000,0000,0000 (Fig.27). If the pixel is full, the A/D converter would assign the value 1111,1111,1111 to it, and there are 4096 different possible combinations in between. Dividing 50,000 by 4095, you'll get 7.5 electrons. Increasing the resolution of the A/D converter from 12 bits to 16 bits would not do us any good because in practice, there are inherent noise in the system that are not less than 7.5 electrons.

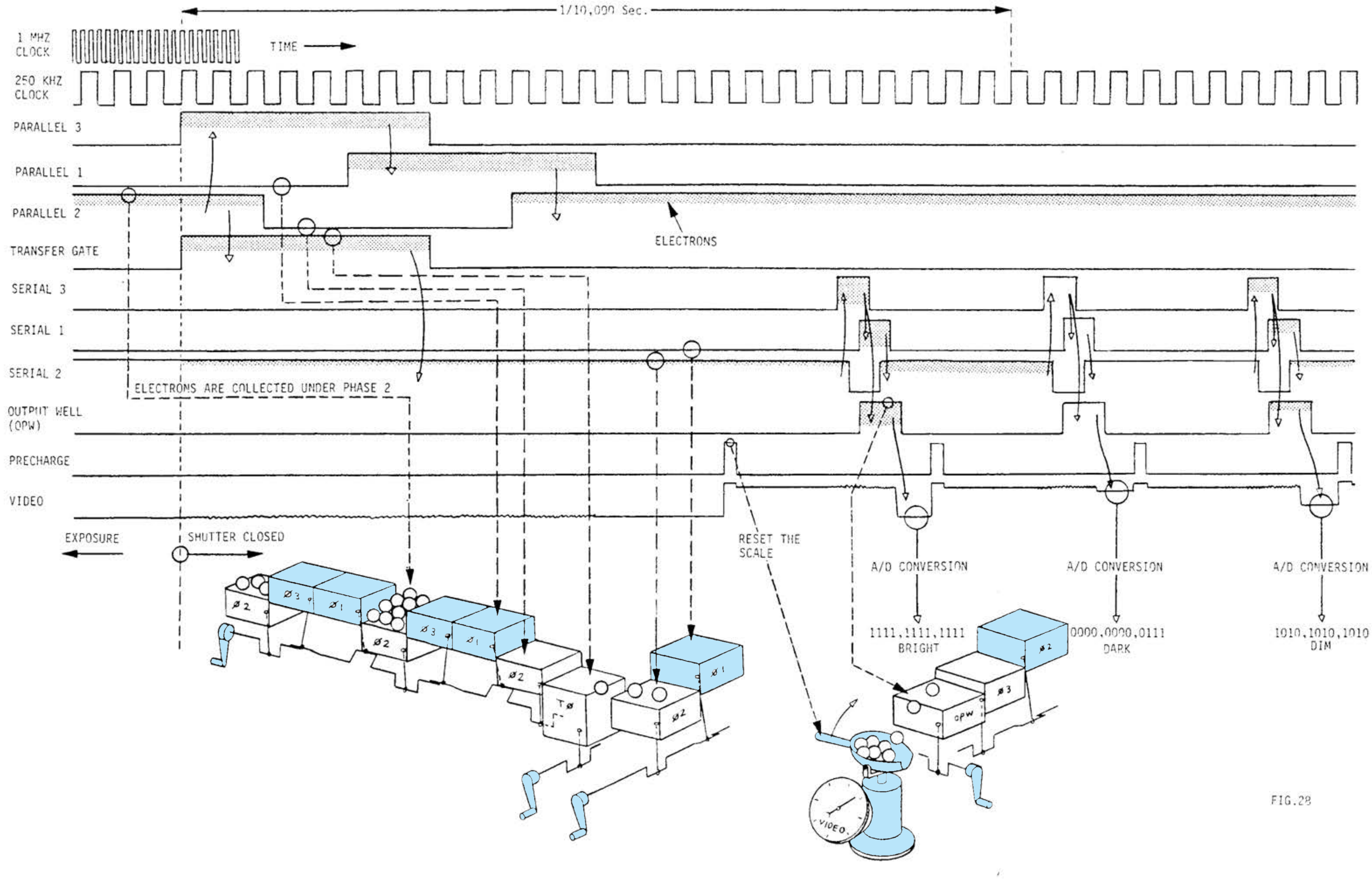
CCD DRIVE SIGNALS

Figure 28 shows the actual drive signals that appear at the CCD pins. During the exposure, phase 2 is held positive to collect the electrons, and all other signals are low. To read out the image, the logic board generates a sequence of signals to move electrons from one pixel to the other (similar to pistons in the mechanical model). To better understand this, you can place a plastic ruler vertically over the wave forms, and move it from left to right. What you'll see at any given time, are the voltage levels of the CCD phases, or the height of the pistons. If the voltage level is high, it is like the piston being down, and vice versa. The measuring device for the video signal is in reality a capacitor, which is charged up to an exact positive value by the precharge signal. When a pixel arrives at the capacitor, it pulls down the capacitor voltage depending on how many electrons are in that pixel. The voltage across this capacitor is then, the video signal.

You can see this difference in the video level generated by a dark, bright, and dim pixel (Fig. 28). The capacitor is charged over and over again, to measure each new pixel. Because the A/D conversion time is limited to the short video pulse generated by the arriving pixel, the video signal is temporarily memorized by a sample an hold circuit. This circuitry gives the A/D converter enough time to convert the video to a digital number, while the capacitor gets recharged to receive the next pixel.

