Corona KH-4B Satellites

The Corona reconnaissance satellites, developed in the immediate aftermath of SPUTNIK, are arguably the most important space vehicles ever flown, and that comparison includes the Apollo spacecraft missions to the moon. The ingenuity and elegance of the Corona satellite design is remarkable even by current standards, and the quality of its panchromatic imagery in 1967 was almost as good as US commercial imaging satellites in 1999.

Yet, while the moon missions were highly publicized and praised, the CORONA project was hidden from view; that is until February 1995, when President Clinton issued an executive order declassifying the project, making the design details, the operational description, and the imagery available to the public. The National Reconnaissance Office (NRO) has a web site that describes the project, and the hardware is on display in the National Air and Space Museum.

Between 1960 and 1972, Corona satellites flew 94 successful missions providing overhead reconnaissance of the Soviet Union, China and other denied areas. The imagery debunked the bomber and missile gaps, and gave the US a factual basis for strategic assessments. It also provided reliable mapping data. The Soviet Union had previously "doctored" their maps to render them useless as targeting aids and Corona largely solved this problem.

The Corona satellites employed film, which was returned to Earth in a capsule. This was not an obvious choice for reconnaissance. Studies first favored television video with magnetic storage of images and radio downlink when over a receiving ground station. Placed in an orbit high enough to minimize the effects of atmospheric drag, a satellite could operate for a year, sending images to Earth on a timely basis. But television resolution at that time was finally judged inadequate for reconnaissance purposes.

The Air Force then came to favor the use of film which would be developed, scanned, stored on tape, and radio down-linked when over a ground station. This approach provided higher resolution than television video (even though some resolution was lost in transferring the data to tape) and could still deliver the imagery to the ground on a timely basis. But there were two problems. One was the transmission rate limitation of radio downlink at that time. The other was that the mission life was limited by the amount of film carried. Nevertheless this approach continued to be pursued by the Air Force under the apparently unsuccessful SAMOS program.

The third option was to return the exposed film to Earth in a capsule. Concerns about capsule reentry were being addressed under the ballistic missile program. And because the mission life would be short, only a week or two, the orbit altitude could be lower, thereby increasing the resolution. The Air Force faulted the fact that the imagery would not be received on a timely basis. And of course a new satellite had to be launched every time it was necessary to obtain updates. Nevertheless this was the approach adopted for Corona, which under President Eisenhower disappeared from public view as a "black' program under CIA management.

There were six Corona satellite models, each incrementally improved over its predecessor. KH-1, 2 and 3 carried a single panoramic camera and differed in some of the camera, film and image motion compensation details. KH-4 added a second panoramic camera for stereo imaging. KH-4A used higher resolution film and added a second recovery capsule, which allowed the mission duration to double. KH-4B with its wider body incorporated constant rotating cameras with less vibration. Also the film resolution was further increased.

KH-4B Overview.

The KH-4B satellites, which flew between September 1967 and May 1972, were the most advanced of the series. They were in high inclination elliptical orbits with perigee located at some north latitude of prime interest (emphasis on the USSR) so as to produce the highest resolution over these locations. The orbit of the first KH4B mission had a perigee of 150 km an apogee of 389 km at an inclination of 80.1 deg, which were typical of the 16 successful KH-4B flights.

The KH-4B featured a pair of counter-rotating panoramic cameras, one tilted forward 15° and the other tilted aft 15° to produce stereo imagery. At 150-km altitude the minimum slant was 156 km. Each camera scanned 70° swaths perpendicular to the satellite ground track as depicted in Figure 1. When at perigee the scan length ground projection was 218 km and the minimum swath width was 14 km. To ensure no gap in ground coverage the camera rotation rate had to be 192 deg/s (my calculation).

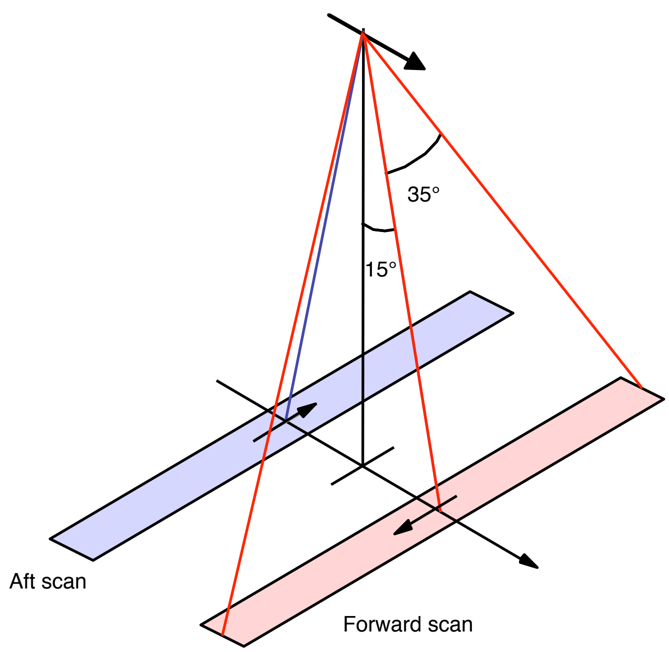

Figure 1. Ground Swaths Produced by Dual Panoramic Cameras

The KH-4B used slow (about ASA 2) black and white film with a resolution of 160 line pairs/mm. The average spacing *p* between grain centers, along orthogonal directions, is equal to the reciprocal of twice the film resolution. This spacing is analogous to pixel pitch in a digital system. For a film resolution of 160 lp/mm, p is 3.125 μm. Documents written in the Corona film era defined ground resolution differently than in today's digital world:

