Picture Perfect

It will be the ultimate Kodak moment when the IKONOS satellite captures its first 1-meter image.

By Frans Jurgens, technology writer and consultant, Rochester, N.Y.

The focal plane unit (above) containing the digital imaging sensors is located at the base of the IKONOS telescope. Insulation and heaters keep the image-processing electronics at a constant operating temperature. The IKONOS telescope (inset) formats and focuses the captured Earth imagery onto digital imaging sensors inside the box-like focal plane unit at the telescope's base.

Imagine a telescope no bigger or heavier than a small desk, yet powerful enough to tell the difference between a car and a truck from 400 miles in space. The challenge of building such a telescope was part of an even larger project facing system designers and engineers at Rochester, N.Y.-based Eastman Kodak Co. (Kodak).

Relying on 35 years of remote sensing expertise and in-house resources, Kodak designed and built identical digital camera systems for use aboard IKONOS 1 and IKONOS 2, Thornton, Colo.-based Space Imaging's eagerly awaited 1-meter remote sensing satellites.

Each camera system comprises an optical telescope, panchromatic and multispectral imaging sensor arrays, and processing electronics. But the IKONOS cameras are unique in several ways. The near-perfect optical sharpness of their telescopes has never been achieved in any space camera. And, instead of acquiring multispectral imagery in three bands (red, green, blue) across separate photo detectors, each focal plane features four bands (including the near-infrared band) on a single integrated array, a manufacturing coup for the industry.

Optical Perfection

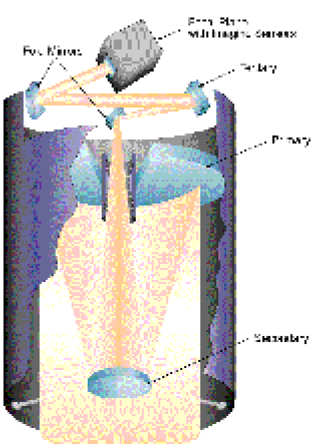
Kodak engineering teams worked for two years to create a 10-meter focal length telescope for each IKONOS camera by perfecting a three-mirror optical form rarely used in visible-light telescopes. The optical design forces captured light to bounce on three curved mirrors, each featuring a complex geometric surface. The three mirrors render the image free of astigmatism, a focusing defect common in two-mirror systems.

To keep telescope length to a compact 1.5 meters, designers added two small flat mirrors to bounce the formatted image sideways across the telescope's interior before coming to precise focus on the digital imaging sensors. This compact packaging approach reduced overall telescope length by more than a factor of three and weight by almost a factor of two.

Kodak engineers also applied two mirror fabricating techniques requiring high-precision optics fabrication expertise. In the first process, called "lightweighting," special machinery removed 85% of the glass from the core of the largest mirror, about the diameter of a small coffee table. Thin faceplates then were fused to each side of the core. This process reduced the telescope to its final weight of just 240 pounds.

In the second technique, each curved mirror was polished to atomic-level accuracy by ion figuring. The Kodak-developed process bombards the surface with an accelerated beam of neutralized argon ions that removes unwanted glass one molecule at a time to reduce optical distortions. "If you enlarged the primary mirror to 100 miles in diameter, it would feature bumps no higher than eight-hundredths of an inch," says Andy Lloyd IKONOS telescope team leader at Kodak. The result will be imagery sharper than any other commercial remote sensing camera can deliver.

Mirror Alignment



The IKONOS telescope features three curved mirrors to capture and focus high-resolution

Alignment error of each curved mirror is so small it must be measured in wavelengths of light. "It's equivalent to placing a human hair under one end of a 20-foot plank of wood," says Lloyd. Specifically, the mirrors must not deviate by more than a handful of arc seconds during the rock-and-roll ride into orbit, when settling into zero gravity, across 50° temperature swings inside the spacecraft, or resulting from vibrations caused by spacecraft maneuvering and telescope pointing.

Building a telescope stable enough to hold alignment in these conditions without deforming the mirrors required extensive thermal and structural analysis. Applying advanced optical mounting technology pioneered by Kodak for NASA's Chandra X-Ray Observatory (previously AXAF, to be launched in May 1999 on the Shuttle Columbia), Lloyd's team designed special mounts, joints and padded flexures bonded with low-shrinkage adhesives.

Because two of the mirrors can be refocused on orbit, Lloyd's team developed custom test equipment to measure tip and tilt errors in two axes in the focus-tracking mechanisms. "To validate the mirror control mechanisms, the test system precision had to be on the order of arc seconds," says Lloyd.