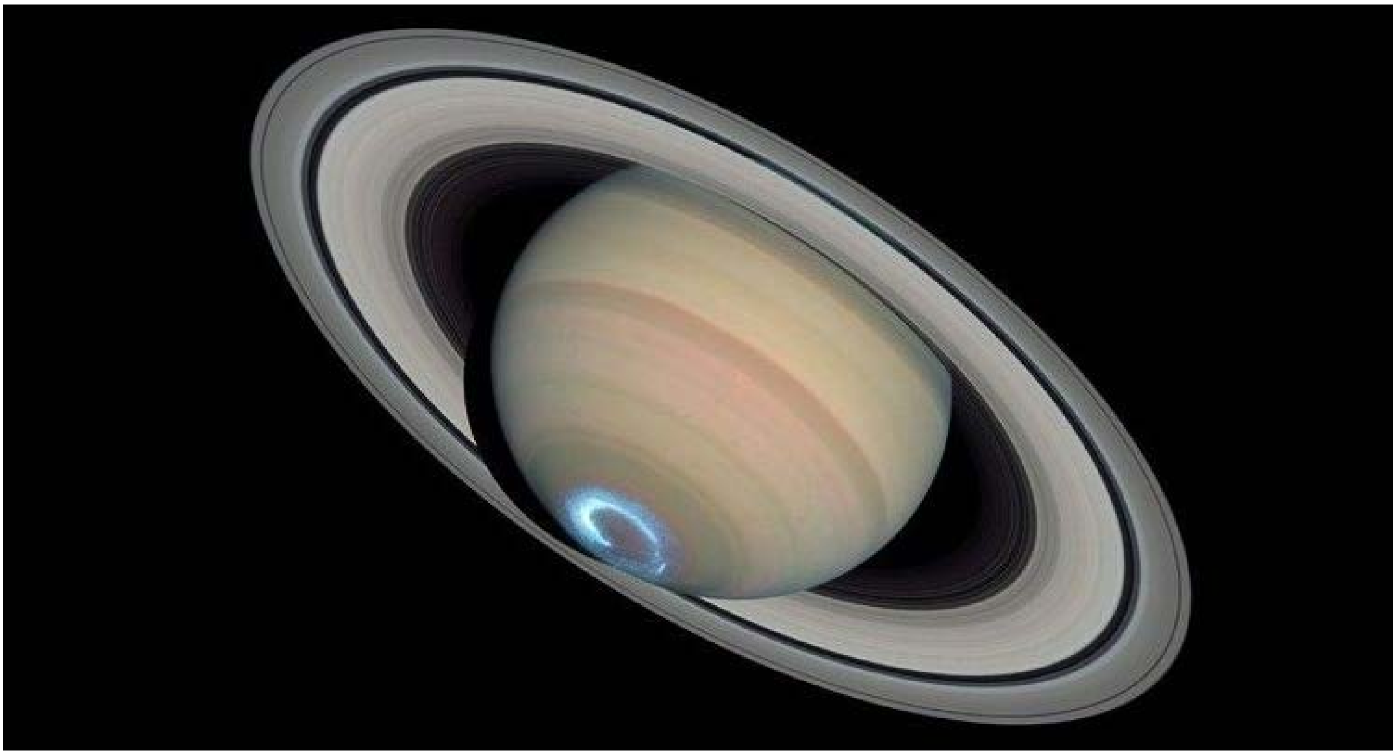
SENDING DOWN THE IMAGES

As I mentioned earlier, the horizontal register is purposely made longer (877 pixels). During the readout of the CCD, the first 64 pixels are ignored except pixel number 17, which is written to RAM, and sent down as an engineering data. The next 800 pixels, are A/D converted, and sent to the telescope as one line of the image. The last 13 pixels are unex-



1/10,000 Sec.
1 MHZ CLOCK
TIME
250 KHZ CLOCK
PARALLEL 3
PARALLEL 1
PARALLEL 2
TRANSFER GATE
SERIAL 3
SERIAL 1
SERIAL 2
OUTPUT WELL (OPW)
PRECHARGE
VIDEO
ELECTRONS
ELECTRONS ARE COLLECTED UNDER PHASE 2
EXPOSURE
SHUTTER CLOSED
RESET THE SCALE
A/D CONVERSION
1111,1111,1111
BRIGHT
A/D CONVERSION
0000,0000,0111
DARK
A/D CONVERSION
1010,1010,1010
DIM
VIDEO

FIG.28



Aurora occuring on Saturn's southern pole captured by HST using WF/PC I in the widefield mode. Image Courtesy, NASA

posed pixels, and are used to determine the dark current of the CCD device for that exposure (Fig.29). The dark frame value can be subtracted from the CCD image to get the true image intensity. A typical dark frame value is around 300 ON, or 300 x 7.5 = 2,250 electrons. The camera heads are read out one at a time, and it takes about 20 seconds to read each CCD. Since the instrument has only 2K memory, it transmits every pixel immediately after the A/D conversion (except the 17th pixel in every line). Because the logic board sends the data out in a 16 bit format (Fig.29), the 12 bits out of the A/D converter are copied twice in the middle of the 16 bit slot (bits 4,5,6, and 7 are the same as 8,9,10, and 11). In addition to the video signal, there are many engineering information, such as which camera took the picture, the temperature of the CCD during the time of exposure, the shutter speed, what fitters where used, and hundreds of other information (Fig.29). The logic board is shown on page 30. The result is a block of data 800 by 800, and 16 bits deep. This is only the WF/PC data. There is also the Standard Header Packet (SHP), which contains the time, date, user scientist's name, pointing and orientation of the telescope, and the status of the rest of its many instruments, and so on. The final raw data stored for a single image (four CCDs) is over six Megabytes.

Sending Images to Earth

The telescope images are relayed through the TDRS (Tracking and Data Relay Satellite) positioned in a Geosynchronous orbit, to White Sands radio telescopes, and then to the Goddard Space Flight Center via another communication satellite (Fig.30). The image is finally sent to the STSI (Space Telescope Science Institute) in Baltimore, Maryland. All this causes less than a 3 second delay.

