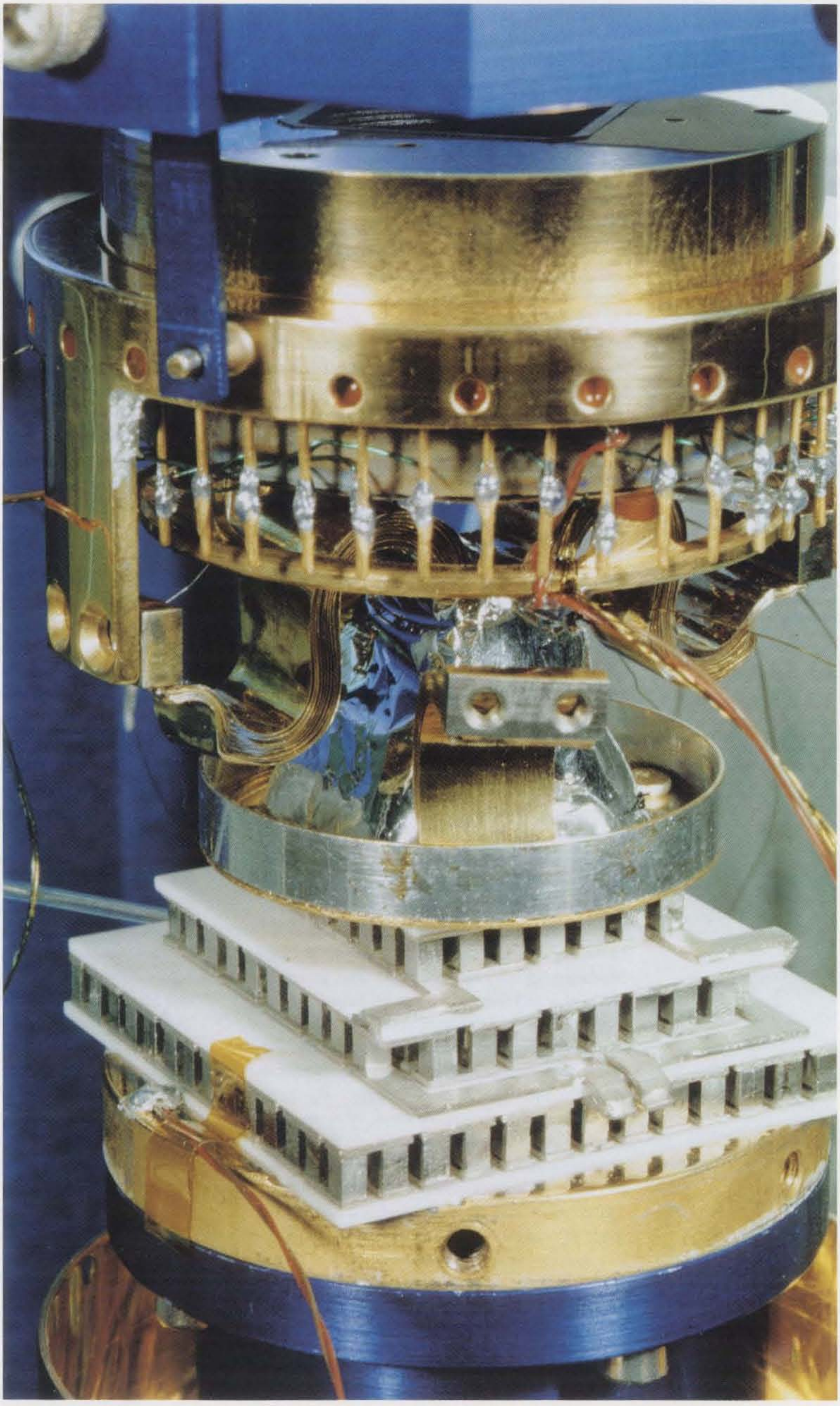


Camera Ready (Telescope Not)

"When the two cultures try to work together, lots of learning has to go on on both sides."

One of the Wide-Field/Planetary Camera's sensors is located behind the pins in this CCD package (see photo on page 36 for scale). The white pyramid at the bottom is a thermoelectric cooler, which keeps the CCD at −100°C.

