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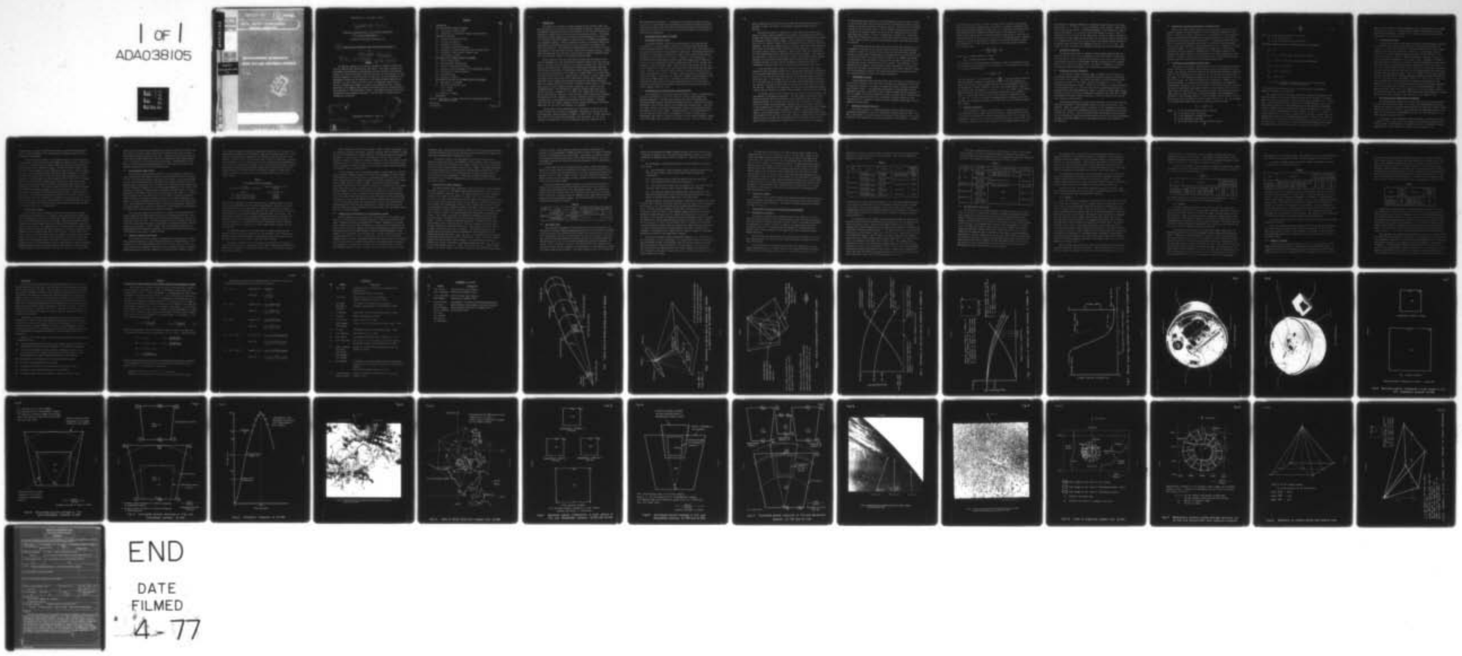

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by

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SUMMARY

The Skylark sounding rocket has been developed to produce a stable platform for high-altitude remote-sensing experiments. This Report describes the development and performance of photographic payloads carried on three Skylark rockets, one fired from Woomera, South Australia and two from Mercedes, San Luis Province, Argentina. The methods used for prediction of the performance of the photographic systems and the estimation of the required camera exposures are detailed. For each rocket firing the choice of photographic emulsions and filters is detailed and examples are given of the imagery obtained. Measurements made on the imagery have validated the methods used for the prediction of the performance of the photographic systems. The imagery has been assessed and interpreted by the Geography Department of the University of Reading and its findings are referenced.

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1 INTRODUCTION

The growth of the science of remote sensing has been closely linked over the past eighty years with that of man's aerospace capability, ranging from early photographic experiments carried out from balloons to the precision mapping and atmospheric sounding carried out from lunar and planetary orbiters. Terrestrial photographic remote sensing from aircraft has been developed into a versatile tool allowing conventional mapping at typical scales of 1:50000, photogrammetric and topographic mapping. Airborne geophysical surveys are routinely made using magnetometers and radiation detectors to aid in the search for magnetic and radioactive minerals. Conventional aerial photography is used also for land-use, land-capability and agriculture surveys, chiefly in developing countries. Experiments have been made into the uses of multi-spectral scanners, sideways-looking radar and microwave systems for the purposes outlined above.

Remote sensing of the earth from space altitudes has been shown to have certain advantages over more conventional techniques, which offset the disadvantages of (usually) lower resolution at the target and higher cost; these are the synoptic and time-specific capabilities of observations from space platforms. The altitude of satellite- or rocket-borne remote sensing systems allows large areas of the earth's surface to be imaged on a single frame or in a single scan, in a short time interval (i.e. synoptically), and there is a body of remote sensing opinion which states that certain large-scale features and lineaments are detectable on such imagery which cannot be detected on the higher resolution mosaic of imagery obtained from aircraft altitudes; further, the act of mosaicing many frames to produce imagery covering a large area is a tedious and time consuming process. The time-specific capability enables large areas of the earth's surface to be imaged in a very short time compared with the weeks or months which might be required to collect the data using conventional techniques. The importance of this capability is in the collection of data on transient phenomena such as crop abundance and possibly natural disasters. Orbiting satellites have the further capability of the repeated monitoring of such phenomena when the use of the time dimension is necessary.

Various remote sensing experiments were undertaken from space altitudes during the NASA Gemini and Apollo programmes, culminating in the launch of the Earth Resources Technology Satellite (ERTS-1) in March 1972. Further experiments were made during the NASA Skylab programme, and experiments are also being planned for implementation on the ESA Spacelab, which will form part of the

NASA Space-Shuttle programme. A sounding-rocket platform for remote sensing was expected to share many of the advantages of satellite platforms but would be cheaper, would allow a more free choice of observation time, need a much shorter preparation and launch time and hence would be more flexible in its response to time-specific requirements.

2 THE SKYLARK REMOTE SENSING PLATFORM

2.1 The Skylark sounding rocket

The Skylark sounding rocket which was developed at the Royal Aircraft Establishment for upper atmosphere research is now produced by the British Aircraft Corporation (BAC) and has been used since 1957, in over 300 launches, to carry numerous astronomical and ionospheric experiments. The Skylark vehicle has a diameter of 0.43m and is propelled by a range of solid fuelled rocket motors and boosters which enable it to be used in a single- or multi-stage mode. It is an unguided vehicle which may be launched from fixed ranges such as Woomera or Kiruna or, via a transportable launcher designed and built by BAC and RAE, from temporary or special purpose ranges. After the motors have burnt out they are usually separated from the head of the vehicle which contains the payload; thereafter, the parts of the vehicle follow a ballistic trajectory and may be soft landed using parachute systems. The mass of the head, which is constructed on a modular principle, is usually in the range 100 to 300kg, allowing apogees in the region 400 to 200km respectively. The heads of Skylark vehicles are often stabilised by attitude-control systems employing gas jets to provide control torques and obtaining their positional information from the sun, the moon, the earth's magnetic field or a star.

2.2 Development of the Skylark remote sensing platform

The development of the Skylark sounding rocket to produce a remote-sensing platform was undertaken to meet the needs of a proposed Anglo-Argentinian geoscopy experiment. The Argentinian Comision Nacional de Investigaciones Espaciales (CNIE) proposed that Skylarks should be fired in Argentina to produce photographic data delineating part of the Pampas wheat-growing area. This area was almost circular, of diameter approximately 700km, and the ground-resolution was required to be 100m or better. The agreed purpose of the experiment was to provide data which would enable an assessment to be made of high-altitude photography from rocket or satellite platforms for uses such as synoptic, large-scale land usage, crop, geological and mineral surveys. The launch site chosen was the Argentinian Air Force base at Mercedes, San Luis Province, and it was intended to impact the vehicle in the sparsely populated region south of Mercedes.

The modular principle of construction of the Skylark head allows a wide variety of remote sensing equipment to be carried, in cylindrical bays of 0.4m diameter and standard lengths varying between 0.13m and 0.52m which may be sealed at atmospheric pressure before flight, or flown unsealed as required. Bays of other than the standard lengths can be manufactured to house particular items of equipment. The bays are clamped together by manacle rings, with power and signal lines being led through the bays by means of butting connectors. The build of the remote sensing version of Skylark is shown in Fig.1 with two standard bays of 0.52m length shown housing undefined remote sensing equipment. The length of the head shown is 3.9m and it could carry a mass of 50 to 75kg of remote sensing equipment to an altitude of about 250km using the rocket motors which were currently available for this vehicle: equipment of greater mass could be accommodated using more bays, but the apogee achieved would have been lower.

A new attitude-control system for the head of the Skylark vehicle was designed in Space Department at RAE to meet the geoscopy experiment requirements; it used Earth-albedo horizon sensors and a cold nitrogen jet system to align the yaw axis of the head with the local vertical. This attitude-control system is detailed in Ref.1. The maximum yaw axis to local vertical alignment inaccuracy is $\pm 1.35^{\circ}$ about each of the pitch and roll axes, and the peak angular velocities are reduced to less than $0.25^{\circ}/s$ about the pitch and roll axes and $0.1^{\circ}/s$ about the yaw axis. Rotation of the head about the yaw axis in pre-programmed angular steps at pre-set intervals is possible over an angular range of greater than 360°.

The design concept of the attitude-control system was closely linked to the requirements of the geoscopy experiment. The peak angular rates quoted above provide sufficient short-term stability to the platform to enable calculated ground resolutions of 15 to 45m to be achieved over the required area from an altitude of 250km, using photographic emulsions which are currently available. It was recognised that in order to image the required circular area onto a single frame from the expected apogee of the head of 250km, it would be necessary to employ a lens of approximately 140° field of view on a camera whose optical axis was aligned with the yaw axis of the head. However, calculations of the resolving power of such a lens when used with standard aerial emulsions showed that the ground resolution requirement of 100m could not be met by such an arrangement.

The method which was adopted was to mount cameras with narrower fields of view in the head with their optical axes inclined to the yaw axis as shown in Fig.2, leading to a pattern of ground coverage as in Fig.3. Rotation of the head about the yaw axis by a suitable angle θ would enable a similar pattern of ground coverage to be obtained adjacent to the first, and repeated rotations by the same angle would enable a circular coverage area to be built up. Calculation showed that by employing an array of cameras whose fields of view were scanned in this fashion, ground resolutions significantly better than 100m could easily be achieved.

The required angular manoeuvres about the yaw axis were determined by the arrangement of cameras and the angular fields of view of the lenses employed. A period of either 12s or 20s was allocated as the interval between yaw-axis manoeuvres, these figures being based on consideration of the anticipated fields of view of the lenses, the frame repetition rates of the cameras, the angular accelerations of the head about the yaw axis and the mass of nitrogen gas for providing the control torques which could be carried. For simplicity, it was decided that the cameras' cycling should be made independent of the yaw-axis manoeuvres; the stable period between manoeuvres would enable sufficient frames for the experimental purposes, and frames exposed during the manoeuvres would have degraded ground resolution and could be discarded.

3 PHOTOGRAPHIC PAYLOADS

The photographic camera has been widely used for aerial reconnaissance and survey tasks during the past sixty years, and hence the literature on this topic is large but scattered. A review of the physical aspects of aerial photography may be found in Ref.2. The performance requirement of the payloads in these experiments have been stated above, and of these, probably the most important is that for imagery with ground-resolution of 100m or better; hence, the method used for estimating the ground-resolution attainable by camera systems, and the measures which are necessary to ensure that this theoretical performance may be achieved are given below.

3.1 Modulation transfer-functions

The resolving power of a lens-photographic emulsion combination may be conveniently determined by the use of modulation transfer-functions (MTF). The MTF of any element in an optical system is defined as: the modulus of the Fourier transform of the image-spread function appropriate to that element[3]. A method, which has been criticised[4], but which is widely used[5] to predict the resolving power of lens-emulsion combinations, is to employ a lens MTF in combination with an emulsion threshold modulation (TM) curve for a sinusoidally modulated target. this method was used throughout the design stages of the payloads. In this method the MTF and TM curves are plotted as shown schematically in Fig.4 and the intersection point of the two curves is taken to be the maximum spatial frequency, measured in cycles per millimetre, of imagery of sinusoidally modulated targets, with modulation $M = 100\%$, which may be detected on the photographic emulsion. M is defined thus:

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100\% \qquad (1)$$

where I_{max} = maximum luminance of target

I_{min} = minimum luminance of target.

The reciprocal of the maximum spatial frequency is taken as the smallest resolution element that may be detected on the emulsion. M is related to the contrast of the target by the equation:

$$M = \frac{C - 1}{C + 1} \times 100 \qquad (2)$$

since the contrast C is defined thus: $C = \frac{I_{max}}{I_{min}}$. It has long been recognised that the apparent contrast of targets when viewed through the atmosphere is reduced (see section 3.2) principally by the effects of atmospheric scattering and absorption of light[3]; therefore, to predict the maximum spatial frequency for targets with, for example, $M = 23\%$ (i.e. $C = 1.6$), the MTF curve ordinates must be multiplied by the factor 0.23, which modifies the curve as shown in Fig.4. It can be seen that the effect of the reduction of modulation from $M = 100\%$ to $M = 23\%$ is to reduce the maximum spatial frequency of the data recorded on the emulsion, and hence to increase the size of the smallest resolution element.

3.2 Contrast attenuation

The scattering of light in the atmosphere is a complex phenomenon which does not lend itself to simple theoretical analysis. Qualitatively its effect is to reduce the intensity of reflected image-forming light and to increase the atmospheric luminance, hence reducing the apparent contrast of the target[6]. The scattering, and hence the contrast reduction is wavelength-dependent, with the scattering by a 'Rayleigh atmosphere', consisting of gas molecules only, being proportional to λ^{-4} where λ is the wavelength of the incident light[3]; hence the contrast attenuation for a 'Rayleigh atmosphere' is more severe for light of shorter wavelengths. It is usual in aerial photography to employ a 'haze' or 'minus-blue' filter in front of the camera lens, in order to absorb radiation of wavelength less than 500nm, and hence reduce the effects of contrast attenuation. It was assumed that by the use of such filters, the minimum apparent contrast of the ground scene from above the atmosphere would be 1.6, i.e. $M = 23\%$. The figure $M = 23\%$ was used in all subsequent calculations of system performance.

3.3 Atmospheric turbulence

The MTF associated with the passage of image-forming light through the turbulent layers of the earth's atmosphere is not a well-defined constant function (see Ref.7), but it is empirically understood not to have a severe effect on the ground resolution of photographic systems, providing that the turbulent layer is not close to the camera lens[3]. The effect of atmospheric turbulence was therefore neglected throughout the calculations of ground resolution.

3.4 Estimation of ground resolution

In this Report, ground resolution (GR), is defined as the reciprocal of the maximum spatial frequency of sinusoidally modulated targets on the ground, which can be just resolved. The ground resolution is obviously dependent upon the apparent contrast of the target, and was calculated for $C = 1.6$, the assumed minimum apparent contrast. The MTF of the lenses to be used was obtained from the manufacturers, or, where the data were not available was measured in Instrumentation and Ranges Department of RAE. A tungsten filament lamp, suitably filtered, was used to provide a broad-band illuminant in the range 380 to 750nm. Measurements were made at several positions in the focal plane of the lens and over a range of lens apertures.

The threshold modulation curves for the emulsions to be used were obtained from the literature[8,3], thus enabling a family of curves such as Fig.5 to be obtained. Hence the maximum spatial frequencies of the information in the focal plane of the lens-emulsion combination under the stated conditions were obtained as shown also in Fig.5. The relationship between the maximum spatial frequency of the lens-emulsion combination and the ground resolution for oblique photography, as used in these experiments, is a simple geometrical one and is detailed in the Appendix.

3.5 Degradation of ground resolution due to camera motion

Motion of a camera during exposure causes image-motion in the focal-plane and hence degrades the resolving-power of the lens-emulsion combination. The effect of image motion may be introduced into the estimation of system resolving-power by calculating the MTF appropriate to the expected motion of the camera platform and convoluting it with the lens MTF[3,9]. However, the method which was used to estimate the degradation was simply to calculate the apparent ground-motion of the target during the camera exposure and to use an empirical criterion[2] to establish whether or not the degradation was significant. The empirical criterion is that degradation is insignificant if the apparent motion of the target during camera exposure is less than 60% of the ground resolution at that position. Using this criterion it was established that the maximum photographic exposure time that could be used in these experiments was 8ms.