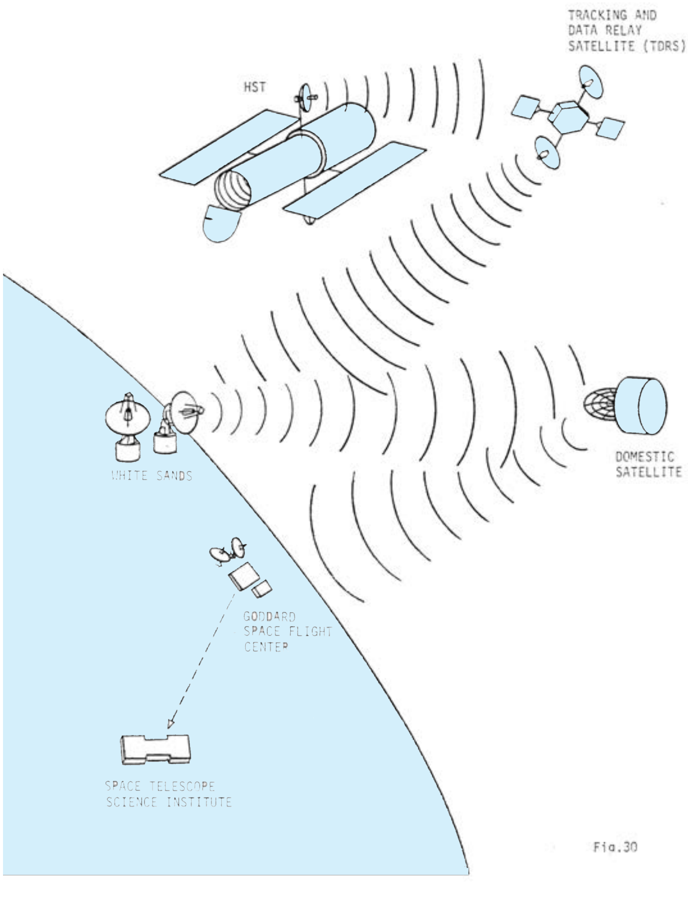


Fig.30

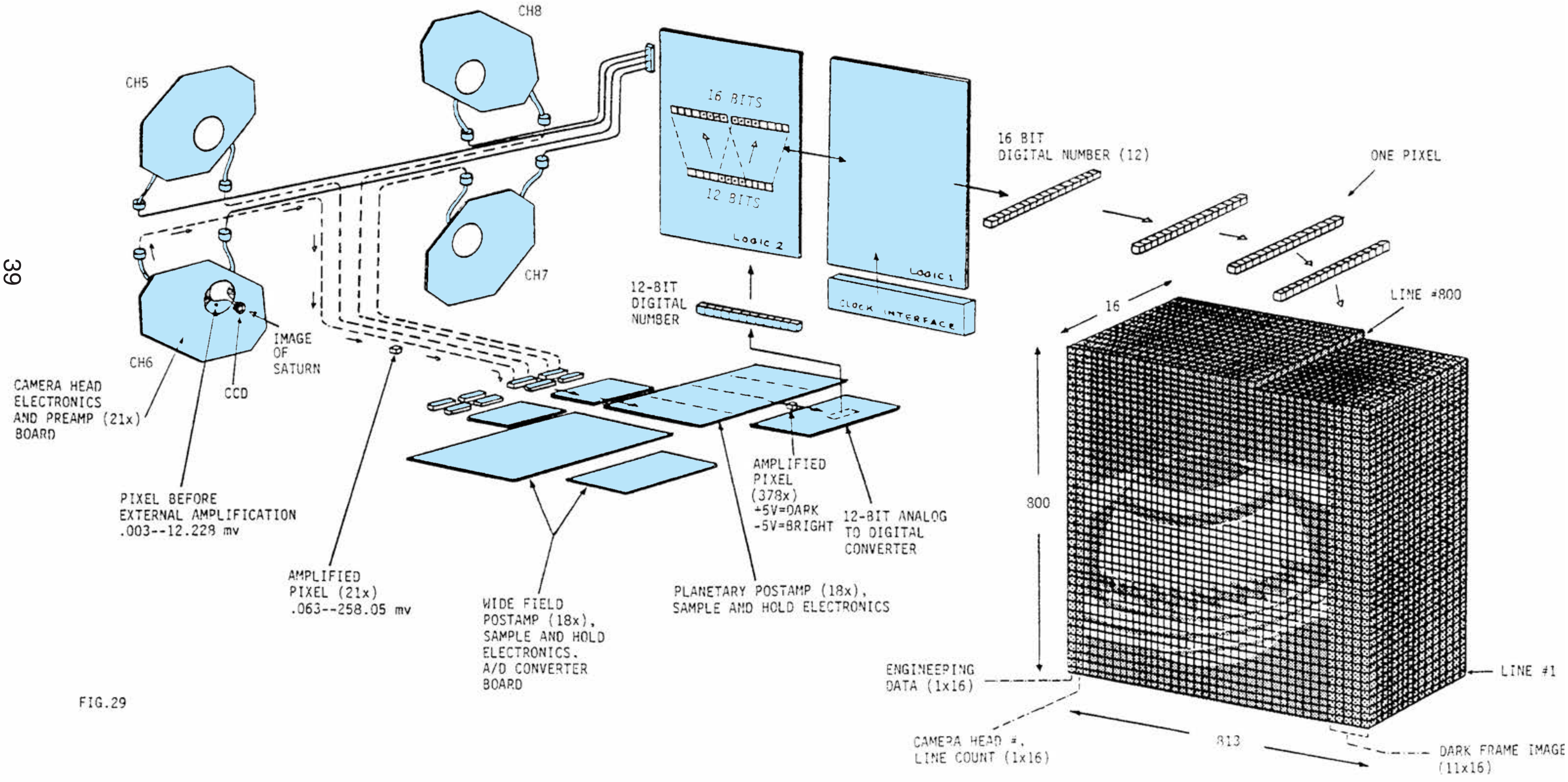
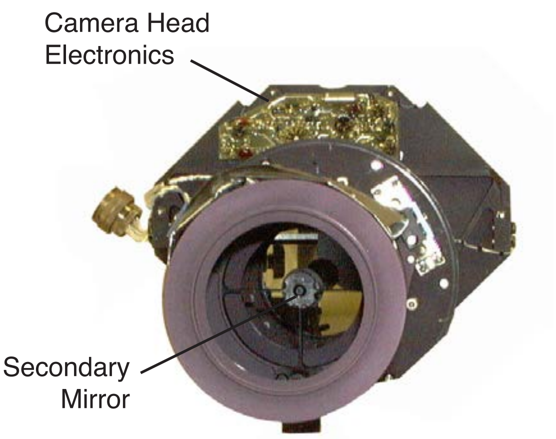