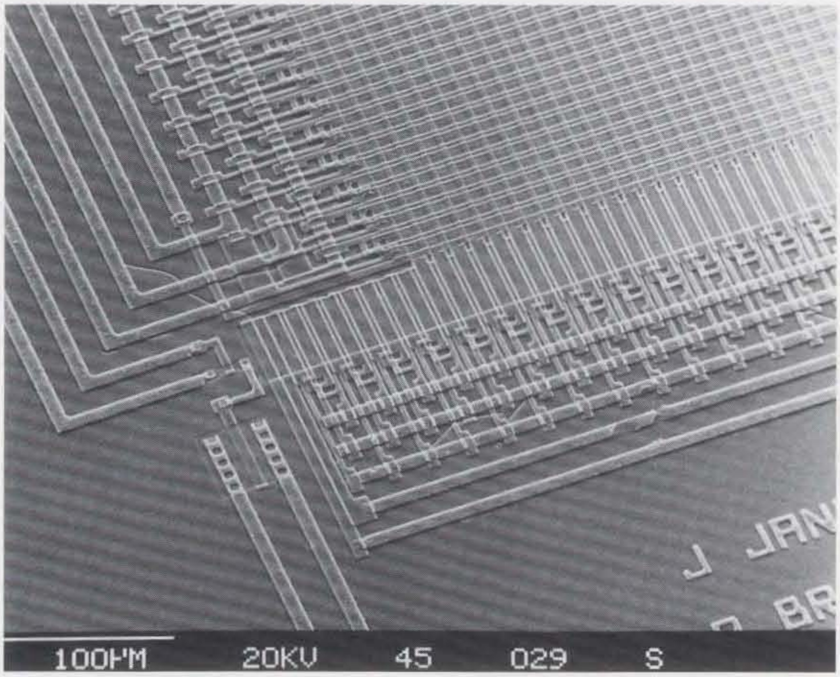
"And I said, 'You're out of your mind. Neither one of us works in that world; we don't want to spend our time up there dealing with that bureaucracy and counting beans and making viewgraph presentations and not being allowed to make marks on a blackboard and all that sort of stuff.'"

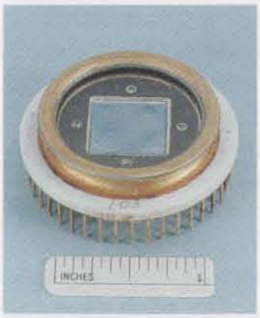
Initially, Professor of Planetary Science Jim Westphal was not exactly enthusiastic about the prospect of working with NASA. That was in 1977. On April 25, 1990, however, when the Hubble Space Telescope was finally launched into orbit 381 miles above the earth's distorting atmosphere, it carried the product of a remarkably successful collaboration between Caltech and JPL that won over even such a stubbornly free spirit as Westphal. That product—the Wide-Field/Planetary Camera (WF/PC, pronounced "Wiffpick")—was capable of imaging stars about 10 times fainter than the 200-inch Hale Telescope can resolve, and, in its other, higher-resolution mode, of observing Jupiter with as much detail as could Voyager five days before encounter.

But heaped onto all the project's other delays came the discouraging discovery in June that a "spherical aberration" blurs the focus of the Hubble's mirrors, which will make the telescope's spatial resolution no better than that of ground-based telescopes—about 1 arc second. (If the entire error is in the primary mirror, it corresponds to a mirror curvature that is too shallow by about two microns from center to edge.) The show will go on, although drastically cut back, for the instruments operating in the ultraviolet (which is important because UV astronomy can't be done from the ground at all), but Wiffpick, which does its significant work in the visible part of the spectrum, was rendered virtually useless. It is, however, acting as optometrist to the stars by diagnosing the flaw.

Meanwhile, back at JPL, Wiffpick II is already being built, originally intended to relieve the first instrument after three years. With considerably more urgency and some compensating changes to the shape of the optics that will cancel out the mirror's aberration, Wiffpick II may be able to fly to the rescue. The whole show may indeed go on, but three years late; NASA officials call it "deferred science."

