REMARKS ON

THE DEVELOPMENT OF A

HIGH-RESOLUTION RECONNAISSANCE SYSTEM

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SECTION I - HIGH RESOLUTION

What's New

This document addresses itself to the question of developing a new reconnaissance system not only aimed at achieving high resolution on the ground, but of recording these through high-resolution optics on high-resolution photographic materials. These remarks are submitted primarily on the basis that Itek has developed a photographic material of extremely high resolution, with a speed adequate for cameras designed to this high resolution. This film has an adequate grey scale, and in an appropriate system is insensitive to radiation.

Virtues of High-Resolution Sensors

Sensors with high resolution (above 1000 lines/mm) make feasible reconnaissance systems of small size, low weight and requiring small amounts of film. In addition, the necessary mechanical motions are over smaller dimensions, resulting in less absolute vibration, thermal control and power requirements. Weight is at a premium in reconnaissance systems, for although bigger boosters will become available, the load could be more profitably used for other collateral sensors, or for fly's eye cameras covering wider fields with stereo and various spectral ranges.

For a given ground resolution from a typical satellite heights, the size of the camera goes down as the square of the sensor resolution as measured say in lines/mm. For example, with a sensor providing 1000 lines/mm, 10 meter ground resolution can be obtained with a microscope objective as a lens, with a focal length of 1 cm. A ground resolution of 1 meter requires 10 cm focal length. The weight of such cameras would be only a few pounds. The amount of film required is also reduced by the square. For a nominal sensor resolution of 1000 lines/mm, with optics to match, the amount of film needed to record the USA and 10 meter ground resolution is only 0.1 m^2; for 1 meter ground resolution the area of film is 10 m^2.

There are important secondary advantages in reducing the size of a camera. Smaller elements may be more easily fabricated. There is a big advantage in refraction systems, in that a wider variety of glasses or crystals are available from which to make the elements of the lenses.

SECTION II - THE NEW ITEK PHOTOGRAPHIC MATERIAL

Characteristics

The new Itek process is superior to silver halide in some characteristics, equal in others and inferior in only one. It is very much simpler than silver halide in regard to the preparation of the photosensitive material. Development is basically the same, requiring liquids. However, the development process is more flexible, allowing variation of photographic properties to be achieved by modifying the development rather than the coating. It is quicker to develop and fix because there is no gelatin emulsion, which is the source of the rate-determining step of chemical diffusion. The cost of the photochemicals and coating is much less than that of silver halide. The cost of development and fixing materials is about the same. The material can be sensitized to make it panchromatic by the same kinds of dyes as used for silver halide.

In performance the new process is superior to silver halide in having much higher resolution for a given speed. Moreover, at the highest resolution it still retains a grey scale (which the Eastman Kodak emulsion 649, for example, does not). This is the factor which makes it important to consider such a high resolution sensor in reconnaissance systems.

The Itek system is not only novel, but it is basic in the sense of allowing much greater insight into the physics and chemistry of photography than has been possible over all the years with silver halide. Because of the separation of the underlying physical and chemical processes, it appears that our understanding is so much greater that the avenues along which to proceed to improve performance are quite evident, so that substantial improvements are to be expected.

However, the process as it is today is satisfactory for high-resolution systems. There is no testing technique adequate to measure the resolution of the material, but it is better than 2000 lines/mm (probably 10,000 lines/mm). Its speed is 25 mcs.* Figure 1 shows how the new Itek material relates to photographic emulsions currently of interest in reconnaissance.

Speed-Resolution Relations

High resolution of sensors cannot be obtained without sacrifice of speed (i.e., amount of light needed to produce a dense enough image). There seems to be general relation, shown in Figure 1, for each class of sensors relating the exposure* (photons/cm^2) to resolution (lines/mm),

$$E = k\sigma^2$$

where k is an empirical constant for each class of sensors related to the physical structure of the photosensitive materials. The relationship is much more complicated than this, especially in the case of silver halide which has a non-linear response, as will be discussed later. The rough relation is used here to show the trend of the proposed analysis.