CH5
CH8
CH7
CH6
16 BITS
12 BITS
Logic 2
Logic 1
Clock Interface
16 BIT
DIGITAL NUMBER (12)
ONE PIXEL
LINE #800
16
800
813
LINE #1
12-BIT
DIGITAL
NUMBER
IMAGE
OF
SATURN
CCD
CAMERA HEAD
ELECTRONICS
AND PREAMP (21x)
BOARD
PIXEL BEFORE
EXTERNAL AMPLIFICATION
.003--12.228 mv
AMPLIFIED
PIXEL (21x)
.063--258.05 mv
WIDE FIELD
POSTAMP (18x),
SAMPLE AND HOLD
ELECTRONICS.
A/D CONVERTER
BOARD
PLANETARY POSTAMP (18x),
SAMPLE AND HOLD ELECTRONICS
AMPLIFIED
PIXEL
(378x)
+5V=DARK
-5V=BRIGHT
12-BIT ANALOG
TO DIGITAL
CONVERTER
ENGINEERING
DATA (1x16)
CAMERA HEAD #,
LINE COUNT (1x16)
DARK FRAME IMAGE
(11x16)

FIG.29

Image Courtesy, JPL

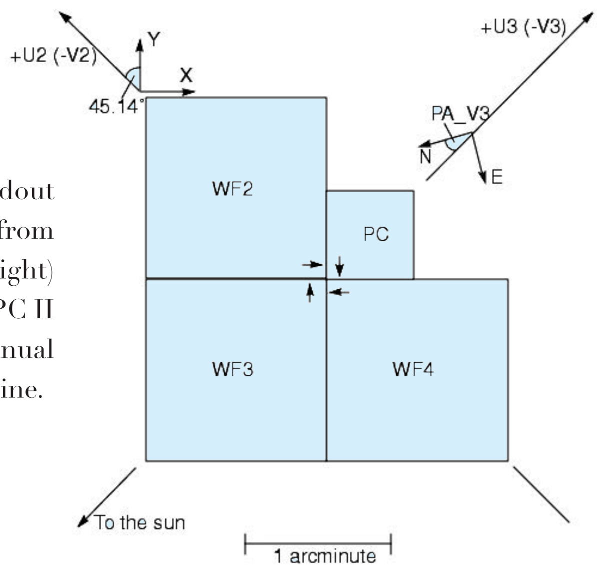
FINAL ALIGNMENT OF OPTICS IN SPACE TO CORRECT FOR HUBBLE'S SPHERICAL ABERRATION

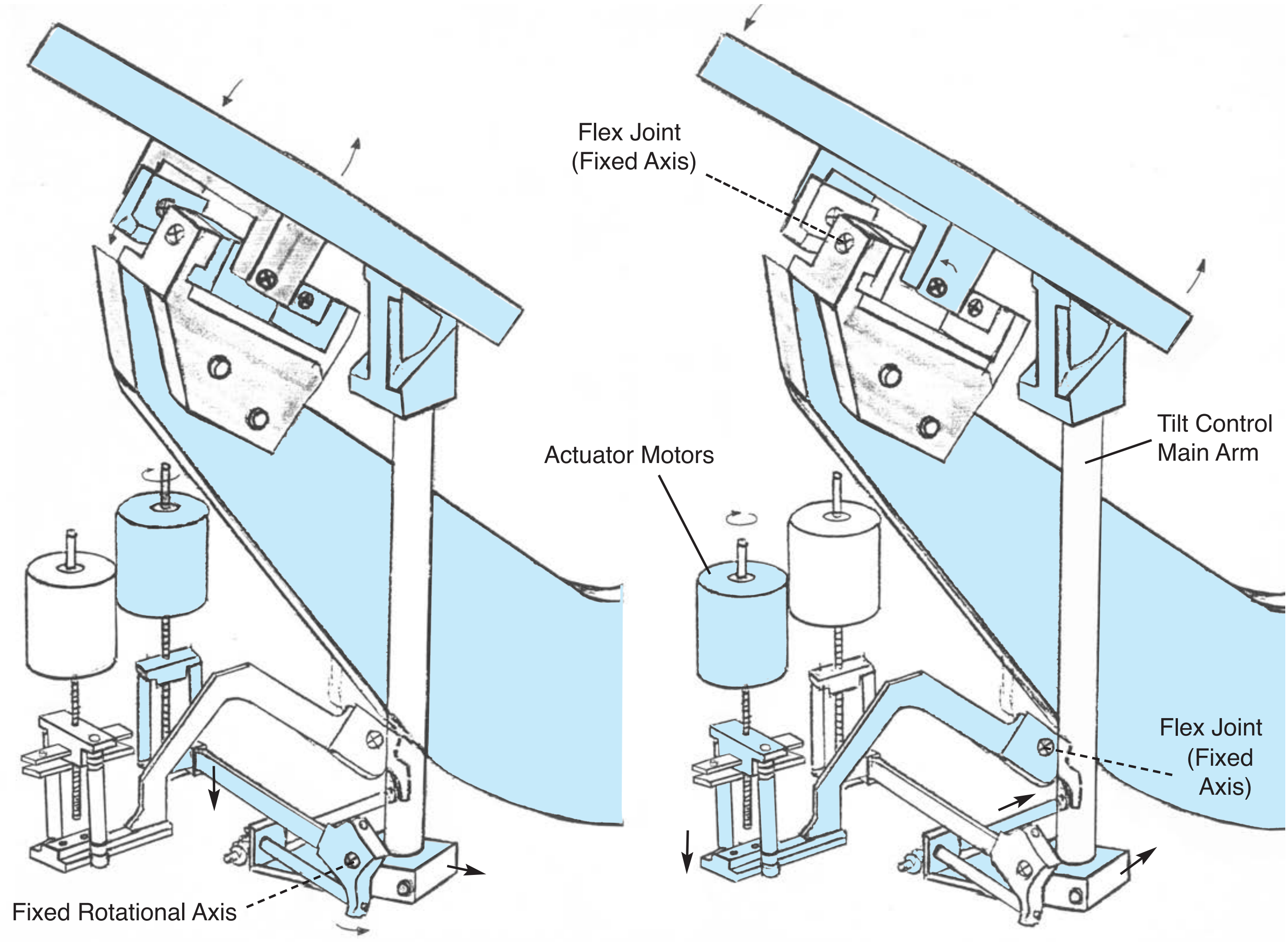
The engineers at JPL had made a commitment to make sure the WF/PC II will rescue Hubble. All the nice features of WF/PC I design we discussed here (such as a rotating pyramid mechanism, and focusing capability, and 8 camera heads) could no longer be enjoyed in WF/PC II. So here is what they had to do to make it work: The secondary mirrors in relay optics were figured to cancel out HST's spherical aberration. Then they utilized a fixed pyramid plus a tiltable pick-off mirror (opposite page) to align the chief ray coming from Hubble to WF/PC II relay optics (below) plus three tiltable fold mirrors (fold mirrors are shown in Fig. 8, 9, 10, 11). They utilized the tiltable fold mirrors to center the chief ray to each relay optics carrying WF3, WF4, and PC sensor (below-right). That's how all the images coming down from the 15 years operation of WF/PC II looked like (see page 9 for an actual image).