In the 13 years he spent on a project he didn't want to be involved with in the first place, Westphal got used to deferrals. It was CCDs (charge-coupled devices), a new solid-state detector, which JPL had and Westphal didn't, that dragged Westphal kicking and screaming into collaboration. The solid-state revolution had not yet quite reached astronomy in 1977. Telescopes and spacecraft were still using photographic film and vacuum tubes, although Westphal had begun experimenting with silicon sensors at Palomar. But in the early seventies, the JPL image group under Fred Landauer was looking for a better sensor for the Jupiter Orbiter Probe (renamed Galileo and launched last fall) and was investigating the CCD, a solid-state device that had been invented at Bell Labs. Intrigued by its potential, JPL began work with Texas Instruments (under NASA funding) to develop it for spacecraft imaging, and by the





A highly magnified corner of a CCD shows part of the grid of pixels (800 × 800, each 12 microns in size). The charge created by a photon striking a pixel is transferred through the grid and finally dumped into the horizontal register along the bottom. It then goes through a capacitor (the backward L left of center) and out through a control gate (leading off the bottom). Below is the whole CCD—the blue square in the center.

time Westphal entered the scene already had some samples measuring 100 × 160 pixels. Engineer Jim Janesick was a key player in the development of CCDs at JPL. A member of the imaging group and an amateur astronomer as well, he took one of the devices home and built what was probably the first CCD camera for his own little telescope. When he saw what it could do, he "got really, really excited." But Janesick saw a wider field of application than just Galileo. "Once we got some money to start developing the CCDs, the next thing was to convince the astronomical world and the scientific world that the CCD was the thing of the future."

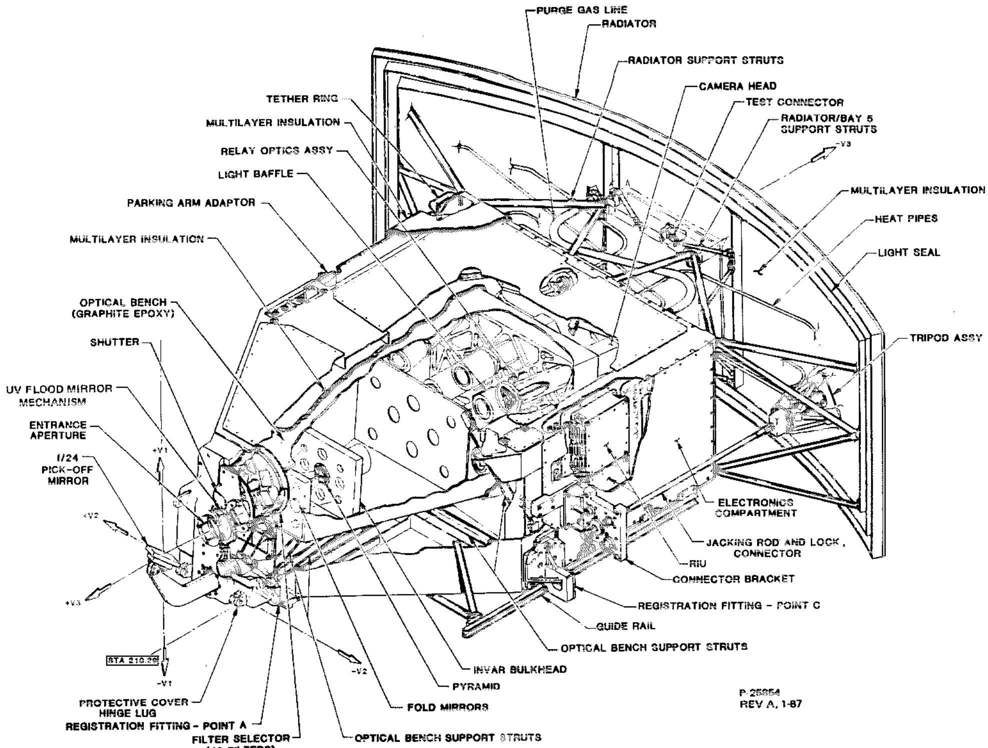
It was indeed, and Westphal knew it as soon as he went up to JPL at the behest of a suspicious Committee on Lunar and Planetary Exploration (of the Space Science Board of the National Academy of Sciences), to figure out what they were doing at JPL with this new sensor. Westphal reported what he had seen to Jim Gunn (then professor of astronomy at Caltech and now at Princeton), who after a few seconds of calculating declared that CCDs "are going to wipe out every other detector astronomers use." And the two desperately wanted "to get our hands on those things and get them on the 200-inch." A short time later Janesick found himself down on campus at Westphal's lab helping Gunn and Westphal build a camera.

