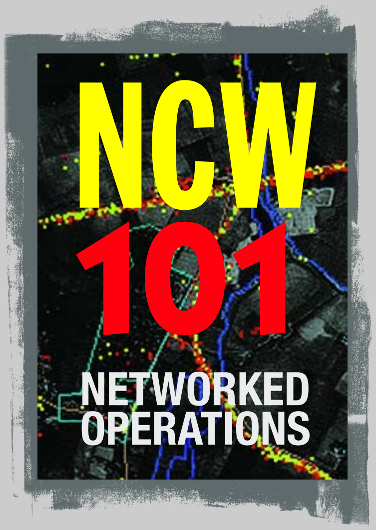

Optical Imaging Sensors

NCW 101 part 5

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Aerial optical imaging has come a long way since Sidney Cotton crafted the first modern aerial photo-reconnaissance system during World War II. In networking terms the recent shift from wet film imaging media to digital media has been a driving impetus for network connectivity between platforms and systems.

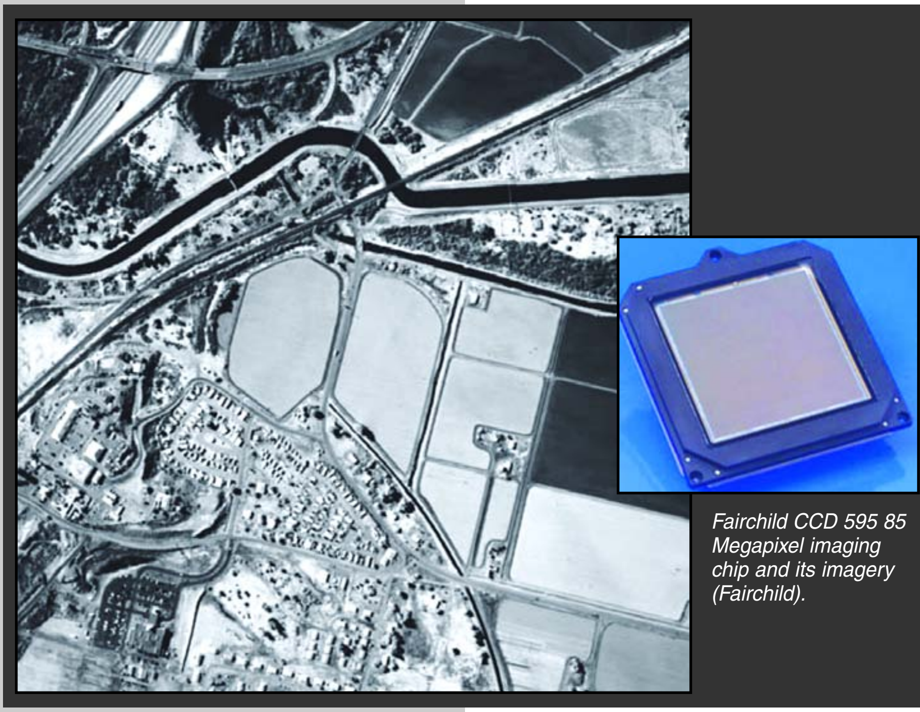
At the most fundamental level Network Centric Warfare is about moving information around quickly to create an advantage in combat, by being able to react faster than an opponent. That information in modern combat is often dominated by imagery. Having a network is moot, if there are not enough sensor systems gathering information connected to the network, and sensors that gather imagery perform poorly.

The array of contemporary imaging sensors used is vast. These include video cameras, framing cameras, stepping cameras, panoramic cameras, linescanners, and hyperspectral imagers. Optical band coverage spans the submicron wavelength visible sunlight band down to longwave infrared. Millimetric wave imagers in development, push band coverage down to 3 mm wavelength.

Within the visible and infrared bands, the principal distinction between sensors lies in the imaging device or medium and the optical materials used. In terms of design and construction, often such sensors are nearly identical, or very similar.

Many contemporary digital imaging sensors used in ISR systems are rebuilds or redesigns of legacy wet film devices, in which the wet film medium has been replaced with a scanning or solid state Focal Plane Array imaging device, and a digital interface allows the sensor to directly produce digital imagery for storage or network transmission.

The evolutionary path of optical imaging sensors now spans over a century, with two periods of rapid evolution. The first was World War II, when modern fixed wet film camera technology evolved rapidly, including new capabilities such as motion compensation and stereo framing. The second period of rapid evolution spans the 1960s Cold War period when infrared imaging cameras and linescanners were introduced. Finally, the last two decades have seen a dramatic shift away from wet film media to digital imaging media.