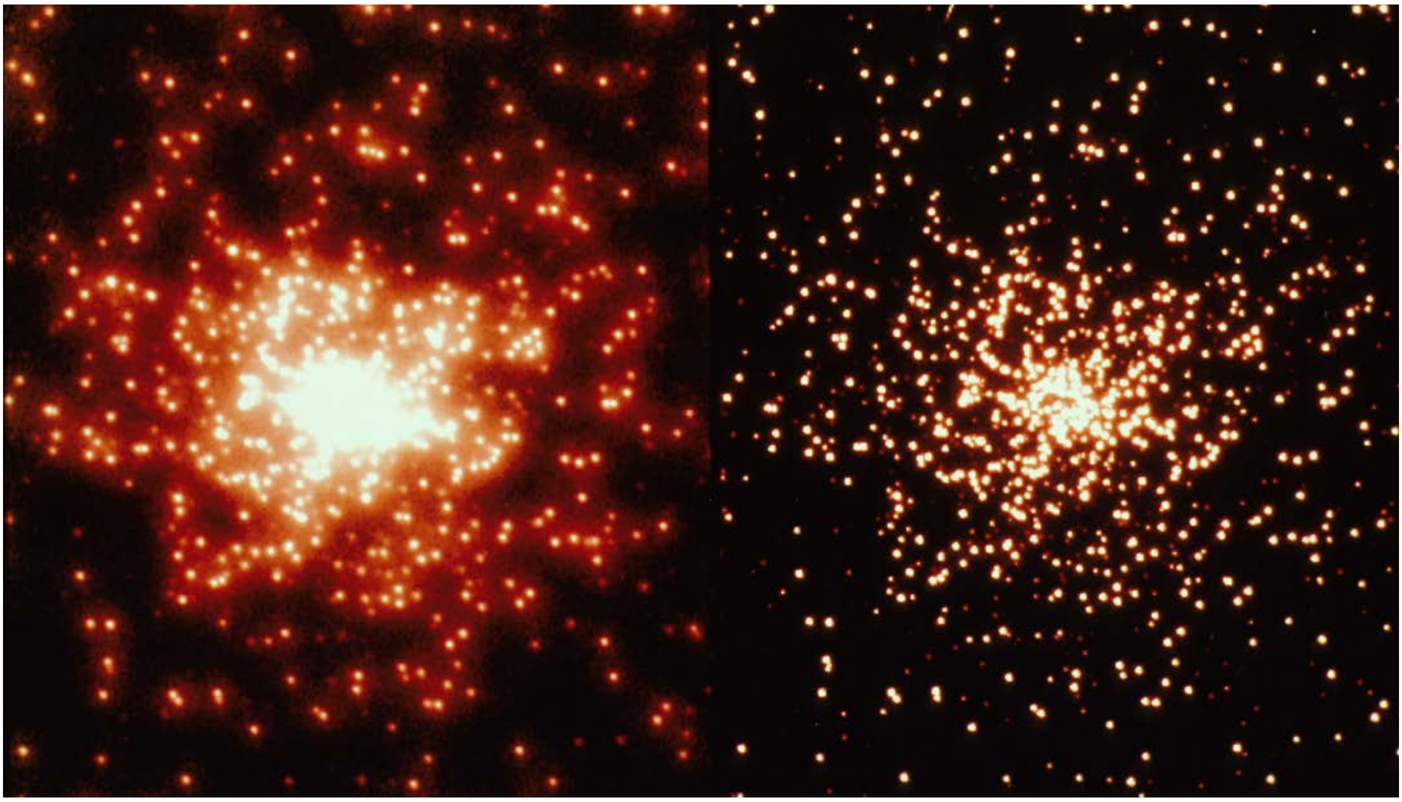
Relay optics with secondary corrective surface

Image readout direction from CCDs (right) refer to WFPC II user's manual available online.



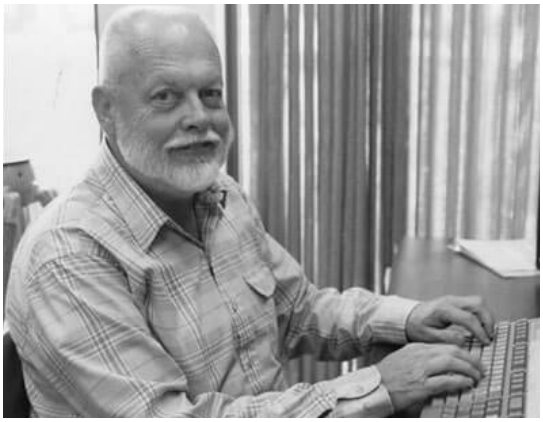


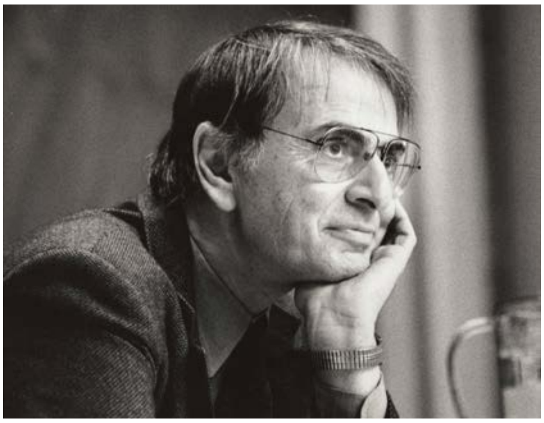
To guarantee results, engineers at JPL developed a tillable pick off mirror to center the aberrated HST chief ray with the field of view of relay optics with corrective mirrors. Compact "X" shaped flex joints were made by Bendix.