*meter candle seconds equivalent to 4×10^{11} photons/cm^2 of green light

**When the units of exposure are expressed in photons/cm^2, there is of course an oversimplification, an average wavelength being implied. The final theory would make use of integrals over the spectrum of reflectance of the object, the transmission of the optics and the sensitivity of the sensor. To relate the conventional photographic units to physical units, we note one meter-candle-sec = 4×10^{11} photons/cm^2 for green light.

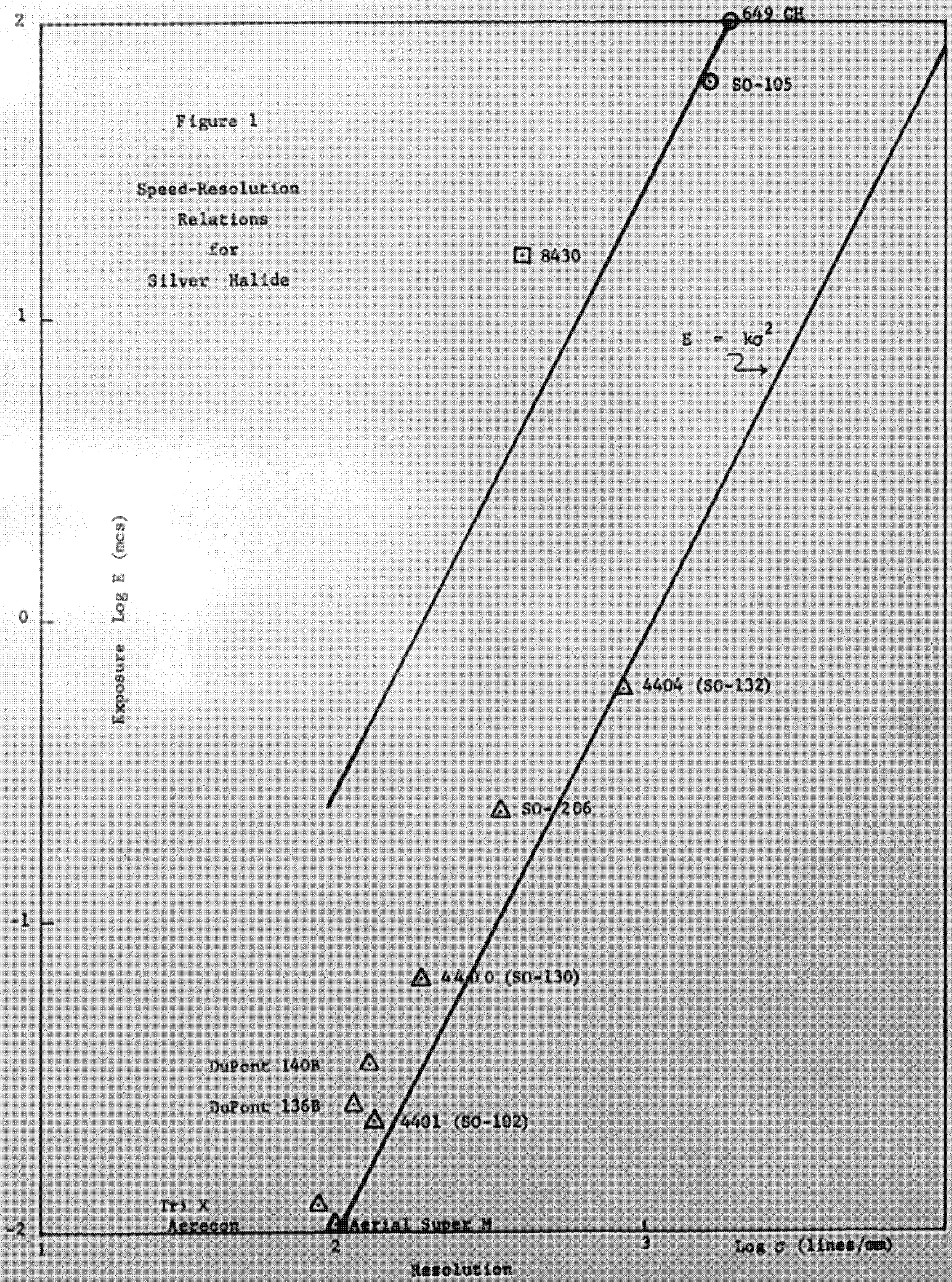
Figure 1
Speed-Resolution Relations for Silver Halide
Exposure Log E (mcs)
2
1
0
-1
-2
649 GH
SO-105
8430
E = kσ²
4404 (SO-132)
SO-206
4400 (SO-130)
DuPont 140B
DuPont 136B
4401 (SO-102)
Tri X
Aerecon
Aerial Super M
1
2
3
Log σ (lines/mm)
Resolution