$$\Delta = r \cdot 2p / f \quad \text{(film era)}, \qquad\qquad \Delta = r \cdot p / f \quad \text{(digital era)}$$

To facilitate comparisons between KH-4B imagery and imagery from current satellites, the digital definition will be used. At the minimum slant range the KH-4B resolution normal to the LOS was 0.8 m, which is almost identical to the best resolution of the current IKONOS II commercial imaging satellite. However, this does not mean that the image quality is the same, because other factors (diffraction, image motion and signal to noise) come into play. The key parameters for the KH-4B when at perigee are listed in Table 1.

TABLE 1. KH-4B Parameters

Orbit Parameters	units		Reference Document
• Perigee altitude	km	150	TRW Space Log 1957-1987
• Apogee altitude	km	389	TRW Space Log 1957-1987
• Inclination	deg	80.1	TRW Space Log 1957-1987
Semi-major axis, a	km	6647.5	
Orbit period	min	89.8	
Mean orbit rate, n	rad/sec	0.001165	
Perigee velocity	km/s	7.884	
Perigee ground speed	km/s	7.703	
Viewing Geometry			
• Earth centered viewing offset, φ	deg	0.367	
$r_E/(r_E + h)$ at perigee		0.977	
Range, r	km	156	
Off nadir view angle, θ	deg	15.23	KH-4B Camera System, NPIC 1967
Zenith angle, ψ	deg	15.60	
Ground offset, $r_E\varphi$	km	40.9	
Sensor			
• Mean wavelength (assumed)	μm	0.555	Assumed
• Film resolution	lp/mm	160	Corona, Between the Sun and the Stars
• Film width	mm	70	KH-4B Camera System, NPIC 1967
• Exposed film width	mm	54.5	KH-4B Camera System, NPIC 1967
• Film strip frame length	mm	745	KH-4B Camera System, NPIC 1967
• Along track FOV	deg	5.12	KH-4B Camera System, NPIC 1967
• Equivalent pixel pitch, p	μm	3.125	
• F# = f/D		3.5	KH-4B Camera System, NPIC 1967
• Focal length, f	m	0.61	KH-4B Camera System, NPIC 1967
Aperture diameter, D	m	0.174	
Measured optics resolution	lp/mm	280	
IFOV	μrad	5.13	
Optical Q		0.62	
• Scan angle (centered about track)	deg	70.00	KH-4B Camera System, NPIC 1967
Rotation period	s	1.87	Assumes no overlap at perigee
Rotation rate	deg/s	192	
Equivalent line rate	Mlps	0.654	
• Minimum slit opening	mm	4.32	KH-4B Camera System, NPIC 1967
• Maximum slit opening	mm	7.62	KH-4B Camera System, NPIC 1967
Minimum exposure time	ms	2.11	
Maximum exposure time	ms	3.73	
Ground Projection at Perigee			
r•IFOV	m	0.80	
r•IFOV / cos ψ	m	0.83	
GSD	m	0.81	
Ground scan length	km	217.9	
Swath width (center of scan)	km	14.4	
Effective resolution (film and optics)	m	1.07	See Image Quality Section

Payload Configuration.

The payload end of the satellite (Figure 2) stayed affixed to the Athena upper stage bus in its orbit, with the latter providing three-axis attitude control and other services. Figure 3 shows the cross-section of the payload portion only.