A CCD consists of a grid of perpendicular channels on a tiny slab of silicon. When a photon hits one of the individual pixels confined by the channel barriers, it interacts with the silicon to create an electron-hole pair. The charge from the electrons that collect in each pixel's potential well goes up proportionally to the number of photons that hit it, and an image is formed in units of electrons. By manipulating voltages to shift potentials, the charge in each pixel can be transferred out across the barrier phases beneath conductive gates. Each pixel's charge moves sequentially, pixel by pixel, into an amplifier and is eventually reconstituted as video. The beauty of the things is their extraordinary sensitivity to a wavelength range from 1 to 11,000 angstroms (visible light is about 4,000 to 7,000 angstroms). Wiffpick's actual wavelength range extends from 1,150 to 11,000 angstroms—from the ultraviolet to the near infrared. "With a one-electron read noise, [the current CCDs are] the world's most perfect detectors," says Janesick. "It's amazing what the device can do."

Even today Westphal says of the solid-state physics of CCDs that "it's not a science; it's a black art. But it's a wondrous black art. It's still not really something that I have an automatic, clear, warm feeling that we can do what we clearly can do with these devices. We're dealing with two or three electrons at a time—moving them around and doing all kinds of stuff with them. And somehow that just seems like it could hardly be true."

Back in the late seventies almost everyone thought it could hardly be true, with the exception of the Galileo camera team and a handful of astronomers proselytized by Jim Janesick, Jim Westphal, and Jim Gunn (collectively known as the J^3 team). As the Space Telescope struggled into existence, NASA invested heavily in developing a wide-field camera using another kind of detector that wasn't turning out well. ("They never would have made it work anyway," says Westphal.) But during a meeting of a NASA science working group on the Caltech campus, the decision was suddenly made, after a couple of presentations on CCDs, to open up the camera project for competitive bids from principal investigators—scientists who would actually use it. Westphal just happened to be an innocent bystander at this event ("I didn't want anything to do with the Space Telescope; it wasn't my kind of thing; I didn't want to be involved in any way"), but he, Gunn, and six colleagues ended up submitting the successful proposal for the wide-field camera. Its sensors were CCDs.

Westphal's proposal necessarily included JPL, and not just because they had possession of the CCDs. "Of course we weren't competent to do the design," says Westphal. "Designing things that go in spacecraft is a very special art; special talent is needed and a lot of experience. And we



had none of those things." Ed Danielson from JPL helped write the proposal and has remained a part of Westphal's team. And despite Westphal's initial reluctance, the collaboration with the Lab worked—not without problems, but it worked. The project was, according to Westphal, a classic study in Caltech–JPL interaction. "It illustrates not only all the wonders that can be done this way, but also the pain and suffering it takes to make it happen. When the two cultures try to work together, lots of learning has to go on on both sides."

"The science team defined the science objectives; then we converted those into engineering terms."

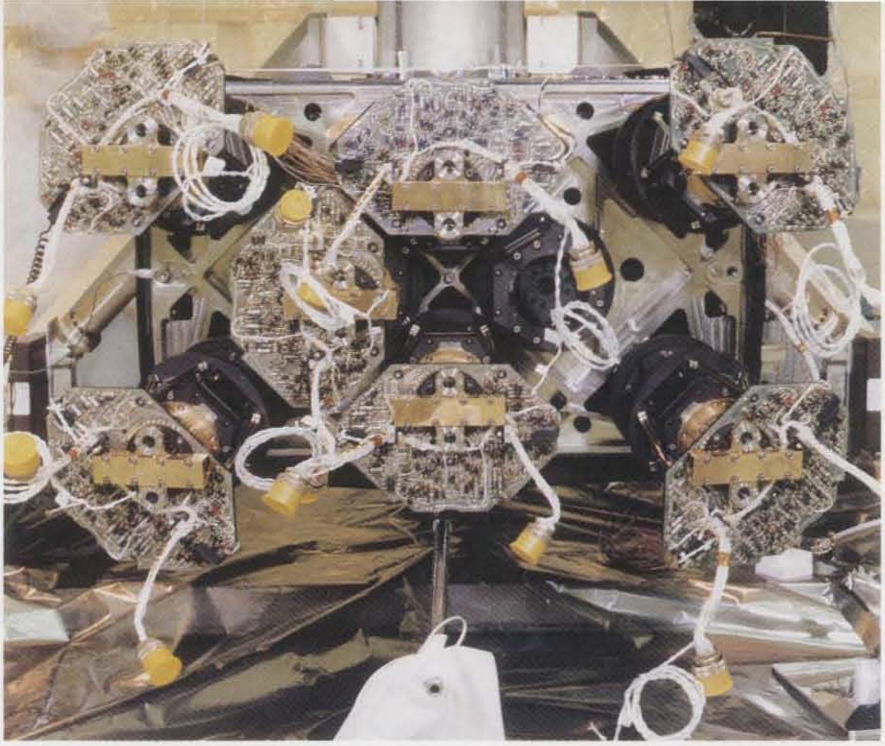
"The science team defined the science objectives; then we converted those into engineering terms," says Dave Swenson, now program engineer in JPL's Office of Space Science Instruments. Swenson, who began working on the camera part time in 1977 and full time in June 1978, was at various times over the course of the project instrument manager, system engineer, deputy project manager, and gofer, he says. "Defining the instrument—how it fits into the telescope—was a long process. What we originally proposed in many ways is not the instrument we ended up building—mostly for engineering reasons."

