Aerial Photography for the Archaeologist

AERIAL PHOTOGRAPHY

FOR THE ARCHAEOLOGIST

A Report from the Museum Applied Science Center for Archaeology

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University of Pennsylvania
Philadelphia, Pennsylvania

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15 May 1975

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INTRODUCTION

Why aerial photography? The main reasons are that the view from the air is usually less obstructed over a large area and that a more map-like perspective is possible.

A major application of aerial photography is reconnaissance, primarily the exploration for undiscovered surface, underwater, or buried structures such as earthworks or building foundations. For environmental or regional studies, photographs of a large area can aid the mapping of its resources and constitute a valuable technique for speeding such surveys. Aerial photos are also valuable for recording archaeological excavations; furthermore, sometimes aerial photos can be the most detailed maps of an area.

In this report I will discuss photographs taken within the range of altitudes between 2 meters and 900 kilometers, how to take them and how to locate those taken by others. The emphasis will be on those subjects not covered as thoroughly in other reports; several introductory reviews will be referenced. The practical applications are described in the body of this report; the technical background to it is detailed in the appendices.

The report was made possible by a financial grant from the National Science Foundation, NSF-GS-36308X-1.

PHOTOGRAPHY FROM LIGHT AIRPLANES

Ever since the airplane was developed, it has been the workhorse of aerial photography. Light airplanes, with room for one or a few passengers, can provide the archaeologist with a revealing and economical aerial view from the height of several hundred meters to several kilometers.

A number of booklets and articles which are currently available are recommended for a how-to-do-it introduction to this subject (Kodak, 1971; Solecki, 1957; Garnett, 1973; Downie, 1968; Blessing, 1972). In the following pages pertinent parts of these writings have been abstracted.

Aircraft

While helicopters allow precise framing and low altitude photography, their high rental cost and vibration make them generally unsuitable. Since small airplanes can fly as slow as 75 km/hour at a height of 150 meters, a helicopter should be resorted to only if it is necessary to fly low and slow.

A variety of small aircraft are currently produced (Colvocoresses, 1974). Two, however, appear to be very widely used for aerial photography: the Cessna 150 and the Cessna 172. Both of these airplanes have high wings and windows that open for clear oblique photographs of the ground. Oblique photos can be taken at any time the plane is flying straight and level; nearly vertical photos, with the camera pointed downward, require that the pilot bank the plane. With permission from the Federal Aviation Agengy, either of these airplanes can have their door removed for an unobstructed view.

Of course, aircraft with low wings and windows which do not open have advantages for some work, but with such aircraft adjustments in the flight

are required to keep the wings and window reflections out of the picture. Even turboprops and jets may be used for aerial photography, but since they are usually pressurized for high altitude flying, their windows will have multiple panes which will not open. Airplanes equipped for commercial aerial photography usually have one or more floor openings for aerial cameras. This is an excellent arrangement for taking vertical photos; understandably, the rental is high.

Cameras

Almost any camera is suitable for aerial photography unless its shutter speed is too slow or it is too heavy and therefore cumbersome to handle in a small cabin.

Many 35 mm cameras are excellent for aerial photography and a wide selection of film is available for them. Many have exposure meters which measure the light coming through the camera's lens; this allows selective light readings. The single lens reflex camera is of great help since the picture can be composed before pressing the shutter. This makes it easier to keep parts of the plane out of the picture. Most such cameras will have a focal plane shutter; this will cause a small amount of distortion in the photographs, since it is inevitable that there will be relative motion between the camera and the scene to be photographed (Clerc, 1970, p. 256). Normally, a lens with a focal length of about 50 mm will be suitable for most work. Telephoto lenses with a focal length greater than 135 mm may be difficult to hold steady. With wide angle lenses, parts of the aircraft may intrude into the picture.

Cameras which use 2½ inch (57 mm) or 70 mm film record a greater amount of detail. However, the selection of 2½ inch film types is not large.

There is a wide variety of film available in the 70 mm size, but they usually require a special order through a distributor. There are many makes of cameras that use 2½ inch film. Some of the better known cameras which use 70 mm film are Hasselblad, Linhof, and Graflex. An additional advantage of 70 mm film is that the magazines will hold enough film for 50 to 70 exposures.

The 4 x 5 inch (10 x 13 cm) format cameras are about the largest which can be hand-held. Many have cloth bellows which must be protected from the wind blowing into the airplane. One military surplus camera, the K-20, has been popular for high resolution photography (Wilkin, 1972; Colwell, 1960a, p. 28). It requires film which must be specially ordered. The K-20 and similar cameras and the equipment for film-processing can be purchased from suppliers such as:

Alan Gordon Enterprises, Inc.
5362 North Cahuenga Boulevard
North Hollywood, California 91601

Air Photo Supply Corp.
158 South Station
Yonkers, New York 10705

Centerline Photo Supply
3812 Central Avenue, S.E.
Albuquerque, New Mexico 87108

Aero-Commercial
6908 East Bloomfield
Scottsdale, Arizona 85254

A serious problem in photography is blurring due to the motion of the airplane. There are three contributors to this malady: the forward speed of the aircraft, the buffeting motion resulting from aerial turbulence, and the vibration of the engine. No matter how carefully the camera is held, some of these motions will be transmitted to it and cause the camera to move sideways or to rotate enough to blur the picture. The worst of these motions are

two rotations, pitch and yaw, which are up-and-down and side-to-side rotations.

Fortunately, it is these two motions that are most effectively reduced by gyroscopic stabilizers. These camera stabilizers utilize fast spinning gyroscopes to dampen or neutralize the rotations. One type, developed by Ken-Lab, Inc. (Old Lyme, Connecticut 06371), is attached to the camera's base and has the effect of increasing the rotary inertia of the camera. Another type, developed by Dynasciences (Blue Bell, Pennsylvania 19422), uses a variable-angle prism, controlled by a gyroscope, placed in front of the camera's lens to optically counteract the effect of rotation. These two stabilizers are so designed that fast rotations are minimized, while the camera can still be panned to follow a scene as the airplane moves by. They are of no benefit with exposures longer than 1/30 second. However, they are excellent for use with telephoto lenses and for the dense filters sometimes required for photographing anomalous patterns in vegetation.

Films and Filters

For general purpose low altitude photographs, black and white panchromatic film is excellent. While yellow or red filters can sometimes improve the contrast of oblique photographs taken through haze, they should not normally be employed for most low altitude photography (Strandberg, 1968, p. 11). This is because the resulting pictures would show very dark shadows, which will make the detection of objects within them difficult. The reason for the darkness of the shadows is that yellow or red filters block out the blue light from the sky which normally brightens shadows in most aerial scenes. On both sunny and hazy days the brightness of the sky has its greatest amplitude at a wavelength of about 450 nm (McDowell, 1974; Birr and others, 1973). Therefore, it might even be of advantage at times to brighten the shadows by photographing through a blue Wratten 47B filter. In fact, for early morning photography it is desirable to photograph either in the blue or even the ultraviolet spectrum (Stringham and Williams, 1970, p. 50).

While most black and white films are sensitive to ultraviolet radiation, not all camera lenses will transmit this short wavelength radiation; furthermore, the camera's focus setting must be calibrated for this invisible radiation (Allman, 1973). A filter is required which will block visible light but allow the ultraviolet to pass: either the Wratten 18A filter (Kodak, 1973a) or the Corning CS7-60 filter (Corning Glass Works, Corning, New York) should do the job. In addition to its value for early morning photography, the ultraviolet spectrum has other advantages for aerial photography: both quartz and calcite are significantly brighter in the ultraviolet spectrum than many other minerals, soils, or plants (Cronin and others, 1968). R.S. Williams has suggested that the high reflectivity of calcite can aid the archaeologist in locating limestone and marble.

Infrared (IR) films can be valuable for oblique photography in some conditions of heavy haze; the contrast of black and white IR films then is an advantage. The increased haze penetration results from both the decreased light scattering at longer wavelengths and the greater contrast within the terrain in the IR spectrum (Specht, 1970). Exposure meters for the infrared are not commonly available, so the film manufacturer's exposure recommendations should be followed. For most 50 mm lenses, the focus setting should be moved to the 20 m mark for IR photography of distant scenes (Kodak, 1972, p. 20).

While some authors have implied that infrared film can indicate the temperature of objects (Simmons, 1969, p. 94: Goodyear, 1971, p. 247), for all practical purposes it cannot. Only objects at a temperature above about 250°C

will readily affect IR film, and even then, long exposures may be necessary (Kodak, 1972, p. 80; Clark, 1939, p. 274). The infrared radiation which IR films detect has a wavelength near the visible spectrum and is called the near or photographic infrared; in this part of the spectrum it is the reflected radiation from the sun which is predominant during daytime photography. At longer wavelengths, in the far or thermal infrared spectrum, it is the emitted heat radiation which predominates; special electronic sensors are used to measure and map this radiation.

Infrared film has been used to detect crop marks which may indicate buried archaeological features such as ditches or walls (Chevallier and others, 1973). However, as explained in Appendix 1, there are good reasons for believing that the infrared spectrum is not generally of additional value for discovering these vegetational patterns. Instead, it appears that the red spectrum, at the edge of the eye's detecting range, reveals markings in soil and vegetation with the highest contrast.

One of the best filters for detecting crop marks with panchromatic film is the Wratten No. 92 filter. This dark red filter has a filter factor of about 80; this means that a film such as Kodak's Tri-X should be given an exposure index of 5 on the light meter, one-eightieth of the usual index. A typical exposure setting of f/2 to f/2.8 at 1/250 second is indicated with good sunlight. If the illumination is less, it may be necessary to change to a Wratten No. 29 filter which has a filter factor of about 25. These special filters will probably yield a better photo contrast than the red filter normally available for cameras such as a Wratten No. 25, or similar.

The photography of underwater objects from an aircraft will also be enhanced by the use of proper films and filters (Helgeson, 1970; Strandberg, 1967a, p. 22). Since the light transmission of water is maximum within the blue or green spectrum (as the water becomes murky, the peak shifts toward the green), a filter should be selected which will transmit only this part of the spectrum. Those that come into consideration are Wratten filters No. 45, 55 and 99. To estimate which filter will be best, the filter should be matched with the perceived water color. There are experimental films which have been developed specifically for water penetration (Boller and McBride, 1974; Specht and others, 1973; Vary and Current, 1970).

A high resolution film-developer combination is supplied by the H & W Company (Katz and Fogel, 1973). The relatively low maximum density of this film indicates that it is best applied when contrast is somewhat reduced by haze.

Most black and white films are developed in such a way that the contrast of the negative results in a gamma or contrast index of about 0.6 to 0.7; this is quite suitable for most low altitude photography. However, when the range in brightness of the terrain is low, a developer with a higher contrast capability is desirable. See the section on photointerpretation for additional information on special processing techniques.

Color aerial photographs have been used by Schoder (1974) to illustrate the architecture at archaeological sites. The special use of filters with color film will be described later.

Flight Procedures

A reflected light reading from an exposure meter taken on the ground before a flight should be close to the light reading measured while at flying altitude. If they differ, the best advice is to select an exposure setting somewhat closer than halfway to the setting measured on the ground (Kodak, 1971). (For more detail about exposure check Appendix 3.)

With many cameras, the sharpest aerial pictures result when the camera's shutter is set at its shortest possible exposure time, as long as that setting is reliable and accurate. Appendix 2 outlines a procedure for determining how much resolution is necessary; it also analyzes how resolution is determined by the camera's lens, film, and exposure settings.

With experimental and reconnaissance photography, it may be desirable to record data on the location and exposure conditions of the photographs (Figure 1). Since it can be difficult to write notes while photographing, a tape recorder will insure that the data are not forgotten. The microphone can be clipped to one's clothing and rested against the collarbone. Keep the microphone out of the wind blowing in the door or window of the airplane in order to minimize the background noise.

Haziness can be detrimental to aerial photography, particularly with moderate altitude color photography. At the same time, haze is often an indicator of stable air; on clear days there may be aerial turbulence which will bounce both plane and camera. If the air is hazy, its effect on reducing contrast is minimized by photographing at a right angle to the sun (Brock, 1967, p. 203). A dense layer of clouds can greatly reduce the brightness at the ground and necessitate a long exposure time; month-by-month estimates of expected cloudiness are available for the United States (Cravat, 1968) and the world (Landsberg, 1945, p. 988).

Stereoscopic photographs sometimes aid interpretation. Vertical stereo photos are the choice of commercial aerial photographers for mapping and reconnaissance; it is also possible to make oblique stereo photographs. The procedure is simply to take a pair of photos in quick succession, keeping the desired scene framed in the camera's viewfinder while circling or flying past it in a straight line. For a 45° oblique stereo pair while flying at a height of 200 m at a speed of 100 kilometers per hour, the time interval

Record at beginning of flight:

- date
- type of aircraft
- light reading taken on ground
- sky conditions, clouds, visibility
- flying conditions, turbulence

Record changes during flight:

- flying height, speed, and heading
- camera, lens, and filter
- film, setting of exposure index
- light reading taken from the air
- exposure settings on camera
- conditions of photo
  - vertical or oblique
  - window open or not

Record for each photo

- frame number and time
- location

Figure 1: Important data for photographic records

between photos should be about one second; for this a camera with an automatic film advance is required. (In non-metric units, a flying height of 1000 feet and a speed of 100 miles per hour also requires a stereo photo interval of about one second for 45° oblique photography.) If the aircraft speed is halved, or the flying height is doubled, the stereo interval time is also doubled. Figure 2 lists some combinations. If there is doubr about the time interval, simply take several photos in quick succession.

In Figure 2, the time intervals are selected to give a perspective rotation of 6° about the scene, although a rotation angle of 10° has also been recommended (Strandberg, 1972). This rotation of 6° is in turn based on a recommended maximum stereoscopic parallax of 2° (Bevan, 1973); it is also assumed that the relief of the terrain is small relative to the flying height.

While it is easy to take stereo photos of a small area, it should also be possible to take a sequence of oblique photos for stereoscopic viewing while flying in a straight line with the camera pointed perpendicular to the line of flight. Vertical stereo photos typically require a 60% overlap, 45° oblique stereo photos (with 35 mm film and a 50 mm lens) require an 85% overlap. With an alternately short and then long interval between oblique photos, a smaller number of pictures will still provide complete stereo coverage.

time interval seconds		Height above ground 500 feet / 150 m	1000 / 300	2000 / 600	4000 / 1200	8000 / 2400
50	80	1	2	4	8	16
75	120	$\frac{2}{3}$	$1\frac{1}{3}$	3	5	11
100	160	$\frac{1}{2}$	1	2	4	8
150	240	$\frac{1}{3}$	$\frac{2}{3}$	$1\frac{1}{3}$	3	5
200	320	$\frac{1}{4}$	$\frac{1}{2}$	1	2	4
$\frac{\text{miles}}{\text{hour}}$	$\frac{\text{km}}{\text{hour}}$					

Aircraft speed

For commercial airliner flying at 750 $\frac{\text{km}}{\text{hour}}$ and 10,000 m elevation (or 500 $\frac{\text{miles}}{\text{hour}}$ and 35,000 feet elevation), time interval is 7 sec.

Figure 2: Time interval between photos for making stereoscopic pairs with the camera pointed for 45° oblique photography.

PHOTOGRAPHY FROM BALLOONS

Archaeologists have been taking photographs from balloons since the late nineteenth century. Early photographs were taken of the Roman Forum (Adamesteanu, 1964) and Stonehenge (Capper, 1907). Even before these, in 1852, John Wise made a drawing from his balloon of surface patterns which marked an Indian encampment (Newhall, 1969, p. 68). However, the balloon appears to have been first used for the serious work of photographing excavations in 1929 (Guy, 1932).

The principal advantage of a balloon is that, in calm weather, very steady and well-controlled photographs are possible at low altitudes. Since the size and cost of a balloon increase with its payload, it is desirable to fly a small balloon with only enough lift for a camera. This will require remote control operation for triggering the camera's shutter and a tetherline to lower and position the balloon.

The most commonly used lifting gases for balloon photography have been hydrogen or hot air. Helium is not flammable, but compared to the same volume of hydrogen it has 7% less lift and costs about three times as much. The inflation of a balloon 2.5 m in diameter requires eight cubic meters of helium costing about $90. While helium is plentiful in the United States, it is difficult to obtain in other countries. Fortunately, a hydrogen-filled balloon can be designed to resist static electricity and flames which might ignite hydrogen, and thus can be operated fairly safely.

The big disadvantage of hydrogen ballooning is its requirement of heavy tanks of the compressed gas. In comparison, a hot air balloon must have over twice the volume for the same lift, and the air is commonly heated with propane, a liquified gas used worldwide in cooking stoves. Hot air balloons can be tethered in winds of over 20 km/hour (Godfrey, 1970), but they are more difficult to operate under these conditions than a hydrogen-filled balloon. This is because of the greater mass and wind drag of the hot air balloon. Also, the wind cools the heated air causing the balloon to lose lift. Yet, the low operating expense of hot air balloons is a big advantage and they have been used to support both man carrying (Whittlesey, 1971) and unmanned platforms (Whittlesey, 1973a).

Kite balloons get part of their lift from a light gas and part from aerodynamic lift (Silbert, 1969). These balloons have the advantage of being lifted by a breeze, unlike a spherical balloon which will be driven toward the ground in a wind.

Several federal regulations apply to both tethered balloons and kites flown in the United States (Office of the Federal Register, 1973). These common sense rules warn airplanes and helicopters of the presence of a kite, balloon or tether line. At night or when the visibility is low, they should not be flown. The air traffic controller of a nearby airport should be notified if the balloon or kite is to be flown higher than 50 m. Pennants are required along the tether line at 15 m intervals.

While it may be possible at times to loft a small, untethered hot air balloon, most unmanned balloons will require a tether line. If the air is calm, the tether line will appear in the photo. However, if the wind is strong, the balloon will be at a low angle to the ground at the end of its tether. (See Appendix 5 for additional information on balloons and wind.) In a light breeze, a balloon can be held stationary at the apex of three tether lines forming a pyramid (Ross, 1969). The angle of the lines must be low enough so that all three are kept in tension.

A hot air balloon can be deflated immediately after each flight; a hydrogen balloon intended for use for more than a day requires a sheltered

mooring to protect the balloon and its valuable gas from possible over-night wind gusts.

If a vertical photo is desired, a gimbal can be constructed with the camera's weight slightly below the pivot point (Whittlesey, 1970). A simple hanging bar with universal joints will also hold the camera and frame vertical if the breeze isn't strong (Walton, 1969). If a strong wind is blowing, camera tilt due to wind pressure can be minimized by suspending the camera in a cylinder, like a clapper in a bell (Whitmore and Thompson, 1966, p. 9).

In calm air, exposure times as long as 1/60 second are possible; if the camera is high, it can be watched through a telescope and triggered when not swinging. A wide variety of camera triggering techniques have been tried. Radio control works at great distances, but interference from other transmitters is possible. Electric solenoids are rugged, but their triggering cables are heavy. Pneumatic releases are reliable but limited to a distance of about 50 m. Electric timers or fuses are simple but allow little control of camera triggering. The camera should be fixed to signal that it has taken a picture; a flash of light (Sonu, 1969, p. 95) or a released piece of paper (Guy, 1932) are possibilities.

PHOTOGRAPHY FROM KITES

A kite can provide the least expensive way of taking aerial photos from altitudes in the range 10 m to 200 m. A breeze blowing faster than about 15 kilometers per hour is usually necessary. This will usually rule out photographing through water because of the wind ripples; also, if the wind is too strong, dust from an excavation can partly obscure the ground. With a kite the only continuing expense is for film.

Archaeological photography from kites was suggested over thirty years ago (Bascom, 1941), but application has been more recent (Kramer, 1967, p. 28). Many types of kites which have been built for sport flying can be put to work lifting one to three kilograms of equipment by increasing their size or stringing several in tandem on a single line (Rotch, 1900; Woglom, 1896). It is important that a kite be easy to dismantle for transport: several recently designed types are particularly suitable. These include the Parawing, Parachute Kite, and Parafoil (Newman and Newman, 1974, p. 190). The Parafoil is like a series of wind socks sewn together on their sides; the pressure of the wind inflates these tubes into a wing-shape with high lift. Since it does not have rigid supports, it packs very compactly. It is available from Jalbert Aerology Laboratory, Inc., 170 N.W. 20th St., Boca Raton, Florida 33432.