Fairchild CCD 595 85 Megapixel imaging chip and its imagery (Fairchild).

In practical terms, a contemporary digital imaging camera used in a recce pod, fixed installation or UAV may well share much of its optical design with a predecessor from the 1950s or 1960s. The high cost of reconnaissance grade optical components, both in design and manufacture, almost guarantees that older designs will remain in use, or evolve.

There are thus two key aspects in understanding modern imaging sensors. The first is the imaging medium its capabilities and limitations. The second is the optical design and the types or style of images it can produce. This issue will explore technologies used for visible band or daylight imaging, with the caveat that many such systems now include infrared imaging media as well.

Visible Band Imaging Media

Until recently, high quality imagery could only be produced by wet film media. The evolution of wet film for reconnaissance applications began in earnest during the 1940s, and with decreasing film grain size and thus increasing resolution, film formats have steadily decreased in frame size. Most films used for such applications are monochromatic (black and white) as this provides for the highest possible resolution using a given dye technology, and it also captures light which in a colour medium would fall between the peaks in colour dye sensitivity. Recent film types have dyes designed with some near infrared sensitivity to improve penetration of atmospheric haze. Modern media have extremely high resolving power, usually specified in line pairs per millimetre (lp/mm). Examples are the exceptional Kodak 3409 at 320-640 lp/mm, the Kodak 3404 at 55-130 lp/mm, and the Kodak 2412/3412 at 125-500 lp/mm. However, atmospheric conditions, limitations in sensor mechanics, optics and image motion effects mean that the resultant imagery does not reach the resolution potential of the film.

Film formats have evolved considerably over the past few decades. Early films used formats as large as 9 x 18 inches, with later systems standardising on 4.5 inch and 70 mm film formats, the latter based on cinema technology. Films for bomb damage assessment cameras are usually 70 mm, 35 mm or 16 mm.

Wet film media still set the benchmark for capability in imaging sensors. If we consider a 4.5 x 4.5 inch framing camera, loaded with a 320 lp/mm down to 55 lp/mm film medium, the equivalent in a digital imaging system are Focal Plane Array devices with resolutions of 36,500 x 36,500 or 1.3 Gigapixels down to 6300 x 6300 or 40 Megapixels, respectively. For a 70 mm medium with a 2:1 aspect ratio, the equivalent to a 120 lp/mm medium is a 8400 x 16,800 CCD totalling 141 Megapixels. In comparison, commodity digital cameras are in the 4-6 Megapixel class, and professional equipment from Hasselblad or Mamiya in the 22 Megapixel class.

However, the greatest limitation of wet film media, in networking terms, is in time: acquiring the imagery, returning to base, processing and interpreting the imagery, then disseminating the intelligence – a process that can take hours from photo shoot to intel delivery.

The most widely used CCD (Charge Coupled Device) imager in recce applications is the Fairchild CCD 595 9216 x 9216 or 85 Megapixel imaging chip, fabricated on a 5 inch Silicon wafer, and designed to replace commonly used 4.5 inch recce film media.

The CCD remains the mainstay in commercial and military visible band imaging, both static and video based. CCDs are termed 'bandgap detectors' due to the physics of their operation, which require that the semiconductor material used has a bandgap energy parameter smaller than the energy of the impinging photons of light. When a photon hits such a material, it dislodges an electron, which can be captured and used to sense the photon impact. Most common photodetectors use this effect. What distinguishes a CCD from simple photodetectors is that it is a slab of Silicon covered with an elaborate and dense grid of circuits. The CCD detector is thus divided into a regular pattern of cells, each corresponding to a pixel. Each cell has an electrode that accumulates electrons produced by the photoelectric effect. Once an exposure is completed - no differently than a shutter opening in a wet film camera - the contents of these pixels are read out, line by line. CCDs are named after the readout technique they use, in which pulsed electrical signals are used to simultaneously force the charge under each electrode to 'jump' to its immediate neighbour, in lockstep, not unlike a 'bucket brigade'. At the end of each line the electrical signal on the last cell represents, with each readout pulse, the brightness detected by the corresponding cell. Additional electronics are then used to switch to the next line, once a line has been read out. The analogue readout is digitised using an analogue to digital converter.