In terms of its science objectives the Wide-Field/Planetary Camera was built pretty much as proposed. It's the size of a telephone booth, weighs about 600 pounds, and consists of two cameras in one, each with a different focal length, sort of like a camera with interchangeable lenses—a wide angle and a telephoto. The incoming light beam is "folded" from the telescope's 2.4-meter primary mirror to the secondary mirror and then to a pickoff mirror, which deflects it into Wiffpick's aperture. After passing through one or a combination of several of 48 filters, perched on a spindle like a stack of records (for polarization and spectroscopy and for picking out particular wavelengths), the beam is focused on a pyramid "light switch."

In the f/12.9 wide-field mode the light reflects off the pyramid's four faces through the outer four holes (see diagram), through a set of optics that sets the focal length, and then onto four camera heads, each containing an 800-×-800-pixel CCD; in the wide-field camera each of these pixels is 0.1 arc seconds across. Although the image is optically split apart into four (with an overlap of a few pixels), it can be put back together in a computer to make a mosaic containing the information of all 2,560,000 pixels. The field of this camera is not really wide; it's limited by the size of the CCDs (each CCD covers a quarter of a 2.6-arc-minute square), but it's wide in comparison to the field of its companion camera and can cover a substantial piece of sky.

Rotating the pyramid 45° reflects the light beam into the inner four holes to the planetary camera's four heads, which with a focal length of f/30 can cover only one-fifth as much of the sky. The pixels of the CCDs in these camera heads are, however, 0.043 arc seconds across, providing 2½ times greater resolution.

Putting all this into engineering terms and integrating it with the telescope itself was not a piece of cake. Take the filters, for example. "We were really having trouble with the filter mechanism, figuring out how to do it," says

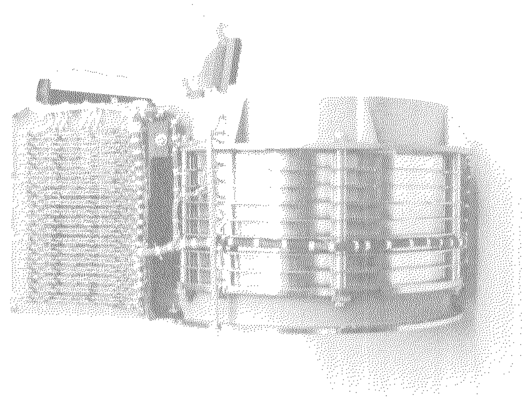


Wiffpick's eight camera heads assembled and in place (right). The photo below shows one of the camera heads before assembly. At top right is the heat pipe saddle, which removes the heat from the thermoelectric cooler; next to it are the electronics. The thermoelectric cooler and the CCD assembly (wires attached) are in the center.

Swenson. He describes one design approach called the "Wurlitzer" for its jukebox-like arm that snatched up one filter from the stack and dropped it into place. "But this thing had 121 springs in it, and if any one of those springs had busted, it would have jammed the whole thing," says Swenson. Jim Gunn, an astronomer, not an engineer, eventually came up with the concept for the final mechanism, which applies magnetic fields to the filter wheels to move them.