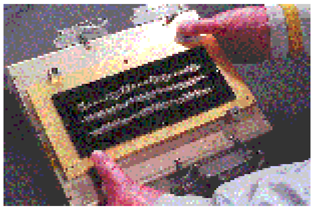
Spectral Filters

The IKONOS challenge also extended to the Kodak team responsible for making the camera's imaging sensor module. Led by Bryan Howe, the team created a series of quartz filters for the multispectral imaging sensor array, which consist of charge-coupled device (CCD) imaging sensors with thousands of pixels, each a fraction imagery sensors at the focal plane. Kodak added two flat mirrors to "fold" the imagery across the inside of the telescope, significantly reducing telescope length and weight.

of the width of a human hair. The filters ensure that light striking each pixel is transformed into four spectral bands--blue, green, red and near infrared.

"The objective is to acquire high-resolution Landsat-compatible imagery across these four bands in the .45-.90 spectral range," says Howe. "Each filter must transmit about 85% to 90% of the light it receives, which is three times better than organic filters found in commercial digital cameras. They must produce purer reds, greens and blues to reveal information useful to geologists, agronomists, environmental scientists and others. And the filters must reject the Sun's unwanted ultraviolet and infrared light."

Achieving all this on one multichip array suitable for IKONOS's image scanning technology required an advanced thin film coating process. Performed at Kodak's Micro Technology division, the process atomizes silica-based compounds in a vacuum chamber and lets the particles fall in even layers onto a piece of glass. Each spectral band required no fewer than 66 filter layers in separate strips across the glass. Each 66-layer stack is no thicker than 4 microns, a fraction of a hair's width.



At the focal plane, light captured by the IKONOS telescope falls onto thousands of hair-sized pixels that comprise the panchromatic and multispectral imaging sensor arrays. The sensors are coated with advanced filters specially constructed by Kodak to admit or reject specific wavelengths of light.

The highly complex process required 300 individual process steps to build five filter stacks on the same piece of glass without error, while controlling layer thickness to angstroms, a unit of length equal to one hundred-millionth of a centimeter, according to Howe. The fifth stack, a panchromatic band applied to the flip side of the glass, turns the blue and near-infrared filters on and off at specific wavelengths.

Thermal and Noise Control

The CCD sensor chips forming the multispectral and panchromatic arrays are aligned carefully as part of a box called the focal plane assembly. To maintain the arrays' precision alignment on orbit, Kodak engineered the area immediately around the arrays to maintain a constant 68°F. Without protection from exterior temperature fluctuations, the arrays would expand and contract, shifting the chips (and imagery) out of alignment. Temperature variations of just a few degrees also would affect the quality of each picture element in its digitized form, resulting in patterns of varying light intensity across the image.

The thermal control system has a dual function--to remove and add heat. Conduction straps dissipate a continuous 100 watts of heat generated by the electrical circuitry, which processes more than a gigabit of image data every second (before digital compression) through 36 high-speed channels. To control temperature uniformity at box margins, engineers attached thermostatically controlled heaters. Thermal control was difficult because very low levels of electronic noise inside the box had to be maintained, according to Don McKeown, Kodak's manager of advanced sensor development. Consequently, the team paid special attention to interior structural design, circuit board component choices and shielding.

Image Compression

Capturing high-resolution ground imagery at the rate of a gigabit per second is one thing. Compressing the image data to a size that can be transmitted to Earth in real time with no detectable loss of image quality is quite another. To accomplish this feat, Kodak Research Labs developed an algorithm to compress the 11-bits-per-pixel image to 2.6 bits per pixel. Equally significant, the algorithm is processed by a series of compact, low-powered application-specific integrated circuits (ASICs). By these integrated chips, image data are compressed at a speed of 115 million pixels per second, providing four times more saleable images per orbit, according to McKeown.

In addition, developers had to achieve required levels of system reliability. Measured in terms of probability of successful operation over the satellite's five-year mission, the camera electronics have a 98% reliability factor, according to McKeown.

Low Cost, High Performance

Kodak met the IKONOS camera challenge without inventing new technologies by relying on advanced engineering knowledge the company developed for NASA space programs and remote sensing projects dating back to the 1960s.

"We accepted the challenge, and then pushed existing state-of-the-art technologies and engineering practices even further to produce the finest space camera ever built," says McKeown. "Ultimately, what makes the IKONOS camera a success is achieving high levels of performance at a relatively low cost."