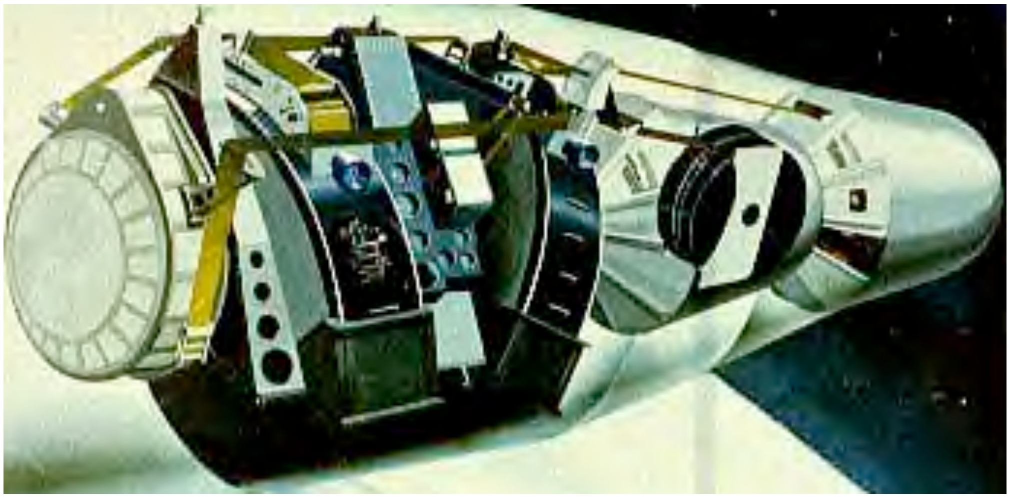

Figure 2. Artist's Drawing of the of the Corona KH-4B Payload (national air and space museum, nasm)

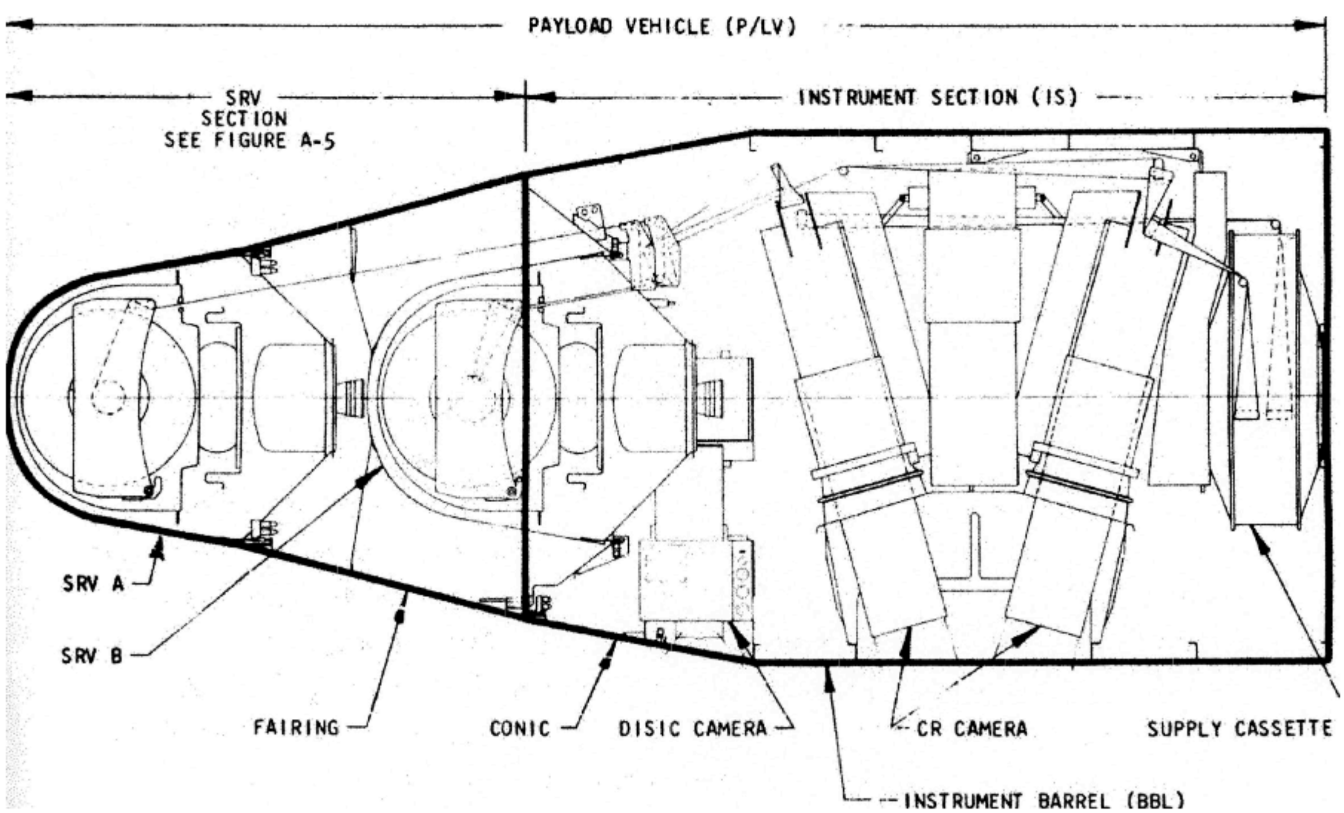

Figure 3. Schematic of Corona KH-4B Payload (national air and space museum, nasm)

A complex film feed system (Figure 4) transported the exposed film to one of two take-up cassettes, one in each of two recovery capsules. Each cassette could contain approximately 4900 m of film. When the cassette in the forward capsule was filled or if the user wanted certain collections sooner, the film was cut and the forward capsule was de-orbited and recovered. From this point forward the film was fed to the aft cassette and it too was de-orbited when filled.