Most small cameras are suitable for photography from kites except the box cameras with slow shutter speeds which may result in blurred pictures. If many photos are to be taken, time can be saved with a camera which has an electric or spring motor to advance the film after each exposure. While electric motor drives are available for many 35 mm cameras, spring driven cameras of the several models that have been produced over the years, are

now found primarily through second hand camera dealers. One type which is available now is the Robot, manufactured in Germany. In the United States it is available from Karl Heitz, Inc., 979 Third Avenue, New York 10022.

Once the camera is lofted, it must be triggered to take a photo at the desired time. One of the earliest and simplest techniques employed a fuse which burned a piece of string and caused a rubber band to trip the shutter (Hunt, 1971, p. 72). A string connected to the camera release, however, will be simpler for low altitudes and will allow better control. Pneumatic releases force air through a hollow tube to trigger the camera: the model made by Rowi can be operated from a distance of up to 25 m. The camera shutter can also be triggered by an electrical solenoid which uses a magnetically-driven piston to push the release button (Mangieri, 1970). The ones commonly available allow only a single picture to be taken; they must then be mechanically reset. These two are the Schiansky Teleknips 601 available in the United States from Edmund Scientific Co., Barrington, New Jersey 08007 and the Electro-Gitzo which is available from Karl Heitz, Inc. For distances less than 100 m, an expensive radio control system is available - The Kenlock R-300 Camecon manufactured by the Yokosho Co. It is sold by camera stores in the United States and through the Edmund Scientific Co. Also, a more powerful remote control for cameras and one which is less susceptible to radio interference is manufactured by Jacobson Photographic Instruments, 862 North Vine Street, Hollywood, California 90038.

When kite photography got its start in the last century, the cameras were suspended next to the kite. Later, the cameras were placed a distance down the tether cord so that the kite could stay in the higher and steadier wind while the camera was lowered to the ground. The distance between kite and camera can be from 10 m to 50 m or even more.

If the wind slows suddenly, the camera can sometimes be kept airborne by pulling in the line or running with it upwind; both techniques effectively increase the "wind speed". However, in case of failure, a light but strong frame around the camera will protect it from damage. Figure 3 shows a frame of three rectangular sheets of aluminum, each about 10 x 30 cm, which form a triangle held together with thumb screws and wing nuts for easy assembly. When mounted inside it, the camera's lens is protected from dirt and scratches.

Figure 3 also illustrates a suspension system which keeps the camera aligned with the kite line at the same time allowing it to hang nearly vertical. A camera suspended with a single cord may spin and cause the photos to be blurred. A fin or small parachute connected to the camera will hold it stationary relative to the wind (Purves, 1971), yet a gust of wind may still cause the camera to twist rapidly. However, the angular motion of the main kite line is minimal because it acts like a long lever and the camera aligned with it will be relatively stable. The suspension device consists of two aluminum poles, each about 0.75 m long, connected with cords to form a tetrahedron.

Several hundred meters of strong cord for the tetherline are necessary for photos to be taken from a 100 m altitude. Because of the high tension which may occur, with a thin cord gloves are a must. Many types of cord are available; solid braided nylon line (such as no.3) is strong enough for a 100 kilogram load. Figure 4 shows one type of portable spool for the line: a hand grip and arm strap ease the work of holding a line under high tension.

Since it isn't practical or necessary to be holding the kite line all the time, a ground anchor is convenient. J.N. Rinker has used a metal rod bent into a helical shape for an anchor; this half meter long "corkscrew" is sold in pet shops as a tie point for chaining dogs. For hard-packed soil,

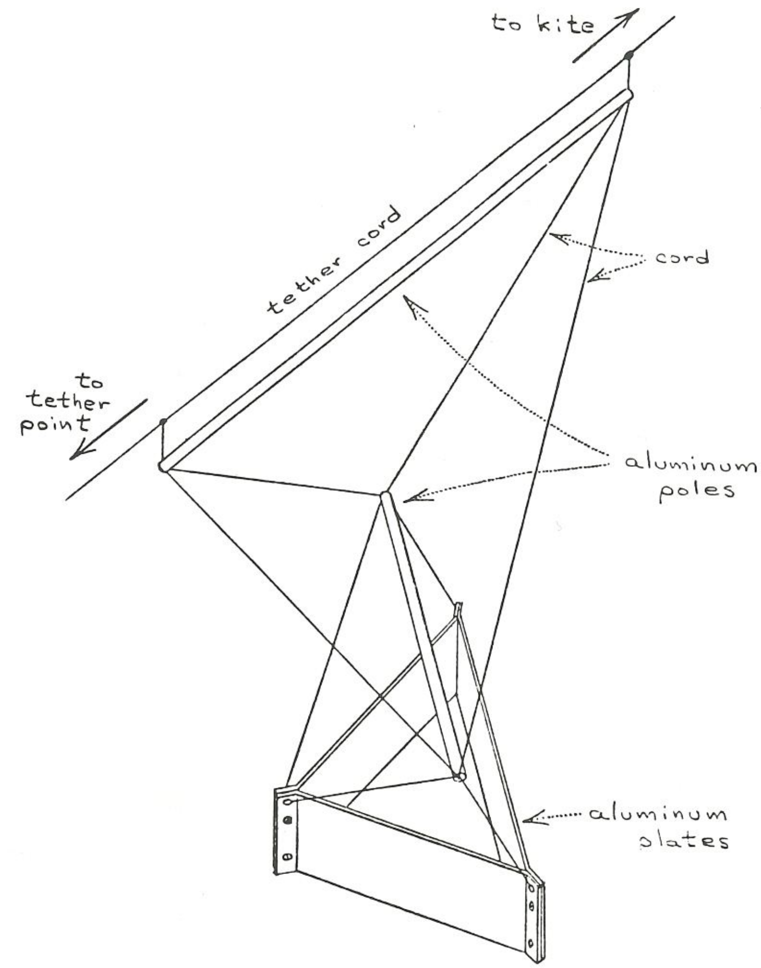


Figure 3: Camera suspension for a kite

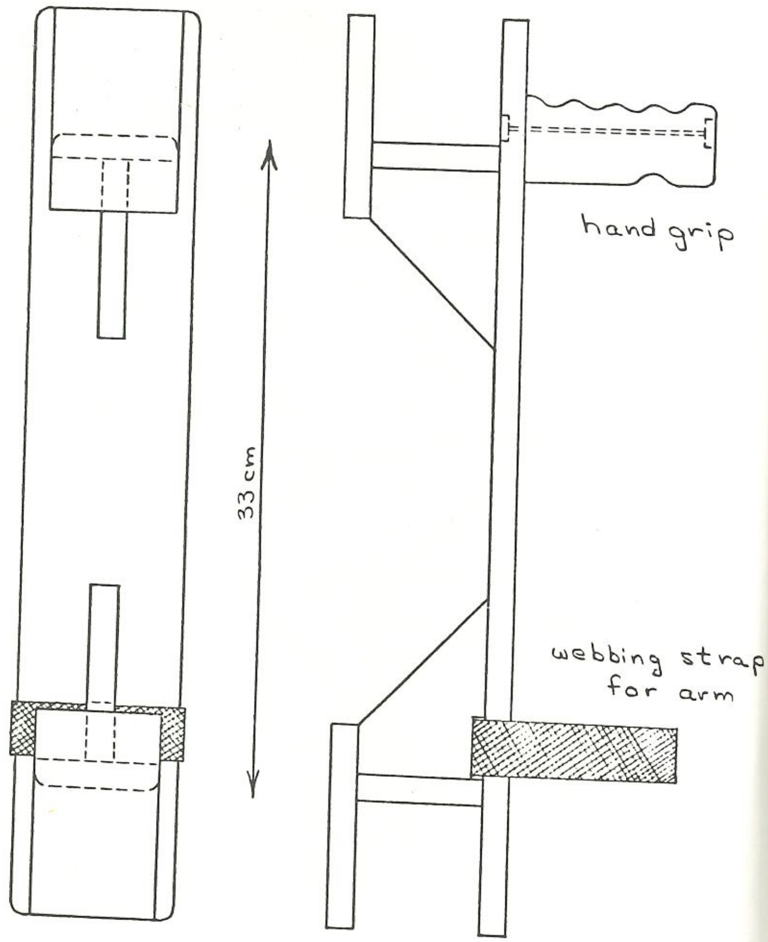


Figure 4: Arm spool for tether line

a smaller version is called for, such as the mountaineering ice piton. Ordinary wood stakes are too easily pulled out when the angle of the tether line to the ground is nearly vertical.

When it is necessary to lower the camera to the ground, the amount of work can be minimized: with the base of the line fastened to the ground, walk downwind along the kite line, pulling it down hand over hand. A special pulley, known as a snatch pulley, can be fixed onto the line at any point and further simplify this task. If the line is short it can be pulled down directly and coiled on a spool; since each turn adds pressure to the spool, this should not be done if the cord tension is high since the spool may eventually be crushed. The storage of cord under tension may also damage it. Power winches are available; they can be used either to pull a kite down or to lift a kite in a calm by putting tension on the slackening tether.

The tension of the kite cord and its angle with the ground determine the weight which can be lifted. Appendix 5 analyzes the aerodynamics involved. Changes in line tension can be detected with a spring scale. Another technique is to pluck the line and time the echo of the return pulse from the kite end of the line. The cord tension is proportional to the square of the ratio of the length of the line to the echo delay time (Richards and others, 1960, p. 241).

Since the kite will be at an oblique angle of around 45°, the person controlling the tether line may not be able to accurately judge the position of the camera. However, another person directly under the camera can direct him with arm signals.

PHOTOGRAPHY FROM HIGH CAMERA STANDS

A variety of camera platforms have been developed for the photography of archaeological excavations from heights of between 2 m and 11 m. A single pole is the simplest support, although a tall pole may require guy lines both to raise it and hold it steady. Both a 5 m pole (Schwarz, 1964) and an 11 m pole (Wiltshire, 1967) have been used in making oblique photographs. Camera stands in the form of an inverted V, or bipods, may also require guy lines unless the footing of each pole is broad enough to prevent the wind from toppling the stand. Two different types, one 6 m high (McFadgen, 1971) and the other 11 m high (Whittlesey, 1966b) have been used for vertical and stereoscopic photography. High tripods can be improvised with a ladder and two poles; they should be strong enough to allow the camera operator to climb the ladder and frame the scene in the camera's viewfinder. A square-based pyramidal platform is very rigid (Conlon, 1973, p. 68; Cooke, 1967).

Because of the small construction expense, these camera stands may be left at the site to record the progress of excavation during the season. With the more elaborate camera supports, careful alignment or timing is necessary to keep its shadow out of the picture. Also, a heavy, complex support requires more people for moving it around the excavation.

PHOTOGRAPHY FROM COMMERCIAL AIRLINERS

Commercial airliners sometimes fly above 30,000 feet (10 km). With luck, a scheduled flight might pass near an interesting region and a photograph of a large area can be made. This may be a valuable illustration of the terrain around an archaeological site.

A window seat ahead of the engines is desirable so that exhaust turbulence will not blur the pictures (Mason, 1970, p. 1). Knowing the flight direction and time of day will enable one to select the shady side of the plane so that there will be no light reflections from the window (Wood, 1968, p. 61). Single lens reflex cameras simplify the framing of the photos; other cameras need careful aiming so that the window frame does not block part of the picture.

The greatest problem of high altitude photography is haze which causes low contrast; the brightness contrast can be as low as one twentieth of that on the ground (Brock, 1967, p. 172). Therefore, if standard black and white films are normally processed, very flat pictures will result. High contrast developing or printing will help, and sometimes even Kodak High Contrast Copy Film can be valuable for some pictures. A yellow filter will block the bluish haze light and increase contrast. Black and white infrared film yields high contrast photos because of two factors: the infrared radiation penetrates the haze better than visible light and the contrast of the terrain is greater, particularly between water and vegetation (Specht, 1970).

Color film, naturally of high contrast, is excellent for this type of photography if the atmosphere is fairly clear. One type of film, Kodak Photomicrography Color Film 2483, accentuates color contrasts (Kodak, 1973b); it is a high resolution but slow speed film and thus should be used only in bright sunlight. With color film, the bluishness of the haze can be reduced with pale yellow filters. With medium haze, a Wratten 2A filter is suitable; with heavy haze a Wratten 2E filter may be used, but it might also cause the pictures to be too yellowish (Smith, 1968, p. 190). No exposure correction is needed with these filters. They are available in gelatin squares which may be held by their edge in front of the camera; special filter frames will help protect the gelatin from scratches.

Color infrared film is particularly suitable for high altitude photography, for it yields a high color contrast between vegetation, soil and water. It is a false color film because the colors in the transparency are different from what the eye saw: infrared-reflecting objects (primarily vegetation) show as red; red objects show as green; green objects show as blue unless they are also infrared reflecting (Fritz, 1967). Since these constitute the three primary colors, visibly blue objects will not show in the transparency and a blue absorbing filter, Wratten #12, is used.

The infrared sensitivity of Kodak Ektachrome Infrared Film has been deliberately manufactured to be about half its sensitivity to red and green light (Fritz, 1973). While this is optimal for typical low altitude and ground level photography, high altitude photos will have a strong blue-green cast unless the sensitivities are balanced (Pease and Bowden, 1969). Figure 5 indicates how this can be done with a sandwich of three filters: Wratten #12, Wratten #80B, and color compensating filter CC40M, all available from Kodak. Filters 80B and CC40M should not be added for low altitude photography with this film (Tschantz, 1972, p. 114). With these three filters the exposure index of Kodak Ektachrome Infrared Film drops to about 18, requiring a midday exposure of around f/2.8 at 1/200 second. If the exposure reading is taken through the filter pack with a cadmium sulfide meter, it should be set at an exposure index of about 160 (Malan, 1974). It is important that gelatin

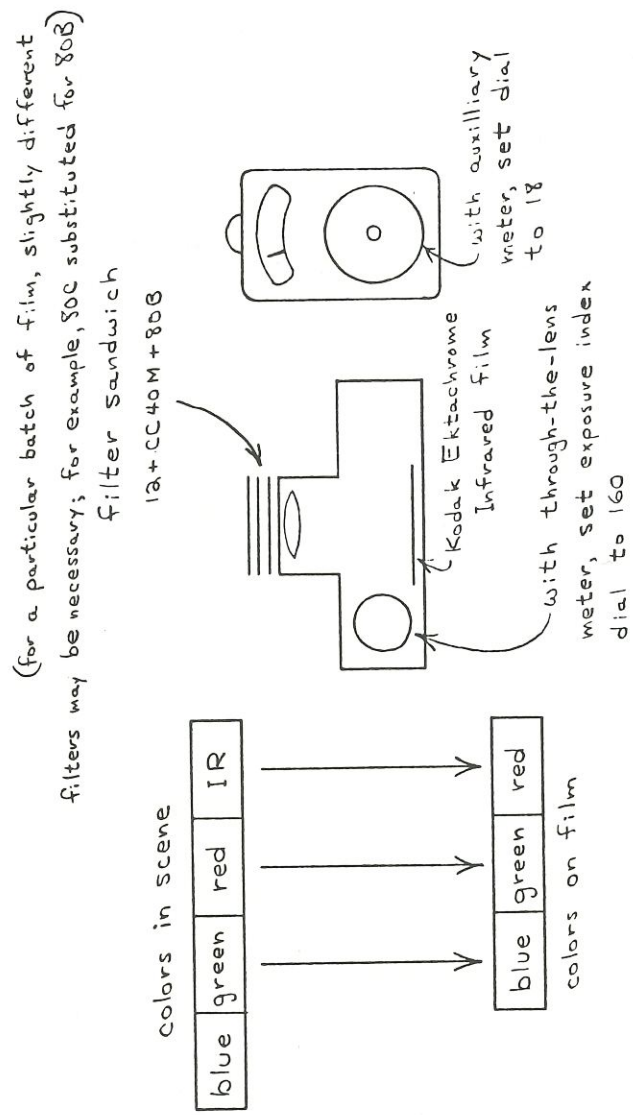


Figure 5: Filters for color infrared film and high altitude photography

filters be used with this film because some glass filters absorb infrared radiation (Pease, 1970). Since the color sensitivity of this type of film changes when it is stored in a warm place, for critical use it is important to buy film which has been kept refrigerated and to keep it refrigerated until it is about to be used. If color balancing and exposure tests are made with one roll from a batch, the rest of the batch is likely to yield good results.

PHOTOGRAPHS FROM SPACECRAFT

Manned and unmanned spacecraft have already furnished thousands of photographs of the earth. The ground area of each photograph is commonly about 200 km square and objects as small as 100 m in diameter can sometimes be detected. This scale and resolution allows the mapping of surface topography and the distribution of vegetation over wide areas. This photography is particularly valuable for those areas for which maps are nonexistent or not up to date.

The first high quality photographs were taken during the manned space flights, Gemini and Apollo, which covered the time span 1965 to 1969. Their ground resolution is good, varying from about 50m to 125 m (Colvocoresses, 1972). However, most do not reach farther than 35° north or south of the equator because of the orbital path of the spacecraft.

Catalogs which list the photographs taken during these space programs are available from the Technology Application Center, University of New Mexico, Albuquerque, New Mexico 87106. They locate and describe the geographical area of each photo, the image quality, and whether the photo is vertical or oblique. The Center also sells color slides and prints and black and white prints.

Many of the best photographs from the Gemini and Apollo flights have been published (Cortright, 1968; Nicks, 1970; Gill, 1968; Gill, 1967). Additionally, detailed analyses of some are available (Bodechtel and Gierloff-Emden, 1974; Hamilton, 1971; Reeves, 1974; Lowman, 1968; Lowman, 1972).

Photographs taken from the Skylab manned space station have a resolution of 20 m to 100 m (Colvocoresses, 1972). These pictures and their descriptive catalogs are also available from the Technology Application Center.

Presently, the greatest quantity of high quality photos are from the first Earth Resources Technology Satellite, ERTS-1, now called LANDSAT-1 (Goddard Space Flight Center, 1971; Darden, 1974). This unmanned satellite is in a nearly polar orbit and has essentially photographed the entire earth. The ground area shown in each photograph is 100 nautical miles square (185 km), that is 1°40" of latitude. The satellite photographs a given area once every 18 days; this is valuable for observing the patterns of change in vegetation. Each picture is taken at about 9:30 A.M. to 10:00 A.M. local time, so that moderately long shadows will accentuate the topography.

The resolution of ERTS photos is about 250 m but some low contrast objects as small as about 150 m are detectable; in addition, linear features as narrow as 15 m may be discerned (Welch, 1972). In practice, roads 11 m wide and ponds 100 m in diameter have been detected (Klass, 1972). The pyramid of Cheops may be one of the few archaeological structures visible in ERTS photos (Lowman, 1966); while its contrast with the surrounding terrain is quite low, at the winter solstice its shadow should be about 260 m long at 10:00 A.M.

ERTS photos of any area may be purchased from the EROS Data Center, Sioux Falls, South Dakota 57198. Enlargements are available at three scales, 1:1,000,000, 1:500,000 and 1:250,000. The 1:500,000 scale is a good compromise, for the scan lines of the TV-like photo which has been telemetered to earth are a limiting factor with the 1:250,000 scale, while some detail is lost in printing the 1:1,000,000 photos. The 1:500,000 scale photo is about 15 inch (38 cm) to a side; a black-and-white print costs $5.00

If a photo of an area smaller than 50 km square is desired, probably it will be included in a single frame. Then, it is easiest to call the EROS Data Center at 605/594-6511; a quick search for the photo will be made with

a computerized index. It is best to specify the region of interest by geographic coordinates.

If a set of photos of an area larger than 50 km square is desired, it is better to send a written request to the Center. The geographic coordinates of a polygon of any size and shape with up to eight corners may be used to delimit the region. The EROS Data Center will reply with a computer print-out (at no charge) which lists all the photos available for the area. Among other things, this listing will indicate the photo identification numbers, the dates of photography, the percentage of the scene which is obscured by clouds and the geographic coordinates of the center and four corners of each photo. While complete catalogs of all ERTS photos are available from the U.S. Government Printing Office in Washington, it takes time to search through them for a specific photo.