Comparison of global cluster M15 before, and after the WF/PC II upgrade. Image Courtesy, STSI

Images, Courtesy, Caltech / JPL





Elenor Helene (1932-2009) was another scientist I had the pleasure working with at Mount Palomar. She had discovered 900 minor planets during her life time, more than everyone before her combined.

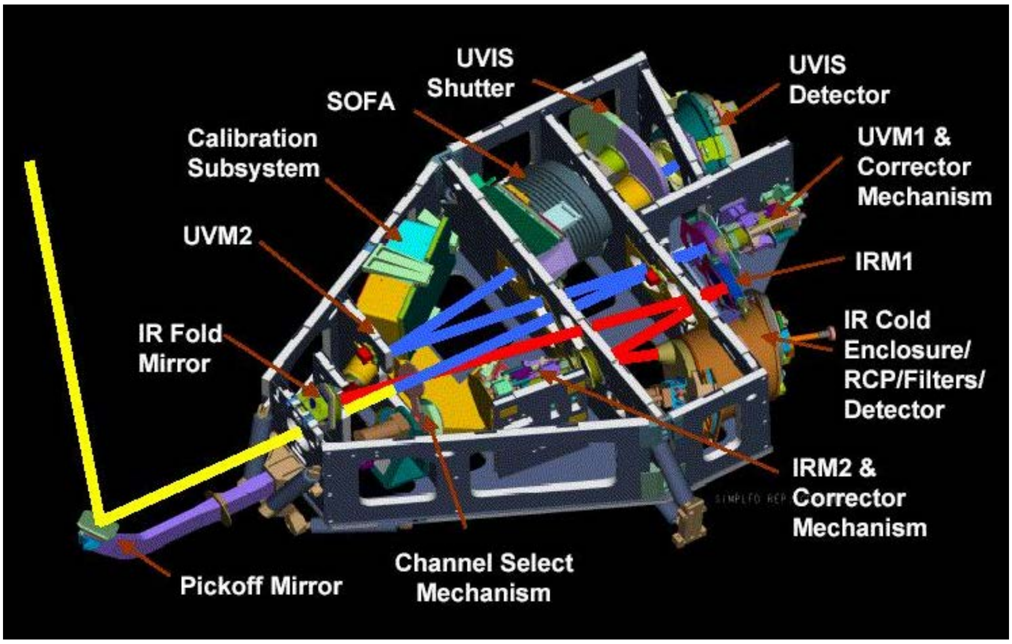
Humanity always at forefront of science and engineering

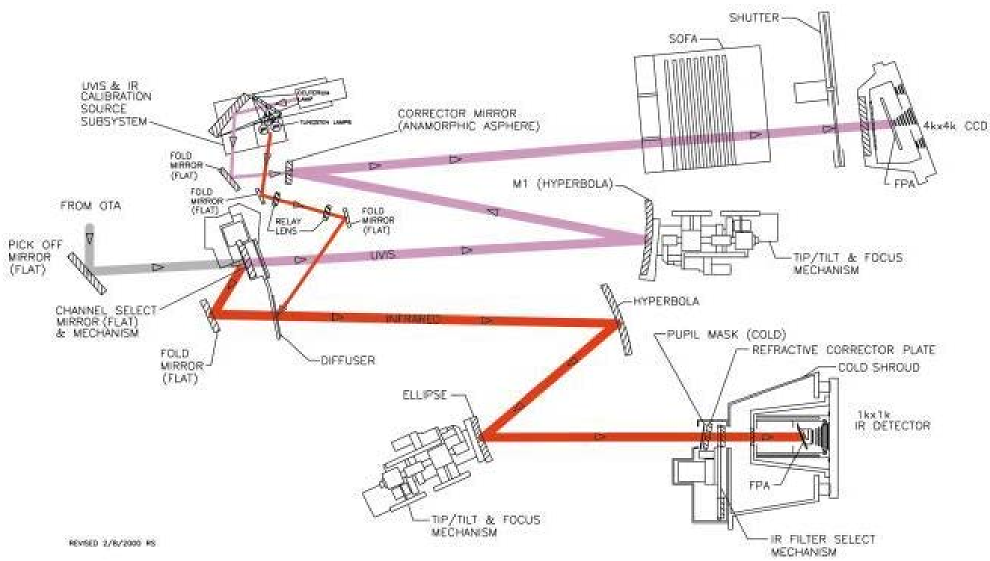
While in the course of our lives we meet so many people, only a few remain in our memories, and that's mainly for their great attitude. One of the nicest people I met during my work at JPL was James Westphal. We had celebrities like Carl Sagan as a visitor who was an ex colleague at JPL, but Jim Westphal was the most credible scientist I ever met. With his white beard, he looked like someone who arrived from a mountain on his mule but with just a short phone call, the most coveted astronomers from Australia showed up on his door. He often spoke of the attitude a scientist should have, and it was being humble, and truthful. He said one day during the final years of WF/PC I development, an engineer walked in my office, and placed his badge on my desk, and said: "You could fire me if you want, but I just realized that the back illuminated CCD chip we use in WFPC will not have good quantum efficiency in orbit, and we won't be able to use it. It's all my fault because I could have told you this a year ago, and I didn't tell you then, but now I am sure we will have problems".

Once he told me that, my wife and I went out that evening, and bought the most expensive champagne we could find. The next day, we announced a huge group party, and introduced him as our team hero! I told everyone if he hadn't said anything now, we would have been in turmoil if HST had reached the orbit, and he has saved us millions of dollars by telling us about it. In fact the QEH UV flood pipe was installed to resolve this issue. A few weeks later, Jim said, someone else walked into my office, and placed his badge on my desk, and told me about another problem, and we had to go out and buy another bottle to cellebrate! "A good manager should not avoid hearing problems". Then he went on to say how the initial problem with Hubble was because NASA's management didn't want to hear problems. In fact, after finding out they had a problem with Hubble, they were launching another instrument that hadn't been tested, and they decided to test it, and found problems with that one too.