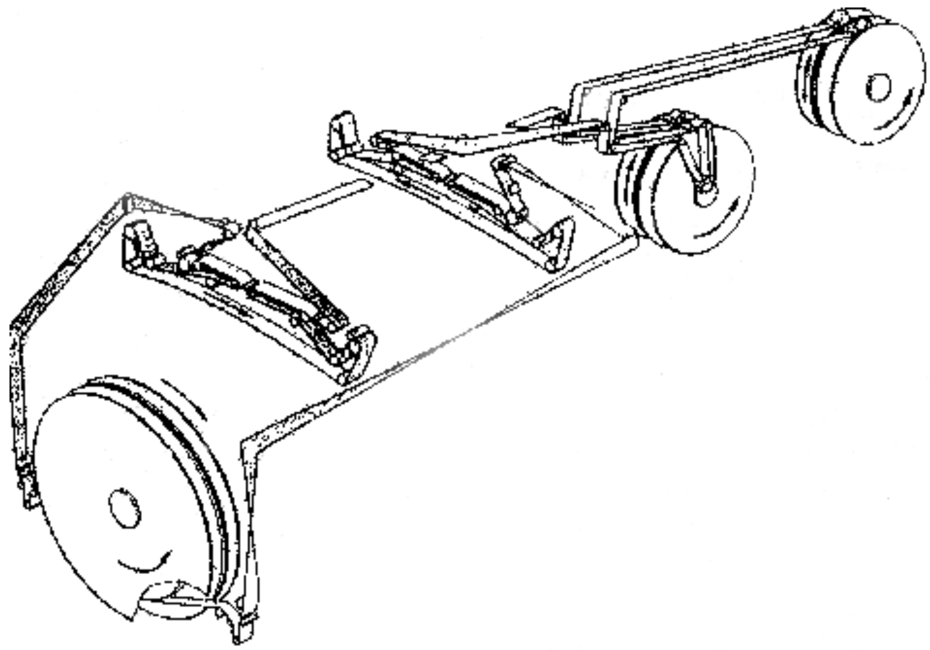

Figure 4. Film Feed System

Panoramic Camera.

The ingenious part of the CORONA imager is its "swing lens" panoramic camera that provided a very wide field of view (FOV) image in one direction using a narrow FOV lens set; thereby collected high-resolution imagery at an incredibly high rate. Its principle is explained with the help of the simple lens diagram in Figure 5. The film is draped over a circular guide between the loaded film spool and the take-up reel. The distance between the film and the lens is equal to the focal length *f* of the lens assembly. The subtended angle of the portion of the film on the circular guide defines the total panoramic scan angle. The lens and shield rotate through the total scan angle at a constant rate Ω_{scan}. The film is stationary during each 70° scan, and is advanced between scans. The slit opening in the shield allows only a portion of the film to be exposed at any one instant. The exposed slit width (in the cross scan direction) was 54.5 mm. The exposure time is

$$t_{\exp} = \frac{s}{f \cdot \Omega_{scan}}$$

where *s* is the slit opening in the scan direction. On the KH-4B the maximum *s* was 7.62 mm. For the 0.61-m focal length and a maximum rotation rate of 192°/s (3.35 rad/s), the maximum exposure time was 3.73 ms.