ERTS-1 takes four black-and-white photographs of each scene; differently colored filters select parts of the visible and infrared spectrum. These are: green (called Band 4), red (Band 5), partly red and infrared (Band 6), and infrared (Band 7). If a single, general purpose photo is desired, the red photo (Band 5) is the best. However, for specific applications, one of the others may be better. For example, the green band shows the best detail of water depth and clarity, the infrared band the greatest contrast of shorelines, the red band and the combination red and infrared band the most detailed information on topography, roads, towns, and vegetation. An additional advantage of the infrared Band 7 is that visibility through haze and light clouds is enhanced (Colvocoresses, 1973).

Three of the four photos mentioned above can be combined into a color photo. Since the blue part of the spectrum is missing, the photos will not have natural color; the blue light is mainly a result of the atmosphere, therefore its rejection actually makes the photos clearer. The EROS Data Center has these color photos available for only several hundred selected areas of the thousands which have been taken in black and white. They cost $15 for the 1:500,000 scale. More expensive, but customized color prints are also available from General Electric Photographic Engineering Laboratory, 5030 Herzel Place, Beltsville, Maryland 20705.

Color photos are usually printed so that objects which are primarily green (such as oceans) appear blue. Red objects are relatively rare; they print green. Objects which reflect the sun's infrared radiation print red; healthy vegetation, while visually green, is much brighter in the infrared spectrum and shows as red. The color changes are summarized in Figure 6.

For archaeology, ERTS photos are valuable as up-to-date maps suitable for regional studies. As illustrations, their topographic and land-use information complement the political information available on conventional maps. Detailed interpretation of these photos requires ground level familiarity with at least part of the terrain; this knowledge can then be extrapolated to the unknown regions by the recognition criteria listed in the section on photo interpretation. There are now many reports of ERTS photo analyses (Freden and others, 1973; Finch, 1973; Freden and others, 1974); while they are primarily concerned with topics such as geology, geography, oceanography, urban studies, and agriculture, the analyses can be related to archaeology.

Object	"False" color of satellite photograph
cities	blue-grey
healthy vegetation	bright to deep red
thin or drying vegetation	pink, tan
clear water	dark blue to black
muddy water	light blue
bare rock and soil	white, grey, bluish, black
snow	white
clouds	white with black shadows

Figure 6: Color correlations in ERTS photos

(MSS bands 4, 5, and 7)

SOURCES OF AERIAL PHOTOGRAPHS

Many governmental agencies and commercial firms have large collections of aerial photos. Individual copies can be purchased from them for much less expense than a special photo-flight would cost.

Most of the photos have been taken with cameras whose image area is nine inches (23 cm) square. The photos are commonly sold as contact prints; their resolution is very high, and they can be studied with a 2x or 4x magnifying lens without the graininess of the film showing. Most are black and white, taken with panchromatic film; a yellow filter had usually been used to increase contrast in the presence of bluish haze. In general, these types of black and white photos are the most useful ones for archaeology.

Most commercial photographs have been taken primarily for topographic mapping. In order to map the land surface rather than the tops of trees, the flights are usually undertaken in early spring and late fall. Unfortunately, these are the wrong times to try to see anomalous patterns in vegetation for clues to surface and buried archaeological remains. Yet, soil patterns are detectable on photos taken in spring and fall. Also, earthworks and building foundations under deciduous trees can only be seen then (Reeves, 1936).

Photographic scales in the range of 1:15,000 to 1:20,000 are suitable for the initial reconnaissance of a large area for features as small as 5 m in diameter (Harp, 1968; Strandberg, 1967b); for reliable and detailed interpretation, photo scales ranging from 1:7,500 to 1:10,000 are more suitable. While much of the aerial photography from governmental agencies in the United States is at the 1:20,000 scale, some photographs at smaller scales are available.

In the United States, several government agencies have separate collections of aerial photos, often differing in the areas covered. Two index

maps, Status of Aerial Photography and Status of Aerial Mosaics, indicate which agency has the photos for a given area. These two maps are available free from the Map Information Office, U.S. Geological Survey, Washington, D.C. 20242

Sources and procedures for locating and ordering aerial photos have been outlined for the following areas: USA (Avery, 1968, p. 100); Canada (Avery, 1968, p. 104); British Isles (Coles, 1972, p. 28; Stewart, 1973); and the world in general (Colwell, 1960a).

Commercial firms which engage in aerial photography will usually sell copies of their films. The "Aerial Surveys" section of a telephone directory will help locate these firms.

INTERPRETATION OF PHOTOGRAPHS

A person who tries to interpret patterns which appear on aerial photographs for clues to buried or submerged traces of civilization may encounter many false leads. Some of these are quite natural, the result of geological processes and the actions of wild animals. In the last century, many new patterns have been generated by man; since their cause can be at or near the surface, they can be the most distinct ones.

There are a number of criteria which form the basis for clues of archaeological remains. These are: size, shape, orientation, location, color, texture, contrast, and time of appearance. It is only the accumulated knowledge of the archaeology of an area which allows an interpreter to evaluate each of the parameters. In addition, the history, geology, and current usage of the land furnish information necessary to dismiss the false leads. Interpretation is based on extrapolation of the known. It is only by the definite identification of a pattern, usually by examination on the ground, that other similar patterns can be tentatively identified.

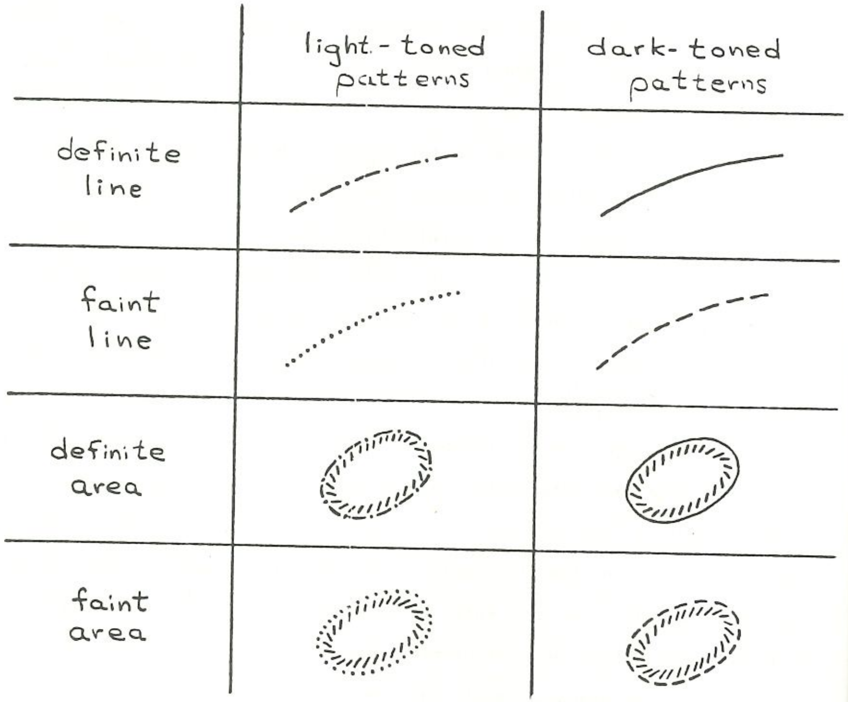
There are several general works which review the archaeological interpretation of aerial photos: Deuel, 1969; Goguey, 1968; Solecki and others, 1960; Bradford, 1957. A number of other references contain detailed descriptions of photo interpretation in specific geographical regions: England (St. Joseph, 1945; Margary, 1967), France (Agache, 1971; Chevallier and others, 1969), Ireland (Norman and St. Joseph, 1969), Iran (Schmidt, 1940), the American Arctic (Harp, 1969), the Mississippi River Basin (Strandberg, 1965), Peru (Kosok, 1965), Latin America (Denevan, 1970), and Mexico (Armillas, 1971; Gummerman and Neely, 1972; Siemens and Puleston, 1972). A much more complete bibliography is given by Schorr (1974).

Most commercially available photographs have been taken from an airplane flown in a straight line with its camera pointed straight down. The series of photos which result form a strip with each photo overlapping the next by about 60%. The common area between each pair of photos can be viewed stereoscopically (Ray, 1960). Three-dimensional viewing has two advantages: subtle slopes which are impossible to see in a single photo can be detected and the misleading markings due to film imperfections can be discovered. The only equipment that is necessary for stereo viewing is an inexpensive lens stereoscope, which is simply a pair of magnifying lenses, one in front of each eye.

The eye discerns linear patterns easily, sometimes even apparently nonexistent ones (Lowell, 1908). Faint, broken lines are sometimes more easily detectable by viewing a photo at a low angle to its surface (Tator and others, 1960, p. 258; Hunter, 1970).

A revealing overview of a number of patterns in soil or vegetation which appear on aerial photos taken at different times is provided by transferring their shapes to a line drawing. It is important to distinguish dark from light tones and thin lines from areas. The symbols in Figure 7 suggest some ways of doing this. The grey tones in a black-and-white infrared photo may be opposite from those in a panchromatic black-and-white photo, this must be allowed for in the drawing. Also, in some cases the tone of the markings can become reversed during the growing season of the vegetation.

Tonal contrasts in photographs may be emphasized for interpretation or printing. Some of the processes which are possible with simple photographic darkroom techniques will be discussed first; next, the more involved procedures of processing by computer will be outlined. These methods are not magic; they cannot increase the information contained in the original photos. They should be secondary to attempts at improving the original imaging equipment.



Shading indicates extension of tone marked by the boundary

Figure 7: Symbols for the interpretation of photographs

High contrast film and paper, commonly employed in the graphic arts, constitute the bases for one darkroom technique (Lundqvist, 1972). A recently introduced copy film is sensitive to a very small range of density in the original transparency or print. The film, Agfacontour, has been developed by Agfa-Gevaert for its application to isodensity mapping (Ranz and Schneider, 1971). Unlike standard high contrast processing which converts all grey tones to either black or white, this film converts a narrow and controllable band of middle tones to black and the rest to white (Nielsen, 1972; Nadji and others, 1973). A similar result is possible with conventional film by employing the Sabattier effect (Lau and Krug, 1968).

With many photographs, the density range over a large area is great while in a small area of the photo the contrast may be too low for easy interpretation or publication. Film sandwiches comprising a pair of films, one a positive, the other a negative, may correct this problem. From the original negative, a positive transparency is made by contact printing. If the positive and negative films were sandwiched together in perfect alignment and both had the same contrast, a resultant print would show only a uniform grey tone. However, deliberate misalignment of the pair of films accentuates small scale changes in density while minimizing differences between large areas. If the films in the pair are moved slightly sideways out of register, the print will have the appearance of a bas-relief (Weller, 1970; Honigsfeld, 1973; Dellwig and others, 1970). A small space is put between the films in a technique called "unsharp masking"; it is used for contrast control in the printing of color photographs (Yule, 1967, p. 74). The vertical spacing between the positive and negative may amount to only about one quarter of a millimeter; this causes one of the components to be slightly out of focus when the contact print is made using a diffuse light source (Langford, 1972, p. 211). Contrasts of the fine detail of the photo are enhanced as in the sideways shifting technique, but there is no dependence on shift direction. There are other variations of this basic technique: the positive transparency of the pair may be both diffused and at a lower density (Gibson, 1968, p. 332); one transparency may be slightly diffused so that spacing is not necessary, or a positive of one photo may be paired with the negative of another for a resulting print which shows the difference of their densities (Silvestro, 1969). These techniques are summarized in Figure 8.

A result similar to unsharp masking is possible with a machine called the LogEtronic printer; the exposure in each part of the printed photo is controlled by the scanning light spot of a cathode ray tube (Craig, 1955).

With fast modern computers, photographs can be transformed and compared by almost any method the mind can conceive of. The literature in this field is so voluminous and technical that only three general review publications are listed here (Rosenfeld, 1969; McGillem, 1973; Simonett, 1974). A higher order of picture processing makes possible the automatic recognition of some patterns in some photographs. Once again, there are many books on this subject and only one recent overview is listed here (Duda and Hart, 1973).

Techniques using digital computers require that each point in the pictures be converted into a numerical value indicating its density; it is also possible to effect elaborate transformations on photos by purely optical means, truly optical computing (Shulman, 1970; Goodman, 1968; Pincus and Dobrin, 1966). One application of this technique is that given the size, shape, and orientation of a pattern, a complex photo can be instantly searched for the location of a match to the given pattern (Vanderlugt and others, 1965).

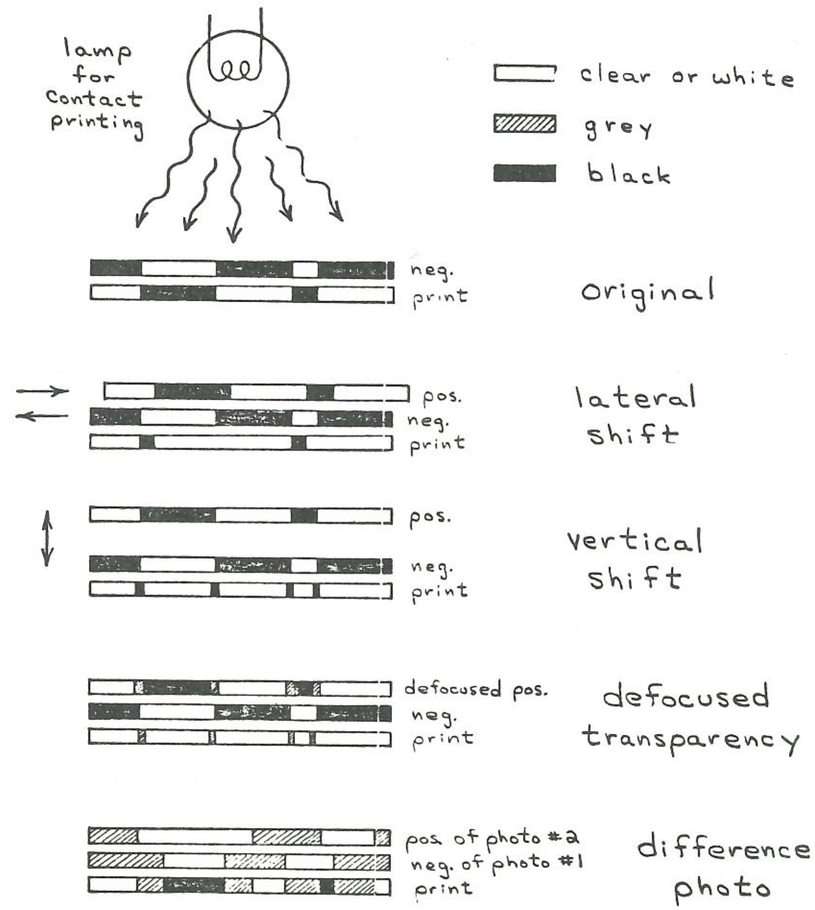


Figure 8: Special techniques for printing photographs

Photogrammetry is the technique of making geometrical measurements and also maps from photographs; today, almost all primary maps are created from photographs.

The basic procedure for archaeological photogrammetry have been outlined by Whittlesey (1966a) and Yacoumelos (1972). A more general introduction to photogrammetry is given by Thompson (1966) and Wolf (1974).

Two different types of maps result from photogrammetry. Planimetric maps have had the distortion of the photographic perspective removed; thus horizontal distances and angles are accurate for a small area on the globe. Road maps furnished by gasoline stations are typical examples of planimetric maps. Topographic maps show relief of the terrain by contour lines, that is, lines which connect points of equal elevation. The quadrangle maps of the U.S. Geological Survey are such maps. Topographic maps, with their detailed information on heights and slopes, are much more difficult and expensive to prepare than planimetric maps. Also, topographic maps are poor for illustrating an abrupt change in height such as an excavated wall. For these reasons, archaeological reports contain mainly planimetric maps.

Can vertical photos be traced directly to make planimetric maps? This will depend on how level the ground is and on how much accuracy is desired. Perfectly level ground will furnish an accurate map limited only by the distortions of the camera (Karara and Abdel-Aziz, 1970). Undulating ground will not allow for as precise a map; here the error may be as much as the ratio of local ground relief to the height of the camera. If the relief is 0.5 m and the area is photographed from a height of 10 m, an error of 5% is possible; if the radius of the photographed area is 10 m, the error may be 50 cm. However, small areas within vertical photographs taken from high altitudes can be fairly accurate maps. With the aid of shadows it is also possible to estimate the height of some abrupt features on a single photograph (Parry, 1972).

Most commercial maps are constructed from vertical stereo photos. If the area to be mapped is included in a pair of photographs taken from two positions separated by a horizontal distance, accurate measurement of relative height between any pair of points is possible.

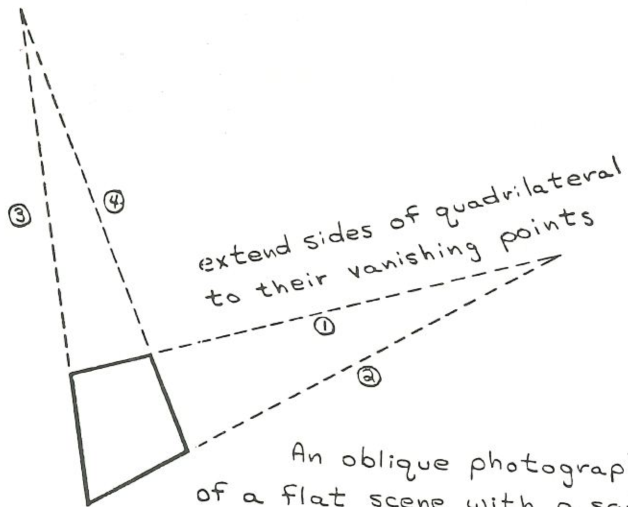
With moderately flat ground, even oblique photos can be converted into planimetric maps. Some specific lengths and angles can be determined mathematically (Janke, 1972), and the skew of the photograph can be rectified graphically (Williams, 1969; Baker, 1972; Zeller, 1952, p. 229) if optical techniques will not work (Hallert, 1960, p. 111). Graphical rectification of oblique photographs is illustrated in Figure 9. The circled numbers indicate the construction sequence of the lines.

The preparation of topographic maps from photographs requires much more effort and equipment. The following companies supply a variety of the required photogrammetric equipment.