Modern CCDs include all of the control and readout electronics, etched with the imaging array on to a single chip. This is why commodity CCD technology is so cheap, as a single chip is effectively a self-contained camera.

The CCD has been surpassed technologically by similar CMOS technology imagers, and more recently the very different Quantum Well Imaging Photodetector (QWIP), the latter emerging in infrared applications.

Like wet film cameras, CCDs require some finite exposure time to capture enough photons to produce a useful image. If the scene brightness is low, longer exposures are required to get good contrast. This can present issues as a CCD cannot be read out instantaneously, and the larger the CCD the longer it takes to read out the picture, limiting frame rates on larger CCDs to frames per second.

The issue of readout speeds sets hard limits on frame rate performance versus resolution for a given generation of CCD or CMOS/QWIP technology. The sensitivity of each pixel sized imaging site on the device is determined by its area; the larger it is the more photons it can capture during an exposure, and the shorter the exposure can be for a given scene brightness. For video applications with frame rates between 25 and 120 frames per second, much larger pixel area is required compared to a recce framing camera where smaller pixels are necessary, and lower frame rates well under 25 per second can be tolerated. To put this in context, the cited Fairchild 9216 x 9216 chip is internally divided into eight sections, each with independent readout electronics, which clock pixels off the chip at up to 40 MHz each, this complexity being essential to achieve a usable exposure time.

The commonly held belief in some circles that conventional video CCDs in targeting pods are a direct substitute for specialised recce CCDs is uninformed. While such devices have some capability, a 1 Megapixel chip cannot do the job of a 40 Megapixel chip. Emerging HDTV camera chips are an important advance, but are at best a partial substitute for specialised devices.

The long term outlook is that we will see improving density and speed in imaging chips, limited by the density of available chip fabrication technology. Near term, with HDTV growing in the market, video rate imagers in the 1800 x 900 pixel class will become very cheap, with commodity camera imagers progressively growing into the 20+ Megapixel density class of current professional equipment.

An F/A-18F Super Hornet launches from the flight deck of the USS Kitty Hawk equipped with a Shared Reconnaissance Pod (SHARP), a multi-functioned reconnaissance pod used on the F/A-18F Super Hornet for tactical manned airborne reconnaissance. (Jonathan Chandler, US Navy)

A "ScanEagle" Unmanned Aerial Vehicle payload is either an inertial stabilized electro-optical camera, or an infrared camera. The gimbaled camera allows the operator to easily track both stationary and moving targets. Currently in use by U.S. Marine Corps in Iraq. (Daniel McLain, US Navy)

Framing Cameras

Framing cameras are in many respects the oldest and simplest of reconnaissance cameras, but still involve complexity well beyond handheld camera technology. Much of the current global inventory are rebuilt film cameras with digital backs, allowing the retention of existing hardware investment.

Like less complex cameras, framing cameras use a compound lens system with some, typically fixed, focal length to achieve an intended field of view and field of focus at the intended range for its usage, focus usually being fixed at the expected aircraft operating height for the particular sensor/lens combination. The lens design is often optimised to provide best sharpness at the red/yellow end of the colour spectrum to better penetrate haze. Classics in this category like the KS-87 series, still very widely used with digital backs, may use 6, 8, 12 or 18 inch focal length lenses.

Where framing cameras, be they wet film or digital, differ from conventional cameras is in the use of forward motion compensation. This technology evolved during World War II when a technique was needed to deal with blurred images resulting from a fast moving aircraft carrying the camera at low altitude. It is also a problem with long focal length lenses that also produce high image motion rates.

One FMC option is to open the shutter and then drive the photographic film across a shutter slit at the imaging plane at a speed relative to that of the image movement. Another option in framing cameras is to move the film as the focal plane shutter is fired.

The FMC formula commonly used is:

FMC = 1.67 V/H x Fl x sin(fi)

Where V is aircraft velocity in KTAS, H is aircraft altitude in feet, Fl is lens focal length, fi is the depression angle, and FMC is the forward motion compensation speed of the film in inches/sec.

Forward motion compensation has migrated to digital CCD based designs, using electronic techniques to emulate the effect of a film-based system. Rather than move a film, the CCD is aligned so that the readout lines are parallel to the direction of motion, and the 'bucket brigade' is used to migrate the charge across pixels at the appropriate rate to match the effect of moving film.