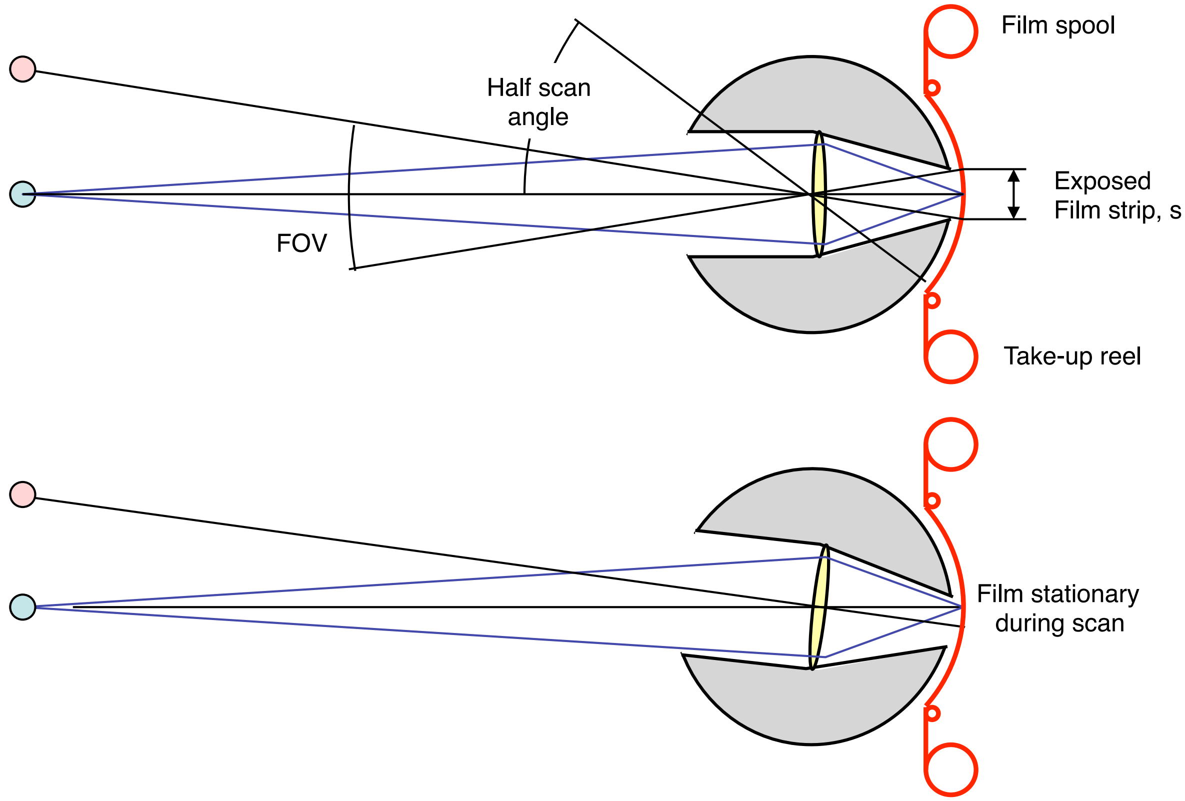

Figure 5. Swing Lens Panoramic Camera Concept.
Lens rotates about a point one focal length forward of the film.

In this simplistic representation the lens is the center of rotation located a distance to the film equal to the focal distance f. So as the lens and the shaded shield rotate a target point (say the blue spot in Figure 5) appears stationary on the film over the exposure angle s/f. Consequently it is possible to achieve adequate exposure times even with the high rotation rates required to provide coverage without gaps. And indeed this feature is precisely what makes this concept viable.

The optics must provide good image quality over a field of view defined by $FOV = w_{film} / f$. For the useful film width of 54.5 mm (full width was 70 mm), the required optics FOV was a modest 5.1°. Something more than the single lens in Figure 5 is required to provide adequate image quality over this FOV. The Petzval lens configuration (Figure 6) with two widely spaced positive lens sets was chosen by Itek (Figure 6). It had a 3/2 lens set plus a field-flattening lens near the image plane. Under high contrast conditions, this combination tested to 280 lp/mm; very close to the theoretical diffraction limit of 313 lp/mm at a wavelength of 0.555 μm. And the relatively low F-number (3.5), made it possible to use a slow film with a high film resolution (160 lp/mm). The sensor resolution (optics and film together) was 120 lp/mm

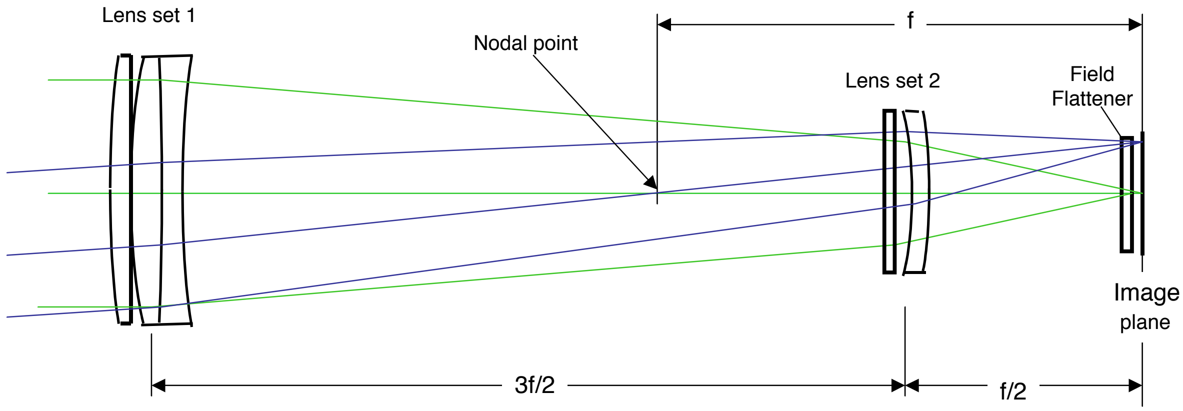

Figure 6. Petzval Lens (Approximate Representation of Corona Design)