Forestry Suppliers, Inc.
Box 8397
205 West Rankin Street
Jackson, Mississippi 39204

The Ben Meadows Co.
Post Office Box 8377, Station F
Atlanta, Georgia 30306

Alan Gordon Enterprises, Inc.
5362 North Cahuenga Blvd.
North Hollywood, California 91601



An oblique photograph
of a flat scene with a square
figure in it has that square
skewed into a quadrilateral

Figure 9a

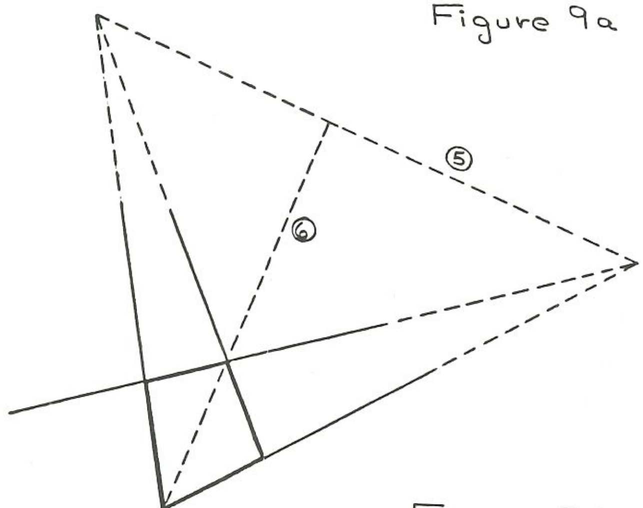


Figure 9b

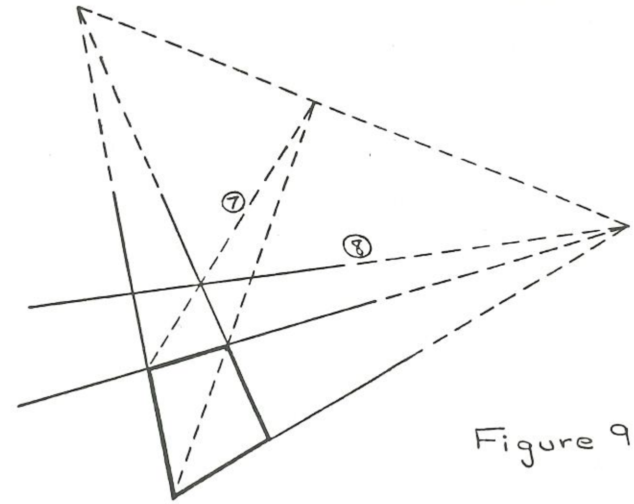


Figure 9c

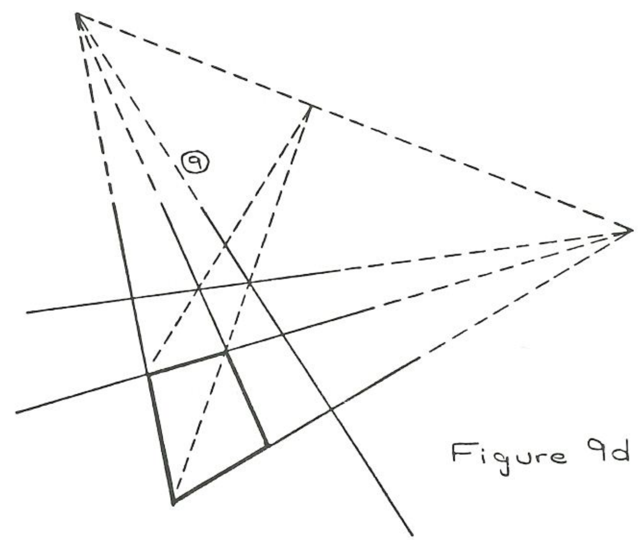


Figure 9d

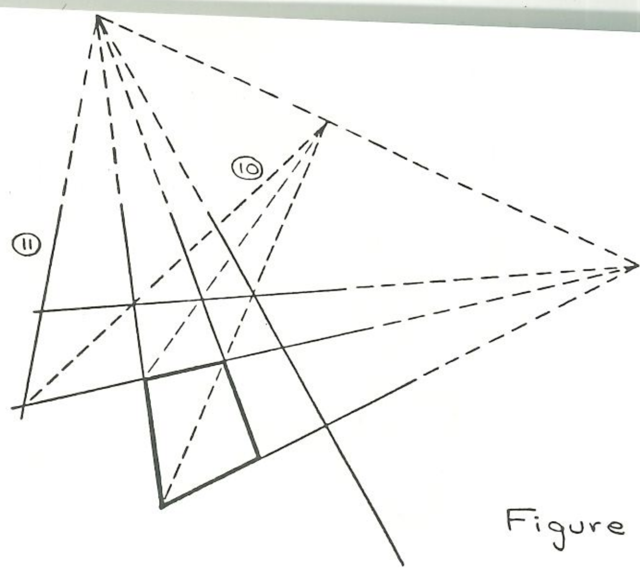


Figure 9e

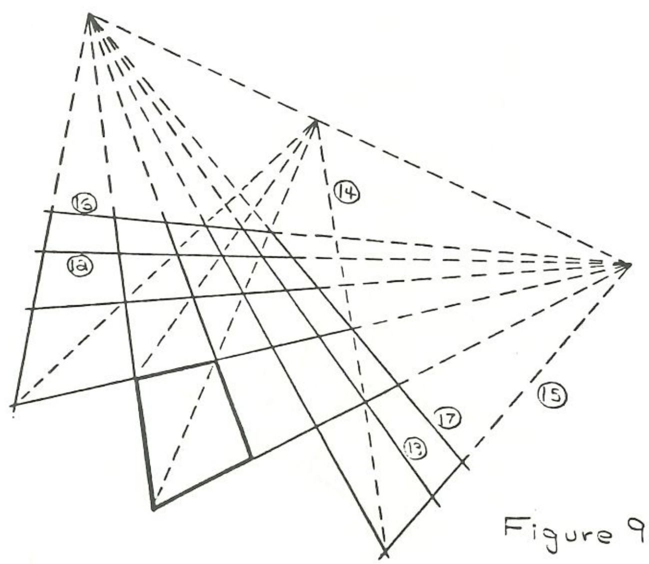
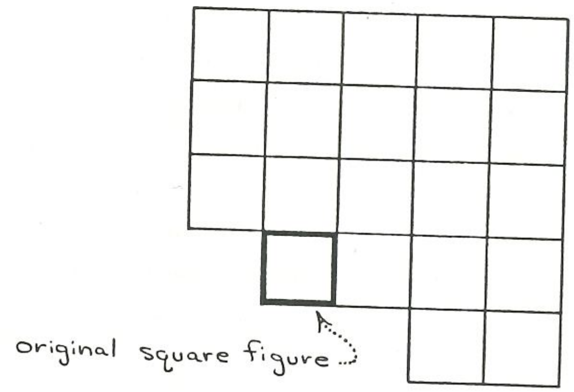


Figure 9f



The shapes and patterns in each quadrilateral can be transferred to this square grid to yield a map of the flat area in the oblique photo.

This procedure has only two requirements: the scene must be moderately flat, and an accurate square (or rectangular) figure must be placed within the scene.

Figure 9g: An example of the rectification of an oblique photo

NONPHOTOGRAPHIC IMAGERY

Remote sensing has a much wider scope than aerial photography, for it offers many ways of detecting distant objects and their patterns in addition to photography. For instance, remote sensing techniques are applied to the problem of locating, sometimes indirectly, large buried bodies of ore through aeromagnetic surveys (Dobrin, 1960, p. 321), electromagnetic methods (Parasnis, 1966, p. 294), and gamma-ray spectrometry (Adams and Gasparini, 1970). Because of the low angular resolution of these instruments, they appear to be unsuitable for airborne sensing in archaeology; they are, however, valuable for ground level surveys.

There are three imagery systems which have sufficient resolution from aircraft altitudes to be applicable to some archaeological problems. These are thermal infrared imagery, microwave radiometry, and radar. All three require much more equipment than does aerial photography and thus normally the imagery rather than the equipment is bought. All of the systems have unique advantages which are outlined below.

Thermal infrared imagery, or thermography, gives a direct indication of the combined effect of ground temperature and composition (Bastuscheck, 1970). At wavelengths longer than three micrometers, which is six times longer than the wavelength of green light, the radiation from objects is primarily self-emitted rather than just the reflection of the sun's energy (Holter and others, 1970, p. 128). This emitted radiation is simply radiant heat, which we observe every day and relate to temperature. It is less easily detected that the amount of heat given off also varies with the chemical composition and physical structure of the object; this effect makes the interpretation of thermography more complex.

The thermal infrared spectrum, also called the far infrared, will in

practice form no image on infrared film, which is sensitive only to the near or photographic infrared spectrum. Thus, a heat sensitive sensor is commonly employed to scan the two-dimensional scene; this is why the resultant images show a raster pattern similar to a TV screen. Aerial thermography has revealed soil patterns of prehistoric fields (Schaber and Gumerman, 1969). Also, these scanners have application in the laboratory for the examination of paintings (van Asperen de Boer, 1968).

Thermography can best be applied to archaeology for the detection of patterns in the moisture content of soil and its effect on plants growing in it. While growth marks in crops are only visible for a short period during each year, thermography may detect moisture contrasts after each rainfall. This capability is based on the fact that wet soil has a greater heat capacity than dry soil; therefore, in the evening when these surveys are often done, the moist soil may reveal a buried ditch because it will be detectably warmer (Sabatini and others, 1971, p. 76). This principle has helped locate springs in the desert (Wermund, 1971) and near-surface groundwater (Chase, 1969). The spatial resolution of thermography does not approach that of photography; it can be improved somewhat if temperature sensitivity is less important (Stingelin, 1969).

All warm objects give off radiation over a very broad spectrum. There is still detectable radiation at the long wavelengths which can be picked up by microwave radio receivers. These microwave radiometers can also scan an image in a similar way in which an infrared scanner does and yield a similar, but lower resolution image (Schanda, 1972). While this technique is unable to detect underground caverns (Hruby and Edgerton, 1971), it is valuable for detecting the near-surface moisture content of the soil (Poe and others, 1971).

Radar, in particular Side-Looking Airborne Radar (SLAR) can give a high contrast image of surface topography (Brown and Porcello, 1969). While currently available side-looking radars cannot penetrate foliage, they can "see" through most clouds (Viksne and others, 1970). The resolution of radar is typically about 12-15 m (Morain, 1974, p. 135), and therefore less than that of most photography. Abrupt changes in topography, even a clearing due to a village in a tropical rainforest, are easily detected.

APPENDIX 1 - THE DETECTION OF CROP MARKS

Soil Texture and Moisture and Plant Development

At one causal level, anomalous patterns in vegetation can result from inhomogeneity in the physical structure of the soil caused by human intervention (Strunk-Lichtenberg, 1965). A soil which is uniform in each of its horizontal layers does not produce irregular patterns of plant growth. Both man and nature can alter this uniformity. Wind and water may erode pockets and gulleys through the strata which later are refilled with soils of different texture or structure. Man digs pits and trenches, sometimes through a fertile and loose-textured topsoil into the subsoil. These may later be refilled by man or nature, but again the soil structure is changed, for the disturbed subsoil will probably be replaced with either a loose or a fine-textured soil richer in organic matter. When fertile topsoil is displaced by walls, roads, and building foundations and when these are later buried the vegetation will reflect the lack of a nourishing soil.

It is uncertain how long these physical alterations remain. The altered soil resulting from man's excavations may last indefinitely, although there is initially a fast rate of recompaction. Some of the marks detectable today were caused by man's excavations of several thousand years ago.

Plowing remixes the soil and gradually erases anomalous soil texture within its vertical zone (Richey, 1961). The detection of soil patterns underneath the plow zone is facilitated by plants whose roots extend through the plow zone. The extent to which roots penetrate into the soil is controlled primarily by soil texture, structure, and moisture; the extent of root development can affect drought resistance and the growth rate of vegetation. For instance, a fine-textured dry clay blocks the growth of roots, but a loose sandy loam will encourage their propagation both vertically and laterally (Weaver and Clements, 1929, p. 228).

An example of the dependence of plant growth on soil texture is the case of polygonal patterns caused by the casts of now-melted ice wedges in the soil of Sweden (Svensson, 1972). In this case, the finer soil texture of the polygonal casts retains soil moisture longer into the spring and the spring-sown cereals growing in such soil are dense and tall. The autumn-sown cereals and grasses do not show differential vegetation patterns.

While soils containing much clay may have a greater water content, plants may find it more difficult to utilize, for much of the water is adsorbed to the fine soil particles. Also, while a porous soil can have a greater total water content than a compact soil, during a moderate drought the compact soil may be left with a greater water supply (Hillel, 1972, p. 63). The addition of organic matter changes soil porosity and may also increase its moisture capacity (Buckman and Brady, 1969, p. 174). These dependencies on soil texture have a direct application to the visibility of anomalous vegetation patterns caused by buried earthworks. Porous soils derived from schist or volcanic tuff show archaeological patterns most clearly in a year when the soil is wetter than usual (Martin, 1971). Markedly stratified soils, such as those with a thin layer of loess or loam overlying gravel or chalk, always show very pronounced crop marks, particularly in dry years; however, a homogeneous soil of loess or loam produces very few markings.

Most plants require that moisture be present at their roots' tips for continued growth of the roots. They cannot penetrate dry strata, although once the roots reach a moist stratum at a greater depth, dry soil nearer the surface has less effect. This is important because soils often dry out near

the surface first. In general, the greater the soil moisture, the deeper the roots penetrate (Russell, 1961, p. 453).

Different plants send their roots to markedly different depths. The roots of alfalfa commonly go as deep as two to four meters (Weaver, 1926; Miller, 1938, p. 139); this is deeper than most other field crops. The roots of other cultivated plants such as wheat, barley, oats, rye and clover usually stop at about two meters of depth (Miller, 1938, p. 139; Russell, 1961, p. 406). More important is the depth at which most of the roots are concentrated, which is the zone of greatest water absorption. For wheat, rye, and oats, this is about one meter; for alfalfa it may be two meters (Miller, 1938, p. 143).

The zone at which soil anomalies will alter the growth of the overlying vegetation is from the bottom of the plow zone to the depth of one or two meters. Crop marks will usually result from archaeological remains in this zone. While many plants, in particular trees, can send their roots to much greater depths, they are usually unsuitable for archaeological reconnaissance. This is because the leaf canopy is so large and the roots draw moisture from such a great range in depth that the spatial resolution of the growth patterns is reduced. However, patterns in tree growth may indicate wide structures such as roads (Newton and Raphael, 1971).

While differences in the chemical composition of the soil resulting from man's activity may also cause anomalous growth of vegetation, many of these compounds are soluble and are quickly leached from the soil. However, there are cases in which higher concentrations of persistent chemicals are detectable at the surface by changes in plant growth, differences in plant species, or directly as a change in soil color (Press, 1974).

Time Factors in the Visibility of Anomalous Patterns

The visibility of crop marks can change considerably over a period of a week or two (Hampton, 1974). The optimum time for photography at any location depends on the climate and crop types and can vary over a period of 1½ months from year to year (Martin, 1971). In central southern England, the best time to observe crop marks is about mid-July (Hampton, 1974; Evans, 1974); in southern Wisconsin, it is between the first of May and mid-June (Kiefer, 1972); in European climates, the best period is from May to July (Martin, 1971). Patterns in vegetation are visible longer during a wet year.

The time of photography must be closely coordinated with the normal planting and growth of crops. Tables of sowing and harvesting dates are available for different crops in different areas of the world (Park, 1969). Scollar has determined the periods of visibility of archaeological markings for a variety of field crops (De Breuck and Daels, 1967, p. 127). These patterns are present from the time the crop has grown enough to cover the soil until the middle of the drying stage, before harvesting. After harvesting, few traces remain visible.

In the absence of soil anomalies wheat and barley yield a uniformly toned crop; the fine texture of these cereals is an excellent canvas on which fine detail can be painted by buried ditches and walls. Row crops have a coarser texture due to the greater spacing of individual plants, and crop marks may be more difficult to detect. Native, uncultivated vegetation may be quite drought-resistant and anomalous growth patterns caused by water stress are rarely seen. However, sometimes a distinctly different species of natural vegetation will reveal a buried structure (Yarnell, 1965; Chikishev, 1965).

Anomalous patterns may also be seen on bare soil. They show when the soil is neither uniformly wet or dry, often best two to three days after a rainstorm, as the soil begins to dry out (Kiefer, 1970).

The Spectral Reflectance of Green Vegetation

Green plants are green because they absorb much red and blue light but reflect somewhat more green. This property of plant color is shown more precisely in the spectral reflectance curve (Figure 10). Note that green plants are quite reflective in the near-infrared; while the human eye can not see this radiation, film emulsions can be made sensitive to infrared and the resulting pictures will show the vegetation to be brighter than almost anything else.

The infrared reflection of vegetation in the near or photographic infrared spectrum, 700-900 nm, is primarily the result of the internal physical structure of leaves. The radiation is scattered from the many air-water interfaces between the cells within the leaf (Wiegand and others, 1972; Gausman, 1973). This is analogous to the whiteness of snow, which is a result of scattering at air-ice interfaces in the visible spectrum. At visible wavelengths, absorption and reflection predominate at the upper surface of a leaf and scattering is low.

The physical structure of the cells in the leaves of grain crops and grass changes when the plants approach maturity and also when a drought causes wilting of the plants; this collapse of the cell structure can reduce the scattering of infrared radiation. While wilting can be seen as crop markings which indicate buried archaeological structures, infrared photography can be an unreliable detector. This is because drying conditions can cause the infrared reflection to increase at first and then

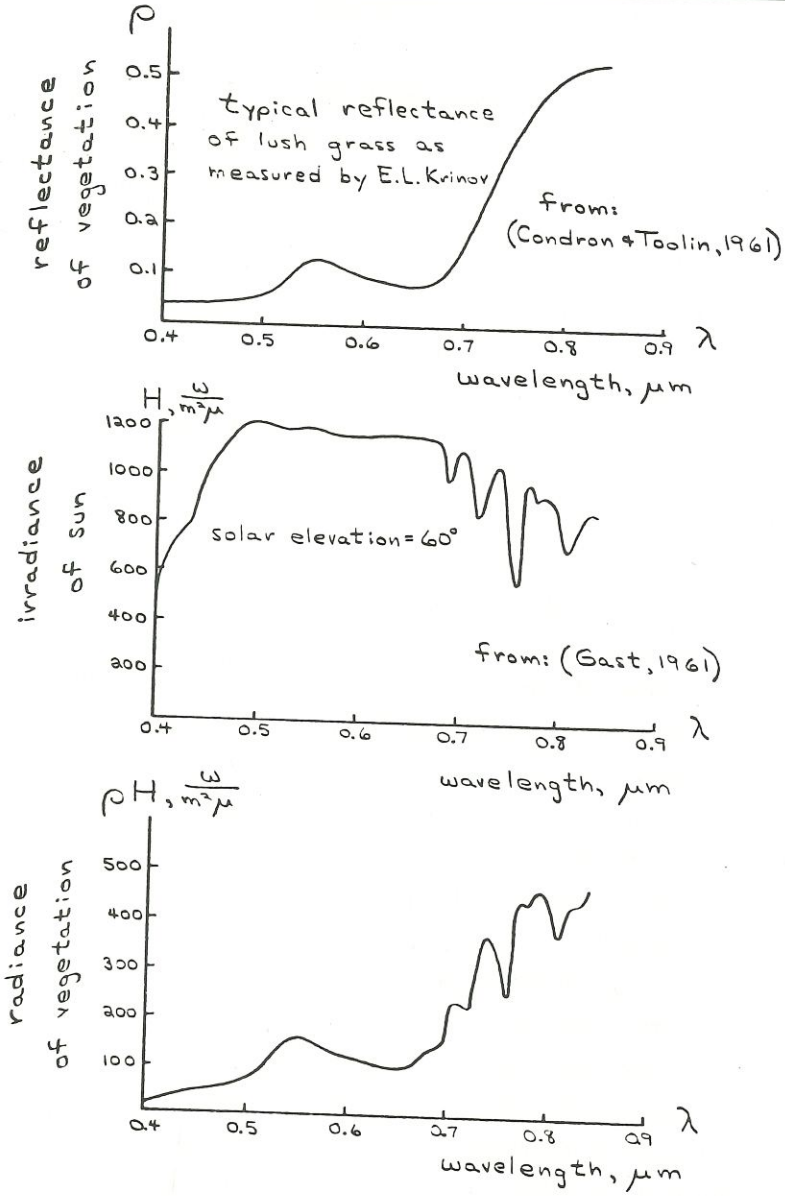


Figure 10: The reflectance of vegetation

later decrease with continuing drought (Gausman, 1974). Thus, there will be times when the infrared reflection of vegetation over a buried ditch will be the same as the reflection of the adjacent dehydrated vegetation; crop marks will then be undetectable. Experiments have shown that the color changes which appear on color infrared film are primarily due to changes in visible light reflection rather than in the infrared spectrum (Knipling, 1969).

The reflection of vegetation at visible wave lengths is primarily controlled by light absorption due to cell pigments, primarily green chlorophyll and yellow or red carotenoids (Myers, 1970, p. 262). Fluorescence of the chlorophyll is also a factor (Livingston, 1949; Howard, 1970, p. 63); the spectrum of excited fluorescence reaches a maximum between about 650 to 675 nm (Hemphill and others, 1969). The concentration of chlorophyll is related to the moisture content of the vegetation: low water content destroys some of the chlorophyll (Tucker and others, 1973).

The preponderance of evidence indicates that moisture stress first appears in the visible spectrum, particularly in the far red, and then with advanced wilting and drying, in the photographic infrared spectrum. An explanation for this may be that partial wilting of vegetation causes an increase in the ratio of the concentration of carotenoids to chlorophyll. While the function of the carotenoids is not definitely known, they appear to aid photosynthesis (Galston, 1964, p. 44) and also possibly keep sunlight from destroying chlorophyll (Wilson and Loomis, 1967, p. 46). The causal sequence may proceed as follows: In some areas vegetation begins to wilt owing to the lack of soil moisture, the stomata on the underside of the leaves close to conserve water, and photosynthesis is reduced because of the lack of absorption of carbon dioxide from the air. Then the concentration of chlorophyll, which absorbs light for the photosynthetic reaction in the blue and red portion of the spectrum, is reduced or the concentration of yellow or red carotenoids is increased. The net result of these two factors is an increase in the reflectivity in the red spectrum of the partially-wilting vegetation.