3.6 Estimation of photographic exposure times

The cameras to be used in these experiments did not have automatic exposure control and hence the required camera exposures had to be estimated and set pre-flight. The luminous flux which falls onto the photographic emulsion is dependent upon: (a) the illumination of the ground scene, (b) the surface reflectivity of the target, (c) the atmospheric properties, (d) the optical properties of the lens and filter system. The solar horizontal-plane illuminance is commonly used in aerial photography as a measure of ground-scene illumination; its magnitude in clear-weather conditions, is a function solely of the solar-altitude and therefore may easily be determined from standard tables of solar-altitude versus latitude, time of year and time of day[3]. The variation of target reflectance over the very large areas of terrain which were to be photographed in these experiments was obviously not well defined; however, it may be assumed that the range of reflectance likely to be encountered will not be greater than 15:1 [3]. B_0 , the luminance of the target when viewed from above the atmosphere may be written:

$$B_0 = I_s R_g T_a + B_a \qquad (3)$$

where I_s is the incident horizontal-plane illuminance
R_g is the ground object reflectance
T_a is the atmospheric transmission factor
B_a is the atmospheric luminance
I_f the camera focal-plane illuminance may be written:

$$I_f = \frac{B_0 T_\ell}{4 A_R F} \qquad (4)$$

where A_R is the relative aperture of the lens
F is the filter factor
T_ℓ is the transmission factor of the lens.

Using these equations and the following values for the parameters

A_R = 11

F = 9 measured value, see section 4.3 below

I_s = 64500 lux (assuming a 9 am local-time experiment)

R_g = 0.24 (from Ref.3)

T_a = 0.5 (from Ref.6)

B_a = 2570 cd/m^2

T_ℓ = 0.84 (assuming a 4% intensity loss at each air-glass and glass-air interface in the lens)

it was deduced that an exposure time of 4ms would produce a photographic exposure of 0.01mcds on the emulsion.

The characteristic relationship between the integrated illuminance of the radiation falling upon the photographic emulsions and the density of the image which is produced is expressed in a density versus $\log_{10}$ (exposure), or D versus log E curve such as that shown in Fig.6 for a reversal emulsion. This figure shows also the variation of the resolving power of the emulsion with exposure. A typical exposure range for high-altitude and space photography of the earth is $\Delta \log E = 0.204$, and adjustment of the parameters A_R and F in equation (4) and suitable choice of the camera exposure time is necessary to ensure that the exposure range falls onto the linear portion of the D versus log E curve of the emulsion to be used, and that the maximum exposure E_{max} falls close to the toe of the curve. A trade-off is often necessary between choosing the optimum lens aperture for the resolving power of the system and an exposure time t which is short enough to prevent degradation of the resolving power due to image motion (see section 3.5). Exposures were estimated in this manner using the manufacturer's published D versus log E curves, and also by extrapolation from aircraft trials (section 4.5).

3.7 Sensitometric control

In order that consistent data might be obtained from photographic emulsions it is necessary that strict control over their processing be maintained, as variations in the processing procedure may produce speed, fog level and contrast changes in black and white films and, in addition, colour balance changes in colour films. Similar changes of properties also occur as films age. The control procedure is to apply a standard step-wedge, consisting of a series of differing controlled exposures to all lengths of film. Throughout the experiments with which this Report is concerned a standard PH400 wedge was used, which was illuminated by a calibrated tungsten filament lamp filtered to simulate a source of colour temperature 3500 K. Where the use of a filter with a particular film was intended, then the light source of the wedging machine was additionally filtered using an identical filter. After the 'wedged' film has been processed, the resulting densities of the wedge steps may be measured using a densitometer, and the D versus log E curve drawn. From the D versus log E curve, the speed, contrast and fog level may easily be deduced, and compared with the manufacturer's data. All the films which were employed during these experiments, (with one exception) were processed in automatic processing machines. These machines provide closer control over temperature, solution strength, agitation and processing time than is possible using conventional hand-processing techniques and ensure a uniform treatment of all portions of long lengths of film.

4 THE SKYLARK SL1081 REMOTE SENSING EXPERIMENTS

Skylark SL1081 was intended to be a test vehicle for the new systems which had been developed and which were to be used in the Anglo-Argentinian geoscopy experiment; namely, the attitude-control system of the head, the roll-rate control system for the vehicle during its boost phase and the photographic system. This Report is concerned with the photographic system only: the performance of the other systems is reported in Ref.1.

The purpose of the photographic system experiments on SL1081 was: firstly to prove, in flight, the correct functioning of the cameras and associated hardware; secondly, to demonstrate that the methods used in calculating the camera exposures were correct; thirdly, to assist in the evaluation of the attitude-control system of the head and fourthly to provide data which would assist in the development of the interpretation techniques required for the experiments in Argentina.

The camera system consisted of a refurbished Royal Air Force F24 aerial reconnaissance camera fitted with a Ross XPRES f/4 aperture lens of 127mm focal length, and a Hasselblad camera, model 500 EL/70M fitted with a Zeiss Planar f/2.8 aperture lens of 80mm focal length. The Ross lens has an angular field of view of 70° and images onto the 142mm square frame format of the F24 camera; it is not of the most modern design, but had the best performance of currently available lenses whose field of view and focal length approximated to those required. The Zeiss Planar lens has an angular field of view of 52° and images onto the Hasselblad format of 55mm square; this type of lens has been used extensively in Gemini and Apollo space photography experiments and had good manufacturer's MTF data. Both lenses coupled relatively wide angular fields of view with MTF performance adequate to allow ground resolutions close to 100m when used in conjunction with appropriate aerial emulsions. These choices of lens led to a calculated ground coverage pattern on the earth's surface as in Fig.10, which shows that the radius of coverage from the nadir point N of the head was 310km, and that angular displacements of the head about the yaw axis of less than or equal to 59° between stable positions would be necessary to build up the required circular coverage pattern.

4.1 The F24 camera system

The F24 camera body was unmodified save for the provision of a steel retaining strap (in addition to the camera's own retaining device) which held the camera magazine in position. The body was bolted to a Dural plate provided with a hole through which the lens was located. The plate was mounted inside a standard 0.52m length Skylark body section which had been modified to provide a lens cone and aperture. The opposite face of the plate carried a rotating filter wheel, driven by a small electric motor, which ran in the space between the front element of the lens and the rear face of the lens cone. The F24 camera bay is shown in Fig.7. The filter wheel houses six equally spaced 76mm diameter photographic filters, and on initiation runs continuously at 4rev/min, power being supplied by the batteries carried in the head. The wheel is fitted with six adjustable cams on its circumference, each of which operates a single microswitch mounted beneath the wheel once per revolution, thus initiating the F24 camera exposure sequence at 2.5s intervals. The camera is driven via a flexible drive shaft by its own electric motor powered by the batteries carried in the head, and the sequence of shutter release, film wind and shutter reset occurs as each filter moves between the lens and lens cone. Laboratory tests on the camera and filter wheel assembly showed that there was no vignetting of the exposed frames due to the motion of the filters during the exposures. Measurements were also made in Instrumentation and Ranges Department to determine the accuracy of the exposure times provided by the focal-plane shutter.

4.2 The Hasselblad camera system

The Hasselblad camera type 500 EL/70M is a battery-powered single-lens-reflex camera which uses 70mm film stock in cassettes which hold up to 5m length of film. The camera body may be fitted with a wide range of Zeiss lenses having built-in Synchro-Compur shutters. The camera was modified for space use by the manufacturers by the removal of the internal mirror mechanism and focussing screen and the mechanical locking of the lens focussing mechanism after the lens had been focussed for objects at infinity using a broad-band 'daylight' source. Further modifications undertaken at RAE included the mounting of the camera in a composite Dural and glass fibre case which holds the lens firmly in position, allows the camera controls to be locked, provides a method for the rigid attachment of the camera to a Skylark bulkhead and provides a protective cover for the camera magazine. These measures were taken in order to increase the mechanical integrity of the camera system and to protect the camera and its film magazine from the impact of the head with the ground after its parachute descent.

The camera was mounted on a bulkhead in a standard 0.2m long Skylark body section which had also been modified to provide a lens aperture and cone, there being provision for a single fixed filter to be mounted between the lens and the inner face of the lens cone. The camera sequence of shutter release, rewind film and re-set shutter was initiated by a pulse which was derived from each alternate sequence pulse applied to the F24 camera; hence the Hasselblad exposures were synchronised with alternate F24 exposures. The Hasselblad camera system mounted in the Skylark body section is shown in Fig.8.

4.3 Choice of emulsions and filters

The initial choice was to employ a panchromatic emulsion in the F24 camera and an emulsion sensitive to near infra-red radiation in the Hasselblad. It was intended to use six narrow-band-pass filters in the filter wheel of the F24 in order to produce six separation negatives at each yaw-angle position, in spectral bands having small overlap but spanning the visible spectrum. However, because of a trade-off between the mass of nitrogen gas required for the attitude-control system and the stable period available at each of the yaw-angle positions, it was found to be impractical to ensure that six exposures could be obtained at each position. Hence, as there was sufficient time to ensure at least three exposures, it was decided to use two identical sets of three relatively broad pass-band filters in the six apertures of the wheel. Each filter consisted of Kodak 'Wratten' photographic quality gelatin material cemented between plane-parallel optical-quality glass, the resulting sandwich being 76mm in diameter and 6mm thick. The choice of emulsions and filters for use in the F24 camera system is shown in Table 1 below.

Table 1

F24 camera emulsion and filters

	Emulsion	Spectral sensitivity (nm)
	Kodak plus-X aerographic, type 2648	400-700
	Filters	**Pass waveband (nm)**
(1)	Kodak 'Wratten' No.12	500-700
(2)	Kodak 'Wratten' No.58	470-610
(3)	Kodak 'Wratten' No.25	590-700

Kodak plus-X aerographic was chosen because of its extended sensitivity in the spectral region 600-700nm over conventional panchromatic emulsions, its medium speed, high contrast which would help to counteract the effects of contrast attenuation, and its resolving power, which was well matched to that of the Ross lens according to the published threshold modulation data for the film. The pass bands of filters 2 and 3 compared closely with the spectral sensitivity of channels 4 and 5, (500 to 600nm and 600 to 700nm respectively) which were at that time proposed for the NASA Earth Resources Technology Satellite (ERTS-A), and thus would allow a comparison to be made between imagery obtained via the two platforms.

The Geography Department of the University of Reading, which had been awarded a University Research Agreement for the assessment of the imagery from SL1081, requested that 'panchromatic' imagery should also be obtained, and this was effected by the use of filter 1 (pass band 500 to 700nm).

The optical transmission of the filters was equalised by the addition of neutral density material to the gelatin filters before cementing them between the glass discs, this being necessary because there was to be no automatic exposure control on the cameras.

This procedure was effected by exposing a length of plus-X aerographic film to a series of standard step wedges, using the standard 3500 K illuminant filtered by each of the Wratten 12, 58 and 25 filters. The film was machine processed and the three D versus log E curves were produced. From the curves it was possible to measure the change in exposure necessary on two of the wedges in order to make the three D versus log E curves coincident at any particular density level, and hence to deduce the density of the neutral density filters which would be required in order to achieve this.

It was intended to use the Hasselblad camera to obtain imagery in the near infra-red (700 to 900nm), because of the well known advantages of this waveband for the detection and classification of growing vegetation[10], and again to provide a comparison with the imagery obtained by the ERTS-A satellite in its band 6 (700 to 800nm) and band 7 (800 to 1100nm). The emulsion chosen was Kodak aerochrome infra-red, type 2443, which is sensitive to radiation in the waveband 500 to 900nm when used with a Kodak Wratten 12 filter; it is a 'false-colour' reversal emulsion with its three emulsion layers sensitive to green, red and infra-red radiation. When the image has been formed by the colour subtractive process[11] an object which reflects green light will appear blue in the developed transparency, an object which reflects red light appears green and objects with infra-red reflectance appear red; therefore good contrast is provided between growing vegetation which has high reflectance in the near infra-red and bare soil and sand which reflects chiefly red and green light, and thus appears green-blue on the developed imagery.

4.4 Analysis of the performance of the photographic systems

The Ross XPRES lens was focussed, and its curvature of field and MTF were measured in Instrumentation and Ranges Department of RAE using broad-band 'daylight' illuminant covering the waveband 375 to 750nm. Examination of the MTF curves showed that the on-axis performance at an aperture of f/8 approached the limits set by diffraction, whereas the off-axis performance was relatively poor. Refocussing the lens by 0.25mm produced a better off-axis performance at the expense of the performance for near-axial rays. The MTF curves were scaled for a target modulation of $M = 23\%$ as described in section 3.1; the threshold modulation curve for plus-X aerographic emulsion was obtained from the literature[5] and the curves plotted as shown in Fig.5; hence the maximum spatial frequency of the information at a number of positions in the focal plane of the F24 camera were obtained as shown in Fig.9. Similar calculations were undertaken for the

Hasselblad camera using the manufacturer's MTF data for the lens and a published threshold modulation curve for the aerochrome infra-red emulsion[5], leading to the focal-plane maximum spatial frequencies of Fig.9.

The ground coverage of the photographic systems was calculated from geometric considerations (see the Appendix) of the fields of view of the cameras' optical systems, the inclination of the cameras' optical axes to the yaw axis of the head and the assumed height of the head (i.e. 250km). The ground resolution of the photography was calculated using the maximum spatial frequencies in the focal plane of the lenses, the focal-length of the lenses and the geometric scaling factors (see the Appendix). Using these methods, diagrams such as Figs.10 and 11 were produced showing the ground coverage and ground resolution of the camera systems.

4.5 Calculation of camera exposures

The camera exposures were calculated in the first instance using the method outlined in section 3.6. The manufacturers published data were used to obtain for each emulsion a value for E_{min}, the minimum exposure required to produce a density on the linear portion of the D versus $\log E$ curve, and this was related to the camera lens aperture and shutter speed using equations (3) and (4). An alternative method which was used was to extrapolate the results obtained from conventional aerial photography trials in order to obtain the required exposures for photography from an altitude of greater than 200km. Wherever possible the camera types to be flown in the rockets were used in these aircraft trials, loaded with a 'wedged' length of the chosen emulsion and fitted with the appropriate filters. The aircraft was flown at an altitude of 6000m and the cameras were given the angle of inclination to the vertical which they would have in the rocket. A series of exposures were made varying by ± 1 f-stop about the calculated nominal, with a solar altitude of 45°, over a mixture of terrain (sandy beaches, ploughed and cultivated fields etc.) whose reflectivities were typical of those to be expected for the real targets. The emulsions were given the standard machine processes, their step wedges were read and plotted and the maximum and minimum densities, D_{max} and D_{min}, in the imagery were read using a densitometer and plotted on the D versus $\log E$ curves. Thus, the optimum exposure for that altitude could be chosen, or the modification required to optimise the exposure calculated. An optimum exposure has both D_{max} and D_{min} on the linear portion of the D versus $\log E$ curve with D_{min} close to the bottom of the linear region of the curve[2]. Having determined the optimum exposure for this altitude, a Kodak exposure computer was used to extrapolate the altitude of the photography to 17000m and hence determine the change in exposure required for photography from this altitude. The changes in exposure required for photography from altitudes greater than 17000m are negligible, since for photographic purposes the effective scattering atmosphere ends at approximately this altitude[3].

It was found that the two methods yielded similar results (agreeing to within one f-stop); hence for the majority of cases either method could be used. The infra-red colour emulsion however was of very high contrast and required an exposure correct to plus or minus ½ f-stop. For this emulsion the practical method yielded the more consistent results, and hence it was used throughout the trials as the preferred method.

Having determined the required exposure by the methods outlined above, a trade-off was necessary between lens aperture and shutter speed in order to optimise the ground resolution of the photographic system. The aperture and shutter speed were chosen so that the calculated ground resolution attainable with a particular lens aperture was not degraded by the image motion occurring during the associated shutter opening. The finalised details of the SL1081 camera system are shown in Table 2.

Table 2

Camera	Lens	Film	Filters (+ neutral density)	Exposure
F24	Ross XPRES Maximum aperture: f/4 Focal length 127mm	Kodak Plus-X aerographic Type 2648	Wratten No.12 (+ ND 0.7) Wratten No.58 Wratten No.25 (+ ND 0.4)	4ms at f/11
Hasselblad	Zeiss Planar Maximum aperture: f/2.8 Focal length 80mm	Kodak aerochrome Infra-red Type 2443	Wratten No.12	2ms at f/11

4.6 The SL1081 trial

The evaluation programme for the imagery, which had been developed by the University of Reading Geography Department, necessitated the collection of 'ground-truth' data both on the ground and from aircraft, over selected sites in the area to be photographed, both pre- and post-launch of the rocket vehicle. This data was collected by Reading University personnel working in collaboration with the Mineral Physics Section of the Australian CSIRO during the period November 1971 to May 1972 and is compiled in Ref.12. The Skylark vehicle was integrated and tested at RAE and was then transported to Woomera where it was prepared for launch by a team of RAE and BAC personnel. The chosen emulsions were cut to length and exposed to the standard step wedge at RAE; they were sealed into film cans and transported to Woomera in an ice-cooled picnic hamper by a courier. On arrival at Woomera the emulsions were stored in a freezer at -20°C until required for use.

The photographic requirements which were to be met during the trial are stated below:

(a) the firing was to take place with a solar elevation between 35° and 65° (for good terrain contrast coupled with relatively high solar illuminance);

(b) the horizontal ground visibility should be greater than 20km (i.e. there should be little haze at ground level);

(c) there should be as little cloud as possible, but certainly less than 3/8 cover over a circular area of radius 300km based on Woomera;

(d) the conditions should be favourable for an early recovery of the payload from down-range in order that the exposed emulsions should not be subject to daytime surface temperatures for a long period.