The advent of digital camera equipment has produced other enhancements. Classical framing cameras carried in reconnaissance aircraft camera bays or pods were fixed in direction, pointing forward, down, or at oblique angles out of the side to achieve intended coverage. Many recent camera designs are built with optical systems gimballed on a stabilised platform, to permit reduction or removal of jitter and to also allow the camera to be pointed or panned. This approach is especially favoured for high flying UAVs. Systems in which the direction of the camera can be controlled precisely, permit the construction of mosaic images, in which the camera steps through a series of angles to image an area much larger than the field of view of the camera, within the several seconds it takes to produce the individual exposures. The mosaic is then a composite image made up of individual tiles, each a single exposure.

Mosaic techniques are especially valuable where the resolution of the imaging chip is limited, but often require significant overlap between tiles to ensure that detail is not lost.

Another technique of considerable value is synthetic stereo imaging, which can be produced by a digitally controlled framing camera. Stereo imaging first emerged during the 1940s, as it provides a photo-interpreter with depth, and to an extent, height perception of the imaged scene. This can be far more revealing than a single frame image, especially when trying to locate camouflaged targets or accurately assess damage effects after a strike.

Digitally controlled framing cameras can be panned and thus track an aimpoint as the aircraft flies past, taking multiple consecutive images. A photo-interpretation station can then select frames, separated by several exposures, to emulate the stereo effect of a pair of cameras.

Cheap computing power has permitted an additional enhancement, historically only used with expensive satellite imagery. This enhancement is the use of software that corrects for lens imperfections and design limitations, such as field of focus. Indeed, this technology is now available commercially for a wide range of commodity camera lenses. In application, digital imagery produced by a framing camera is processed by a computer to correct known lens idiosyncrasies and improve image sharpness.

Framing cameras will continue to be widely used, as the image quality and sheer volume of imagery they produce cannot be matched by targeting imagers. Future developments will include higher resolution imaging chips.

LOROP Cameras

Long Range Oblique Photography cameras (LOROP) emerged during the Cold War as a means of avoiding overflight of contested or hostile airspace. A LOROP camera is essentially a framing camera with a very long focal length telescope attached to it, designed to produce images from distances of tens of nautical miles, usually at shallow depression angles.

The challenge with all LOROP cameras is packaging. While most designs use variations on the theme of Cassegrainian or Newtonian telescopes, with large primary or secondary mirrors, length becomes an issue, especially when the system is to be carried by a fighter or smaller bomber.

A typical contemporary design has a focal length of several metres, folded at least once to produce a telescope of one or more metres in length. An oblique mirror is usually employed to point the camera out of the side of the pod, bomb bay fairing or fuselage of the carrying aircraft. Key design issues for LOROP cameras relate to the size of the primary imaging aperture, as this determines how many photons can be captured and thus achievable contrast at long ranges, the jitter stabilisation capability of the mirror control system, and atmospheric pressure effects on the lens/mirror system at high altitudes. As readers with experience using large telephoto or zoom lenses will appreciate, aperture size and jitter can significantly degrade image quality.

The best known LOROP camera in Australia is the Goodrich Corp DB-110/RAPTOR (Reconnaissance Airborne Pod for Tornado), trialled during the late 1990s on the F-111 but never adopted as an operational system by the RAAF. The DB-110 in its basic configuration has 110 inch focal length in the visible bands, and 55 inch in the infrared band, using an 11 inch diameter aperture. Another system trialled in Australia and not acquired (as yet) is the 10 inch aperture dual band system carried as part of the Raytheon Integrated Sensor Suite (ISS) payload on the RQ-4 Global Hawk. This system uses a Kodak CCD sensor and midwave infrared sensor.