In aerial photography other factors, in addition to changes in the spectral reflectance of the vegetation, affect the apparent reflectance. Exposed soil associated with young or thin crops (MacLeod, 1972), and dust on the crop (David, 1969), do influence reflectance but usually do not obliterate the anomalous patterns in the vegetation caused by buried structures. The height of vegetation, as determined by the distribution of soil moisture in a field, can yield patterns whose appearance does not change much tnroughout the spectrum. A more important factor is the change in leaf angle which accompanies dehydration (Knipling, 1970); drying leaves may assume a cylindrical shape (Weaver and Clements, 1929, p. 357). During a hot day, wilting, drooping leaves are differentiated in aerial photos because of the dependence of reflectance on the angle between the sun, plant, and camera. For this reason, aerial photography during a hot, dry afternoon may show crop marks best (Kozlowski, 1968, p. 5). These physical changes in the plant will usually be reversed during the night, although a cumulative deficiency of water will eventually cause a permanent wilting (Slatyer, 1969).

The visibility of crop marks can be correlated with rainfall; a good index of this weather-induced effect may be calculated by combining both cumulative precipitation and an estimate of potential evapotranspiration as measured with an evaporation pan. These two variables will allow a guess at the important parameter, effective soil moisture.

Examples of Optimized Detection

Many different researchers have found evidence that the red part of the visible spectrum can yield much information about the growth of plants and the condition of the soil:

Photographs taken in the red part of the spectrum gave the best correlation between film density and soil moisture in a field of grain sorghum (Werner and Schmer, 1972). The blue, green, and near infrared bands were of less value.

The wavelength band 650-675 nm furnished the greatest sensitivity to growth changes and maturity of grassland in California (Roberts and Gialdini, 1973).

The greatest contrast between "disturbed" and undisturbed alfalfa was found between 600 and 700 nm with a peak at about 650 nm (Langley, 1962).

Nitrogen deficiency in the leaves of the sweet pepper plant was best indicated in the red end of the visible spectrum (Myers, 1970, p. 265).

Iron deficiency in sorghum, contrasted to that of normal sorghum, shows best in the red spectrum (Gausman and others, 1974).

Typically the greatest contrast between soil and vegetation appeared in the spectral band 590-680 nm (Vinogradov, 1969).

Over the entire visible and photographic infrared spectrum, the red band 620-720 nm allowed for the best estimate of the amount of organic matter in the soil (Baumgardner, 1972; Roth and Baumgardner, 1971).

Of a number of bands from the ultraviolet through the thermal infrared, it is the red band, 620-660 nm, which provided the greatest contrast between types of soils and their differences in moisture (Tanguay and others, 1969).

Other investigations have indicated that other combinations of the visible and infrared spectra are optimal for the interpretation of certain conditions:

The ratio of spectral reflectance at 655 nm as compared to that at 545 nm provided a better indication of crop maturity for wheat, sorghum, and soybeans than any other region of the visible and near infrared spectrum (Kanemasu, 1974).

For some types of sand and clay, the ratio of the spectral reflectance of wet as compared to dry material is at its maximum in the red and near infrared regions of the spectrum (Piech and Walker, 1974); however, for other soils, sands, and clays this ratio is nearly constant over the photographic spectrum (Condit, 1970).

The correlation between the reflectance in the band 600-700 nm compared to that at 800-900 nm is low for corn, cotton, peppers and sorghum throughout the growing season (Allen and others, 1970). This low correlation indicates that the ratio of reflectance in these two bands is a sensitive indicator of plant growth variables.

The correlation between the green biomass of the prairie grass, blue grama, and spectral reflectance is highest in the blue, red and near infrared parts of the spectrum (Tucker and others, 1973).

Moisture differences within bare soil are more emphasized with color infrared film than with black and white infrared film and regular color film (Sewell and Allen, 1973).

Ektachrome infrared photographs of cotton plants show the best correlation between soil moisture and film density when infrared and visible images are compared (Thomas and others, 1966).

The Basis for Selecting Films and Filters

A precise and generalized description of the color of an object is

furnished by its graph of spectral radiance. Visually, this is the intensity of light in each part of the spectrum. The human eye is extremely sensitive to slight differences in color; a trained observer can distinguish ten million colors (Kelly and Judd, 1955, p. 4). However, the eye is not perfect, for objects with distinctly different spectral radiance can appear to be of the same color (Wyszecki and Stiles, 1967, p. 344). As an example of this, if monochromatic red and green illumination is additively mixed, the sum is indistinguishable from monochromatic yellow light (Gregory, 1966, p. 127).

Color film has this same deficiency in color discrimination. Panchromatic black-and-white film is even worse, for many of the colors which the eye can distinguish are averaged to the same grey tone. Intelligent choice of black-and-white films and filters can improve the distinction between two objects of different color by causing them to appear as markedly different shades of gray in photographs, a fact discovered long ago (Luckiesh, 1915, p. 160). In fact, the interpretation of optimally filtered black-and-white film can result in better color discrimination than could be obtained by viewing the same scene with normal eyes.

The spectral radiance of an object is the product of the spectral irradiance of the illuminant and the spectral reflectance of the object. If a pair of objects of different colors are identically illuminated, it is their difference in spectral reflectance which distinguishes them. Then, the general problem is: Given a pair of objects with different spectral reflectivity, which type of black-and-white film and filter will maximize the gray contrast between them? There is a specific answer to this problem (Wessely, 1964). Since the ultimate interpreter of the photographs will be a person, the characteristics of the visual system are of first importance.

Weber's law states that the threshold, or 50% probability, of detecting that there is a difference in brightness between two almost equally bright surfaces is proportional to the brightness of the light (Cornsweet, 1970, p. 83). As Figure 11 illustrates, Weber's law can be restated in photographic terms: Small differences in film density are distinguishable independent of the absolute value of the density.

The derivation of the procedure for maximizing this density difference is given in Figure 12. If the assumptions are valid, the conclusion is that the sensitivity of the film-filter combination should select that part of the spectrum where the ratio of reflectivity for the two objects differs from unity by the greatest factor (Suits and others, 1968; Legault and Riordan, 1964; Langley, 1962). Ideally, a filter with a narrow, sharp transmission spectrum will usually furnish the greatest contrast. In practice, however, a broad-band filter is necessary to enable sufficient exposure with the fast shutter speeds required for aerial photography. This will also lower the contrast in density due to averaging in the reflectivity ratio. Because of the assumption of a linear density function for the film, the spectral irradiance of the illuminant is not a variable in the final result; however, it is indirectly, for there must also be sufficient intensity at the sensitivity peak of the combined film and filter so that the exposure time is short. While the equation is still solvable with the true nonlinearity of the density function, an iterative solution is necessary (Goddard and others, 1973).

At first it may appear that a film developer which maximizes contrast should increase the detectability of reflectivity anomalies. Because of the nonlinearity of the density function, if the gamma is increased too much for a moderately contrasty scene, errors in exposure and development

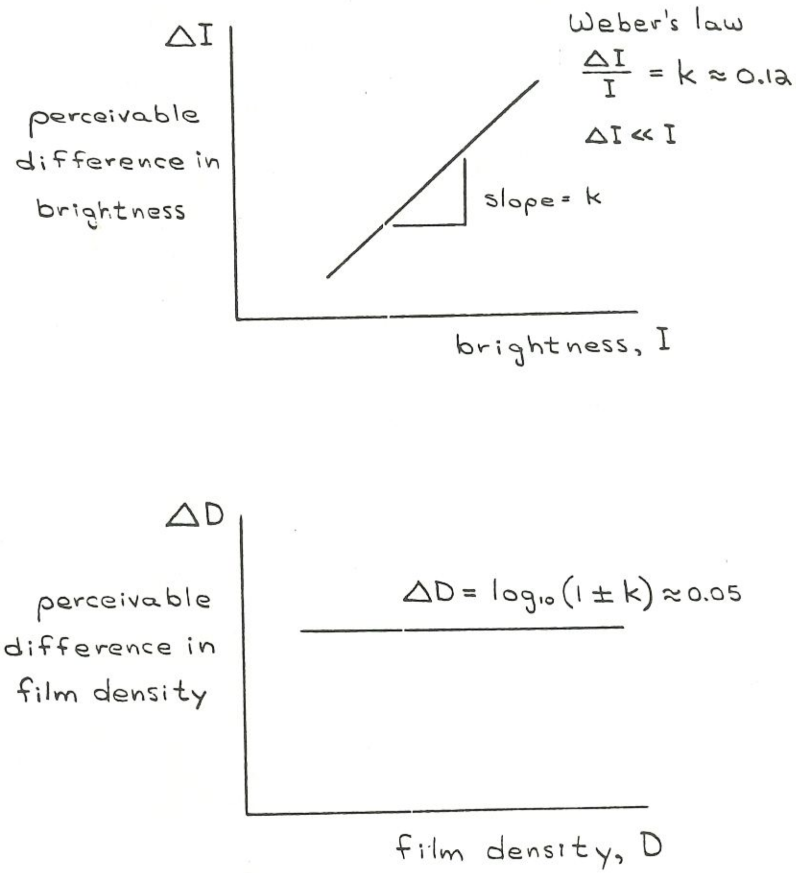


Figure 11: Weber's law restated for photographic film

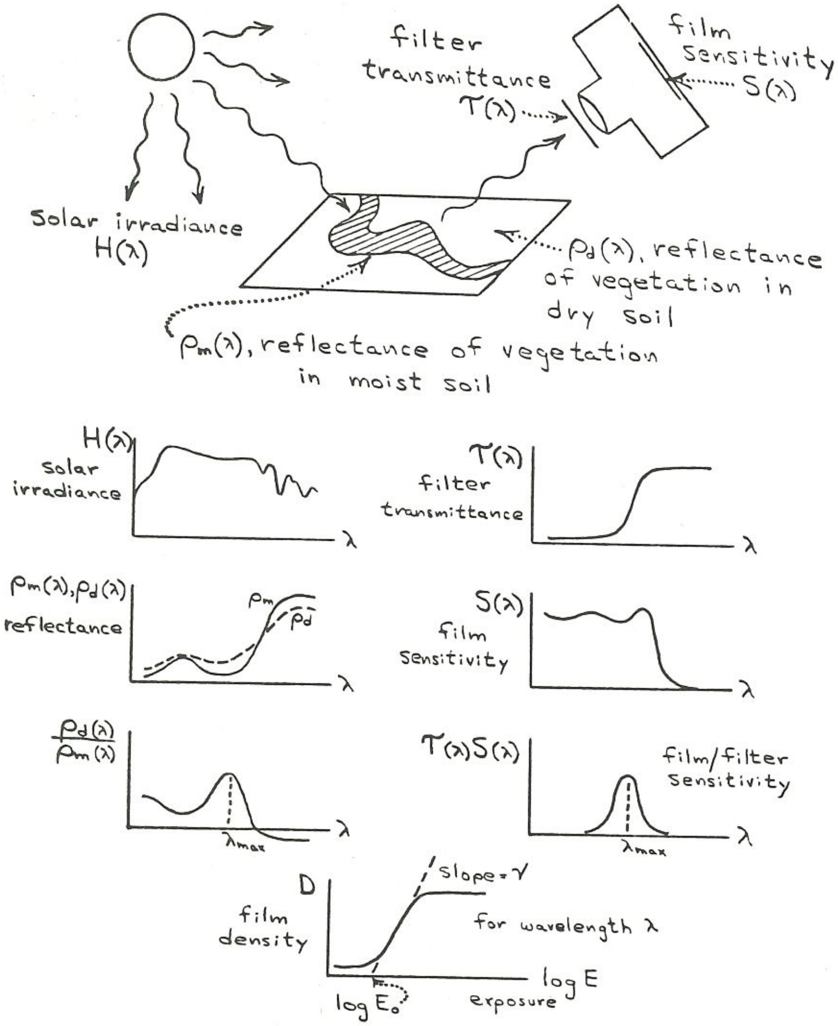


Figure 12a: Film and filter combination for maximizing photographic contrast

The spectral sensitivity, $S(\lambda)$, of a film is

$$S(\lambda) = \frac{1}{E(\lambda)}\Big|_D \qquad \text{(Goddard \& others, 1973)}$$

where

$E(\lambda)$ = exposure which yields density D

λ = wavelength of radiation

The density function of a film can be approximated by

$$D = \gamma(\lambda)\log_{10}\frac{E(\lambda)}{E_o(\lambda)} \qquad \text{(James \& Higgins, 1968)}$$

where

D = transmission density of film

$\gamma(\lambda)$ = exposure gradient, gamma

$E_o(\lambda)$ = inertia of film

With $T = 10^{-D}$ = film transmittance,

$$S(\lambda) = \frac{T^{1/\gamma(\lambda)}}{E_o(\lambda)}$$

Using Van Kreveld's law

$$\int_\lambda E(\lambda)S(\lambda)\,d\lambda = 1 \qquad \text{(Goddard \& others, 1973)}$$

Substituting from above yields

$$\int_\lambda \frac{E(\lambda)}{E_o(\lambda)}T^{\frac{1}{\gamma(\lambda)}}\,d\lambda = 1$$

but

$$E(\lambda) = k\,H(\lambda)\,\rho(\lambda)\,\tau(\lambda) \qquad \text{(Jensen, 1968, p.76)}$$

where

k = constant for exposure time and lens aperture

$H(\lambda)$ = irradiance of illuminant

$\rho(\lambda)$ = reflectance of object

$\tau(\lambda)$ = filter transmittance

Figure 12b

If $E_o(\lambda)$ and $\gamma(\lambda)$ are constant over the integral λ,

$$T^{-\frac{1}{\gamma}} = \frac{k}{E_o}\int_\lambda H(\lambda)\,\rho(\lambda)\,\tau(\lambda)\,d\lambda$$

and

$$D = \gamma \log_{10} \frac{k}{E_o}\int_\lambda H(\lambda)\,\rho(\lambda)\,\tau(\lambda)\,d\lambda$$

If within interval (λ_1, λ_2) $H(\lambda)$ is constant and $\tau(\lambda)=1$, but otherwise $\tau(\lambda)=0$ outside the interval

$$D = \gamma \log_{10} \frac{Hk}{E_o}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)\,d\lambda$$

The density contrast between two objects with different spectral reflectance is

$$D_1 - D_2 = \gamma \log_{10} \frac{\int_{\lambda_1}^{\lambda_2} \rho_1(\lambda)\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \rho_2(\lambda)\,d\lambda}$$

If the reflectivities are constant in the interval (λ_1, λ_2),

$$D_1 - D_2 = \gamma \log_{10}\left(\frac{\rho_1}{\rho_2}\right)$$

Therefore, to maximize the difference in film density between two objects, choose film and filter to select that part of the spectrum where the ratio of the spectral reflectivities is greatest.

Figure 12c: Film and filter combination for maximizing photographic contrast

will cause contrast to decrease in some parts of the photograph. It may be best to process the film to a moderate contrast and then make the final control in contrast when printing the negatives. Another result of increased gamma can be additional graininess which may degrade the interpretation of the photos.

It is important that the spectral band of high film-filter sensitivity not have the ratio of spectral reflectance between the objects to be distinguished both above and below unity, for contrast will then be quickly reduced.

For non-photographic sensors and computer processing of images, other criteria than reflectance ratio, possibly difference in reflectance, may be required to maximize the probability of detection (Klemas and Odell, 1970).

These principles for maximizing photographic contrast can be applied to the problem of detecting patterns of anomalous vegetation which is so important in archaeological reconnaissance. The data in Figure 13 show the spectral reflectance for mature wheat growing in eastern Maryland in soil with both a high and low moisture content (Pitts, 1973; Leeman and others, 1971). These twelve samples were measured with a spectrophotometer in the field while the crop was growing; while there was no archaeological basis for the difference in soil moisture of these samples, the resultant reflectivity contrasts are probably similar to those found in crop marks caused by buried walls or ditches. It would be very valuable to have reflectance data for archaeological crop marks, but presently they are not available.

When the six samples of each type are averaged, the ratio curve illustrated in Figure 14 results. It shows that the reflectance ratio has a reflectance, in %, of wheat growing in soil with a low moisture content

wave-length, μm	sample number 161	162	163	228	229	230
0.4	4	4	4	5	6	6
0.45	4	4.5	4.5	5	6	7
0.5	4	5	5	4.5	6	6
0.55	8	9	8	6.2	8	8.5
0.6	7	7	7	6.5	6	7
0.65	6	5.5	5	3	4	7
0.7	17	9	10	7.5	9	10
0.75	27	30	28	13	16	20
0.8	28	31	30	16	20	27.5
0.85	27.5	31.5	30	14	22.5	23.5
0.9	27	30	28.5	16	23	22

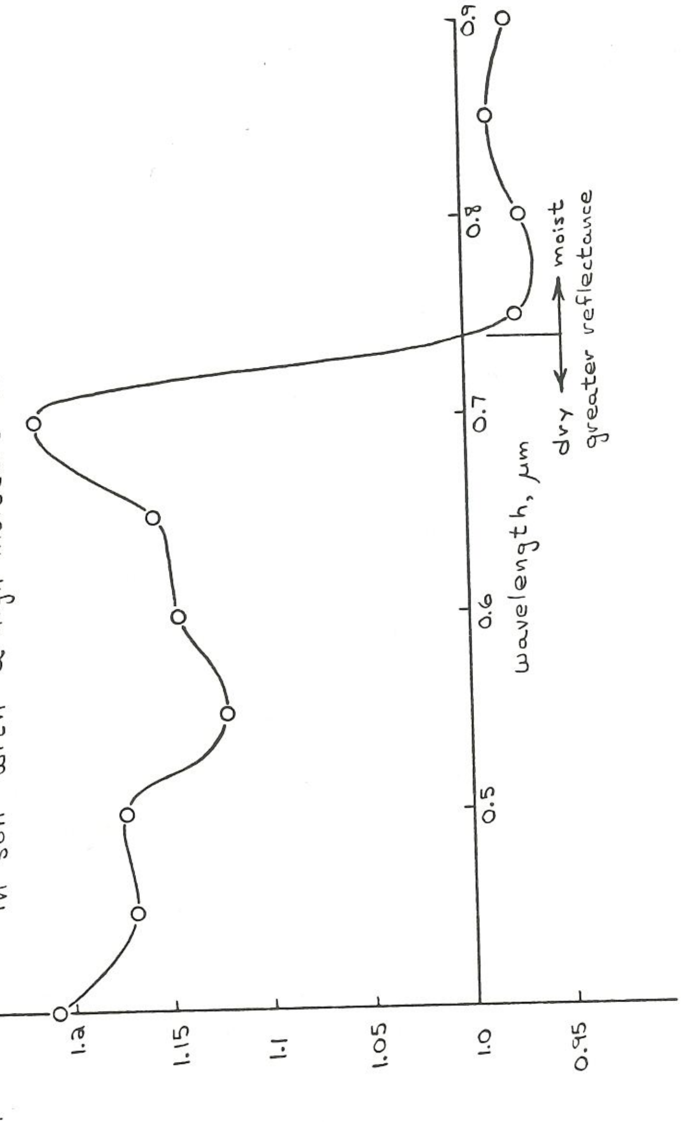
reflectance, in %, of wheat growing in soil with a high moisture content

wave-length, μm	sample number 164	165	166	231	232	233
0.4	4	3.5	3.5	5	4	4
0.45	5	4	4.5	5	4	4
0.5	5	4	4	5	4	4
0.55	8	7	7	7	6	7.5
0.6	7	5.4	5.5	6.5	5	6
0.65	5.5	4	5	3.9	4	4
0.7	11	8.5	8	7	8	9
0.75	36	26	28.6	13	15	19
0.8	38	27	30	17	18.5	26.5
0.85	38.5	26	28	18	16	24.5
0.9	38	26.2	30	18	16	22

sample number prefix is B01643
data from: (Pitts, 1973; Leeman & others, 1971)

Figure 13: The spectral reflectance of wheat

Figure 14: Ratio of the reflectance of wheat growing in soil with a low moisture content to that growing in soil with a high moisture content.



maximum in the far red part of the visible spectrum, but it is also high at the blue end. Note that the ratio is near unity in the infrared; this is an example of how low contrast can result with infrared photography.