Skylark SL1081 was launched from Woomera at 0900 CST on 27 March 1972 (solar elevation 38°) in almost cloud-free conditions over the entire area of interest. The operation of the control system was as expected and has been reported in Ref.1. The head reached an apogee of 279km and a schematic profile of its trajectory is shown in Fig.12. The telemetry signals received from the head during the flight indicated that the cameras had functioned at the correct intervals of 2.5s for the F24 camera and 5s for the Hasselblad camera. The head was detected by tracking radars during its descent by parachute thus enabling the recovery party to reach the head shortly after its impact with the ground. A visual inspection indicated that only superficial damage had been sustained by the camera systems and that the film magazines were firmly in position and undamaged. The magazines were removed from the cameras, wrapped in light-tight material and returned to the range head at Woomera.

The plus-X aerographic film was despatched immediately for processing by Air Photographs Pty. Ltd. of Melbourne, to a specification agreed in advance with Space Department at RAE: the aerochrome infra-red film was returned to the UK and was processed by Fairey Surveys Ltd. The step wedges of both films were read and plotted, and comparison made with standard wedges; this showed that the films had been processed correctly and that no discernible degradation of the latent images had occurred.

81 frames were exposed by the F24 camera and the density range of the images was from 0.3 to 2.5: reference to the D versus log E graph for the plus-X aerographic emulsion showed that the density range of the imagery was contained on the linear portion of the curve and hence that the emulsion had been correctly exposed. 54 frames were exposed by the Hasselblad camera and the density range of the images was from 0.91 to 2.91. These densities are higher than would have been obtained with an optimal exposure but, owing to the high density range of the aerochrome infra-red emulsion, they still fall onto the linear region of the D versus log E curve, and hence the information loss on the imagery is small, being due to the reduction in resolving power of emulsions for aerial photography at image densities greater than about 1.0, an effect which is shown in Fig.6. It was deduced that for optimum exposure and resolution the exposure for the Hasselblad camera should have been increased by ½ to 1 f-stop. An example of the imagery is shown in Fig.13 and the area of South Australia which was imaged in Fig.14.

4.7 Analysis of imagery

Duplicates of the original imagery were produced at RAE by contact printing, and the subsequent analysis and interpretation by groups in the UK and Australia has been based on these duplicates. The results of these analyses are presented in Refs.12, 13 and 14.

5 THE SKYLARK SL1181 AND SL1182 REMOTE SENSING EXPERIMENTS

5.1 Description of payloads

The experience gained from the SL1081 trial and the analysis of its data was fed into the planning of the SL1181 and SL1182 trials to be held in Argentina. The main objective of these trials was to obtain a body of data which would enable an assessment to be made of the role of Skylark for remote sensing from space altitudes; therefore it was decided that the payloads for SL1181 and SL1182 should include cameras employing a wide range of lens focal lengths and photographic emulsions.

The F24 camera bay was retained in the same form as for SL1081 but an option was included whereby the camera could be loaded with Kodak aerochrome infra-red type 2443 emulsion.

A new camera bay was designed which contained three Hasselblad type 500 EL/70M cameras mounted, in a similar fashion to the single Hasselblad of SL1081, inside a standard 0.52m Skylark body section. The lenses were chosen so as to demonstrate a range of possible ground resolution versus ground coverage options when used in conjunction with the chosen emulsions. The choice of lenses and emulsions is shown in Table 3.

Table 3

Camera	Lens	Emulsion	Filter	Spectral sensitivity (nm)
F24	Ross XPRES Maximum aperture: f/4 Focal length: 127mm	Kodak plus-X aerographic type 2648	1 Kodak Wratten No.12 2 Kodak Wratten No.58 3 Kodak Wratten No.25	500-700 470-610 590-700
or F24	Ross XPRES Maximum aperture: f/4 Focal length: 127mm	Kodak aerochrome infra-red type 2443	1, 2, 3 Kodak Wratten No.12	500-900
Hasselblad No.1	Zeiss Sonnar Maximum aperture: f/4 Focal length: 150mm	Kodak aerochrome infra-red type 2443	Kodak Wratten No.12	500-900
Hasselblad No.2	Zeiss Sonnar Maximum aperture: f/4 Focal length: 150mm	Kodak aerial colour type SO-242	None required	400-700
Hasselblad No.3	Zeiss Sonnar Maximum aperture: f/5.6 Focal length: 250mm	Kodak aerial colour type SO-242	None required	400-700

The Kodak aerial colour type SO-242 emulsion is an experimental high-resolution colour material and was chosen so as to demonstrate, when used with the 250mm focal-length lens, ground-resolutions of the order of 20m, this being the minimum figure which could be obtained without it being necessary to reduce the residual angular velocities of the head of the vehicle by refining its control system (see Ref.1).

The orientation of the cameras' optical axes with respect to those of the head were chosen such that the required area of Argentina could be imaged, with there being large areas of overlap in the imagery obtained via the various cameras; thus, direct comparisons could be made between imagery of varying ground resolution in different spectral regions. The angles between the camera axes and the yaw axis of the head were chosen to be 25° for the F24 camera and 45° for all three Hasselblad cameras. The 45° angle of obliquity approaches the maximum angle that can be chosen without causing severe degradation of the ground resolution in the imagery of the edge of the circular area. The maximum spatial frequencies of each of the lens-emulsion combinations was calculated using the methods for section 3.1 and are shown in Fig.15. The calculated ground coverage and ground resolutions are shown in Figs.16 and 17 respectively, from which it can be seen that the required yaw-angle manoeuvres for SL1181 and SL1182 should be of less than or equal to 24° (the figure chosen was 22.5°).

The camera exposures were set on a similar basis to those for the SL1081 trial, making use of the data obtained during that trial and the results of aircraft trials carried out with the aid of Instrumentation and Ranges Department in the UK. The calculated exposures are given in Table 4 below.

Table 4

Camera	Emulsion	Filter (+ neutral density)	Exposure
F24	Kodak plus-X aerographic type 2648	1. Kodak Wratten No.12 (+ ND 0.7) 2. Kodak Wratten No.58 3. Kodak Wratten No.25 (+ ND 0.4)	4ms at f/11
or F24	Kodak aerochrome infra-red type 2443	1, 2, 3 Kodak Wratten No.12	2ms at f/8
Hasselblad 1	Kodak aerochrome infra-red type 2443	Kodak Wratten No.12	2ms at f/8
Hasselblad 2	Kodak aerial colour type SO-242	None	8ms at f/6.7
Hasselblad 3	Kodak aerial colour type SO-242	None	8ms at f/6.7

5.2 The SL1181 and SL1182 trials

The assessment of the imagery obtained via these trials was to be undertaken in the UK by a team from the University of Reading, Geography Department and in Argentina by Staff of Instituto Nacional de Tecnologia Agropecuaria, (INTA). Discussion between RAE and these two bodies had led to an agreed programme of 'ground-truth' data collection to take place both pre- and post-launch of the vehicles. The programme would include: aerial photography at an image scale of 1:20000 over selected sites in the area to be imaged by the rockets, using four Hasselblad cameras installed in an Argentinian Air Force aircraft loaded with the emulsion types to be flown in the rockets; spectro-radiometric measurements of typical vegetation and terrain types both on the ground and from an Argentinian Air Force helicopter; ground sampling by Reading University and INTA personnel with special emphasis on INTA experimental agriculture stations. The locations of the 'ground-truth' sites and aircraft traverses which were performed during the trials period are given in Ref.15.

The emulsion types to be used in the rockets and aircraft were cut to length and exposed to the standard step-wedge at RAE before being despatched to Argentina as personal baggage of the trials team, packed in a case containing solid CO_2 for cooling purposes. These measures were taken to avoid the possibility of the emulsions being fogged by X-ray examination at airports and to preserve the infra-red sensitivity of the emulsions respectively. On the team's arrival in Argentina the emulsions were stored at $-20^{o}C$ until required.

The photographic requirements to be met during the trials were similar to those for SL1081 with the exception of the cloud-cover requirement which was reduced to less than 1/8 cloud cover over the area of interest. The solar elevation angle range chosen for these trials was 35^{o}-65^{o} in order to obtain good terrain contrast coupled with reasonable horizontal plane illumination.

It was decided that the preferred emulsion to be used in the F24 camera was the Kodak aerochrome infra-red, because of its higher contrast (but slightly lower resolving power) than the panchromatic emulsion.

5.2.1 SL1182

SL1182 was launched successfully on 22 March 1973 at 1343 hours local time, with a solar elevation angle of 61^{o}, in almost cloud-free conditions over the target area, and with horizontal visibility estimated by the Argentinian Air Force as being in excess of 30km. The head was located by a tracking aircraft whilst descending on its parachute, and the recovery team was able to reach the head within an hour of the firing. The camera bay was substantially undamaged with the exception of two cracked filters in the filter wheel, and the film magazines were firmly in position. The magazines were removed and returned to the range head at Mercedes where the emulsions were sealed into film cans and returned to the freezer. Post-flight examination of the telemetry records received from the head during the flight indicated that it had probably failed to stabilize correctly. A small length of one of the emulsions was developed and was found to be unexposed (i.e. uniformly black); therefore it was decided to wait until after the launch of the second vehicle rather than return the emulsions to the UK for immediate processing. The probable reason for the failure to stabilize is stated in Ref.1.

When the films were processed in the UK it was found that the photography had been fortuitously partially successful. The unconstrained motion of the head had scanned the cameras' fields of view across the South-American continent from the Pacific to the Atlantic coasts at angular velocities which had not degraded the majority of the imagery. This imagery has proved useful in the assessment by Reading University of the usefulness of space photography at high angles of obliquity for the purposes outlined in section 2.2.

A total of 183 frames of useful imagery were obtained from the four cameras, one frame from the F24 being shown in Fig.18. The density ranges of the developed images were as follows in Table 5.

Table 5

Camera	Emulsion	Density range	
		Minimum	Maximum
F24	Kodak infra-red aerochrome, type 2443	0.61	2.72
Hasselblad 1	Kodak infra-red aerochrome, type 2443	0.36	1.46
Hasselblad 2	Kodak aerial colour, type SO-242	0.55	1.91
Hasselblad 3	Kodak aerial colour, type SO-242	0.55	2.05

All density ranges fell onto the linear portion of the respective D versus log E curves and hence the emulsions were exposed correctly.

5.2.2 SL1181

SL1181 was launched on 28 March 1973 at 1351 hours local time, with a solar elevation angle of 60^{o}, in substantially cloud-free conditions and with an estimated horizontal visibility of greater than 30km, the head reaching an estimated apogee of 240km. The head was quickly located by an Argentinian tracker aircraft after it had been soft landed by its parachute recovery system and the film magazines were returned to the range head at Mercedes. There the films were sealed into cans and despatched immediately via a courier for processing in the UK, together with the emulsions obtained from SL1182.

The processing of the emulsions was undertaken using a Kodak model 1411 machine processor with the Kodak recommended solution temperatures and machine speed. Examination of the step wedges of the first reels of each film type to be processed showed that the infra-red aerochrome, type 2443 had been processed correctly, whereas the aerial colour type SO-242 exhibited a maximum density in the blue-light sensitive layer considerably less than in the green-light and red-light sensitive layers, producing a blue-biased image. The processing of test strips under various conditions led to the conclusion that the temperature of the colour development step of the process for this emulsion should be raised from the recommended $35^{o}C$ to $41^{o}C$, as this produced a 'neutral' step wedge while maintaining the correct density range. The remainder of the type SO-242 emulsion was therefore processed with the higher colour development step temperature.

The number of frames exposed and density range of the imagery on each of the emulsions was as follows in Table 6.

Table 6

Camera	Emulsion	Number of frames	Density range	
			Minimum	Maximum
F24	Kodak infra-red aerochrome, type 2443	100	0.44	2.72
Hasselblad 1	Kodak infra-red aerochrome, type 2443	90	0.25	1.98
Hasselblad 2	Kodak aerial colour, type SO-242	90	0.41	2.13
Hasselblad 3	Kodak aerial colour, type SO-242	90	0.20	1.98

The density range of the imagery on each of the emulsions fell onto the linear portion of their respective D versus log E curves and thus had been correctly exposed. There was considerable redundancy in the number of frames obtained, since a single exposure of the four cameras at each of the 15 yaw-angle positions, coupled with a rotation about the yaw axis of the head of 22.5° between each position would enable the required area to be imaged. In fact, exposures at 14 yaw angle positions of the head were achieved before the film lengths in the Hasselblad cassettes were used up, with four or five frames being exposed by each camera at each position at 2.5s intervals. The remainder of the frames were exposed whilst the head was rotating between yaw-angle positions.

A typical frame from SL1181 is shown in Fig.19 and corresponds to yaw angle position 13 in Fig.21.

The area of Argentina that was imaged is shown in Fig.20 and its relation to the ground-truth aircraft flight lines and ground-survey sites in Fig.21. This figure shows the effect of the variation of the height of the head during the photographic period of the flight, the apogee occurring between yaw-angle positions 5 and 6.

5.3 Analysis of imagery

First generation contact transparency copies of the original films were made at RAE with the assistance of Instrumentation and Ranges Department. A comparison was made of the originals and copies by Reading University[16] which showed that there were no significant differences between the hues and values, but that there were significant differences between the originals and copies in their chroma; however, chroma was the least important of the three colour variables in discriminating between crops, and all subsequent interpretation was undertaken using the copies. The ground resolution of the imagery has been measured by Reading University for targets of low to medium contrast, which are provided by the Argentinian practice of strip cultivation for erosion prevention. These strips have widths and spacings down to about 5m and bear a close resemblance to sinusoidally modulated targets. The widths of the narrowest strips which could be resolved on the various types of photography are given in Table 7.

Table 7

Camera	Lens focal length (mm)	Film type	Measured ground resolution (m)
F24	127	Kodak type 2443	40
Hasselblad 1	150	Kodak type 2443	45
Hasselblad 2	150	Kodak type SO-242	30
Hasselblad 3	250	Kodak type SO-242	15

Comparing the measured values of ground resolution of Table 7 with the calculated values of Fig.17 it can be seen that there is good agreement for the camera employing the true-colour emulsion type SO-242 but less good agreement for the cameras loaded with the aerochrome infra-red colour emulsion type 2443, the measured ground resolutions in the latter case being better than the calculated figures by a factor of approximately 2. This could be explained by the higher contrast between cultivated strips and bare earth in the near infra-red than in the visible part of the spectrum, thus invalidating the assumption of target contrast $C = 1.6$ made in calculating the expected ground resolutions.

The assessment and interpretation undertaken to date by the Reading University group has been reported[17]; it includes: (1) an assessment of the accuracy of crop recognition using the rocket imagery and ground sampled data; (2) crop area and land-use statistics for a sample area of about 11500km^2 in the Province of La Pampa; (3) a semi-automated computer classification using a hierarchical fusion clustering algorithm of individual fields into five classes; (4) a natural resources survey based on a division of the imagery into photo patterns and (5) a feasibility study of the use of the imagery for small-scale map revision.

6 CONCLUSIONS

These trials have demonstrated the technical feasibility of the use of the Skylark sounding rocket head as a stable platform for remote sensing experiments from altitudes greater than 200km. The payloads developed for these trials made use of widely available, relatively simple equipment which worked satisfactorily in the space environment and survived the launch and re-entry with only minor damage to some of the filters. The payloads were designed to demonstrate what might be achieved using specially designed payloads, and subsequent analysis has shown that a custom-built photographic payload making use of the available space in the head could achieve ground resolutions of the order of 2-3m to a radius of 300km from the nadir of the head. There is no technical bar on the payload consisting of a multi-spectral scanner or vidicon system if these were required for a particular experiment.

Assessment of the imagery obtained during these trials has shown that the methods used to calculate the camera exposures were valid and that the assumption that no changes in exposure are required for photography of the earth from altitudes greater than about 17000m was justified. The sensitometric control procedures have proved to be satisfactory in monitoring any changes of properties in the photographic emulsions and providing a control mechanism during their processing.

Analysis of the rocket imagery by the Geography Department of the University of Reading has shown:

(1) the first-generation contact prints of the imagery produced at RAE are not significantly different from the originals for interpretative purposes;

(2) there is good agreement between calculated and measured values of the ground resolution for cameras employing true-colour emulsion, but less good agreement for cameras loaded with infra-red colour emulsion.

The interpretation of the imagery by the University group includes:

(1) a field by field identification of crops;

(2) an analysis of land use in cultivated and non-cultivated areas;

(3) the use of a semi-automated method of crop recognition;

(4) a natural resource survey and mapping of sample uncultivated areas.

Appendix

CALCULATION OF GROUND RESOLUTION AND COVERAGE OBTAINED VIA PHOTOGRAPHIC SYSTEMS

The calculation of ground coverage and ground resolution (GR) is based on simple geometric considerations. Consider a lens-emulsion combination with angular field of view ϕ, lens focal-length f, photographing the earth (which is assumed to be plane) from an altitude h, with its optical axis inclined at an angle β to the local vertical. It is assumed that the maximum spatial frequencies of the imagery at various positions in the focal plane of the combination have been obtained as outlined in section 3.4; for simplicity we assume that these spatial frequencies are n_1 at the centre of the format, n_2 at the edges of the format and n_3 in the corners. Consider the angles subtended at a simple thin lens by the format of the camera system as shown in Fig.22; with the angular field of view (across the diagonal of the format) being ϕ, the angles θ and ψ of Fig.22 are of magnitude:

$$\theta = 2 \tan^{-1}\left[\frac{\tan \phi/2}{\sqrt{2}}\right], \qquad \psi = 2 \sin^{-1}\left[\frac{\sin \phi/2}{\sqrt{2}}\right]. \tag{A-1}$$

Consider photography of the earth's surface as shown in Fig.23, the dimensions of the ground coverage pattern as functions of h, β, θ and ψ are given below:

$$NP = h \tan \beta \qquad GF = \frac{2h \tan \psi/2}{\cos (\beta + \theta/2)}$$

$$NB = h \tan (\beta + \theta/2) \qquad EH = \frac{2h \tan \psi/2}{\cos (\beta - \theta/2)}$$

$$NC = h \tan (\beta - \theta/2)$$

$$BC = \frac{2h \sin \theta}{(\cos 2\beta + \cos \theta)}$$

We define the ground resolution, which is obtained by projecting the reciprocals of the maximum spatial frequencies in the focal plane of the camera onto the earth's surface in two directions at each point:

radially (R) along a vector joining N to the point;
tangentially (T) perpendicular to this vector and in the earth's plane.