The new Itek process provides such a new family of materials, i.e., materials with a smaller k. However, the present material only just becomes practical, because it has not yet been possible to trade off its resolution for speed, getting the resolution in the regime reachable by lens design. We shall now discuss this, and show in particular that a sensor with resolution of 1000 lines/mm must be used in an optical system with an F-number (focal length/ absolute aperture) of unity, performing at limiting resolution. Higher sensor resolutions require proportionately smaller F-numbers, and F = 1 is about the present practical limit.

Optical Resolution

The principal characteristic of cameras is resolution to which there is a fundamental limitation due to the finite wavelength of light λ. Even at best, a point in the source comes out as an Airy disc of finite dimensions. To be more specific, performance is primarily specified as the angular resolution. The angular radius of the central disc (as seen from the center of the collector optics of aperture 2R) is

$$\theta = 1.2\lambda/2R$$

This is the angular radial separation of two points when they are just resolved by Rayleigh's criterion. A more elaborate discussion of resolving power can be found in the literature* and will be used later in this work.

*G. W. King and A. G. Emslie, J. Opt. Soc. Am. **41**, 405 (1951)
ibid. **43**, 658 (1953)
ibid. **43**, 664 (1953)

R. Barakat, J. Opt. Soc. Am. **52**, 276 (1962)
ibid. **53**, 274 (1963)

A more complicated formula must be used for optics with high numerical apertures, such as microscope objectives.

The ground resolution Δ from a camera at altitude h is determined by the limiting angular resolution,

$$\Delta = \theta h$$

or

$$\Delta = 1.2\lambda \frac{h}{2R}$$

Since h is an operational parameter, determined by factors outside of the design of a camera, this simple equation says that ground resolution can only be improved by increasing the absolute aperture of the system 2R. The important parameter in lens design is aperture, not focal length.

It is clear that the resolution of the optics and the sensor must be matched, otherwise the size of the camera is wasted or the speed of sensor is unnecessarily low.

It is customary to specify the performance of the sensor by its spatial resolution, σ lines/mm, measuring the closest packing of black and white bars which can be just resolved. Here again, more sophisticated analyses have been made and will be applied. But this parameter can be used in first order analysis. We have then (multiplying σ by 10 to put it in c.g.s. units)

$$1/10\sigma f = \theta = 1.2\lambda/2R$$

Consequently

$$\sigma = 1/12\lambda F$$

The basic design parameter is not the focal length f, but the one which more nearly describes the difficulty of fabrication, F. This equation also shows that when higher resolution materials are used, F must be proportionately reduced. So there will always be a demand for improved methods in lens design.

Conversely, we can write

$$F \leq 1/12\lambda\sigma$$

which says, given a sensor with a resolution σ, the camera must have a minimum F value, otherwise the resolution of the sensor is wasted at the expense of longer exposures than necessary.

To appreciate orders of magnitude, some values are given in Table 1. It can be seen that much higher resolution is called for than is used in practice partly because really high resolution emulsions have no grey scale.

TABLE 1

Relation Between Sensor Resolving Power and Numerical Aperture

$\lambda = 6000\ \text{Å}$

F Number	Spatial Resolution, σ (lines/mm)
1	1000
3	333
10	100

One conclusion from this table is that only sensors compatible with low F-number cameras are emulsions with high resolutions, and even these are inadequate were it not for the fact that the theoretical limit of angular resolution θ is not often achieved in cameras. It does point out the necessity to improve photographic materials to keep pace with lens design, and this is proposed. Conversely, if a photographic material with 1000 lines/mm is available, it is mandatory to have an F1 camera to use it in.