Heat was also a problem, and the external radiator, which is about the size of a door and forms part of the telescope's outer skin, was added after the original design. The CCDs, which Swenson describes as "the bread and butter of the whole thing," must be cooled to −100° C with a thermoelectric cooler, but the heat from the power to accomplish this must be removed. Heat pipes filled with ammonia run from the thermoelectric cooler to the external radiator, where the temperature varies from −20° C to −60° C, depending on where it's pointing. The ammonia at the warmer end of the heat pipe vaporizes and collects in the cooler end, where it returns to the liquid phase and is then wicked back up to the radiator. No moving parts—perfect for flight.

Solving such problems put Wiffpick behind schedule (the eventual delays caused by the telescope itself and by the Challenger disaster could not, of course, be foreseen) and threatened cost overruns. Bob Lockhart joined the project in July 1980, when Wiffpick got "projectized"—NASA jargon for focusing more attention on it. Lockhart, who is now project manager of the



In SOFA, the Selectable Optic Filter Assembly, the filters are arranged on 12 wheels. Of the five slots on each wheel, four are filters and one is clear.

Visible Infrared Mapping Spectrometer for the Mars and CRAF/Cassini missions, took over responsibility for development of the electronics as well as the CCDs and camera heads. The design was basically complete when Lockhart signed on, but the CCDs were experiencing a major problem with noise. The signal-to-noise ratio of a telescope trying to peer to the edge of the universe is obviously rather important; dim objects at such vast distances can easily be drowned out by a few electrons. Each noise electron was worth half a billion light years.

The noise performance requirement for Wiffpick's camera heads was 15 electrons, but only 25 or 30 had been achieved by 1980, after the system had already been put together. Lockhart and his engineers managed to reduce the noise to 12 electrons (each CCD well holds something like 30,000 electrons). Getting rid of noise is like peeling an onion; about a dozen noise sources (peels) had to be eliminated before the 12-electron level was achieved. This took months. As does Westphal, Lockhart invokes black magic when describing CCDs, but he also mentions hands-on engineering. "We could figure what theory tells you minimum noise ought to be, but when you really implement it, moving the wires a few centimeters can make all the difference in real performance of the system."

"This was pretty much an engineering thing. It was the instrument builders at Caltech working with the instrument builders at JPL."

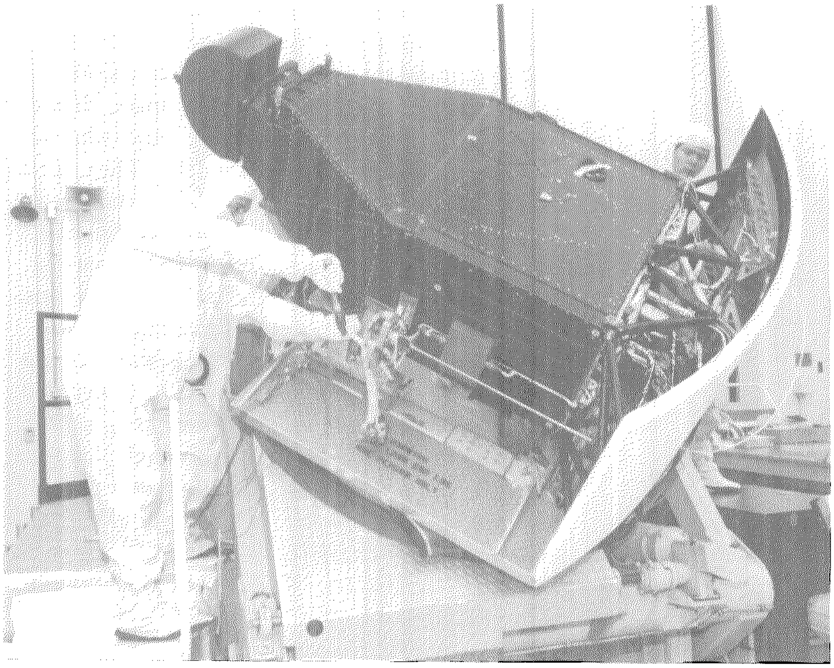
Since there's no way of knowing how to move wires around until the whole system is built, an engineering model for working out all the bugs is necessary for all flight projects. Wiffpick's engineering model was scrubbed to save time and money. But in actual fact, according to Lockhart, it was not. When you start eliminating models, he explains, you are really eliminating them from the last model backwards: first you eliminate the spare, then the flight model, then the prototype. And what you have left is the engineering model. "They call it a 'protoflight' unit," he says. "What that means is that you just build one and you fly that one."