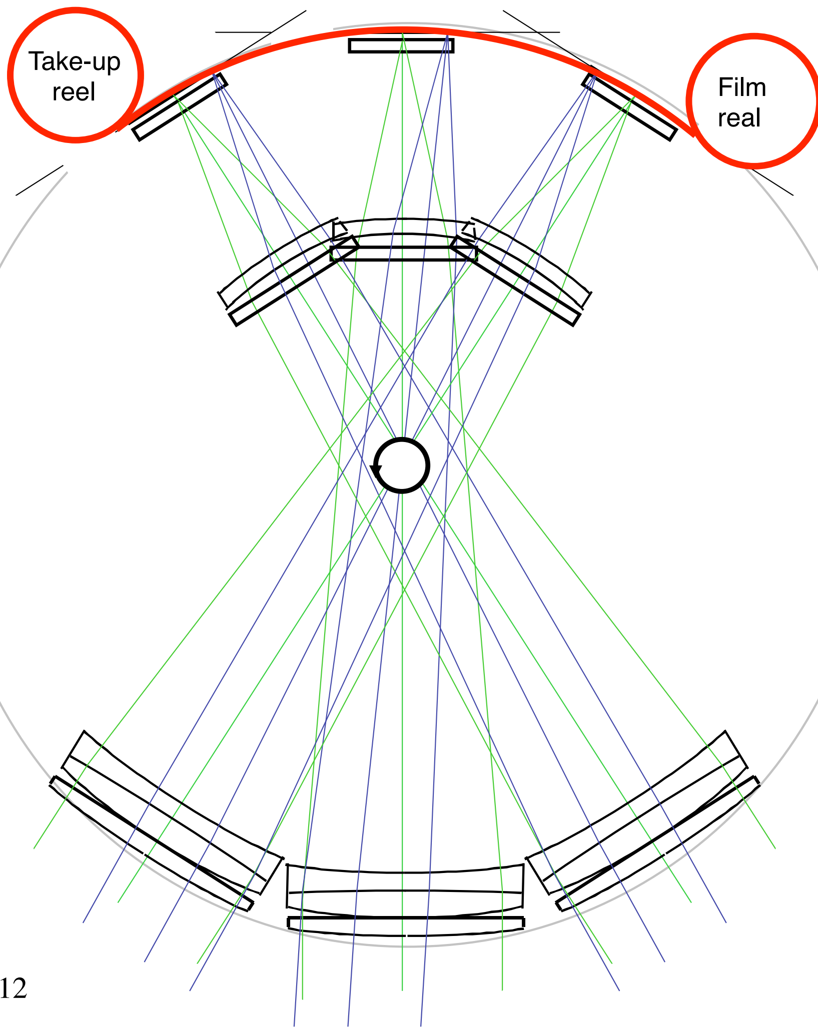

Figure 7. Rotation About the Nodal Point for a Petzval Lens

To implement a panoramic scan, without introducing scan smear across the focal plane, the lens configuration must rotate about the nodal point located one focal length *f* from the image plane. The fact that the total length of the optics spans two focal lengths would seem a disadvantage. However, to minimize dynamic disturbances, the rotating assembly had to be mass balanced about the nodal point, and the Petzval design was an aid in this respect.

The instantaneous field of view (IFOV) is the film line width divided by the focal length. The equivalent line rate (the number of equivalent lines of "pixels" swept out in the scan direction per unit time) is equal to the IFOV divided by the scan rate Ω. At the rotation rate of 192°/s the equivalent line rate is an incredible 0.65 Mlps, while simultaneously allowing integration times up to 3.73 ms. This was possible because the integration time was set by the size of the slit opening. Moreover there is no scan smear when rotating about the nodal point, because the film is stationary during the scan.

Let's put this design in the perspective of today's line-scan charged couple device (CCD) imagers using time-delayed integration (TDI). Current commercial imaging satellites have up to 64 detectors in TDI and line rates up to 20 Klps. At this line rate, the longest integration time is 3.2 ms (close to the KH-4B value). But the line rate for CORONA is 32.5 times faster. A single CORONA frame has 238,400 x 17,400 "equivalent" pixels or over 4 Giga pixels, collected each rotation. Taking into account the 19.4% rotation duty cycle, the collection rate is over 2 Giga pixels/s. No digital system today comes remotely close to matching this rate.

Image Motion Compensation.

While the panoramic camera can accommodate high scan rates without introducing image smear in the scan direction, it was necessary to compensate for the forward motion of the satellite normal to the scan direction. With a satellite ground speed up to 7.7 km/sec, an exposure time of 3.73 ms would introduce a 29 pixels smear. This was avoided by pitching the camera assembly forward at a constant angular rate equal to the orbit speed divided by the altitude during the 70° scan rotation, and then pitching back during the 290° of rotation when the film strip was advanced along the guide. This nodding motion (Figure 8) was implemented using cams on the rotating camera assemblies.