The exposure available is determined by the light-gathering power of the optical system, and the time of exposure. We must now see whether these two parameters are commensurate with reasonable system performance. If **B** is the brightness of the objects, in photons/sec steradian, the number of photons/cm^2 sec falling on the sensor is

$$I = \frac{\pi}{4} \frac{BT}{F^2}$$

where **T** is the transmission of the system, as an integral of the reflectance spectrum of the object and spectral sensitivity of the photographic material. We now equate necessary and available exposure of duration **t** seconds,

$$k\sigma^2 = \frac{\pi}{4} \frac{BTt}{F^2}$$

so that

$$\sigma = \sqrt{\frac{\pi}{4} \frac{BTt}{k}} \frac{1}{F}$$

and from the previous relation between σ and F,

$$t = \frac{1}{36\pi\lambda^2} \frac{k}{T} \frac{1}{B}$$

This equation is of interest, in saying that the exposure time is dependent on the transmission of the optical system, and the fundamental sensitivity of the sensor, apart of course from the brightness of the source. It is independent of focal length, absolute or numerical aperture, or the resolution of any particular emulsion. As long as we stay on the line shown in Figure 1, $E = k\sigma^2$, the exposure time required will be the same, independently of the type of emulsion chosen, provided the resolution of the photographic material is matched by the optics. In other words, the only way to decrease exposure time would be to obtain not a new member of the silver-halide family, but a new type of photo-sensor.

The above discussion can be summarized in the following way: From the three equations

$$\theta = \frac{\Delta}{h} = \frac{1}{10\sigma f} = \frac{1.2\lambda}{2R}$$

we can express the performance parameter of ground resolution as

$$\Delta = 1.2\lambda \frac{h}{f} F$$

where λ is a fundamental parameter, F is a state-of-the-art parameter and f (the focal length) is a design parameter. The state-of-the-art parameter F is limited by both the difficulties of theoretical design as well as fabrication techniques to a minimum value of unity. This would imply that the sensor has a minimum resolution of 1000 lines/mm. In this case, for a nominal altitude of 100 km,

$$\Delta = 10^3/f$$

where the ground resolution Δ and focal length f are both given in centimeters.

This is where the myth of long focal length arises: Given a minimum achievable F, and matching sensor resolution, the problem is to build a camera with longest focal length. Actually this is the same as has been said before--the problem is to maximize absolute aperture.

TABLE 2

Ground Resolution Δ for F1, 1000 lines/mm
Nominal Altitude 100 km

Δ	f
10 cm	1 m
1 m	10 cm
10 m	1 cm

Radiation Resistance

A factor in exploration of the solar system is the environment of radiation effects due to high energy particles, gamma and X rays. Even though the actual photography may be done in a clean environment, the system has to pass through Van Allen belts and solar flares. It is expensive to shield a sensor from radiations, so there is some emphasis on choosing a sensor which is resistant as far as possible to these effects. The difficulty is that, to first order, lack of sensitivity to nuclear radiations is highly correlated with sensitivity to photons. In second order special silver-halide emulsions can be prepared which are relatively more sensitive to visible light than X rays, but this cannot be a prime method of solution.

This remark probably applies to all sensors. There are two approaches. One is to choose a sensor which is deactivated, and not damaged when passing through a radiation belt. The other is to eliminate all exposure caused by passage through the radiation, and prevent exposure to radiation on the return passage through radiation after photography. The Itek material offers both avenues of solution because (a) it can be "cleaned" just prior to use, and (b) the latent image can be stabilized with relative ease immediately after use.

Once silver halide is exposed (as by radiation), the latent image cannot be removed without desensitizing the surface, because the silver used in the development comes from the photosensitive material itself. In the Itek material, the photosensitive material is independent of the developing procedure. Any latent images produced by radiation or light before photography can therefore be eliminated without significant effect on sensitivity. That this can be done simply, with little added equipment, has been demonstrated. In operation, then, all unwanted latent images could be removed on board and a clear photosensitive material supplied to the camera a few seconds before exposure.