During the protoflight unit's final assembly the engineers discovered that the blue-light sensitivity of CCDs diminishes with time and had even disappeared on a few of the sensors during testing. Lockhart and his team (which included Janesick) traced the problem to trapping sites on the back of the CCD, where incoming blue photons get caught. The solution (which was awarded a patent) was to add a light pipe to the side of the instrument to expose the CCDs to sunlight (ultraviolet). Flooding the CCD with UV charges the back side of the CCDs, which repels signal electrons to the front side where they can be collected. This problem was later solved more efficiently starting from scratch on Wiffpick II: bias gates on the backs of the CCDs and a chemical converter enhance the instrument's response to blue light without the necessity of recharging the surface.

Design of Wiffpick I took about three years and actual fabrication another two (it was finished in September 1983), at a total cost of $65 million. During that time Westphal and his staff spent much of their time at JPL. There was a core group of about 40 to 50 JPLers who worked on it most of the way through, and at the peak probably 90. But what they really could have used, according to Swenson, was "a two-inch gnome with a soldering iron to get in and put it together."

"The working relationship [with Caltech] was excellent," says Swenson, who still remembers Westphal's phone number. "Both Gunn and Westphal were good scientists, but they were good engineers also—very good engineers, in fact." Westphal, too, credits the working relationship to a congruence of interests: "This was pretty much an engineering thing. It was the instrument builders at Caltech working with the instrument builders at JPL. Because Gunn and I are hardware people and build things with our hands, we got on with those guys like crazy."

"There were times, though," adds Westphal, "when we thought we understood it a lot better than the folks at JPL did, and there were various clashes as time went on. But we found our common ground, and things were made to work without, I think, any huge pain and suffering. There were days when you wished you had never



"And I'm sure there were many days when the people up there wondered if there were any way in the world that they could send all of the scientists to Chile and leave us there."

Technicians put the final touches on the Wide-Field/Planetary Camera.

started this thing, or you wished you could just kinda walk in and take it away from all these people that wanted to do all this dumb stuff when you wanted to do something different. And I'm sure there were many days when the people up there wondered if there were any way in the world that they could send all of the scientists to Chile and leave us there."

When the shuttle carrying the Hubble Telescope into orbit finally blasted off in April, there must have been an enormous sigh of relief as the scientists and engineers assumed they could now go their separate ways. But now it's back to the drawing boards after all. The relay optics (between the pyramid light switch and the camera heads) of Wiffpick II have already been built but new ones can be made with a different "prescription." That's the easy part. "To the extent that we can determine what's wrong, we can cancel it out exactly," says Westphal.

Determining what's wrong—which mirror (if not both) and the precise nature of the deformation—is the hard part. The best solution will be to find the error in the paperwork documenting the mirror's manufacture, but while that investigation is going on the Wiffpick science team is using the camera to try to diagnose the problem—taking pictures in various positions of focus and then doing computer simulation of the images. At JPL work on Wiffpick II is accelerating. "They're looking to find people for a second shift to speed things up," according to Westphal. "But they need the right people." JPL engineers are optimistic about meeting their scheduled delivery date of late 1992, even with redesigned and rebuilt optics.

At any rate, it will be a while longer before astronomers can start looking for the beginning of time. The 31 hours of observing time that Westphal earned for his 13 years of devotion to the camera will have to wait too. But at least Westphal and Gunn were successful in their ulterior motive of getting their hands on some CCDs; this produced a revolution in ground-based astronomy while the Space Telescope sat waiting for launch. Some 70 telescopes around the country, including the Hale 200-inch at Palomar, will not be put out of business by Hubble after all because they have received a piece of its technology (and they do still have some other advantages over the Space Telescope). "I've even heard people go to such an extreme as to say that if the Space Telescope never worked it was still a success because it brought CCDs to astronomy," Westphal said—words that may have been more prophetic than he intended.

Janesick at JPL is still working on CCDs and doesn't buy the "black art" stuff. Even after 17 years he claims, "About every two months we get a major discovery." He recently solved the long-standing problem of "blooming" or smearing of a bright image. He's also working with some Caltech biologists to furnish microscopes with CCDs to track very fast fluorescent images. And science is not the only beneficiary of CCD research: CCDs, a suspect curiosity 14 years ago, are now a part of all currently manufactured television sets and video cameras. And soon they'll be standard in ordinary 35-mm cameras. □ —*JD*