Jim's passage in 1995 was great loss for the scientific community. There was another Jim at JPL whom I had so much respect for his knowledge but he did have a bit of arrogance. He was good scientist, but he thought he was bigger than life. As a young engineer I went up to him to ask a few questions. I think it was on my second or third visit, that his colleague literally kicked me out of their office. His group really didn't have the right attitude, and were often disliked. A new scientist came to town, named Eric, to join his group but he faced the same kind of attitude, so they gave him a small corner at some basement to do his research. A year later, Eric had developed a new device, and there he was displaying his new invention on front page of the science section of LA times. I soon heard Jim was leaving, and I went to visit him in his office to wish him well. While packing his material from his desk drawer, he told me: "Can you believe this Ali? Somebody from upper management was just here today, and he warned me not to be taking anything that didn't belong to me!" He thought that wasn't really a fair treatment after all the work he had contributed through the years.

I don't think there are winners or losers in life. We are all winners for what we learn from our life's experiences. In our generation, it was the very powerful boxer George Forman who lost to Mohammed Ali, but how he later leaned to turn his life around. Life is not really about being a great scientist or a great boxing champion. It's about who we become as a parent, as a wife or husband, as a friend or coleague, and as a teacher, sharing what we have learned with others.

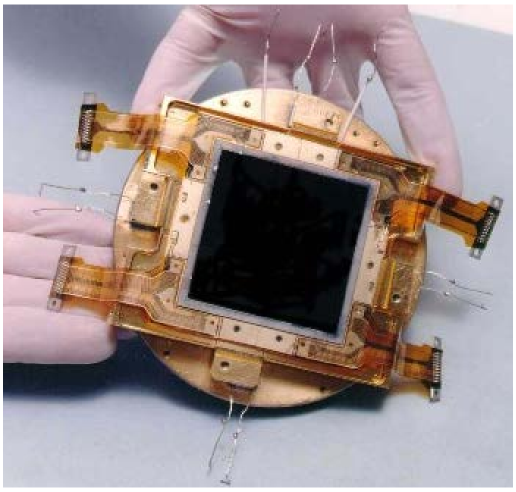




WFC III

In WFC 3 camera there is a single 4K CCD developed by Teledyne e2V, with a wider spectral range, specially in the infrared region. For this reason, the electronics bays, and the power supply box are placed outside the camera enclosure to isolate their heat from the image detectors in the IR region.

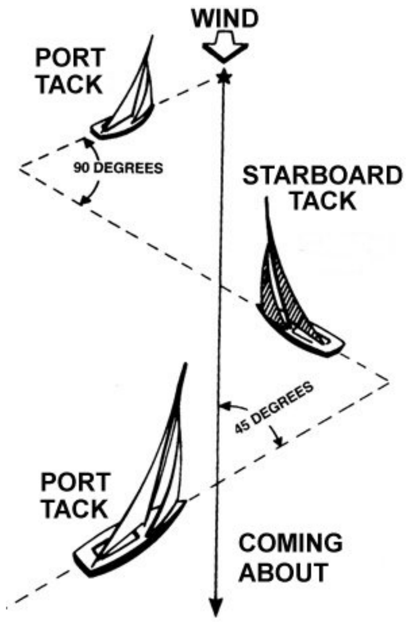
There is a channel select mechanism that switches the beam path between UVIS (Silicon, 200~1000 µm), and IR (HgCdTe, 850-1700 µm) detectors. There are 62 fiters for the UV/Visible, and 15 filters for the IR image sensor. The field of view of the WFC III was also increased. Because of its larger, single chip sensor, the optical lay out is much more simplified, and it is easier to align the optics to cancel out HST's spherical aberration. Three corrective mirrors are placed inside the camera, two with tilt/focus mechanisms. Images, courtesy of JPL.



Large 4012 x 4012 pixel single chip WFC III CCD sensor in place of the 800 x 800 CCDs in WF/PC I, and II.

How to find our way in the ambiguity of spiritual journey

By Ali Afshari



Having lived in both Middle East, and the Western world, I have come to realize as much as the Eastern thought has evolved in its spiritual path, the West has been seeking it through science, and space exploration. As Allen Watts puts it, the bigger telescopes we make, the bigger becomes the universe, and the more powerful microscopes we get, things get even smaller. Knowledge of the self doesn't depend on technology, and as we see it today, technology might even be its obstruction.

As much as Johannes Kepler, Cassini, Hubble, and Einstein have contributed to finding our distance from stars, and our dwelling in time, and space, Rumi, Hafiz, and Omar Khayyam explained the intricacy of our inner self to help mankind reaching his inner peace. Centuries before Galileo, these spiritual teachers tried to liberate religion from its rigid/bureaucratic pathway, while emphasizing the benefits of believing in higher consciousness. Rumi has a story about a man named Nasooh. In his outer appearance, Nasooh looked more like a woman, and to fulfill his undo desires, he acted as a servant inside a public bathing house that served women. He was so popular among the guests for his skillful bathing practice! One of his most devoted customers was the king's beautiful daughter. So this went on for some time without notice.

One day, he meets a man of cloth, and just as good gesture, Nasooh asks him to pray for him. The next day, while the king's daughter was present as their guest, they suddenly announced: "Her majesty's diamond ring has been lost! Shut down all doors, and everyone must be searched till we find the ring!" Nasooh disappeared someplace, for fear of his true identity being exposed. They soon learned of his absence, and while in hiding, he heard everyone's commotion: "Nasooh come out, and show yourself. It's no use hiding!" The tones got closer, and closer to his whereabouts.

It was in such state of hopelessness, that he began seeking refuge to the one, and only source, to be his savior. While in true state of redemption, he lost consciousness. Suddenly, someone yelled so joyfully: "Stop the search, we found the ring! We found the ring!" As he gained back consciousness, Rumi explains, he found other servants kissing his hands in redemption, asking for his forgiveness. They go on to say, the king's daughter is now waiting for you to bathe her. He gracefully thanked for their motions, and asked to be dismissed. He left his post with decency.