After exposure it is necessary to protect the film from subsequent exposure and hence fogging. One solution is merely protection in a heavily shielded chamber. To avoid such shielding, there is the choice of on-board immediate developing and fixing, or of merely stabilizing the latent image. The latter requires less weight of solutions to be carried. Preliminary experiments show this can be done with the Itek material, so that it is proposed to go in this direction.It is quite reasonable to expect that a purely dry stabilizing chemistry can be developed at a later stage.

SECTION III - SYSTEM PROBLEMS

Image Motion

Exposure time is an important deduced design parameter since in operation it results in smear due to vibrations of the sensor relative to the optics, and motions of the whole camera system relative to the object being photographed. There is an upper limit to the time which can be tolerated, dependent on the magnitude of these motions and the technical difficulties of compensating for them. We shall now proceed to determine the magnitude of this problem in terms of the basic parameters.

The optic axis of the camera is travelling with a velocity $\underline{v}$ over the ground. This, in the operational conditions we assume of unforced orbiting, is a function of height above the ground, $\underline{h}$. We shall not give the basic relations of v,h, the gravitational constant and the mass of the object being circumnavigated, since it turns out that for all lunar or planetary orbits considered v/h is of the same order of magnitude, 2×10^{-2} radians/sec, and deviations from this can be easily introduced.

The angular motion of the image in exposure time $\underline{t}$ is then vt/h. If as before θ is the resolved angle, let $\underline{m}$ be the number of resolved angles the image traverses, so that the smear

$$m = \frac{vt}{h\theta}$$

Substitution of the expressions above for t and θ gives

$$m = \frac{1}{43\pi\lambda^3} \frac{v}{h} \frac{k}{T} \frac{1}{B} 2R$$

The intriguing feature of this expression is that the smear of m line pairs of resolution is independent of the focal length and numerical aperture. It is independent of the type of emulsion used, in regard to speed E or resolution σ (but not of the class of sensor characterized by the parameter k).

The first factor, v/h, as we have seen is fixed by operational requirements. The object brightness B is also fixed, at maximum, by the solar constant. As before, the transmission coefficient T is determined by the optics, and k by the type of sensor. The only design parameter appearing is the aperture 2R, which we have had to make as large as possible to get resolution. Substitution of numbers gives a value of m of the order of 500. No system design parameter is available to us to reduce the smear, and it is beyond expectation that any technical parameter can be improved sufficiently (i.e., three orders of magnitude) to eliminate it. (A change of orbit from 40 to 400 nautical miles gives one order of magnitude improvement. A synchronous orbit would reduce the smear to zero.) That is to say, a smear of m = 500 line pairs is to be expected in any system, and no choice of design parameters can reduce it. It is thus mandatory to eliminate smear independently by some kind of image-motion compensation. The magnitude of the effect shows that the direction of the correction is also important--an error of 1/500 radians will give detectable transverse smear, so that the correction must be made vectorially in high-performance systems.

In this derivation, the figure of m = 500 is reached on the assumption that the optics is performing at theoretical resolution. In some systems it would be an order of magnitude smaller, but the above conclusions still hold.

Tolerance in Focussing

In systems with small F-number making use of high-resolution film, the tolerance in maintaining focus, δf, can be calculated, and is approximately

$$\delta f = 1/10\sigma$$

Although this means the use of high-resolution systems demands proportionately tighter maintenance of focal length in absolute value, the fact that the system is smaller in dimension makes this proportionately easier to accomplish. Nevertheless, automatic focussing is highly desirable in future high-performance systems. Automatic focussing to a quarter of a wavelength in a dynamic system has been made operational by use of the Bernoulli principle*.

Photographic Problems

As the resolution increases the effect of defects in the photographic material and dust become more serious, in the sense that more information is lost per defect.

Because the Itek material remains sensitive even after exposure to light, the film can be examined in full daylight for defects before packaging for use. The nature of the material lends itself to much better control as far as emulsion defects go because gelatin is not used (see photographs 1 and 2).

In regard to dirt arising from processing, it seems a shame that any should be allowed to occur in a mission as expensive as reconnaissance. A technique has been worked out on an Air Force contract* using a meniscus filtered immediately before processing which effectively eliminated all dirt during processing of very high resolution photography. This should be adopted in reconnaissance, and would dispose of this question.