Using this procedure for the maximum spatial frequencies of Fig.23 we obtain the following expressions for ground resolution:

(1) At P

$$\text{tangential GR} = \frac{h}{fn_1 \cos \beta}$$

$$\text{radial GR} = \frac{h}{fn_1 \cos^2 \beta}$$

(2) At B

$$\text{tangential GR} = \frac{h}{fn_2 \cos (\beta + \theta/2)}$$

$$\text{radial GR} = \frac{h}{fn_2 \cos^2 (\beta + \theta/2)}$$

(3) At C

$$\text{tangential GR} = \frac{h}{fn_2 \cos (\beta - \theta/2)}$$

$$\text{radial GR} = \frac{h}{fn_2 \cos^2 (\beta - \theta/2)}$$

(4) At F and G

$$\text{tangential GR} = \frac{h}{fn_3 \cos (\beta + \theta/2) \cos \psi/2}$$

$$\text{radial GR} = \frac{h}{fn_3 \cos^2 (\beta + \theta/2) \cos^2 \psi/2}$$

(5) At E and H

$$\text{tangential GR} = \frac{h}{fn_3 \cos (\beta - \theta/2) \cos \psi/2}$$

$$\text{radial GR} = \frac{h}{fn_3 \cos^2 (\beta - \theta/2) \cos^2 \psi/2}$$

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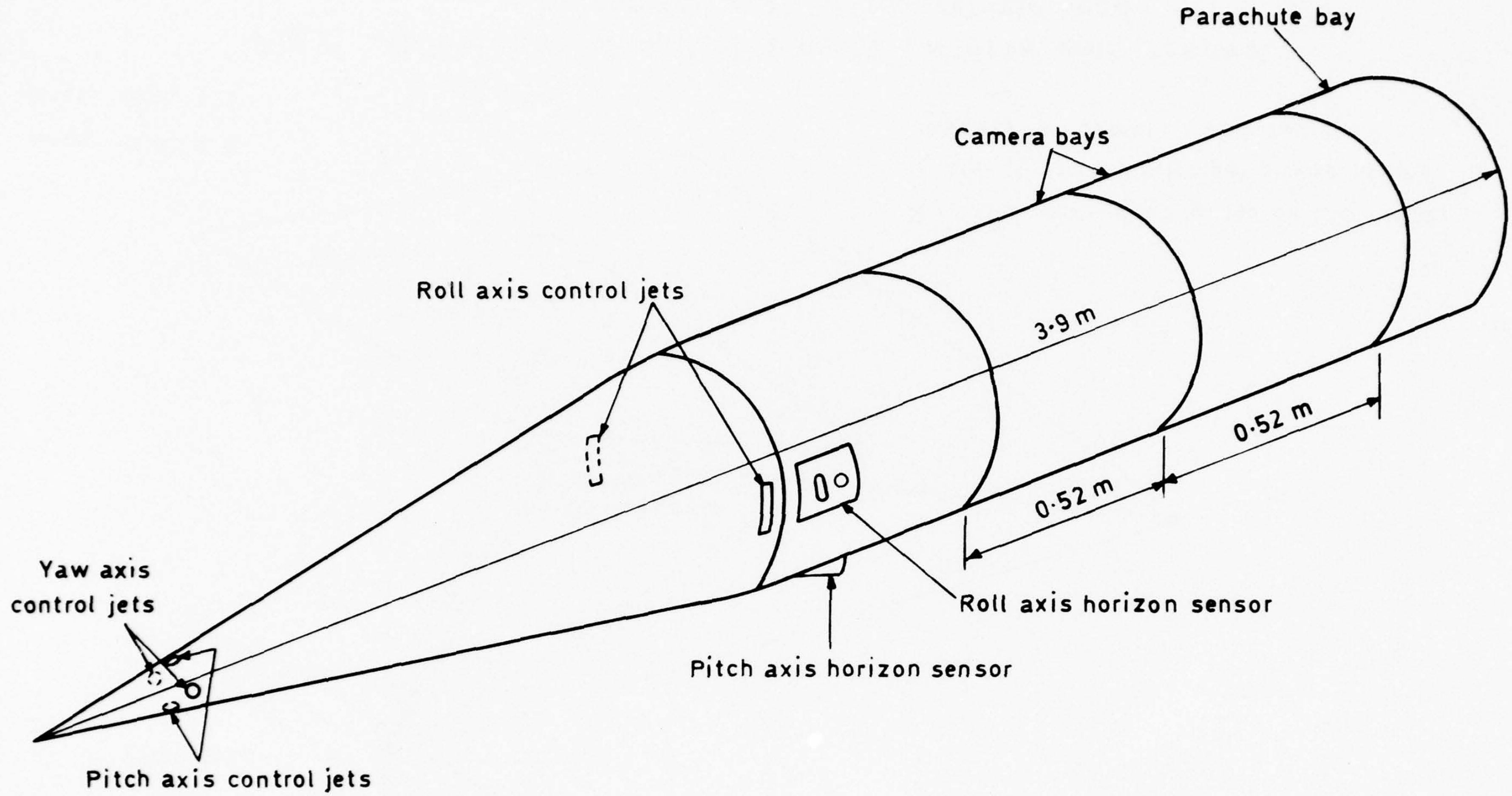
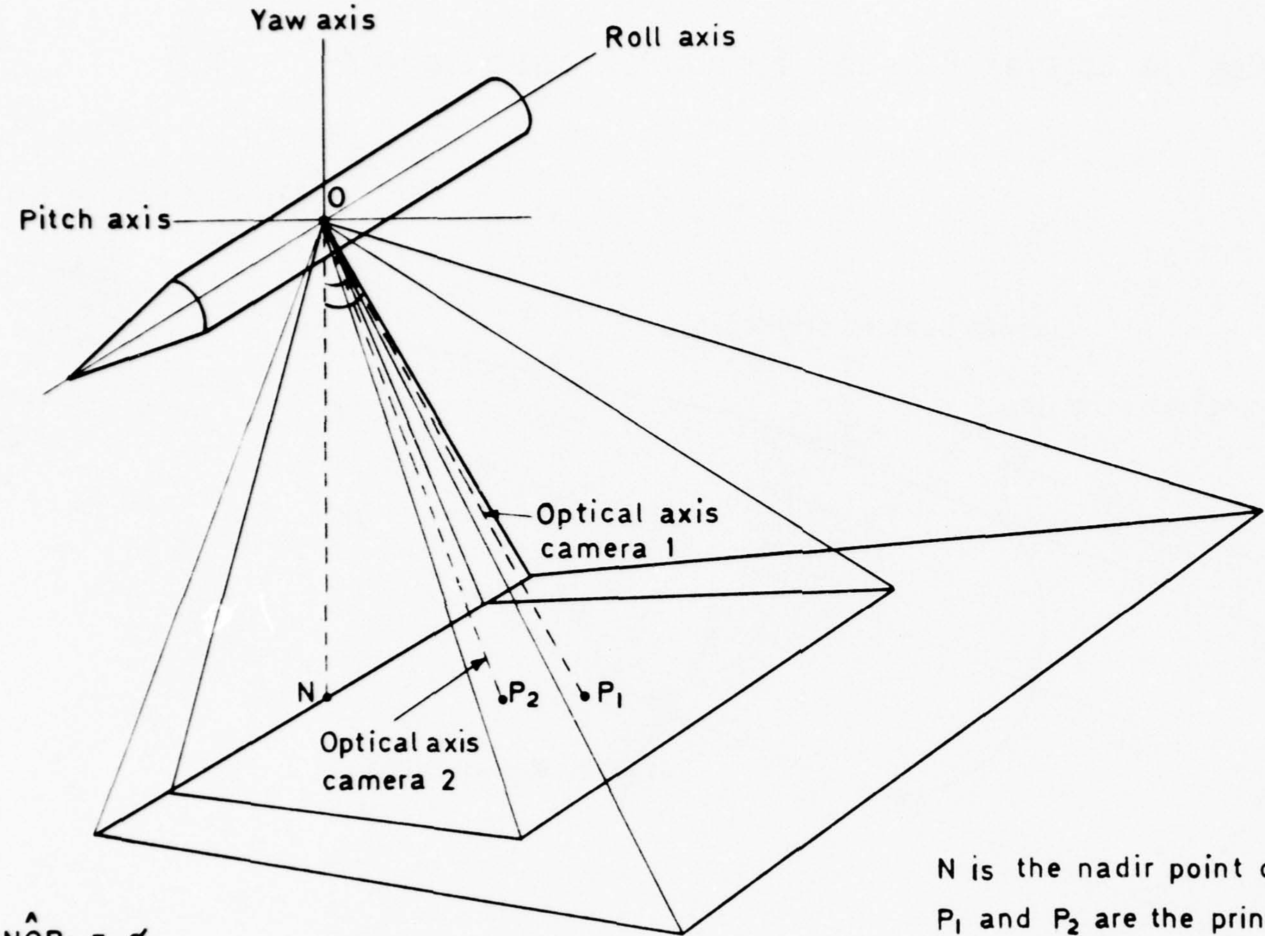


Fig.1 Typical build of remote sensing version of Skylark



Angle $N\hat{O}P_1 = \alpha$
Angle $N\hat{O}P_2 = \beta$

N is the nadir point on the earth's surface
P_1 and P_2 are the principal points of the imagery of camera 1 and camera 2

Fig. 2 Orientation of optical axes of cameras with respect to control axes of the vehicle head

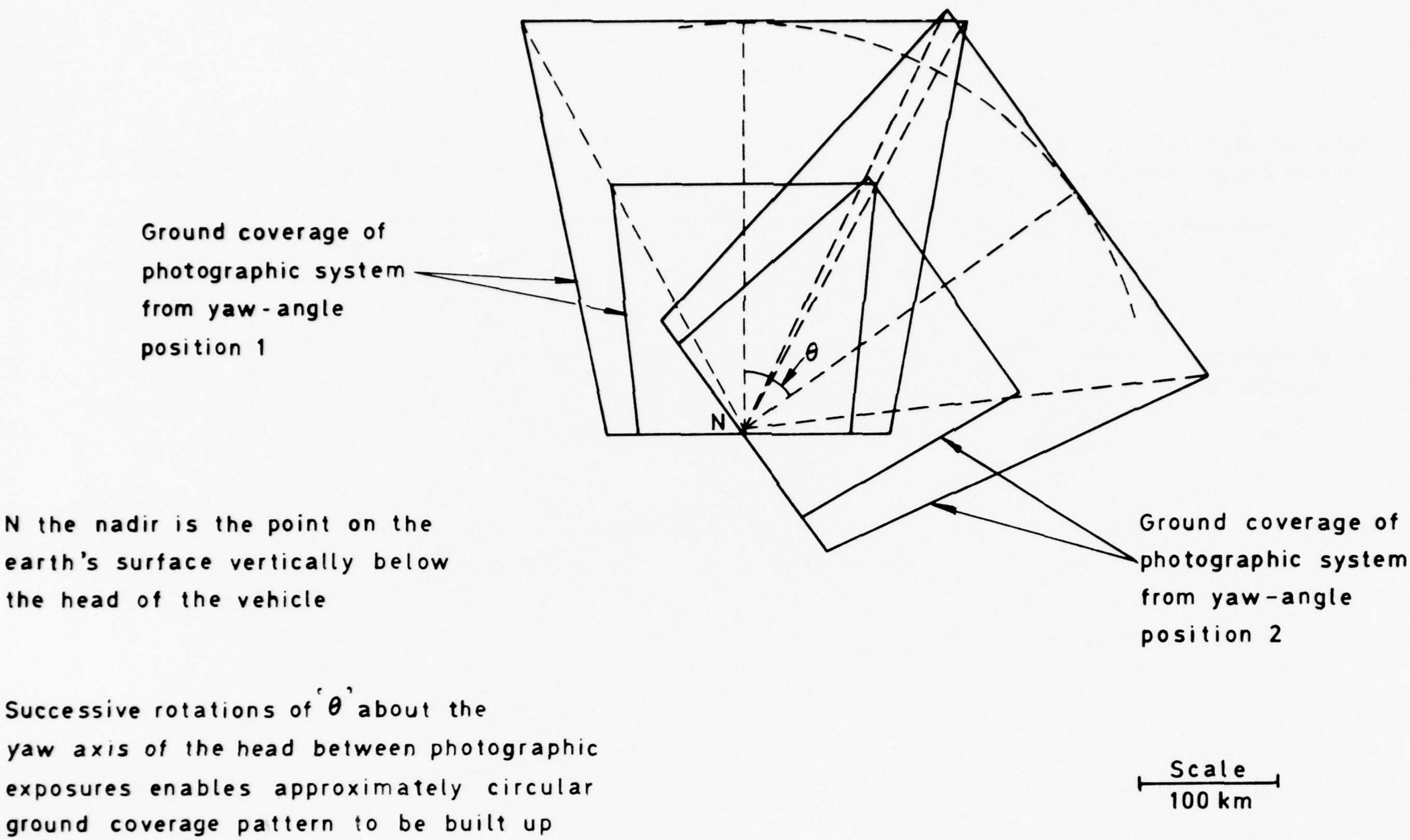


Fig. 3 Ground coverage pattern of photographic system

Fig. 4

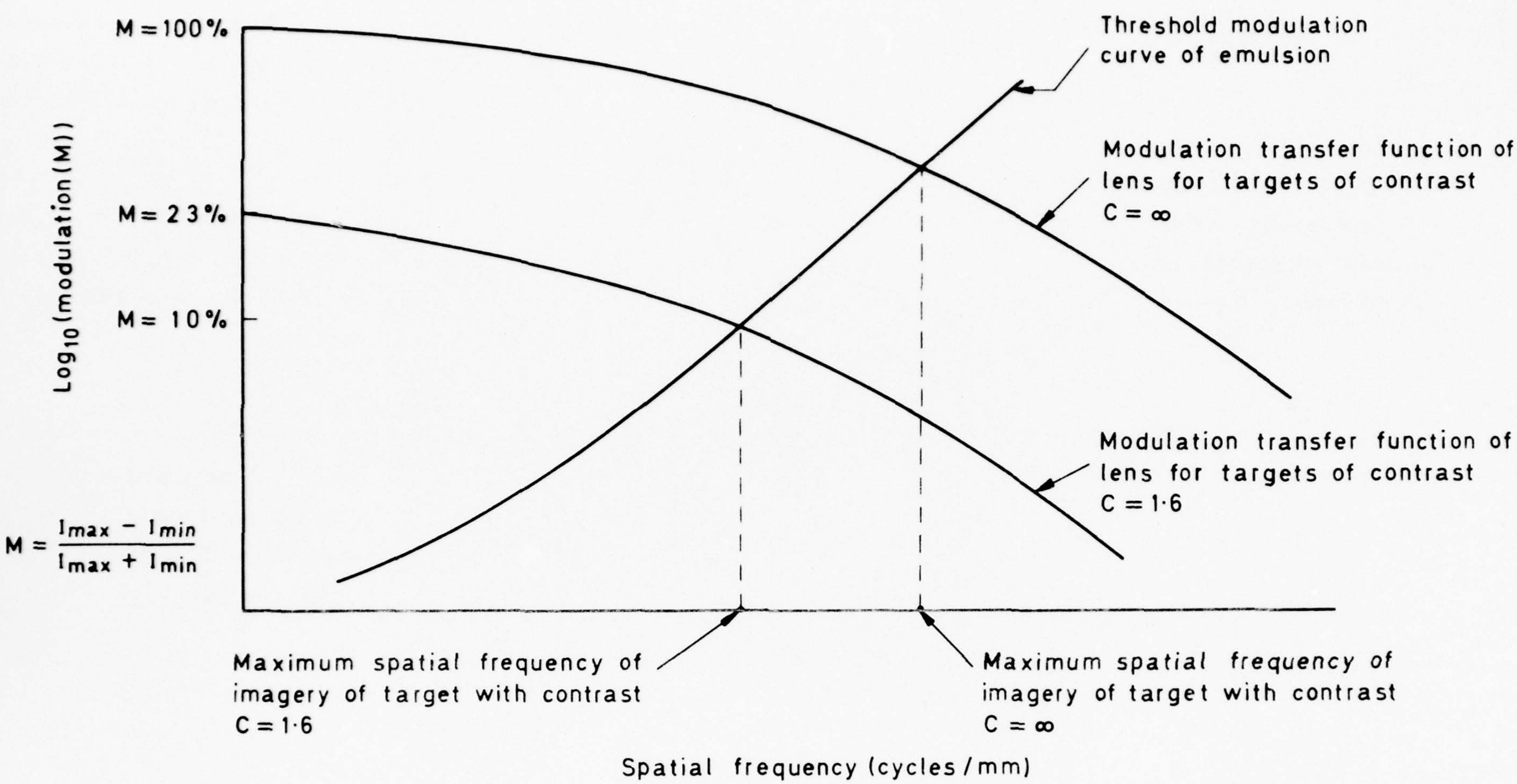


Fig. 4 Estimation of maximum spatial frequency of imagery (A)