With this reflectance curve and the final equation of Figure 12, it is possible to approximate the photographic contrast with different films and filters. With Kodak Tri-X film processed to a gamma of 0.6 and a Wratten #92 (dark red) filter, the reflectance ratio is about 1.19 and the density contrast will be about 0.045, with the crop growing in dry soil shown as a lighter tone. Since a density difference of 0.05 can almost always be detected by a photo interpreter (Cihlar and Protz, 1972), this crop contrast will usually be discernible. Without a filter, the same panchromatic film will give a contrast of 0.039, for the average reflectance ratio is now 1.16. Black-and-white infrared film processed to a gamma of 1.0 and a Wratten #87 filter yields a contrast of only 0.011; the crop growing in dry soil will appear darker. It is important that infrared film not be used with a filter that allows some red light to pass, such as the Wratten #89B filter. This is because an increase in reflectance in the infrared will be offset by a decrease in the red reflectance; the already weak contrast of the infrared may be completely cancelled out.

Note that when the red spectrum is selected by a Wratten #92 filter and Tri-X film, it is the filter which limits the short wavelength sensitivity of the combination and the film which limits its long wavelength sensitivity. In most other parts of the spectrum a band-pass filter would be required to limit the spectral response of panchromatic film.

When contrast-enhancing filters are combined with panchromatic films, the exposure settings of the camera must be increased because of the reduced amount of light reaching the film. While these filter factors can be determined mathematically (Scharf, 1965), it is easier to estimate them

with photographic tests.

Figure 15 lists the factors which were measured experimentally for six filters. Both Kodak's Tri-X and Plus-X were tested, but the factors were found to differ by less than ½ stop for the two films and so an average is listed here. The Tri-X processing yielded a gamma of 0.6 and that of the Plus-X was 0.7. The filter factor was determined by the increase in exposure required to give a film density of 0.8. Since the filter factors vary considerably with the spectral reflectance of the surface, they are listed for both a neutral gray surface and green vegetation. Since many cameras now have a through-the-lens light meter, this table also includes the different filter factor which applies when the exposure meter is filtered. In addition, each filter factor is listed in two different ways: the plus or minus figure is the number of stops that the lens aperture must be opened or closed in relation to the light meter reading with the meter's exposure index set to that of the panchromatic film. For example, a +2 stop filter factor would require the lens aperture to be increased from the unfiltered setting of f/5.6 to a setting of f/2.8. The "times" factor indicates the multiplication of the exposure time indicated by the meter reading (a x4 filter factor would change a 1/500 second exposure to a 1/125 second exposure). Either adjustment, or a partial combination of both, will be necessary. If a single filter will be used for many pictures requiring different exposure settings it will be faster to divide the film's exposure index by the filter factor, in "times" form; then the correct exposure settings will be read directly on the meter.

While the Wratten #70 filter may increase the contrast of crop marks even more than the #92 filter, its filter factor when photographing a gray surface is approximately +13 stops; therefore it can't be used in aerial

Wratten filter	gray surface				green vegetation			
	meter not filtered		meter filtered		meter not filtered		meter filtered	
34 (violet)	+2	x4	$-\frac{1}{2}$	x0.7	+4	X16	+2	x4
92 (red)	$+5\frac{1}{2}$	x45	+3	x8	$+6\frac{1}{3}$	x81	+5	x32
29 (red)	+4	x16	+2	x4	$+4\frac{1}{2}$	x23	+3	x8
25 (red)	+3	x8	$+1\frac{1}{3}$	x2.5	$+3\frac{1}{2}$	x11	$+2\frac{1}{2}$	x5.7
47B (blue)	+3	x8	$-1\frac{2}{3}$	x0.3	$+4\frac{1}{2}$	x23	$+1\frac{2}{3}$	x3.2
58 (green)	$+2\frac{2}{3}$	x6.3	$+\frac{1}{3}$	x1.3	+3	x8	$+1\frac{1}{2}$	x2.8

(will differ with changes in lightmeter, film, developing)

Filter factors adjusted to yield a film density of 0.8; lightmeter was CdS type; illuminant was sunlight (altitude = 60°) and hemispherical blue skylight; grey surface was Kodak 18% Grey Card and green vegetation was lawn grass.

"+" factor indicates the required increase in lens aperture, in stops; a +3 factor would change f/11 to f/4. "X" factor indicates the alternative, an increase in exposure time; a X8 factor would change $\frac{1}{500}$ sec to $\frac{1}{60}$ sec.

Figure 15: Approximate filter factors

photography.

In addition to the technique of enhancing detection with transmission filters, another related method is possible. The light from the scene can be reflected off a surface whose spectral reflectance matches that of one of the objects to be detected; this creates a reflection filter. The reflectance standard can be a sample of the object itself (Hunt, 1966; Hunt and others, 1967). Since the polarization of light reflected from soil changes with its moisture content, a polarizing filter in front of the camera's lens might aid the detection of structures buried beneath bare soil (Stockhoff and Frost, 1971).

APPENDIX 2 - THE RESOLUTION OF PHOTOGRAPHS

Resolution is a measure of the distinguishability of fine detail. It is not necessarily related to sharpness, which is determined by the contrast of coarser detail (Langford, 1972, p. 44, Higgins, 1969, p. 174). When a single number is used to describe resolution, it only partially defines the ability of a photographic lens and film to give high image quality (Brock, 1969). While a more complete description of resolution is possible, a single parameter will be adequate for many applications (Scott and Brock, 1973; Barakat, 1965).

The first question is: How much resolution is really needed? This depends on, first, what the smallest object to be recorded on the photograph is and, second, whether it is only necessary to detect that object or whether it must also be identified (Rosenberg, 1971). The latter is important, for detection can be: "I see a spot on the photograph", while identification is "It is a car and not an elephant". Identification requires about four times greater resolution than detection (MacLeod and Maier, 1969). Once the question of detection or identification has been decided, the nomograph in Figure 16 may be used to aid the calculation of the required resolution. The dashed lines indicate an example of a calculation. The size of the smallest object of interest is 0.5 meter in diameter and it is 200 meters distant; a straight line is drawn between the two points on the pair of scales and the intermediate scale, angular size, is intersected at about 8 minutes. This is the arc width of the object from a distance of 200m; note that the average human eye sees an object whose angular size is smaller than one minute as a featureless point (for example, a pair of stars separated by an arc of one minute or less appear as a single star).

Next, from the mark for the focal length of the camera's lens, in this

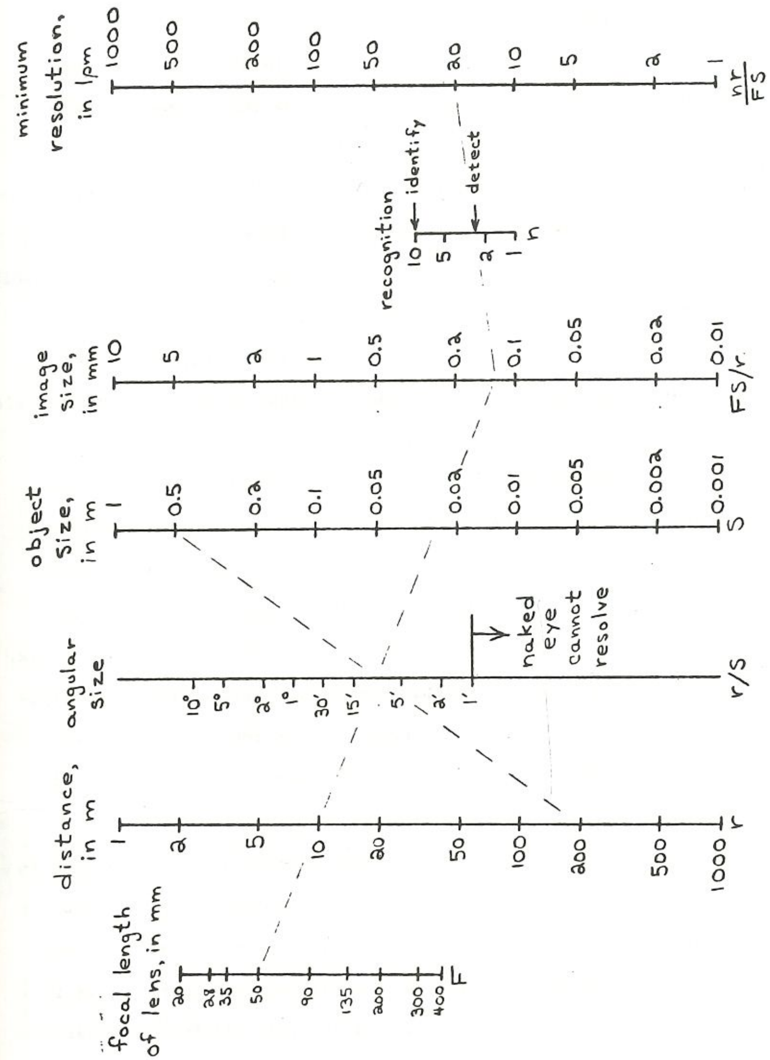


Figure 16: The resolution required in a photograph

example 50mm, a line is drawn through the intersection on the angular size scale until it intersects the image size scale, in this example at about 0.13 mm; this is the size which the object 0.5 m in diameter will have on the film. Note that the size of the film, 35 mm or other, does not enter into consideration.

If it is decided that detection of the object is the only objective, the line is drawn from the last intersection through the adjacent scale at "3", as indicated by the "detect" arrow. This line is then continued to the final scale, yielding a resolution of 20 lpm. The units of this scale are lines per millimeter; this indicates the spacing of parallel lines on the film which must be capable of being resolved in order that it will also be possible to detect the object to be photographed.

If identification of the 0.5 m object is desired, the line would have been drawn through the "identify" arrow at the "10" mark on the recognition scale. The estimates of the added resolution required for identification and detection on this scale are averages which are approximately correct (Brock, 1970, p. 215; Jensen, 1968, p. 6; Soule, 1973); for critical work, a safety factor to the minimum resolution should be added. This is particularly necessary if the object to be detected has low contrast against the background; the nomographs presented here are based on the assumption of high contrast.

Now that the required resolution has been determined, it is next necessary to make sure that the photographic resolution is sufficient. There are four components which determine this: lens, film, depth of field, and the motion of the camera or subject. Figure 17 combines these four factors in a nomograph. First, the combined resolution of the lens and film is determined by drawing a straight line between their values on the appropriate scales.

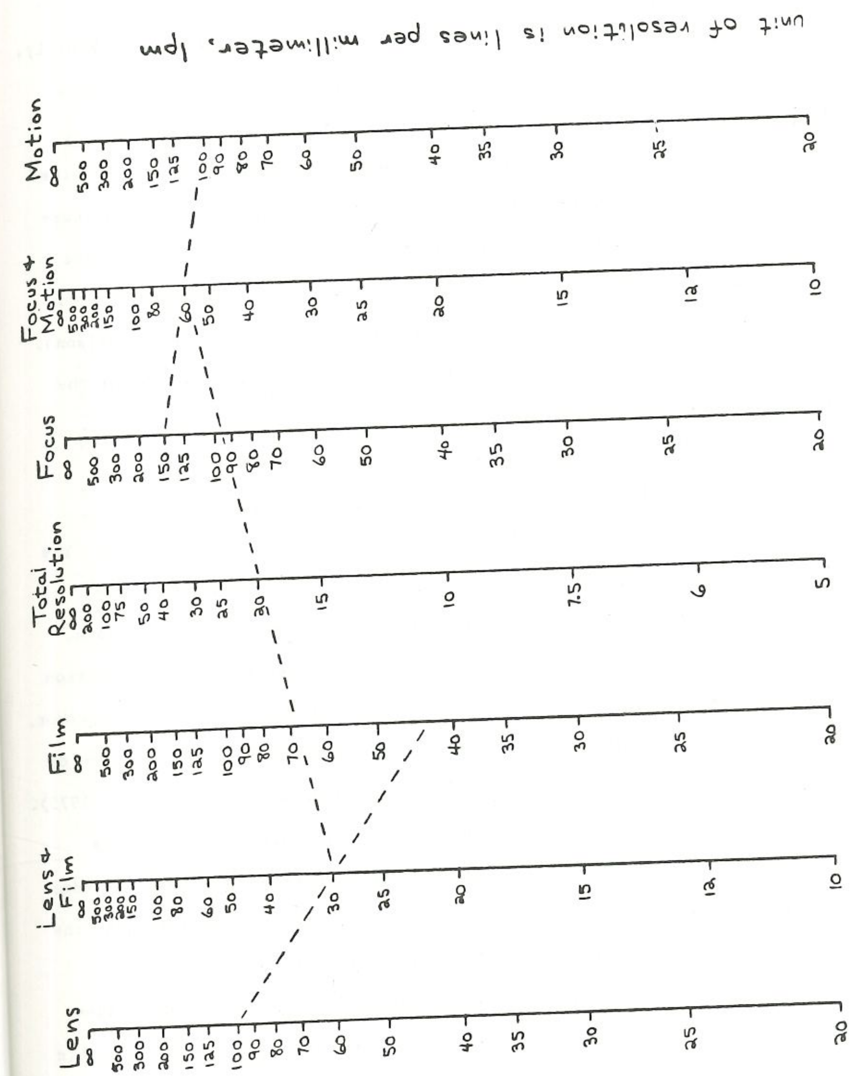


Figure 17: Summation of resolution components

Next, a similar line combines the focus (depth of field) and motion resolutions; the determination of these factors will be described below. Finally, a long line between the previously determined pair of scale intersections yields the "total film resolution" at the center scale.

This nomograph is based on the fact that the reciprocal of the combined resolution is approximately equal to the sum of the reciprocals of the components (Brock, 1970, p. 134). This is only an approximation, as are the results of many of the following nomographs; while the nomographs may not have absolute accuracy, their relative accuracy is valuable for comparisons. Bousky has developed a related set of nomograms which are valuable for the parameters of commerical aerial photography (Colwell and others, 1960).

The resolution of the camera's lens is determined without film in the camera. The camera is pointed at a resolution chart and the image behind the lens is examined with a microscope (Skudrzyk, 1971, p. 228). The charts for determining resolving power typically have a series of black rectangular bars with the white spacing between them equal to their width. The groups of bars have a range of dimensions which determine the resolution of the lens by the point among the bars at which they become blurred together. In order to simulate the conditions of aerial photography, the resolution of lenses can be tested with large resolution charts at a distance (Franz, 1973). Resolution is measured at each f-number or relative aperture of the lens both near the center of the image frame of the camera and also near the edge. The graph in Figure 18 was determined in this way; as with most lenses, the best resolution is between the smallest and largest apertures.

Many photographic magazines publish resolution data for camera lenses which they have tested, although a conversion of their results to a suitable form may be necessary (Modern Photography, 1972). This is because the combined

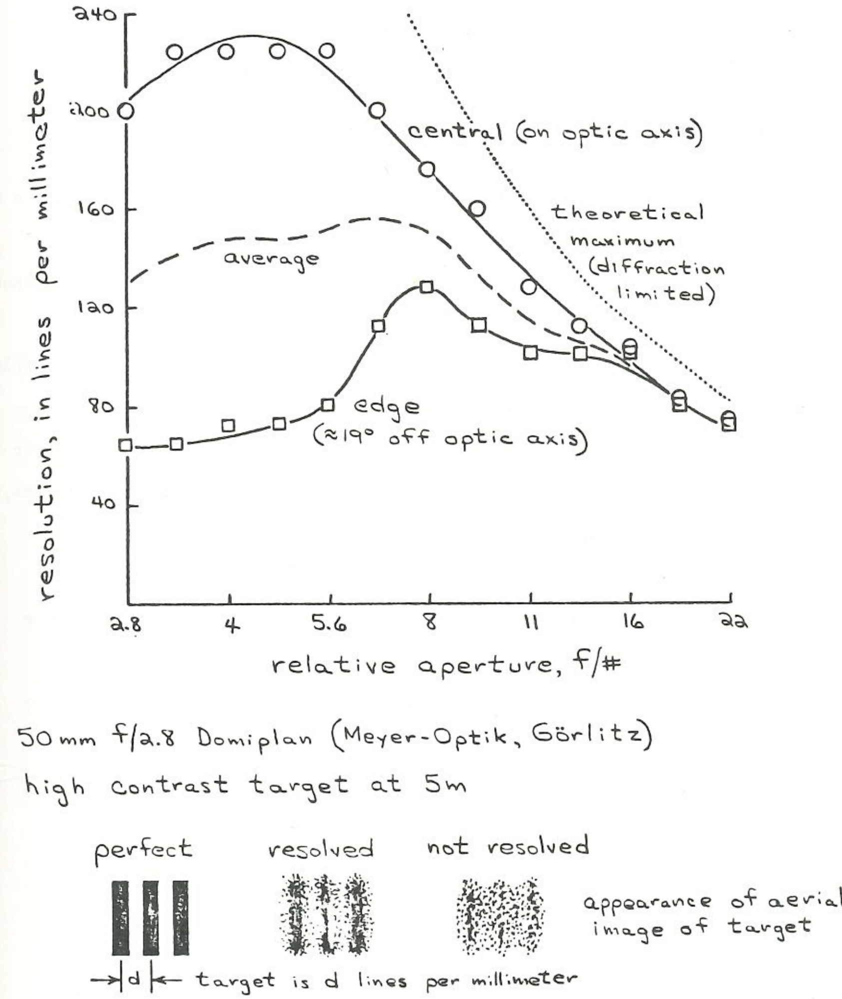


Figure 18: An example of lens resolution

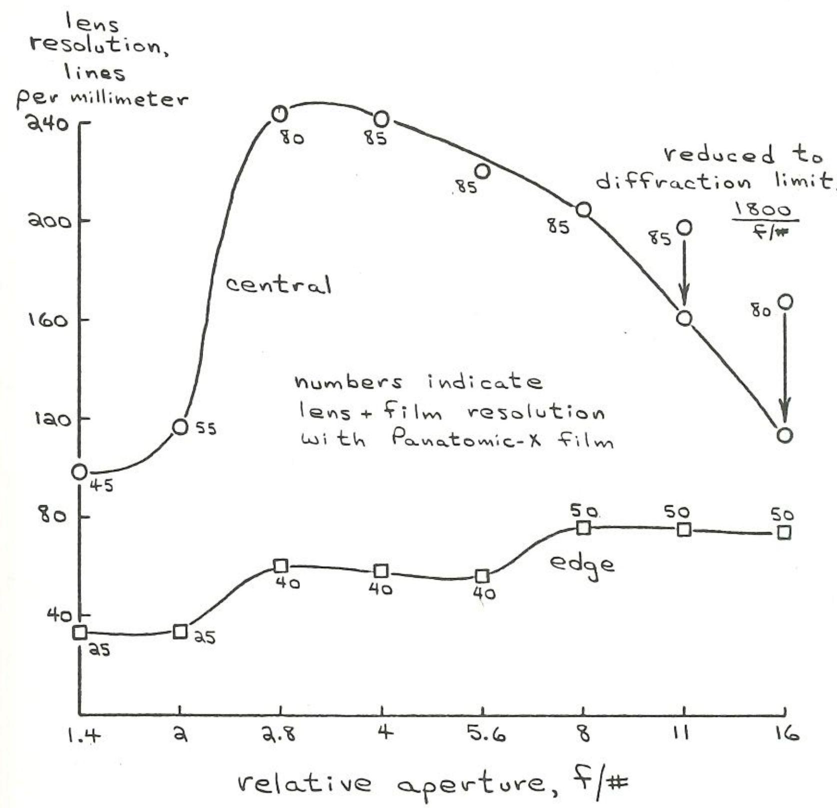
resolution of the lens and a particular film is listed. If a different film is used, the lens resolution may be calculated by following the main resolution nomograph of Figure 17 "backwards" from the combined lens and film resolution. Figure 19 is the result of such a calculation (Modern Photography, 1973). A blank lens resolution graph is illustrated in Figure 20.

If only a single type of film is employed, it is most convenient to measure the combined resolution of lens and film in a single test. There are several calibrated charts available for these resolution standards (Washer and Gardner, 1973; Sussman, 1973, p. 460).

If the resolution of the lens is separated out, the effect of different film types can be compared. Figure 21 shows the approximate resolution for three different types of film (Skudrzyk, 1971, p. 240). Since the resolving power of film is constantly being improved, these curves are actually lower limits; resolution will also change with the type of chemical development the film receives. Note that the resolution of a film in a camera decreases for larger apertures; this is because the image then spreads into a wider cone through the thickness of the emulsion (Skudrzyk, 1971, p. 241).