*Contract AF 30(602) 1823, under cognizance of Intelligence Laboratory, Rome Air Development Center (ARDC), Griffiss Air Force Base, New York, reported on June 20, 1959.

SECTION IV - SYSTEM ANALYSIS

Although the design and construction of cameras are clearly well in hand empirically, there is a need for a formal analysis of camera systems. Such an analysis would be a set of interlocking formulas relating all the parameters of the design of a camera system, combined with the operational, physical and economical restraints. These formulas would show the interactions between the various parts of the system and permit an overall optimization. It is also important to clarify certain issues, by separating the parameters into classes.

A big advantage of such an analysis is that it reveals exactly what is limiting the performance of current systems. Is it something fundamental, such as diffraction theory, or is it a state of technology, such a speed-resolution characteristic of current emulsions? Answers to these and similar questions are not available for our current programs, and it is proposed to determine them.

For this kind of analysis parameters will be classified into the following categories:

a. performance or functional
b. fundamental (physics or chemistry)
c. empirical, or state of the art
d. constrained by technology, economics or ease of use
e. operational, determined by the total system
f. design, consequences of the analysis

The performance parameters are those which we wish to optimize in the camera system, to meet practical requirements. The most important one is ground resolution, and a secondary one is field of view or coverage.

The fundamental parameters are determined by the laws of physics. A primary one is angular resolution, limited by the wavelength of light, which in turn depends on the absolute aperture, 2R.

The empirical parameters are fixed by the state of the art or technology. The most important are those parameters which express the trade-off between speed and resolution of a photographic material. These ultimately depend on fundamental laws of physics and chemistry, and it is important to try to find these dependencies in order to learn the ultimate limitation of the system. At the same time, it is equally valuable to appreciate that materials with better parameters can be obtained by a determined experimental effort. It is a purpose of systems analysis to reveal which empirical parameters are really important, so that we know best where to place our effort. It is a further aim of this program to derive quantitatively the empirical parameters from fundamental relations of physics and chemistry by setting up an appropriate model for the phenomenon.

Certain parameters are constrained by technology, for example the diameter of a large mirror figured to a fraction of a wavelength. The numerical aperture is constrained in that no known methods can give small F-numbers for large apertures. Economics also restricts the construction of large diameter systems with low F-numbers.

Related to these are the operational parameters, which are determined or constrained by other features of the system. In a moon probe, the height and velocity of the camera are such operational parameters. While to some extent these are given, they should be included in the analysis, as they indicate trade-offs between, say, difficulties in orbiting and lens fabrication. Their inclusion helps to prevent sub-optimization.

The design parameters are those whose values are determined as a consequence of the fundamental and empirical parameters by optimization. Such are the focal length, time of exposure and numerical aperture. The design parameters are under our control, and should be looked upon as consequences, not determiners, of the system design. It is important to identify these; otherwise attention and development is directed towards the wrong factors.

TABLE 3

Examples of Parameters

Name	Symbol	Dimensions
Performance		
Ground resolution	Δ	cm
Image motion (number of lines)	m	dimensionless
Fundamental		
Wavelength of light	λ	Å
Limiting angular resolution	θ	radians
Empirical, state-of-the-art		
Sensor figure of merit	k	photons/line pair
Constrained		
Maximum mass	M_{max}	kilograms
Maximum aperture	$2R_{max}$	cm
Minimum F-number	F_{min}	dimensionless
Density of materials	ρ	gms/cc
Operational		
Maximum mass	M_{max}	kilograms
Satellite velocity	v	km/sec
Satellite altitude	h	km
Brightness of object	B	photons/sec steradian
Design		
Aperture	2R	cm
Focal length	f	cm
F-number	F	dimensionless
Mass	M	kilograms
Exposure time	t	seconds
Sensor resolution	σ	lines/mm
Illumination of film	I	photons/cm^2 second

In the previous section we derived certain relationships between the various types of parameters, the most important of which are recapitulated here. First, for a given photographic material there seems to be a trade-off relationship between speed E and resolution σ

$$E = k\sigma^2$$

where k is a state-of-the-art parameter defining the class. From this we obtained an expression for the exposure time

$$t = \frac{1}{36\pi\lambda^2} \frac{k}{T} \frac{1}{B}$$

where T is a state-of-the-art parameter showing the limitations due to transmission characteristics of the optics. The brightness of the object B is an operational parameter we have to live with.