In his famous sonnet, Shakespeare describes true love as: "It is the star to every wandering bark, whose worth's unknown although his height be taken. Love's not time's fool although rosy lips, and cheeks, within his bending sickle's compass come." The spiritual path is sometimes like the way wandering barks zigzag to sail forward against the wind. The turning point in mystical path is usually a wake up call to correct our course, and this is the true nature of guidance. All the troubles, and misfortune can be a sign of our need to make that vital turn to reach higher consciousness. Most people don't realize this, and try to find excuses for it, or call it bad luck. Some might even burn candles to get rid of their bad fortune.

In one of his best stories ever told, Rumi talks about Moses, coming across a Sheppard who was speaking to the source as if he was speaking to an ordinary person. Moses finds his words insulting, and admonishes him. The man runs away in despair. God says to Moses:

Were you sent in order to unite
or to distinguish and divide?!...
I to all their qualities assign
and give a form to their expression
What to some is praise, to you is blame
What's honey to his taste, your poison
Above pure/impure I'm sanctified
Far above all suave- and boorish-ness
I command my servants worship me
not for my profit, but to bless them ...
We've no regard for words or language
We look for spirit and behavior
We see the heart and – if that's humble –
ignore the words used, brash or mumbled ...

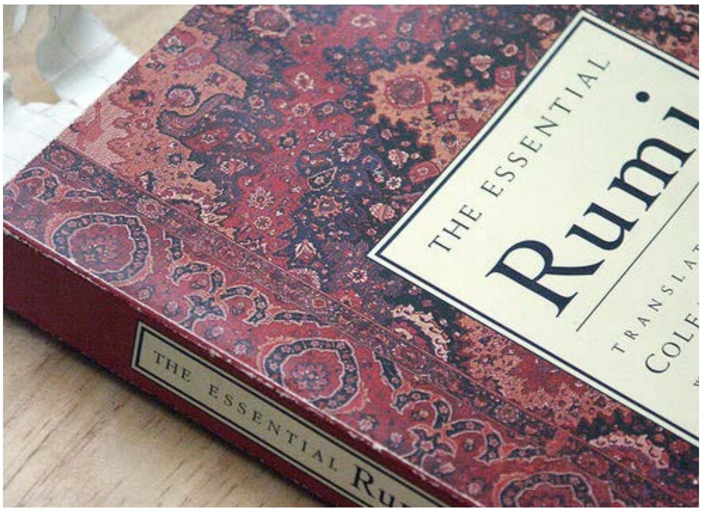
Hindus praise me in the terms of India
And the Sindhis praise in terms from Sindh
Not for magnificats do I make them pure
They themselves become pure and precious
We do not look to language or to words
We look inside to find intent and rapture

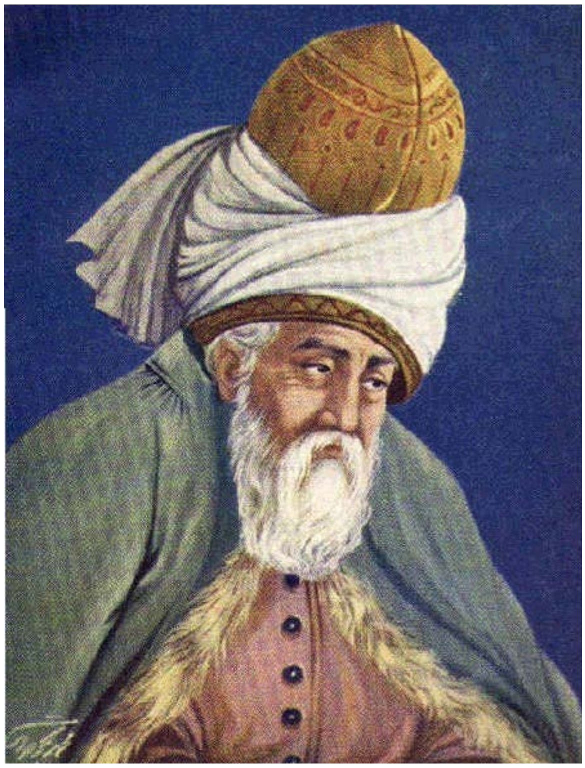
Slapped by the polo stick of His command
Be and it was, we roll through space and Beyond
When the colourless became enmeshed in colours
a Moses came in conflict with a Moses
Gain back that colourlessness you once had
and with Moses and Pharoah peace will reign

Mention of Moses has bogged down your minds
supposing these tales tell of long ago
Mention of Moses, a veil cloaking eyes
But, my good man, Moses' light, look to it.
Both Moses and Pharoah dwell within you
Seek out these two foes in your inner self

Mind of the universe! Point of view
makes all the difference we see between
believing Muslim, Zoroast, and Jew

As I enter the solitude of prayer
I put these matters to Him, for He knows
That's my prayer-time habit, to turn and talk
That's why it's said "My heart delights in prayer"
Through pureness a window opens in my soul
God's message comes immediate to me
Through my window the Book, the rain and light
all pour into my room from gleaming source
Hell's the room in which there is no window
To open windows, that's religion's goal





Persian poet Movlana Jalalludin Rumi 1207-1273

From Masnavi of Rumi, translated by A.J. Arberry, presented by Franklin Lewis, University of Chicago

Events Calendar

January 2019

February

Astro Fest Europe (Telescopes)
Kensington Center, London, Feb 8-9

Photonics West, Bios
US, San Francisco, Feb 5-7

March

World of Photonics China
Shanghai, March 20-22

Photonics Moscow
Russia, March 04-07

OFC
San Diego, CA, March 3-7

April

NAB Cinema and Broadcasting
Las Vegas, April 6-11

May

CLEO
US, San Jose Convention May 5-10

Photokina
Cologne, Germany, May 8-11

June

Inotex
Tehran, June 2019

July

August

Photonics San Diego
US, San Diego August 11-15

September

China Optoelectronic Expo
China, Shenzhen Sep 5-8

October

Interopto Japan
Tokyo, October 9-11

Photonics India
India, Bangalore Oct 17-19

November

Leipzig Watch and Clock Fair
Leipzig, Germany, Nov 22

Medica Trade Fair
Germany, Dusseldorf Nov 18-21