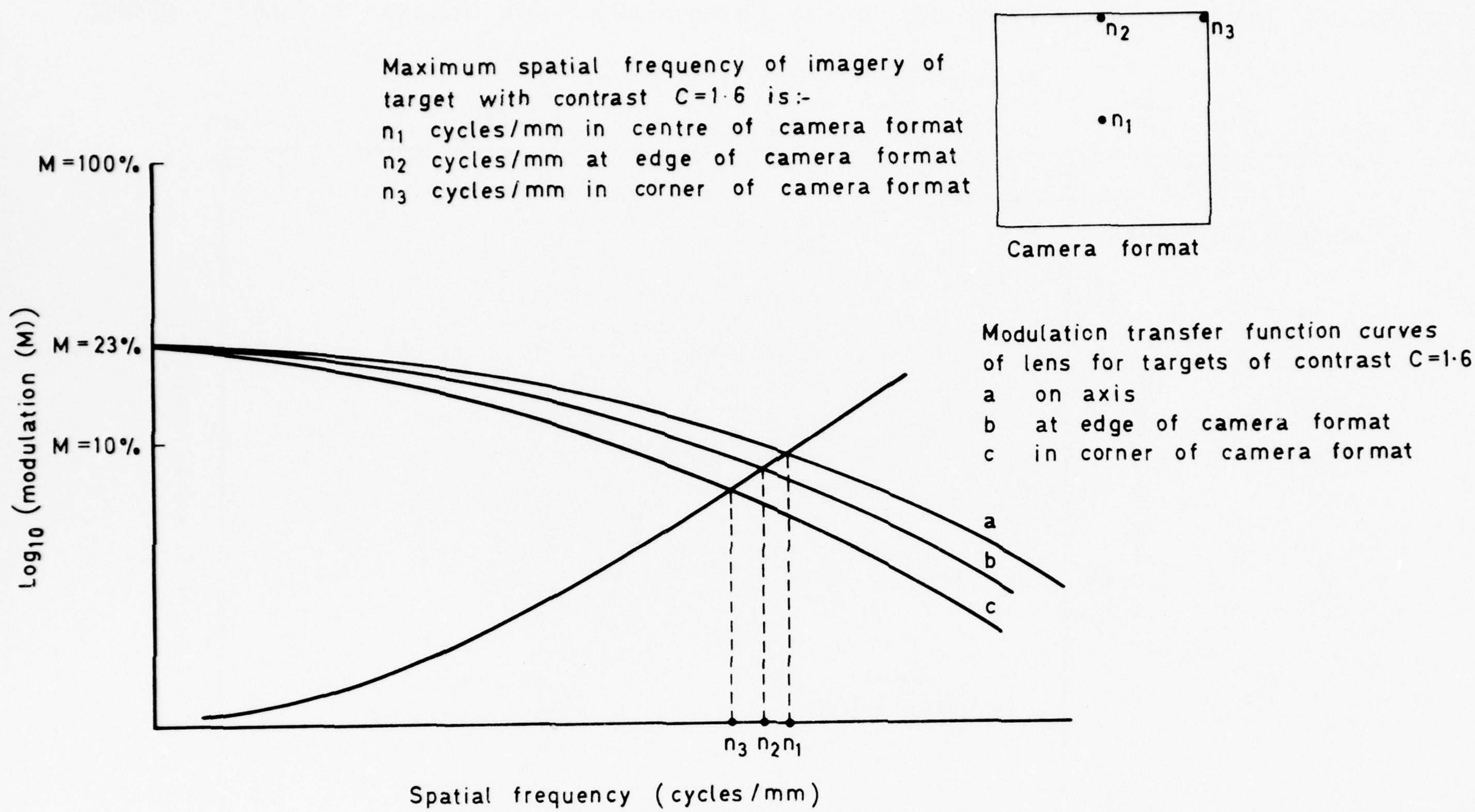


Fig.5 Estimation of maximum spatial frequency of imagery (B)

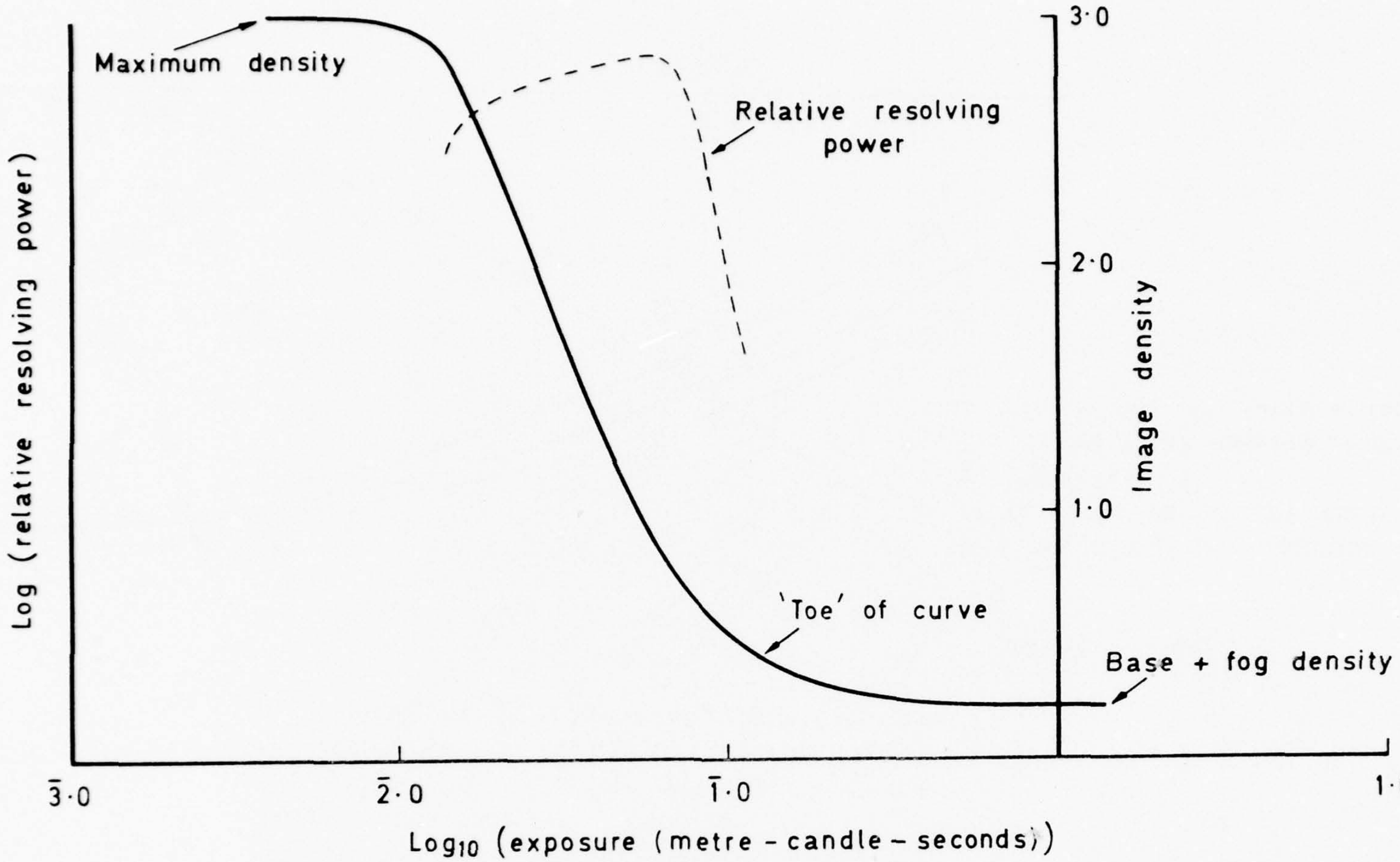


Fig.6 Density versus $\log_{10}$ (exposure) curve for a typical 'reversal' emulsion

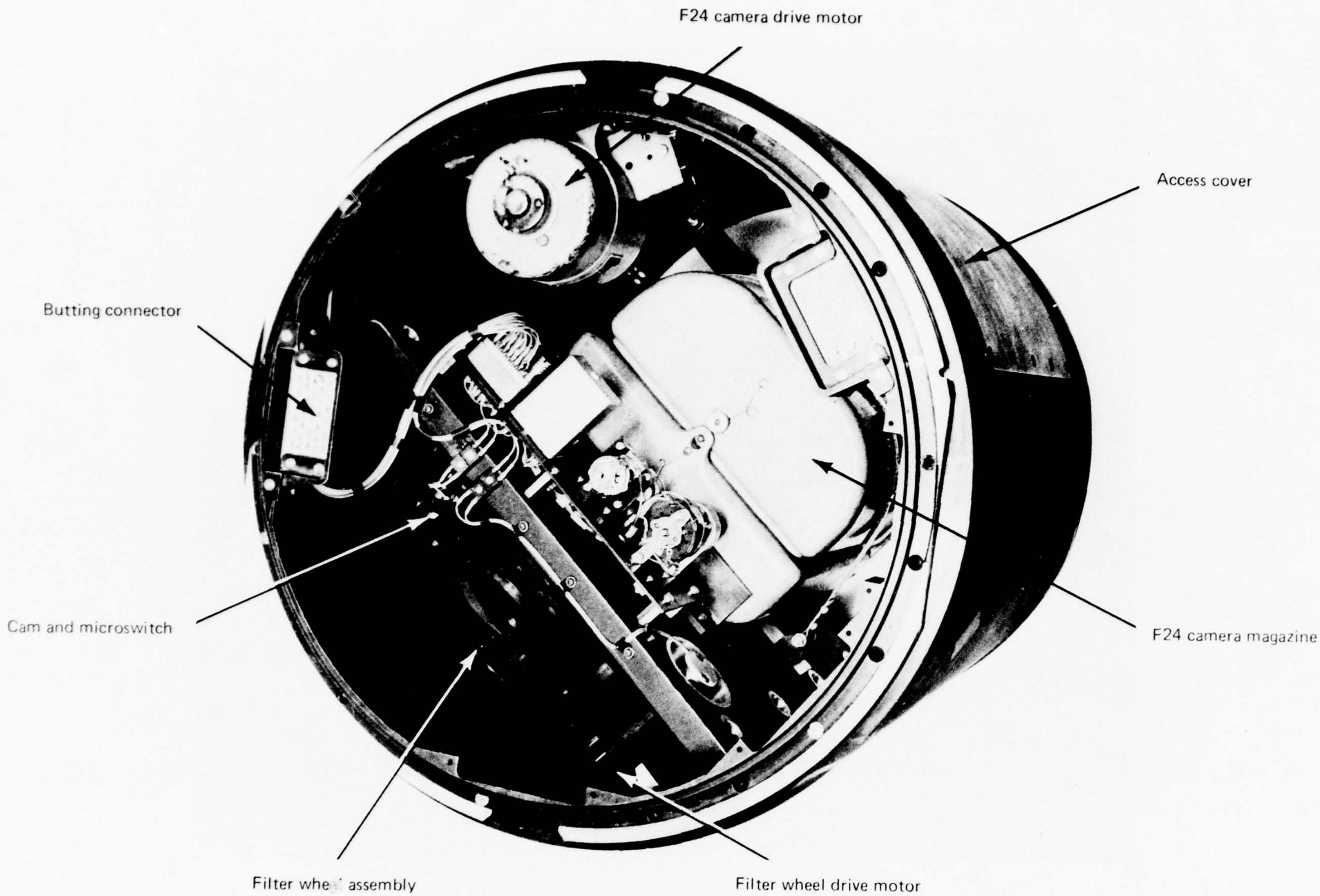


Fig.7 F24 camera system bay

Fig.8

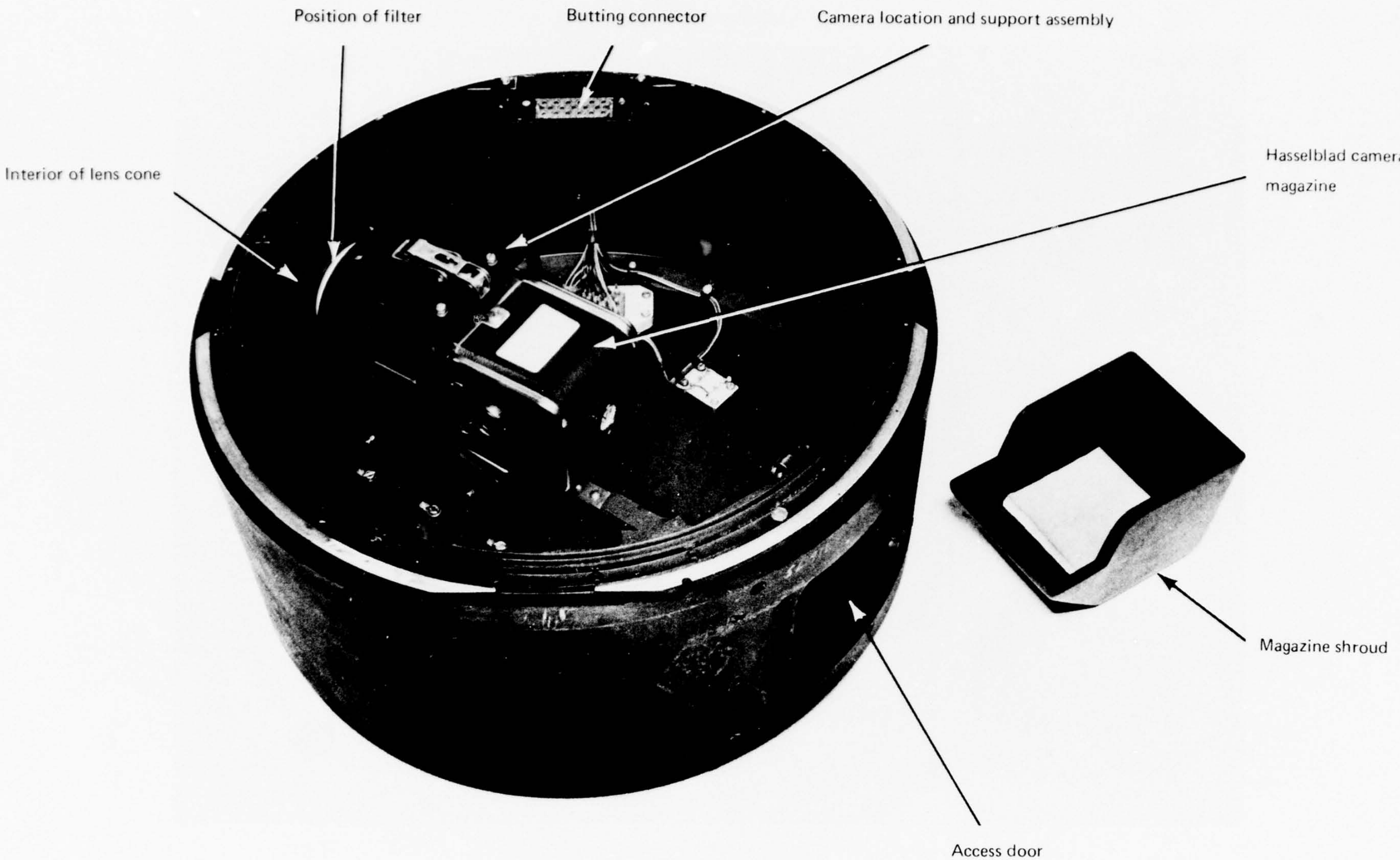


Fig.8 Hasselblad camera bay

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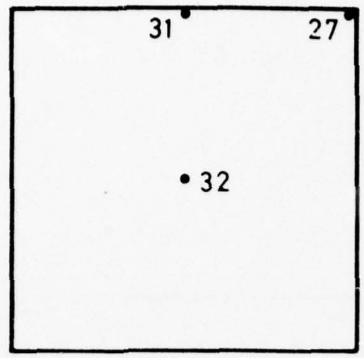

Hasselblad camera format

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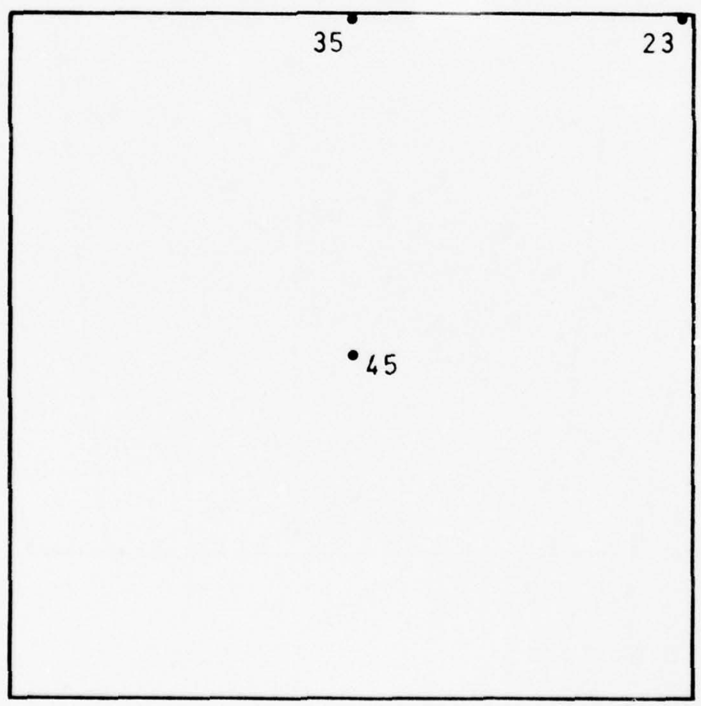