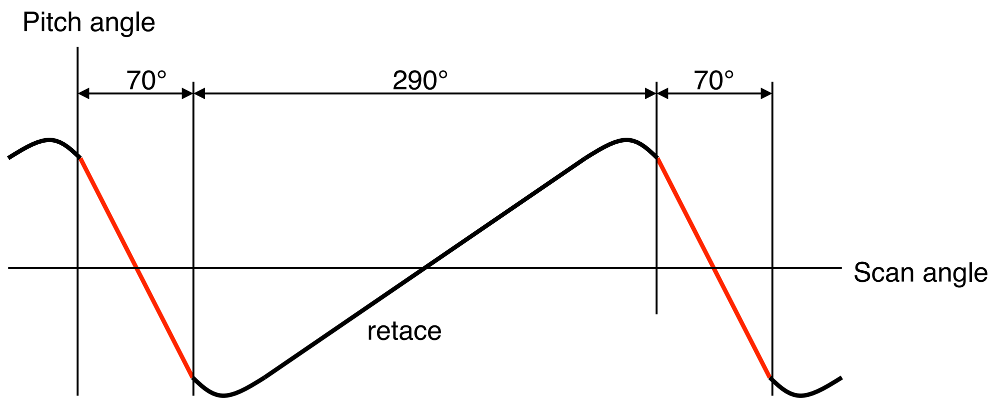

Figure 8. Image Motion Compensation

Attitude Control.

The payload was attached to the Agena vehicle, which provided the final stage of propulsion to reach orbit, and performed the attitude control functions while in orbit. The Agena program was under development before the Corona program was initiated. Gravity gradient stabilization (with the long axis of the Agena aligned to vertical) was being developed to provide on orbit pointing and stabilization in support of the Air Force SAMOS program (a long life mission at moderate altitude). On the other hand, the planned Corona film recovery program would be short duration in a very low Earth orbit, in which the gravity gradient restoring torques would be overwhelmed by the atmospheric torques. Moreover, the Agena had to be oriented horizontally to accommodate the panoramic camera. The short mission life (two weeks or less) made it feasible to employ a 3-axis controlled spacecraft using cold gas reaction jets. A gyro inertial package and a pair of horizon sensors provided error signals.

Imagery Example.

Corona imagery is available from the United States Geological Survey (USGS) web site. Figure 9 shows the footprint of image frame designated 1101-2157DF028 of a portion of the eastern US. It was collected on September 25, 1967 on the first mission of a KH-4B satellite. This satellite is identified in the TRW Space Log by the International Designation 1967 87A. From the orientation of the frame and the orbit inclination, it is evident that the satellite was moving north to south on this pass.

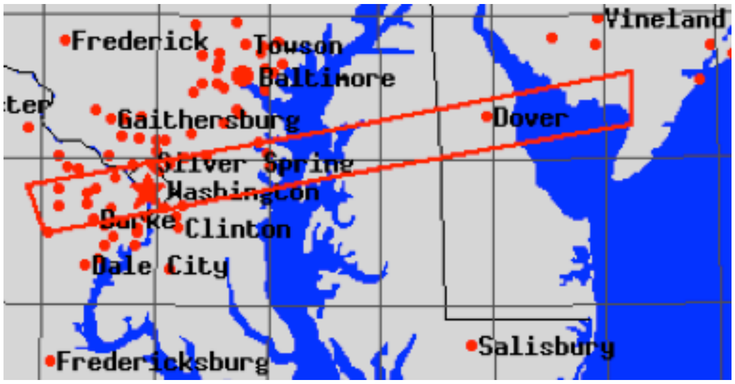

Figure 9. Image Tag DS1101-2157DF028. Here 1101 denotes the first mission of the 1100 (KH-4B) series, 2 is the second capsule, 157 is the orbit revolution, D is the descending (N to S) leg, F is the forward pointing camera, and 028 is the frame.

Neither the precise orbit altitude nor the resolution for this frame is available from the imagery log, but can be estimated from the information available. From the map, the footprint is computed to be 228 km long. Given that the scan length corresponds to a 70° rotation of the camera line of sight, the slant range to the center of the scan is estimated at 160 km and the altitude at 155 km (close to the perigee altitude), and the satellite sub nadir position was 41 km behind of the center of the frame. The geometry is depicted in Figure 10.