Depth of field is usually no problem with aerial photography; usually the focal distance of the lens is set at infinity and no part of the scene will be close enough to be significantly out of focus. However, for low altitude balloon or kite photos or high camera stands, depth of focus is a factor in the photographic resolution. Figure 22 contains a nomograph for resolving this problem.

When an object is in the field of view of a camera, but is not at the focal distance set on the lens, it will be somewhat blurred and each point will be spread over a circular area of the film. The diameter of this



50 mm f/1.4 Nikor-S lens
data from: (Modern Photography, 1973, p. 37)

Figure 19: Lens resolution calculated from the combination of lens and film resolution

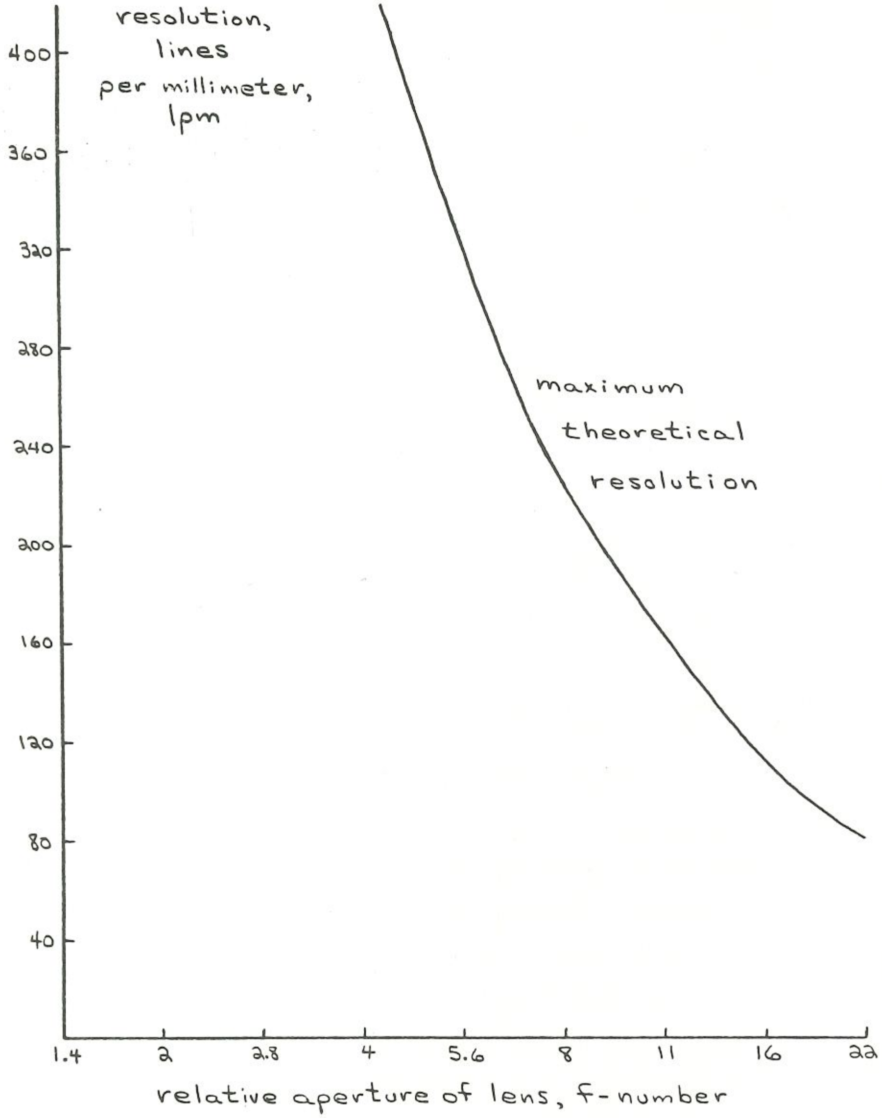
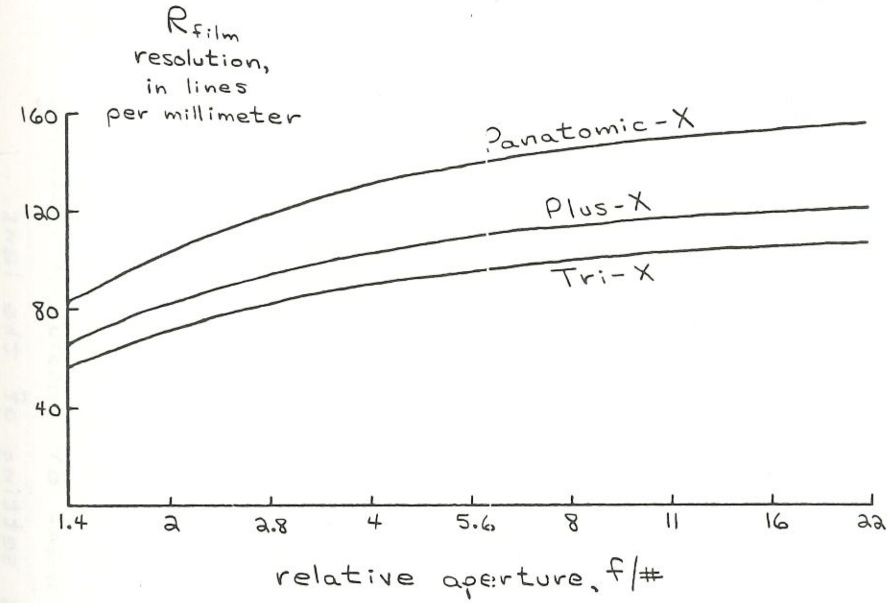


Figure 20: A blank resolution chart for the data of another lens



from $R_{film} = R_{\infty} \dfrac{4f-2}{1+4f+\frac{1}{2f}}$ (Skudrzyk, 1971, p. 260)

f = relative aperture of lens

$$R_{\infty} = \begin{cases} 160 \text{ for Panatomic-X film} \\ 125 \text{ for Plus-X film} \\ 110 \text{ for Tri-X film} \end{cases}$$

R_{∞} will change somewhat as films are improved; resolution of Ilford films are probably similar to the comparable Kodak types.

Figure 21: The resolution of film

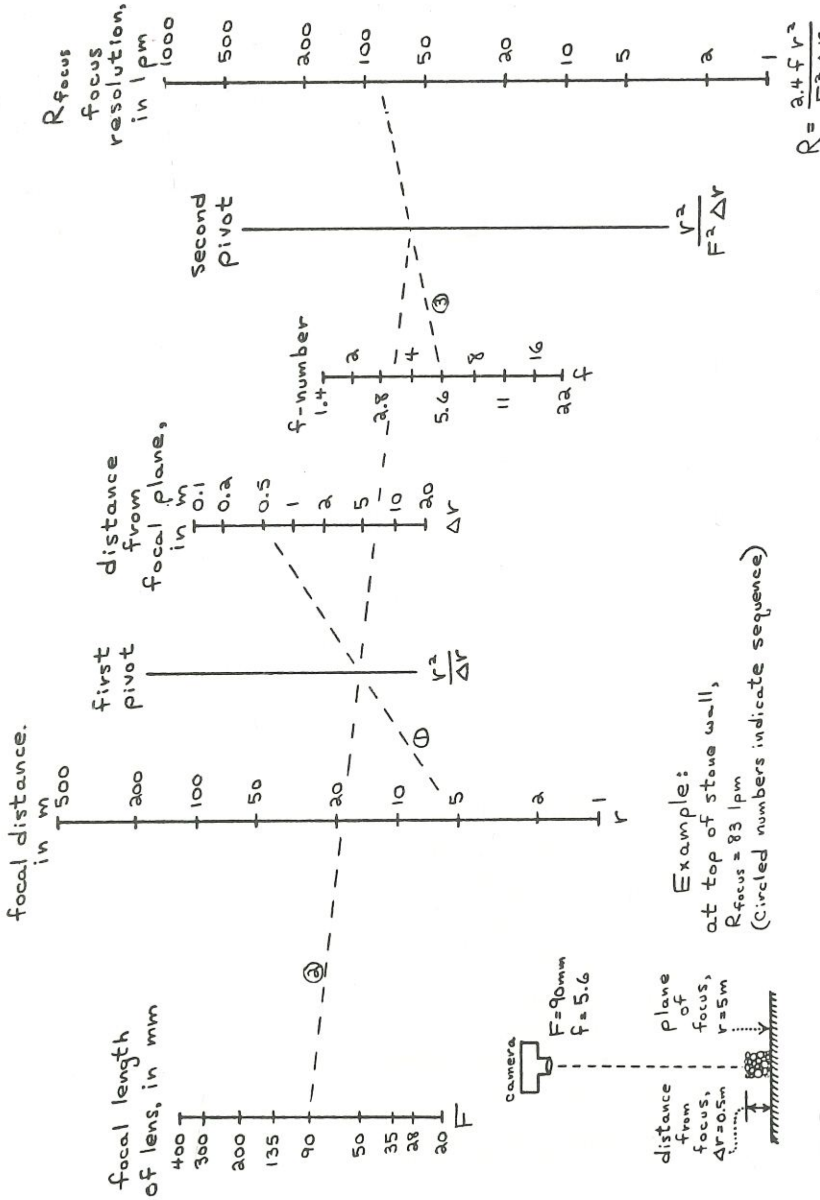


Figure 22: The component of resolution resulting from the focus setting of the lens

circle can be related to a resolution figure (Skudrzyk, 1971, p. 252; Gruner and others, 1966). The depth of field is actually a different distance in front of and behind the focal distance to which the lens has been set; an average is used to simplify this nomograph (Kingslake, 1973).

An example to illustrate the operation of this nomograph is given in Figure 22. A camera is focused on the base of a wall 5 m below the lens. The top of the wall is 0.5 m nearer the camera; this nomogram shows that the component of resolution loss due to the depth of field (at f/5.6 with a 90 mm lens) at the top of the wall is 83 line pairs per millimeter.

The resolution loss due to camera motion is a major variable in aerial photography. The nomograph in Figure 23 allows an estimate for its control. With photography from airplanes, several factors contribute to blurring. First is the forward speed of the airplane; panning the camera can reduce this type of blurring. Second, the vibration of the airplane's engine can be partially transferred to the camera even though the operator is careful not to let it touch the frame of the airplane. Third, airplane buffeting due to atmospheric turbulence can be the major factor during low altitude photography when flying say, below cumulus clouds during a hot afternoon. Unfortunately, this turbulence is so variable that it is almost impossible to estimate the resolution loss due to it; it is best to avoid these high turbulence periods. For a conservative estimate of the resolution loss, the effect of these three motion components should be added.

In using the nomogram, the relative angular velocity between the camera and subject is calculated for the given airplane speed and the oblique distance to the area to be photographed. The angular velocity must be compared with the estimate of the resolution loss due to airplane vibration. The example in Figure 23 shows that both are comparable. The vibration of a hand-held

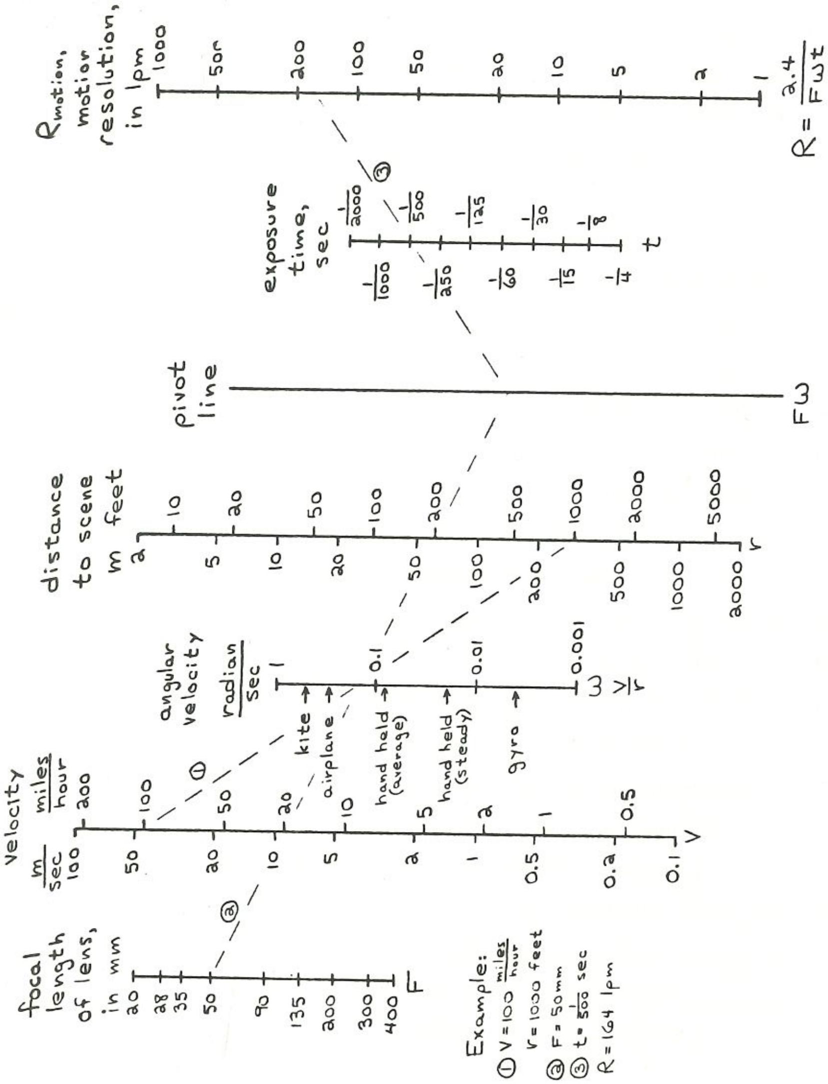


Figure 23: Resolution due to image motion

camera is somewhere between the airplane's vibration of about 0.3 radian per second (Duddek, 1968) and the average vibration of a photograph taken on the ground while holding the camera by hand, about 0.08 radian per second (Skudrzyk, 1971, p. 280). This scale also includes some additional estimates: very careful camera holding can lower the vibration to about 0.02 radian per second with terrestrial photography (Kimata and Keppler, 1974); the motion data for the sway of a kite camera and a gyroscopic camera stabilizer are mere guesses.

Once the total angular velocity factor has been estimated, the focal length of the camera and the exposure time are entered in the nomograph to determine the resolution loss due to camera motion.

This nomograph can also be applied to problems in terrestrial photography when we are dealing with a subject that moves. The angular velocity due to the tangential motion of the subject is calculated first. Next, the angular velocity due to radial motion is determined by entering the radial velocity on the velocity scale and the distance on its scale; the resultant angular velocity which is found at the intersection on the middle scale is then re-entered as another velocity on the velocity scale once more and the second intersection with the same distance setting is determined.

The set of nomograms presented here can be applied to a wide variety of photographic problems. By trying several combinations of lens aperture and shutter speed for a given flight path and film type, it is possible to maximize the final negative resolution. While this iterative operation could be automated with a computer, it may take only a few attempts to find a near optimum by this simple manual technique. An example of this is given in Figure 24.

angular velocity = 0.14 $\frac{\text{radian}}{\text{sec}}$

lens data from Figure 18

nominal exposure with Plus-X is f/8 and $\frac{1}{125}$ sec

Plus-X, E.I.=125

camera settings	R_{motion}	R_{film}	R_{lens}	resultant resolution ΣR
$\frac{1}{125}$, f/8	43	113	150	26
$\frac{1}{250}$, f/5.6	85	109	152	36
$\frac{1}{500}$, f/4	171	102	147	45
$\frac{1}{1000}$, f/2.8	342	93	132	47

Panatomic-X, E.I. = 32

camera settings	R_{motion}	R_{film}	R_{lens}	ΣR
$\frac{1}{125}$, f/4	43	130	147	26
$\frac{1}{250}$, f/2.8	85	119	132	36

Tri-X, E.I.= 400

camera settings	R_{motion}	R_{film}	R_{lens}	ΣR
$\frac{1}{125}$, f/16 + $\frac{1}{2}$	43	104	106	24
$\frac{1}{250}$, f/11 + $\frac{1}{2}$	85	102	135	35
$\frac{1}{500}$, f/8 + $\frac{1}{2}$	171	97	156	44
$\frac{1}{1000}$, f/5.6 + $\frac{1}{2}$	342	92	148	49

49 lpm = highest resolution

Figure 24: A trial-and-error procedure for maximizing resolution

APPENDIX 3 - EXPOSURE FOR AERIAL PHOTOGRAPHY

If the camera flying height is less than 500 m and the haze is low, the brightness and contrast will be close to what one sees on the ground; thus exposure meter readings can be made on the ground or from the air. Higher altitude or a greater amount of haze increases the apparent brightness while reducing the contrast (Wakeman and others, 1972). For these conditions, knowledge of exposure meter and film characteristics can improve photographic quality.

The characteristic curve which relates film density to exposure for a typical black and white film is shown in Figure 25 (Kodak, 1967). If a camera's exposure settings are determined with a lightmeter, any uniformly bright grey surface will yield the same film exposure independent of the absolute brightness of the surface. This exposure value, which has been standardized (American National Standards Institute, 1972) as shown in Figure 25, is for an ideal situation with the camera pointed at a distant object and with the use of a high transmittance, low flare lens. A less ideal, perhaps more typical scene and lens can give an exposure about 17% lower. Additionally, differences in lightmeter calibrations may offset the ideal exposure by as much as 25%. Fortunately, both of these factors are minor. For a scene which is not uniformly bright, meters indicate approximately an average brightness.

Figure 25 indicates the approximate measurement of the ASA speed for Kodak Plus-X film. If the film is processed to a fixed density standard (American National Standards Institute, 1971) which is approximately that of the curve with the gamma of 0.7, then the ASA exposure index is determined by the exposure required to increase the film density by 0.1 over the minimum density.

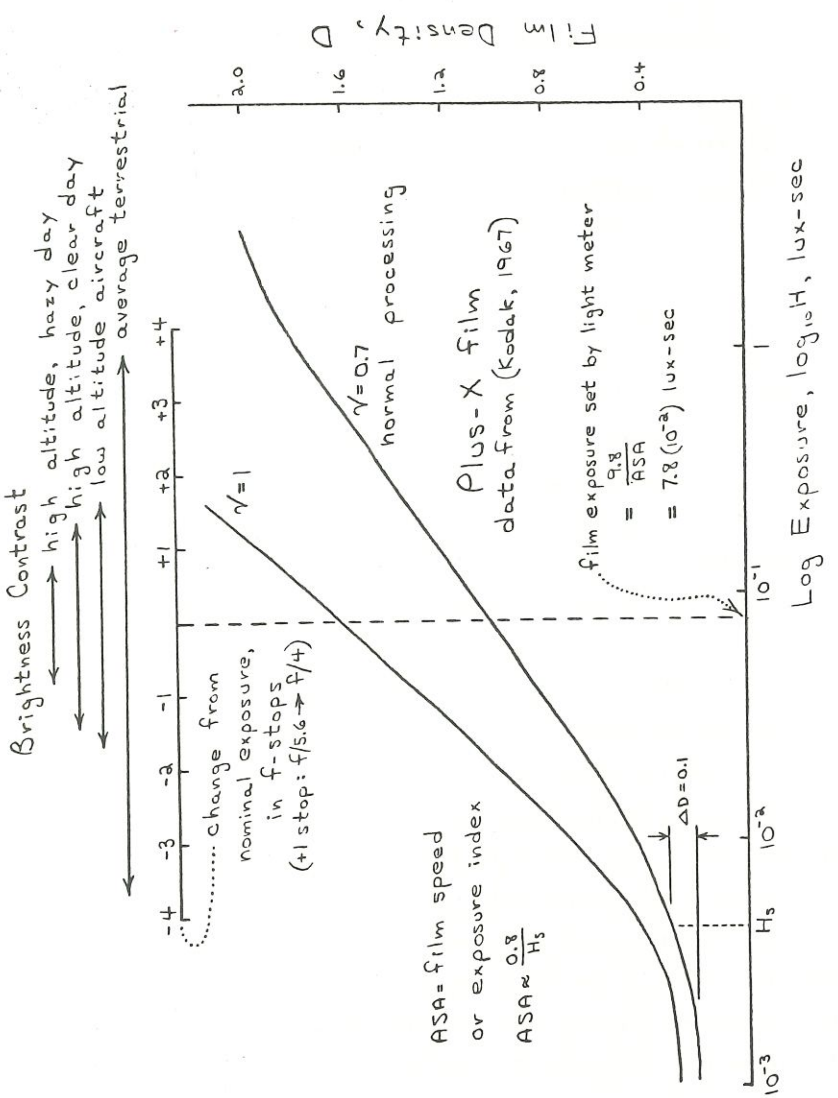


Figure 25: Brightness contrast and film exposure

Figure 25 also shows the brightness range expected with average terrestrial and aerial photography (James and Higgins, 1968, p. 237; Brock, 1967, p. 172; Harris, 1968). Although these values are only approximate, they reveal some important facts about exposure. For example, when a low altitude photograph is taken of a sunlit scene, it can be under-exposed by one or possibly two stops below the light meter reading without serious loss of contrast; such underexposure allows for a faster shutter speed and results in sharper photographs. However, if in doubt, black and white film should be somewhat overexposed rather than underexposed (Todd and Zakia, 1969, p. 170).