F24 camera format

Maximum spatial frequencies are given in cycles/mm

Fig.9 Maximum spatial frequencies in focal planes of F24 and Hasselblad cameras : SL 1081

Fig.10

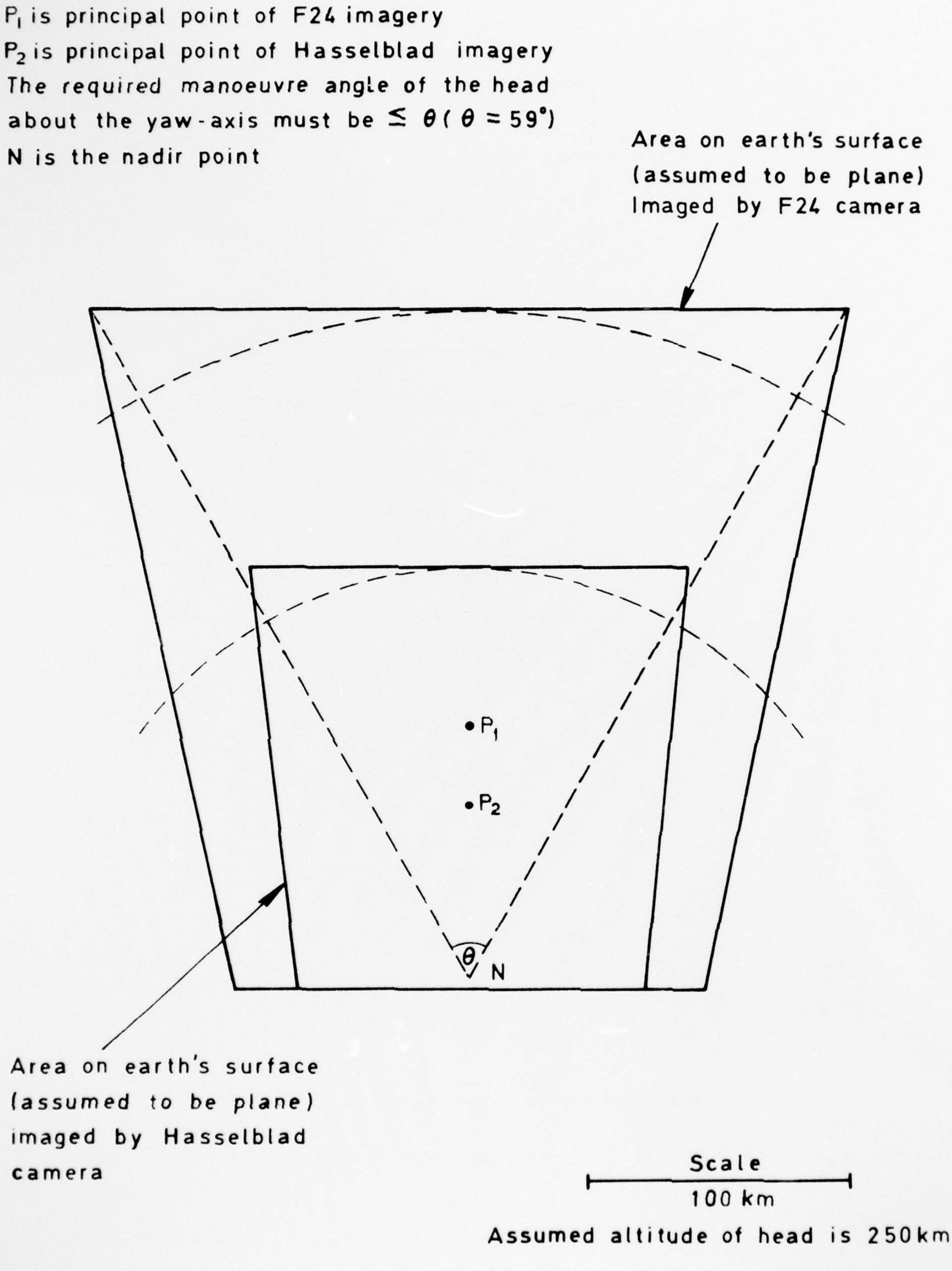

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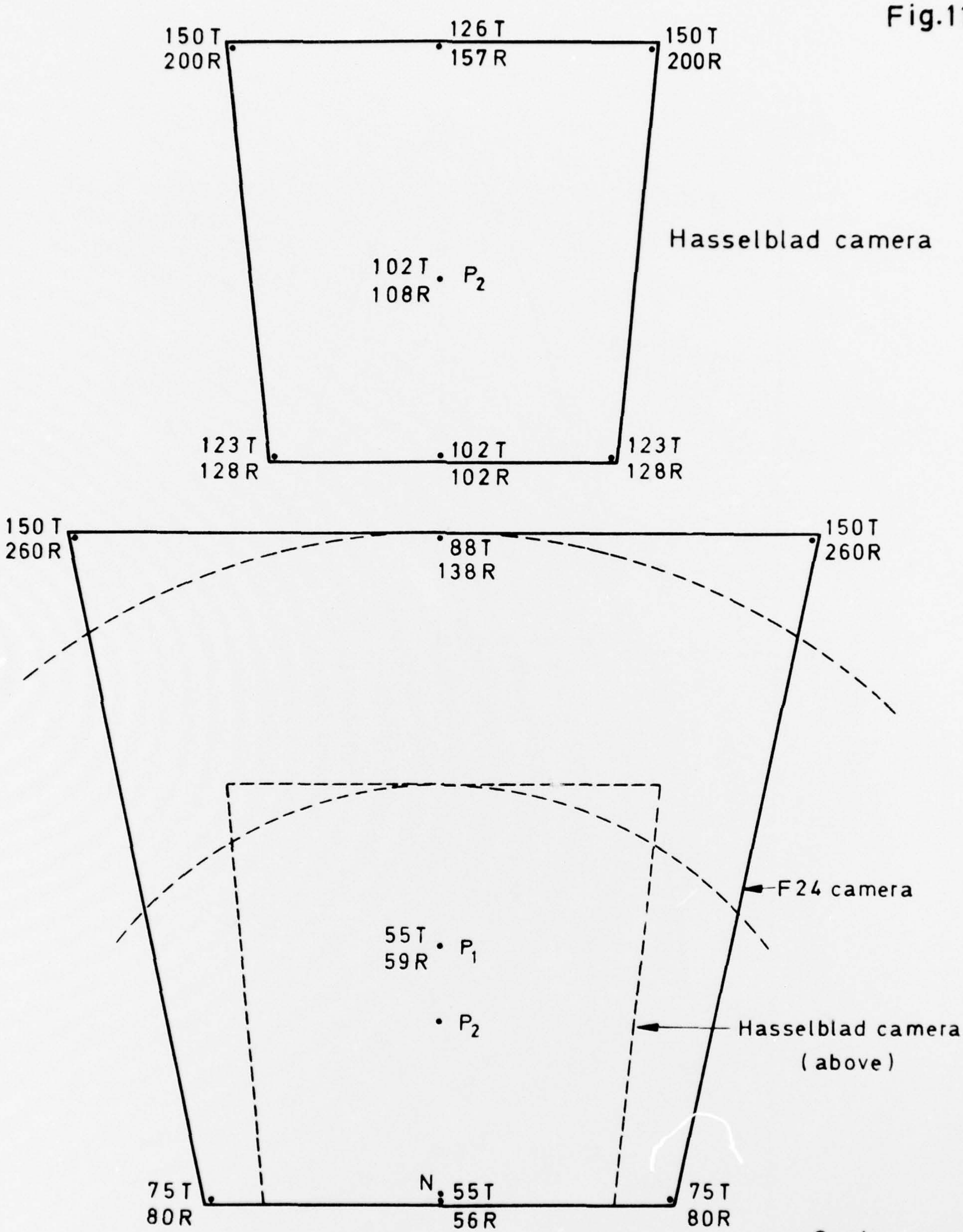
Fig.10 Calculated ground coverage of F24 and Hasselblad cameras: SL1081

Fig.11



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T denotes ground resolution (in metres) measured in tangential direction

R denotes ground resolution (in metres) measured in radial direction

Scale

100 km

Assumed altitude 250 km

Fig. 11 Calculated ground resolution of F24 and Hasselblad cameras: SL 1081

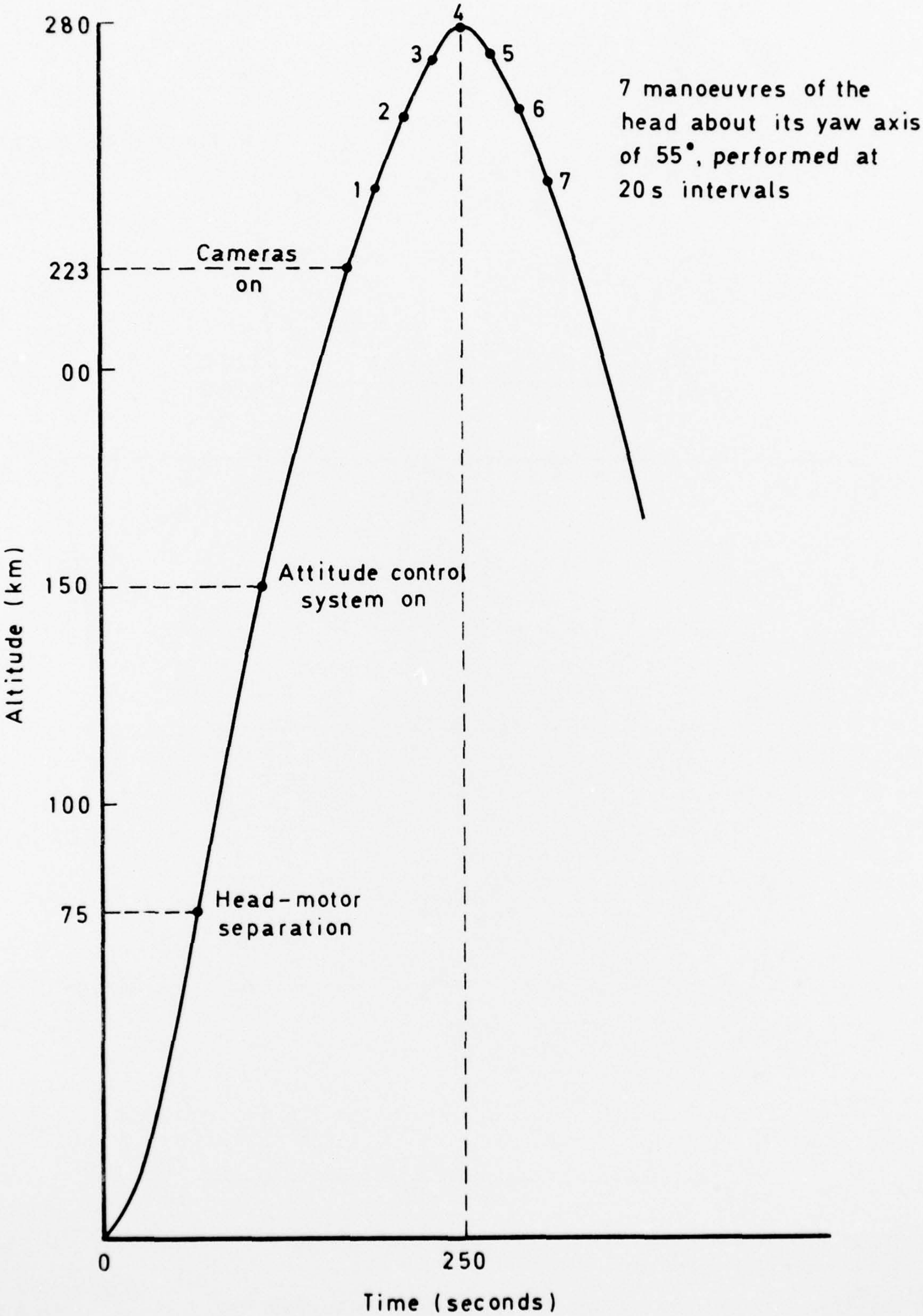

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Fig. 12 Schematic trajectory of SL1081

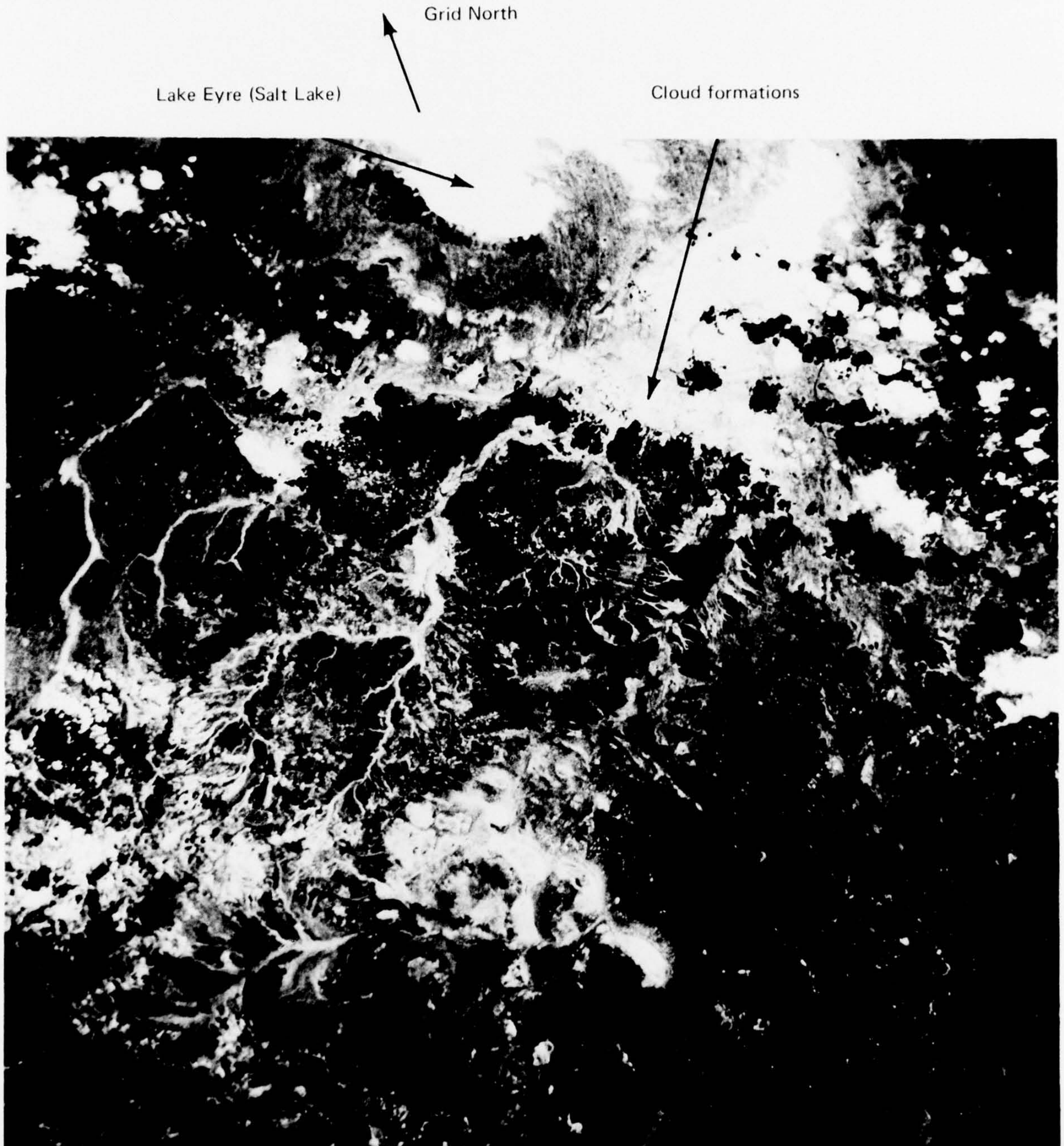


Fig.13 Panchromatic print of Hasselblad imagery obtained from yaw angle position 3 of SL 1081