Matching the resolution of the optics with that of the sensor gave

$$F\sigma = 1/12\lambda$$

showing the F-number of the optical system and the resolution of the sensor have to be related.

SECTION V - PROPOSED SYSTEMS

As outlined in the previous section, we have identified parameters critical for the improvement of cameras in reconnaissance. In previous sections we have proposed immediate attacks to some of these critical areas. We now recapitulate the line of reasoning and proposed solutions, leading to new camera systems of improved performance.

The starting point is the virtue of high-resolution sensors, in reducing the size of the camera weight of film and easing the optical design. A film of resolution of 10,000 lines/mm is available (with a characteristic k superior to silver halide). This resolution is far beyond that in sight for reconnaissance cameras. Thus a nominal value of σ = 1000 lines/mm will be taken. The equation relating σ to F (Table 1) then shows the optics must be at least F = 1, and approaching the theoretical limit of resolution. Microscope objectives are readily available meeting these requirements, so our first proposed system is based on them.

One of the consequences of the last sections is that high-resolution sensors, say of σ = 1000 lines/mm, could be profitably used in camera systems, for the exposure time (if the optics matches in resolution) is independent of σ. Furthermore image motion is independent of σ. In other words, no penalty is assumed, other than the engineering for stabilizing the working distance of sensor from optical elements to one part in σ or better.

On the other hand, the advantages of high-resolution sensors are very significant. For a given ground resolution from a predetermined satellite height, the size of the camera goes down as the square of σ. With the use of photographic materials of very high resolution, the amount of film needed for a desired area of coverage also goes down as the square of σ. We shall now describe some enticing system designs within reach with imminent state of the art.

In order to verify the principles outlined and to get practical experience with the new Itek process as a photographic film, we propose first building a very low cost camera using a commercially available microscope objective. This would have the following performance characteristics.

Microscope-Objective Camera

Nominal resolution	1000 lines/mm
Nominal altitude, h	100 km
Ground resolution, g	10 m
Aperture, F	1
Focal length, f	1 cm
Angular field	6^o
Film field	3 mm
Film resolution, σ	10,000 lines/mm
Area of film for USA	0.1 m^2
Area of film for Moon	1.5 m^2
Weight of film - USA	20 gms
Weight of film - Moon	300 gms

It should be remarked that the angular field of microscope objectives are all the same, and rather small, as they merely match the angular field of the eye. It should not be difficult to widen the field by redesign of the first element with a material of high refractive index. Microscope objectives alone have a high curvature of field, which is normally removed by the eyepiece. It should not be difficult to flatten the field, but in any case bending the film is relatively easy as the exposed portion is only a few millimeters in diameter.

Ten-Centimeter F1 Camera

It is within the state of the art to design and build a camera with a mirror objective with aperture F1 and focal length 10 cm, which would have properties listed below:

Nominal resolution	1000 lines/mm
Nominal altitude, h	100 km
Ground resolution, g	1 m
Aperture, F	1
Focal length, f	10 cm
Angular field	10°
Film field	16 mm
Film resolution, σ	10,000 lines/mm
Area of film for USA	10 m^2
Area of film for Moon	150 m^2
Weight of film - USA	2 kg
Weight of film - Moon	30 kg

This is the camera to make in the next two years.

This system should be fabricated by the techniques suggested below. A glass or boron fiber structure would be the basis of a mirror objective. The surface would be polybutadiene formed by ultraviolet light, under control of laser interferometry, producing an aspheric surface.

One-Meter F1 System

The most serious objective this proposed program could have would be an F1 system of 1 meter focal length. With a ground resolution of 10 cm, such a camera system would meet all the requirements visualized for some time to come.

The various technical difficulties anticipated have been discussed in section III. They will be explored and, hopefully, overcome in laboratory construction of smaller cameras. The proposal to apply new technology to the fabrication of optical elements is inspired by the belief that one can see that in principle these new approaches should enable us to overcome the barriers now facing the construction of compact, very high performance camera systems.