With high altitude photography or a hazy atmosphere, the brightness range can be very small and special processing for higher contrast in the negative is desirable; Figure 25 also indicates the changes in the exposure setting which are possible with a gamma of one.

The spectral sensitivity of lightmeters must be considered so that their capabilities are not misunderstood. Many meters, in particular those built into cameras, have a cadmium sulfide light-sensitive element. Its spectral sensitivity is maximal for green light, much like the human eye, and decreases approximately in the following order: green, yellow, orange, red, and blue (Stimson, 1974; Duddek, 1970). The low sensitivity to blue light decreases the meter's response to haze, and this is of benefit in aerial photography. Unless the film in combination with the camera's filter has a sensitivity which matches the lightmeter, or the spectral irradiance of the scene matches the calibration irradiance of the lightmeter (which is a color temperature of 4700 K), the exposure indication will be erroneous.

With aerial photography, it is also possible to determine exposure settings from the angle of the sun above the horizon. Kodak's aerial exposure computer (Kodak, 1970) includes a set of tables and a circular slide rule for these calculations. Since the computer has been designed solely for high altitude commercial aerial photography, it is calibrated for a different type of film speed rating than the ASA index which is available for most films. However, a good approximation is still possible by entering the known ASA film speed as the effective aerial film speed for which the computer is calibrated. The lens aperture on the camera should then be opened one-third stop more than the computer's indication (for example, a f/4 setting should be increased to f/3.5). This small difference usually does not affect the result.

There are many fine points concerning exposure for aerial photography which seem at first to go against reason and which are often given contrary interpretations by different investigators. For example, a partially cloudy sky can increase the brightness in shadows compared to that found under a clear blue sky (Hulstrom, 1973; Brock, 1967, p. 187).

APPENDIX 4 - MULTISPECTRAL PHOTOGRAPHY

While it is usually possible to circle over an area and photograph it with different films or filters on each pass, it may be preferable to frame the different photos identically so that they can be readily compared. This may be done by "ganging" two or more cameras and by coupling their shutter releases so that they each expose the film simultaneously. In addition to their value for a technical comparison of films and filters, multicamera arrays can be necessary to distinguish between two classes of objects when there is variability in the spectral reflectance within each class (Silvestro, 1969); for example, the two classes might be wheat and alfalfa, each in different stages of growth. Furthermore, with more than two classes of objects, several spectral bands may have to be employed to distinguish them.

There are a number of good introductions to this subject (see Slater, 1972; Slater, 1969; Wenderoth and Yost, 1974). Both 35 mm and 70 mm cameras have been used in multicamera arrays (Fisher and Steever, 1973; Ulliman and others, 1970; Whittlesey, 1973b). A motor drive for each camera is almost essential. Multilens cameras have a very rigid alignment of several photos on a single negative. In one example, four lenses focus their images on a single nine inch (23 cm) wide film (Ross, 1973). Combinations of these two approaches have also been tried; one camera system uses nine lenses and three different rolls of film with a group of three lenses casting an image on each type of film (Molineux, 1965).

The calibration and exposure determinations for camera arrays are more complex than for single camera photography, although the principles have been worked out (Bernath, 1973; Kreitzer and Gilbertson, 1974). Probably the simplest camera for multiband photography is a commercially available stereoscopic camera; while it is practical to use one type of film only, two different filters may be employed.

In aerial photography, it is also possible to combine color film with filters. A two band camera with two slightly different filters has been found valuable in searching for archaeological crop marks. The following combinations have been suggested: color infrared film with a Wratten filter pair 16 and 61; standard color film with Wratten filter pairs 2A and 2E or 8 and 9 (Strandberg, 1972).

A comparison of two or more photographs resulting from multispectral photography is most accurate with special optical equipment. An initial comparison of two photos is done by viewing them with a stereoscope and closing one eye and then the other. While it would be convenient to be able to place a different colored filter in front of each eyepiece of the stereoscope so that the differences between the prints would be apparent as color differences, this will not work with most people, binocular rivalry will be the result (Osgood, 1961, p. 196; Luckiesh, 1965, p. 142). Although some photographic resolution is lost, the best way of viewing multispectral photos employs a group of projectors much like regular slide projectors (Yost and Wenderoth, 1969, Yost, 1972); in fact, a stereo projector is excellent. A different filter is placed in the optical path of each projector and the images are aligned to form a colored picture. The projection filters do not need to be the same as were those in front of the camera lens; this "false color" recombination can in fact aid the viewing of the differences.

Photographs can also be compared by printing the combinations. In addition to the black and white techniques for comparing two photos which were outlined in the section on photo interpretation, color or false color

prints may also be used. A special technique known as isoluminous photography is particularly suitable for enhancing the color differences in pictures (Wenderoth and Yost, 1974; Yost and others, 1973).

APPENDIX 5 - KITES, BALLOONS, AND WIND SPEED

The speed of the wind is important for flying tethered balloons and kites. The maximum allowable breeze for flying a spherical balloon is about three kilometers per hour, while most kites need a wind speed of 20-35 km/hr.

Conditions attendant to a tethered balloon in a wind are illustrated in Figure 26. This analysis assumes that the balloon stays spherical and it discounts surface friction. The effect of lift and drag on the tether line can be added if desired (Silbert, 1969, p. 185). If the weight of the payload and tether line are subtracted from the total lift of the balloon, the angle of the tether line can be calculated. For example when lift equals drag, the line angle will be 45°. Since reeling in a balloon is equivalent to increasing wind speed, the tether angle will decrease. Therefore, reeling in a balloon while the wind is blowing can bring it dangerously close to the ground; thus, it is better to move down wind while reeling in. When the balloon gets near the ground, another effect adds to the difficulty. The wind velocity between the balloon and ground increases: this causes a pressure decrease and the balloon is further drawn toward the ground (Klemin and others, 1939; Tietjens, 1957, p. 109). The same effect results when a balloon is moored; the downward motion may be minimized by attaching a skirt to the ground around the base of the balloon to add wind friction and decrease wind velocity.

The aerodynamic lift of a kite varies with the speed of the wind. In Figure 27 the height to which a given weight can be raised by a kite is calculated.

To determine wind speed, one may use one of the several small commercial anemometers or construct an accurate wind gauge (Strong and Clemens, 1971).

Below an altitude of 200 m, wind speed is most often at a maximum about

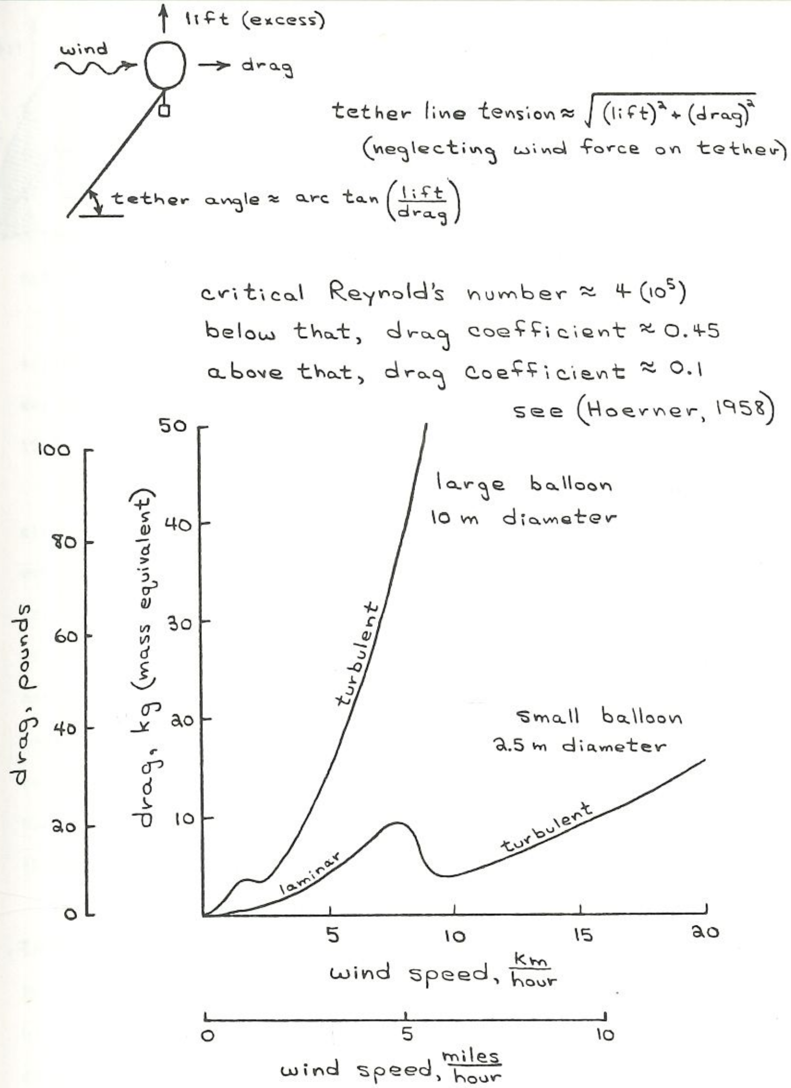
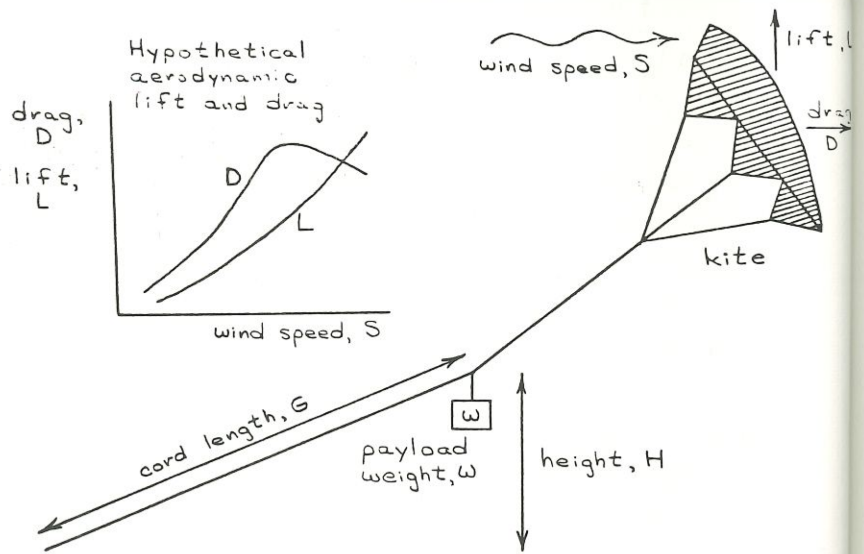


Figure 26: Approximate wind drag on tethered spherical balloons



Neglecting wind force on the cord,

$$\frac{H}{G} = \frac{1}{\sqrt{1 + \left(\frac{D}{L-\omega}\right)^2}}$$

This equation can be combined with the aerodynamic characteristics of the kite to yield the payload height as a function of the speed of the wind:

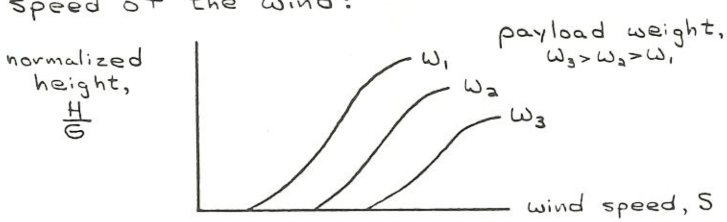


Figure 27: Aerodynamics of kite-flying

2:00 p.m. and at a minimum about 2:00 a.m. However, except for coastal and mountainous regions, wind above the height of about 200 m may be at its minimum speed at 2:00 p.m., just when the surface wind is at its maximum (Lettau and Haugen, 1961). Winds above 200 m are almost always faster than those at the surface.

Friction at the surface of the earth slows wind speed. To a fair approximation, wind speed increases exponentially with height; the exponential parameter is related to the roughness of the terrain (Deacon, 1969, p. 80). Figure 28 shows the effect of terrain on average wind speed.

Gustiness becomes an important factor in handling balloons, kites and airplanes. It usually increases with higher surface friction, such as over woodlands, but decreases with increasing height above the ground (Visher, 1924, p. 54). The scale of turbulence is indicated in the pattern of wind blowing over a field of grass or grain. Trees are also good indicators; if one or two trees are rustling or swaying, and others are steady, local turbulence or a small thermal updraft is indicated rather than a regional wind. Smoke plumes and clouds also indicate the stability of the air. Flat, stratified cloud or smoke layers indicate low turbulence (Scorer, 1958, p. 186).

Clouds can serve as valuable indicators of upper winds. Cumulus clouds indicate the upper limit of most turbulence (Schroeder and Buck, 1970, p. 66). The motion of the clouds reveals wind velocity and shear. Although neither balloon nor kite will normally reach as high as the cloud layer, the clouds do furnish clues to the lower winds. Small, toy balloons filled with hydrogen or helium, when set free, indicate the wind speed along their upward path.

In addition to increasing its speed with height, the wind also changes direction. In the northern hemisphere, the wind direction moves clockwise

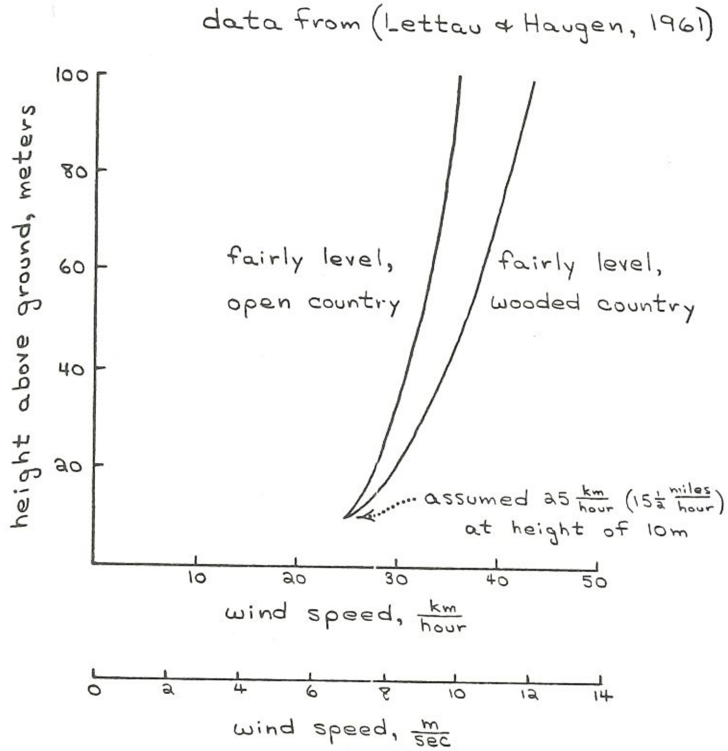


Figure 28: The increase of wind speed with height

about 1-2° per 100 m of height (Deacon, 1969, p. 76). This small shift is unimportant for aerial photography.

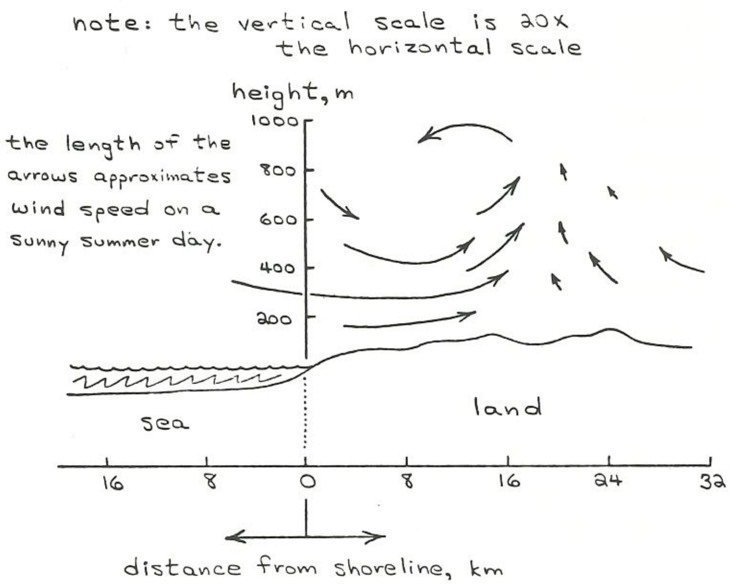
Information on wind speeds in a given region is more difficult to obtain than other climatic data. However, some data are available for the United States (Visher, 1954; Solomon, 1961). The winds of Europe and North Africa have been analyzed by de la Rue (1955).

Mountains and coasts are two areas which provide very regular and predictable breezes which are suitable for flying kites. In the valleys and on the slopes of mountains, the winds blow up hill during the daytime. Near the shores of large lakes and, in particular, near the sea reliable onshore winds blow during the summer daytime. However, the arrival of a frontal system may disrupt the sea breeze. Furthermore, at night or in the winter, the breeze may blow offshore.

Figure 29 illustrates the vertical and horizontal extent of a typical sea breeze. The length of the arrows approximate the relative wind speeds. Note that this type of wind can penetrate a good distance inland; the upwelling air at this front is sometimes indicated by a line of clouds (Wallington, 1961, p. 121). It is important to remember that, while gliders require a vertical updraft for their flight, kites can be lifted by either horizontally or vertically moving air.

The effect of local obstructions on wind must be considered. A cluster of trees can halve wind speed on their lee side and the wind near the ground will not regain its speed before a distance of about 10 times the height of the trees (Geiger, 1965, p. 499). Furthermore, trees can reduce the wind up to a height 50% greater than their own height.

The windward side of a hill provides additional lift for a kite. However, as Figure 30 illustrates, a kite flown on the lee side of a hill may



data from (Flohn, 1969, p. 154)

Figure 29: The wind near the coast of a large body of water

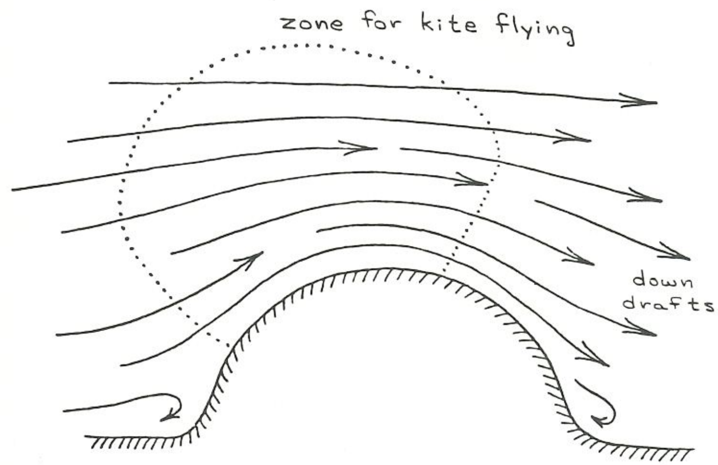


Figure 30: Approximate wind flow over a hill

be deflected downwards. The relatively smooth flow indicated in this figure becomes much more turbulent with high wind speeds (Schroeder and Buck, 1970, p. 98). Wind velocity is greatest over the peak of a hill; with a long hill transverse to the wind, the velocity approaches twice the normal velocity over flat terrain (Allen and Ditsworth, 1972, p. 226).

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