Fig. 14

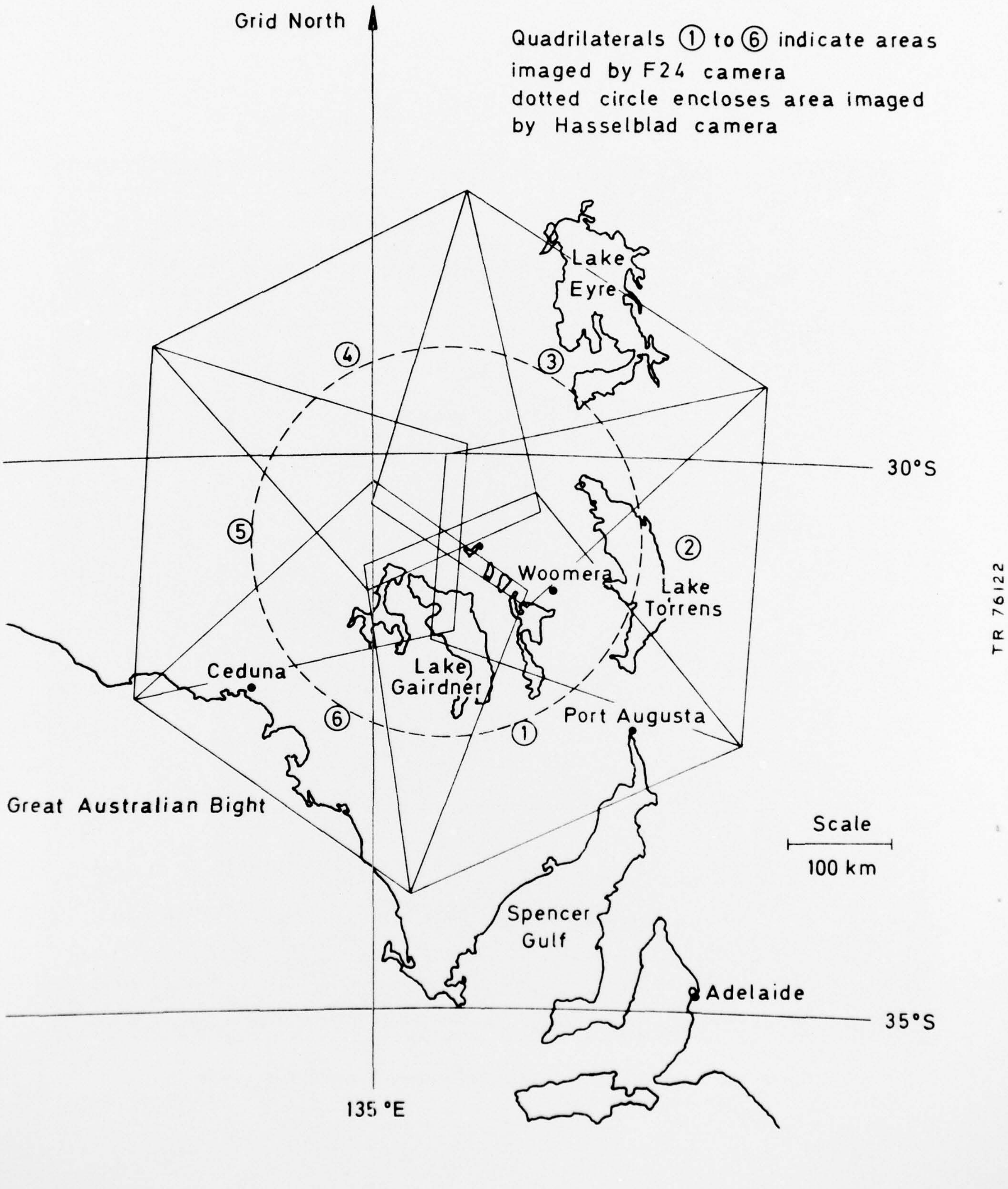
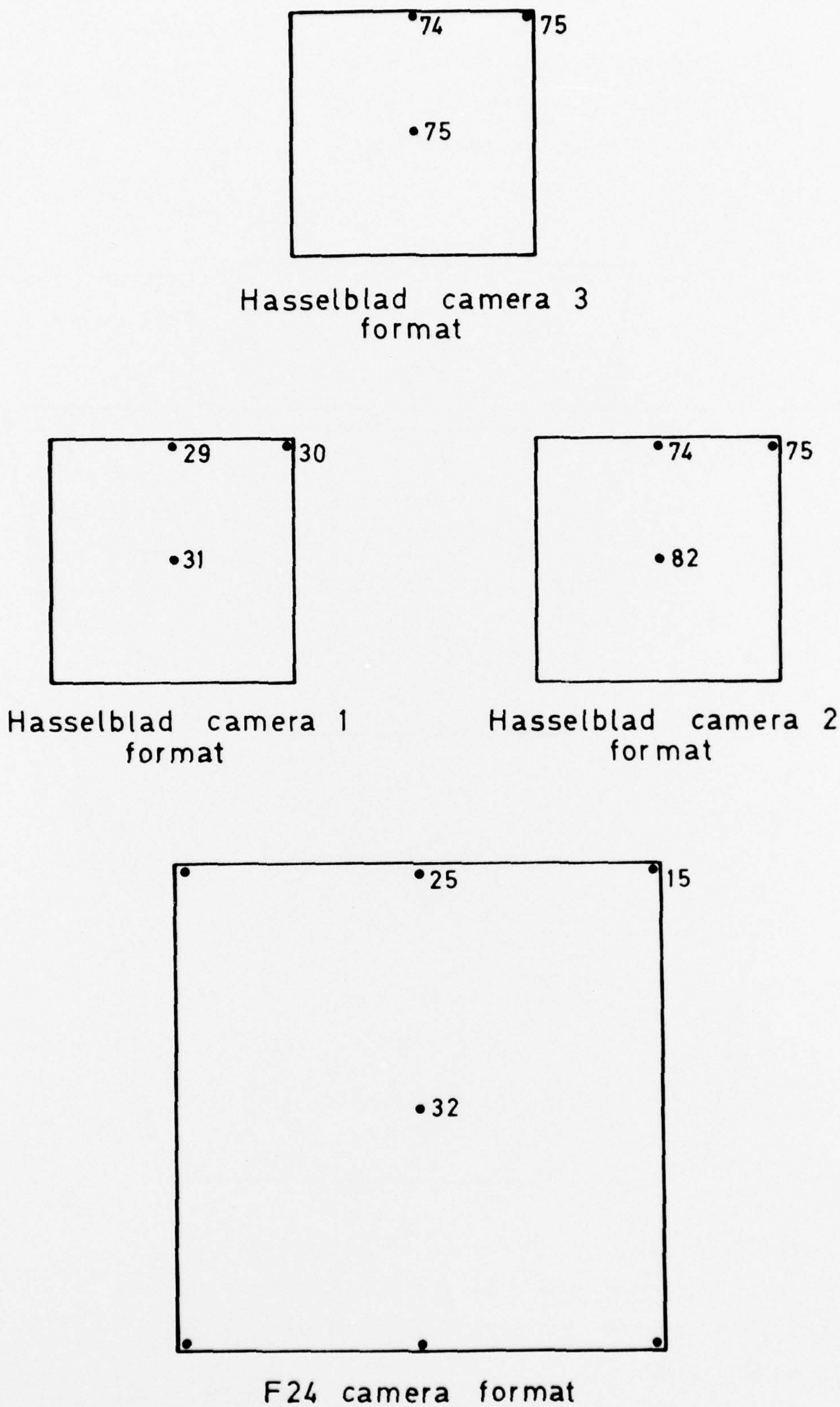


Fig. 14 Area of South Australia imaged from SL1081



The maximum spatial frequencies in the camera formats are given in cycles/mm

Fig.15 Maximum spatial frequencies in focal planes of F24 and Hasselblad cameras : SL1181 and SL1182

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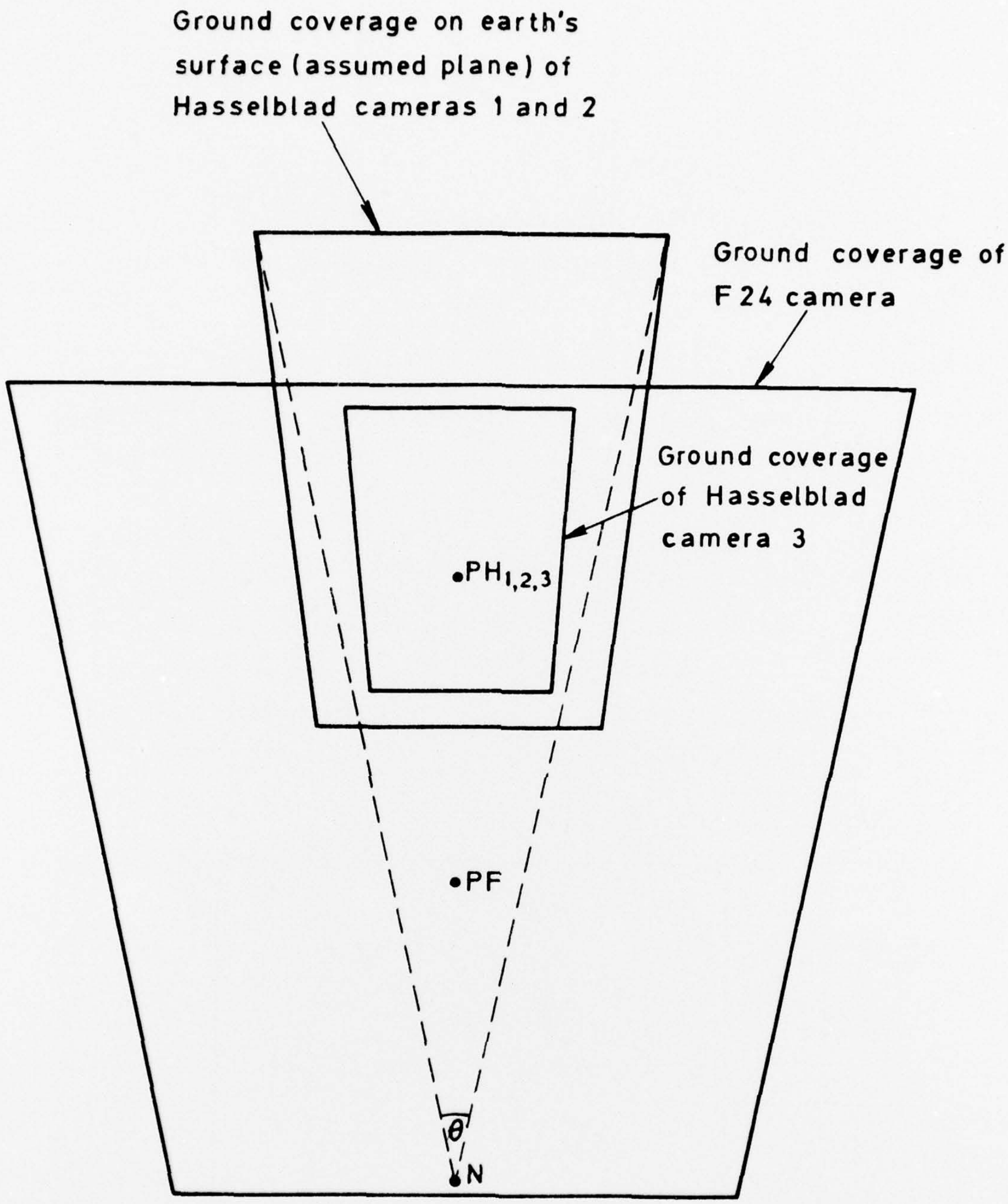
Fig.16



PF is the principal point of the F24 imagery

$PH_{1,2,3}$ is the principal point of 3 Hasselblad's imagery

The required yaw-axis manoeuvre angle must be $\leq \theta$ ($\theta = 24°$)

N is the nadir point

Scale

100 km

Assumed altitude is 250 km

Fig.16 Calculated ground coverage of F24 and Hasselblad cameras : SL1181 and SL1182

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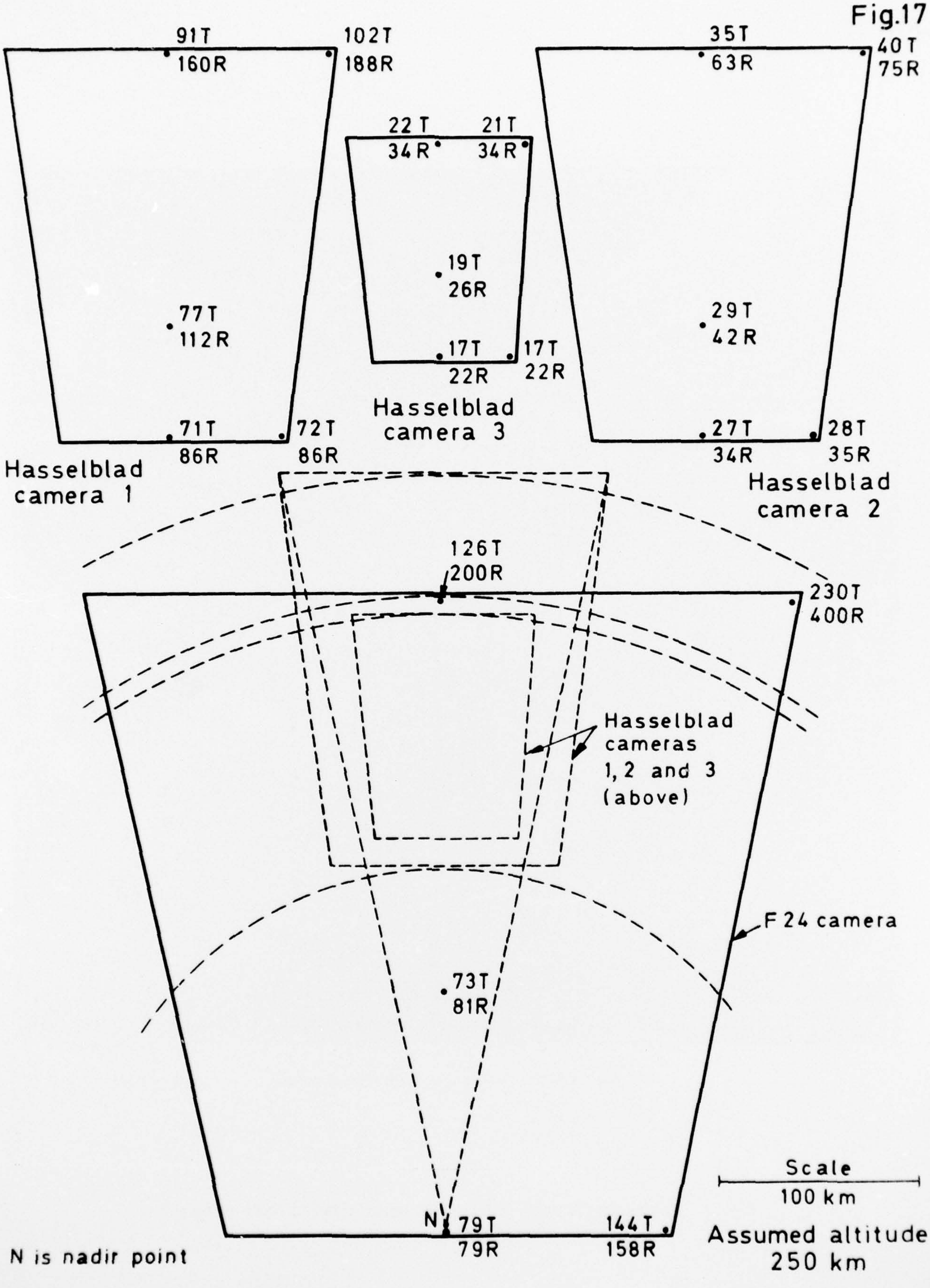

Fig. 17 Calculated ground resolution of F24 and Hasselblad cameras: SL 1181 and SL 1182

Fig.18

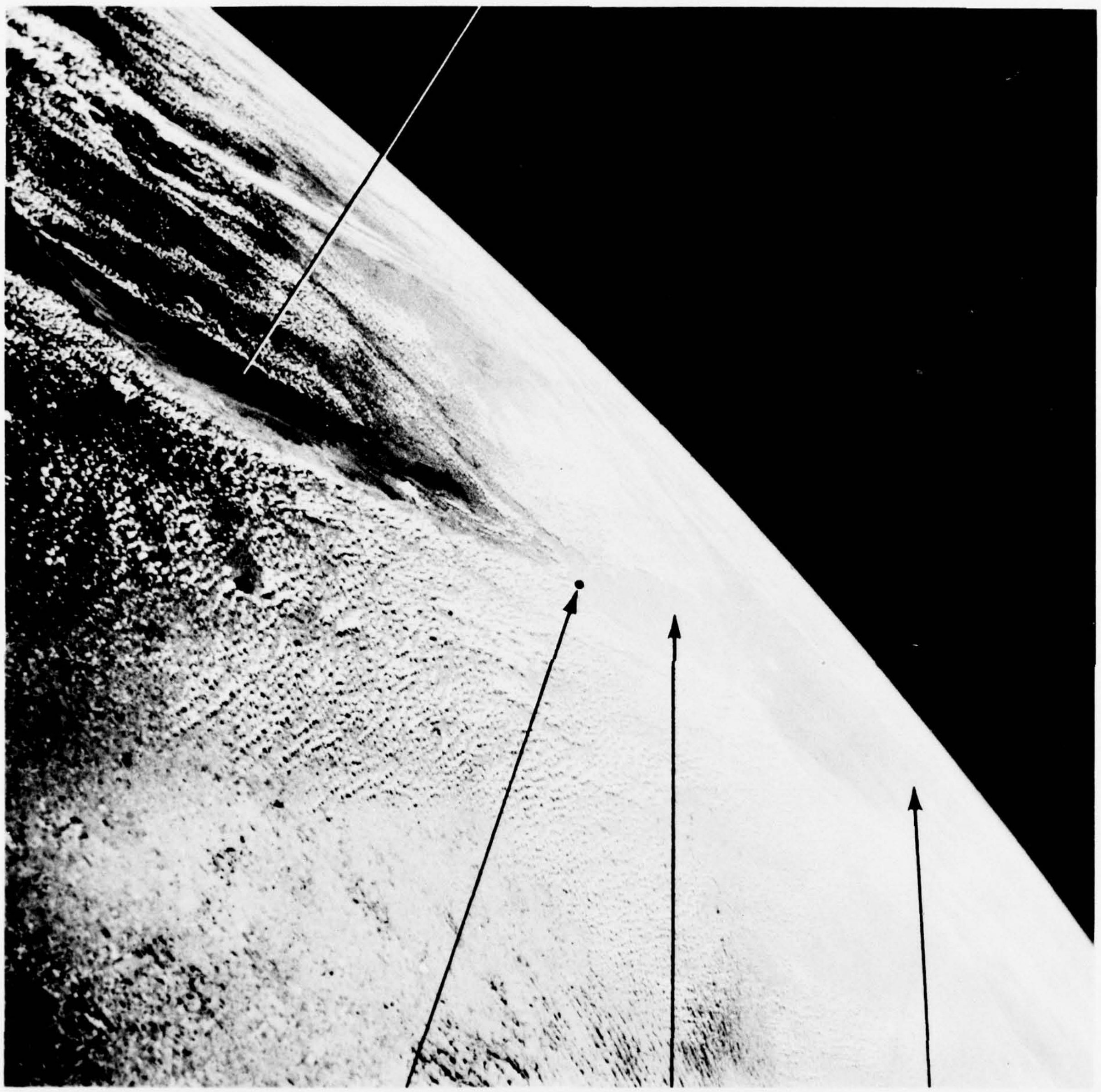

Fig.18 Panchromatic print of Aerochrome infra-red imagery obtained via F24 camera: SL 1182