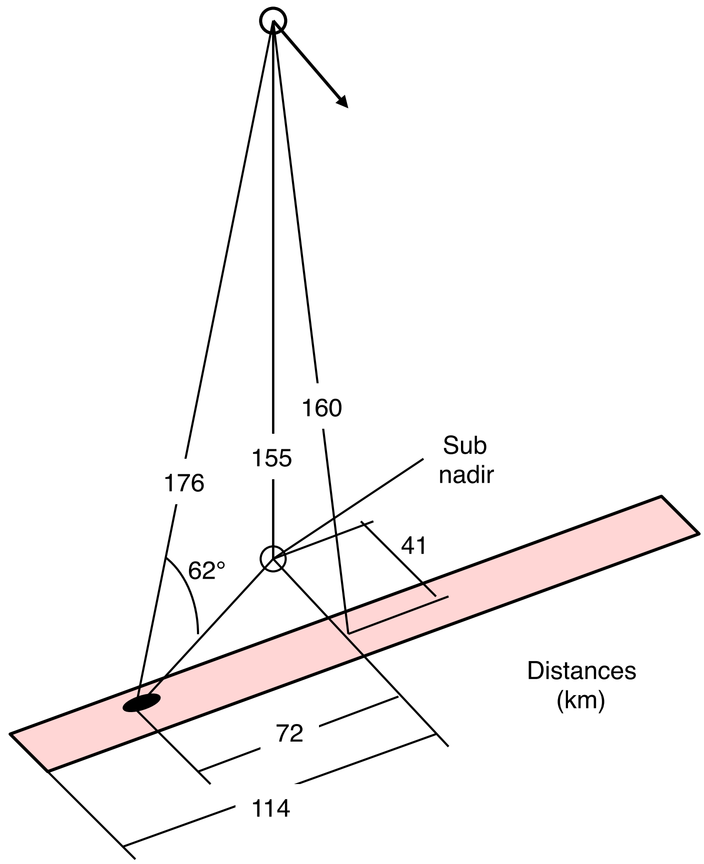

Figure 10. Viewing Geometry for Frame 28. The left of center dot in the scene locates Washington DC some 72 km from the center of the frame.

Figure 11 is an enlargement of the immediate area surrounding the Washington Monument. The slant range to Washington is estimated at 176 km, and the line of sight elevation angle at 62°. The image scale is approximately 11,000:1. Additional information is also available. North is established from a map of the area. The shadow cast by the monument locates the direction of the solar illumination. The angle between the monument shadow and north, and the length of the monument shadow indicates a mid morning image collection. The frame was collected only four days after the Autumnal Equinox, so the Sun elevation angle was approximately 51° (the complement of the 39° site latitude). Finally, the tilt of the monument establishes the viewing direction as from ENE.

With a focal length of 610 mm and a film resolution of 160 lp/mm, the resolution normal to the LOS is estimated to be 0.90 m. By way of comparison, the IKONUS II commercial imaging satellite can provide 0.82-m resolution imagery. To drive this point home, Figure 12 is an IKONOS II image of nearly the same area collected some 33 years later. This too was a morning shot, as evident from the monument shadow. The scales for the two images are approximately the same, though both the Sun and satellite elevation angles are different. The resolutions of the two images are comparable, but the IKONOS image is sharper because other factors besides resolution affect image quality. Nevertheless the KH-4B image is impressive considering the era.

Figure 11. Washington Monument Region (DS1101-2157DF028)
(purchased by author)

Figure 12. Image Collected by IKONOS II (1/1/01).
The top of the image points due south. SpaceImaging

Soviet Zenith Program

During the CORONA era the Soviet Union pursued their own photo-reconnaissance program (called Zenith) also using film return. However, they had frame cameras rather than panoramic cameras, recovered the entire satellite not just a film capsule, and sealed the film and camera in a pressurized capsule rather than exposing them to a vacuum. The latter made sense because their program was a joint venture with their manned space flight activities using the same satellite configuration.

References

Day, Dwayne A, "Lifting the Veil on History: Early Satellite Imagery and National Security", *Space Times*, July-August 1995.

Deutch, John, "The Corona Satellite Reconnaissance Project and Revolution in Intelligence", *Space Times*, July-August 1995.

Broad, William J., "Spy Satellites' Early Role Coming Clear", *New York Times*, September 12, 1995.

The above three references came out at the time when President Clinton declassified the Corona program. They generally tout the importance of the program in the Cold War era.

McDonald, Robert A., editor, *Corona Between the Sun and the Earth: the First NRO Reconnaissance Eye in the Sky*, American Society for Photogrammetry and Remote Sensing, Bethesda MD, 1997. This reference, sponsored by the performing organization, provides an excellent overview of the Corona program and rationale for the design approach.

Davies, Morton E., and Harris, William R., *RAND's Role in the Evolution of Balloon and Satellite Observation Systems and Related U.S. Space Technology*, RAND report R-3692-RC, September 1988. Provides background information concerning the use of a panoramic camera, particularly the HYAC camera, the forerunner of the Corona camera.

The KH-4B Camera System, National Photographic Interpretation Center, September 1967. This is the declassified data book for the KH-4B camera system. It provides the most definitive information regarding the optical system, particularly the details on the film format.

Galiatsatos, Nikolaos, *Assessment of Corona series of satellite imagery in Landscape Archaeology: a case study of the Orontes valley, Syria*, Last updated February 26, 2004. www.dur.ac.uk/nikolaos.galiatsatos/Research/Page1.html. This reference provided the information that the variable slit was used to allow variable exposure times with a fixed camera rotation rate, rather than to produce a fixed exposure time for variable camera rotation rates. The latter would make some sense were there large changes in altitude over the areas of interest.

Herther, Jack C., and Coolbaugh, James S., Genesis of Three-Axis Spacecraft Guidance, Control, and On-Orbit Stabilization, *Journal of Guidance, Control, and Dynamics*, Vol 29, No 6, November-December 2006. Herther played a key role in explaining to the Corona evaluation team how the Agena guidance scheme could be modified to stabilize the it in a horizontal attitude that was required for a low altitude, short duration mission. This paper provides a fascinating account leading up to the Corona era.