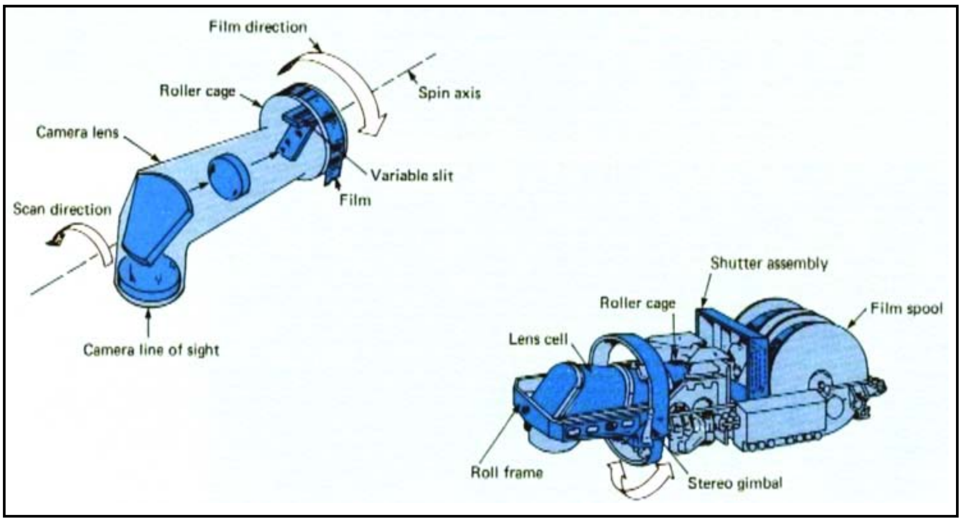
Global Hawk ISS 10 inch telescope imagery (Northrop-Grumman).

Goodrich DB-110 Raptor pod 11 inch telescope subsystem (Goodrich)

Imagery produced by Recon/Optical CA-270 camera (ROI).

Panoramic Cameras

Panoramic cameras are designed to map large swaths of terrain, and typically use very different optical systems compared to other camera types. A typical panoramic camera, such as the Itek KA-80 used in US strategic reconnaissance assets, uses a rotating folded lens and mirror assembly to sweep an arc below the aircraft, perpendicular to the direction of flight. Motion compensation is then effected by rocking the whole rotating optical assembly back and forth along the direction of flight, with the shutter closed for half of the movement.
With the advent of digitally controlled framing cameras capable of mosaic imaging, panoramic cameras have declined in popularity and have not been reported in any recent recce suite designs.



Panoramic camera schematic. (NASA)

Carriage of Camera Systems

Historically, dedicated reconnaissance camera suites were carried in dedicated reconnaissance aircraft, a model initially adopted by the RAF with modified Spitfires and Mosquitos and soon after emulated by the US with the F-4 and F-5 variants of the P-38. Most RAF and USAF strategic and theatre reconnaissance imagery gathered during World War II was by Mosquitos and F-4/5s as these aircraft had the performance to evade opposing interceptors.
This model persisted until the 1980s, seeing the development of dedicated types such as the RF-101 Voodoo, RF-4C Phantom, RF-8E Crusader, RA-3C Vigilante, Australia's RF-111C and most recently the F/A-18D (RC) with the ATARS system. Carried internally, the ATARS suite introduced little if any drag and offered excellent field of view with dedicated windows in the nose of the aircraft.
The more recent trend has been away from dedicated systems, with a preference for podded systems carried by multirole fighters. This has been driven primarily by the cost of integrating camera suites, and volumetric constraints on common fighter types. The F-14 TARPS pod was an early entry, replaced recently by the SHARP pod for the F/A-18E. British Tornados carry the DB-110 pod.
Podded systems typically carry self-contained cooling and control systems, and require primarily electrical power from the aircraft. Their limitations are primarily in achievable field of view and the capabilities of the camera suite, which is often severely limited by pod volume and weight.
UAVs typically carry internal payloads, as these are custom-built ISR platforms. With the exception of the strategic/tactical Global Hawk, most UAVs tend to carry low resolution imaging sensors designed for live video feeds.
Current production systems are mostly fully digital, using CCD daylight imagers and FPA infrared imagers, with fully digital controls. Internal data storage is usually to magnetic tape, although hard disk and solid stage storage are now credible options.
The principal constraint with specialised reconnaissance suites is at this time the provision of adequate digital datalink bandwidth from the platform to the user. There is no production datalink or network technology that can credibly match the rate at which high performance digital imaging sensors collect data.

ATARS system and its imagery (USMC).

The preferred US protocol at this time is TCDL (Tactical Common Data Link) designed for point-to-point down and uplinks, and provides limited capabilities but is usable at 274 Megabits/sec. The JTRS WNW and TTNT protocols will provide usable capability in time, and some intermediate capability will be produced using Link-16 Enhanced Throughput (LET). The most promising technology is the use of phased array radar antennas as datalinks, a scheme initially proposed by this author in 1997 research project, and recently trialled in the US by L-3 and Northrop-Grumman, achieving data rates of hundreds of Megabits per second over extended distances.
Imaging sensors have considerable evolution ahead of them, in imaging devices, supporting data processing, and supporting datalink technology.