Grid North

Spent Raven rocket motor

Fig.19 Panchromatic print of true colour imagery obtained at yaw angle postion 13 via Hasselblad camera number 2: SL 1181

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Fig. 20

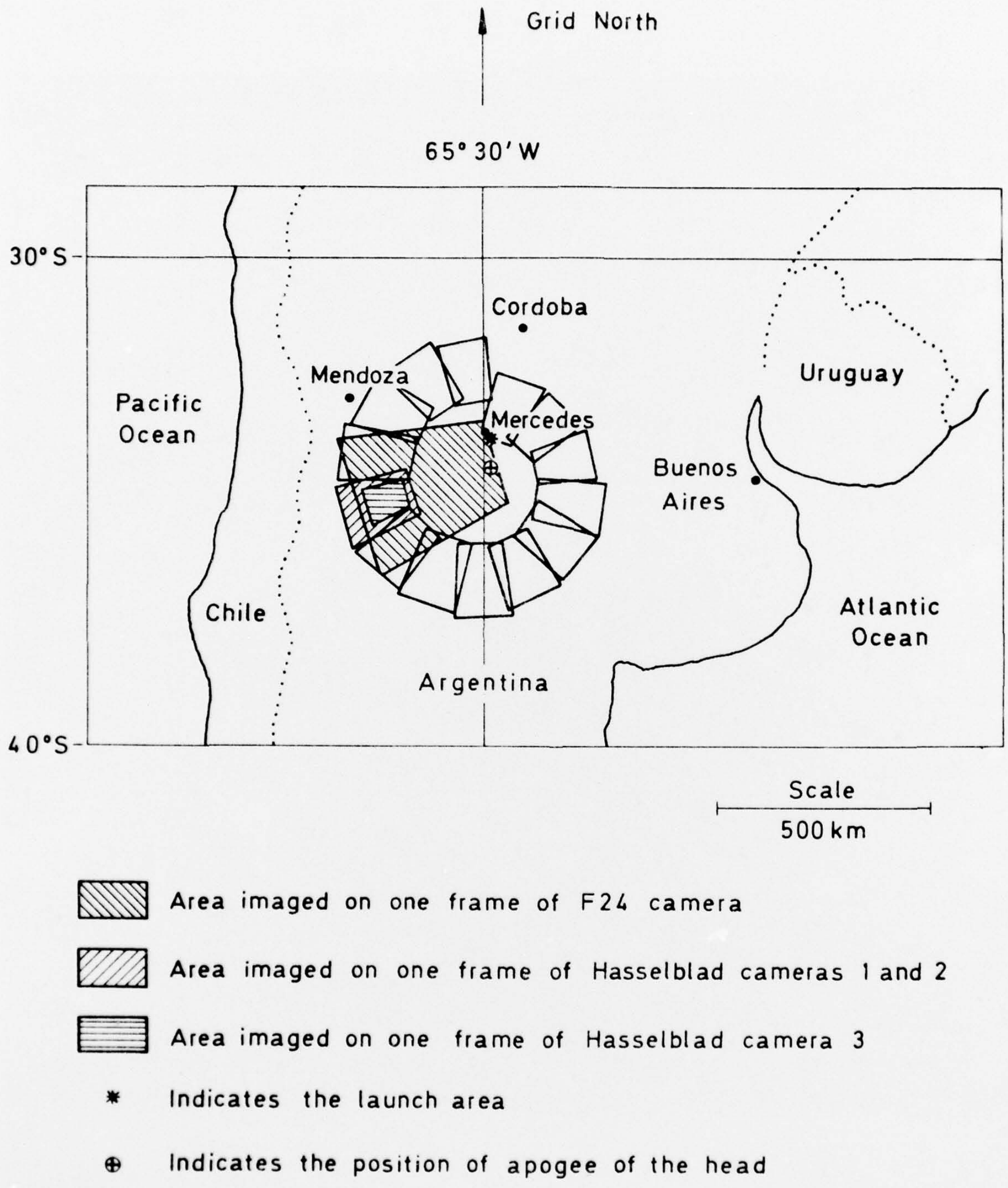

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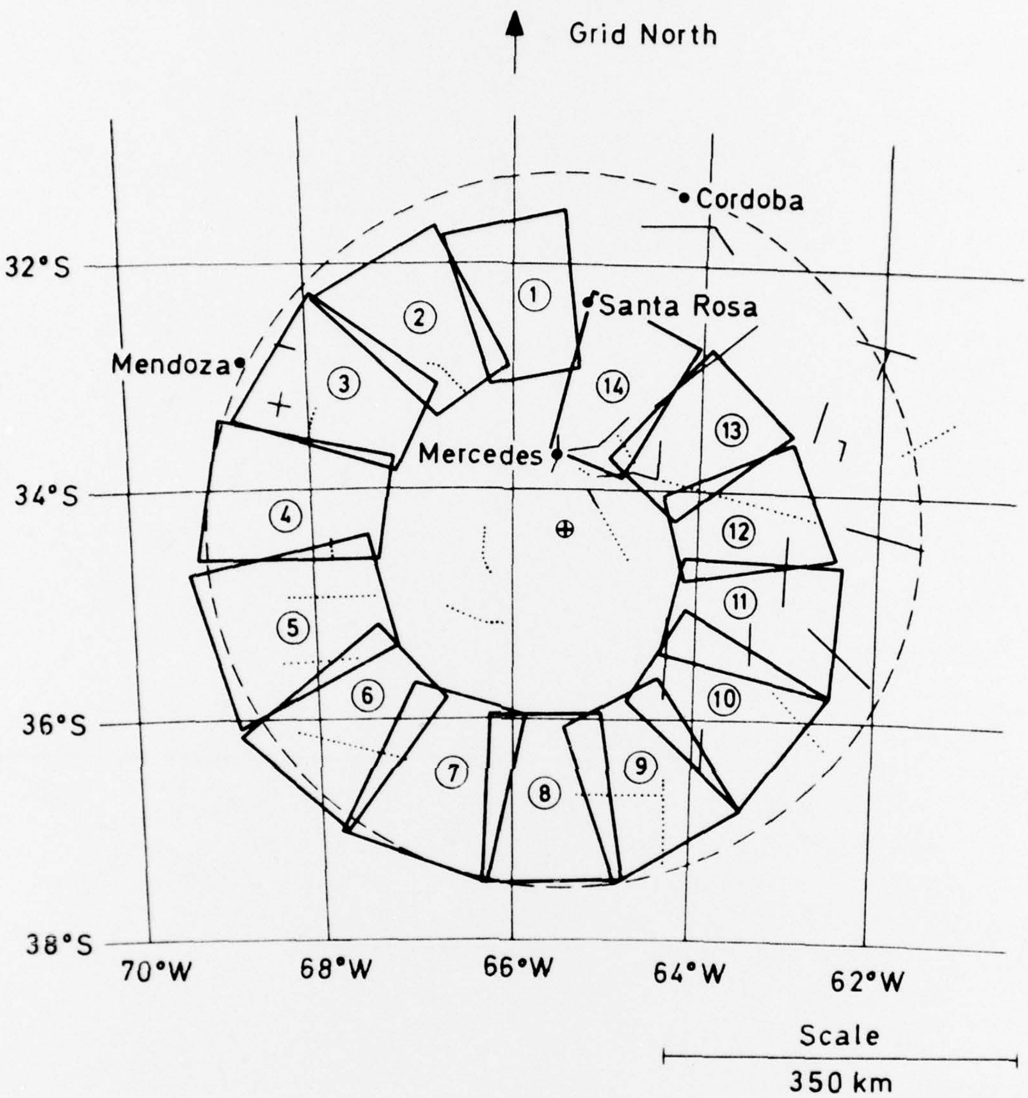
Fig. 20 Area of Argentina imaged from SL1181



Quadrilaterals numbered 1 to 14 represent areas imaged by Hasselblad cameras 1 and 2, coverage by Hasselblad camera 3 and F24 camera are omitted for clarity

———— Aircraft imagery with ground sampled data

·········· Aircraft imagery without ground sampled data

⊕ Position of apogee of head

• Position of towns

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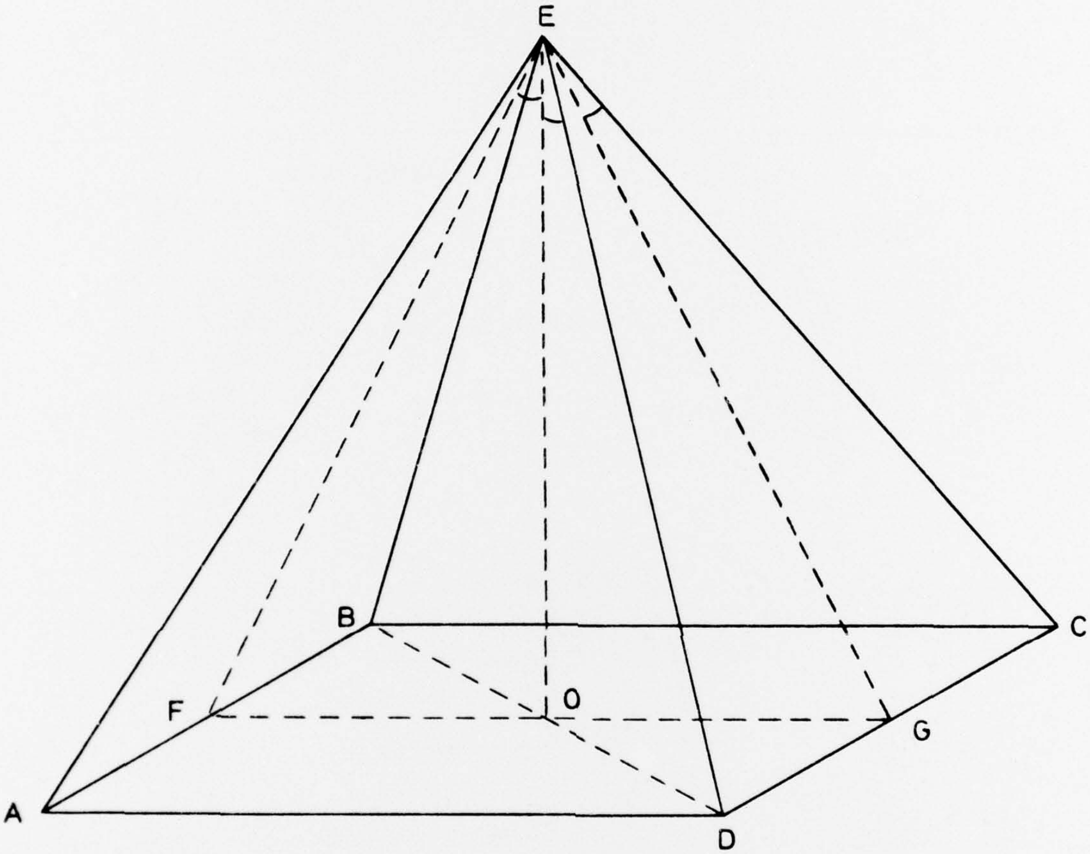
Fig. 21 Relationship between ground coverage obtained via SL 1181 and 'ground-truth' data collection transects

Fig. 22



ABCD is the camera format

E is the position of the camera lens

Angle $O\hat{E}D = \phi/2$

Angle $O\hat{E}F = \theta/2$

Angle $G\hat{E}C = \psi/2$

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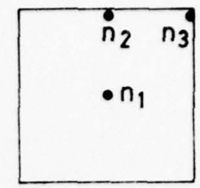
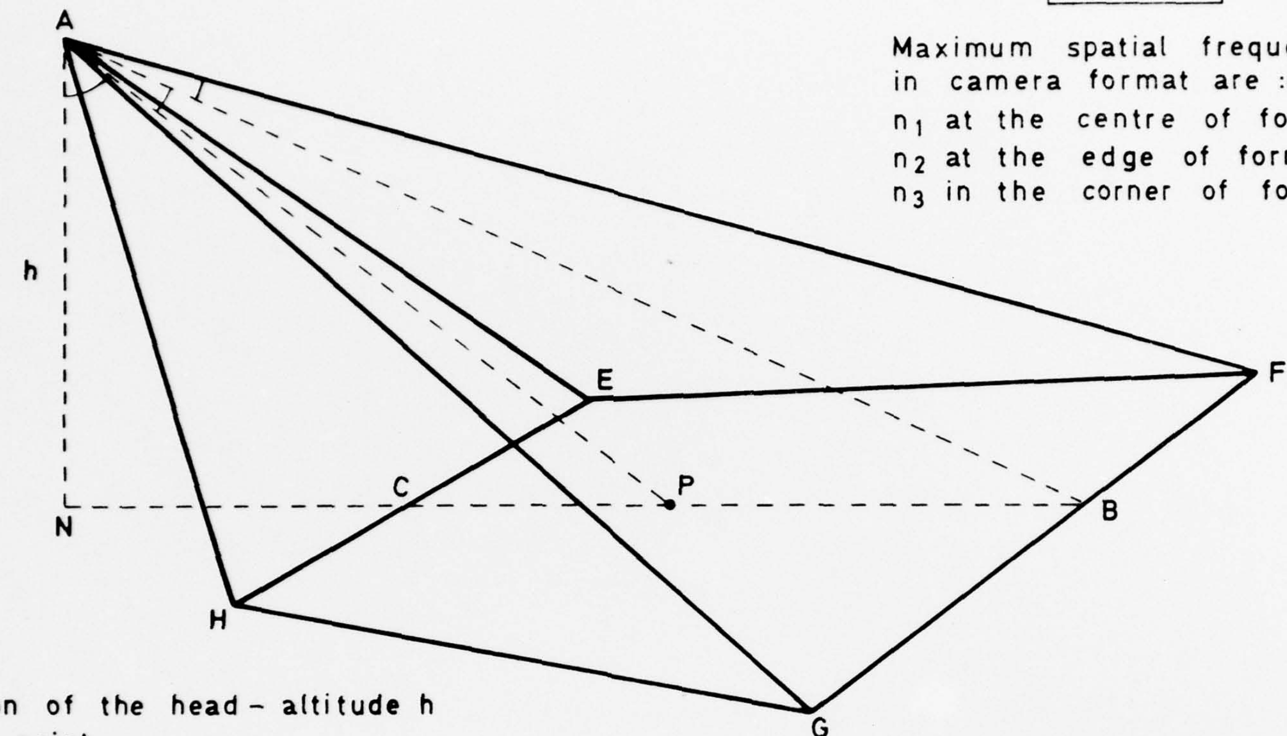
Fig. 22 Geometry of camera format and field of view



Maximum spatial frequencies in camera format are :-
n_1 at the centre of format
n_2 at the edge of format
n_3 in the corner of format



A is the position of the head – altitude h
N is the nadir point
Angle $N\hat{A}P$, the camera offset angle from the yaw axis of the head = β
Angle $P\hat{A}B = \theta/2$, angle $B\hat{A}F = \psi/2$
EFGH is the area photographed on the earth's surface (assumed plane)

Fig.23 Geometry of ground coverage pattern obtained via oblique photography

Fig. 23

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

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17. Abstract

The Skylark sounding rocket has been developed to produce a stable platform for high-altitude remote-sensing experiments. This Report describes the development and performance of photographic payloads carried on three Skylark rockets, one fired from Woomera, South Australia and two from Mercedes, San Luis Province, Argentina. The methods used for prediction of the performance of the photographic systems and the estimation of the required camera exposures are detailed. For each rocket firing the choice of photographic emulsions and filters is detailed and examples are given of the imagery obtained. Measurements made on the imagery have validated the methods used for the prediction of the performance of the photographic systems. The imagery has been assessed and interpreted by the Geography Department of the University of Reading and its findings are referenced.

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