'Photogrammetric Week '95', D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1995

Demands on Electro-optical Cameras for Sensing and Mapping

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ABSTRACT

Electro-optical cameras installed in satellites circling the globe at altitudes of several 100 kilometers have been used for sensing and mapping purposes for more than 20 years already. Technological advances and plummeting prices make the use of electro-optical sensing in planes or helicopters probable for sensing and mapping jobs that complement the time-tested photographic surveys. This paper presents a comparison of photogrammetric cameras with CCD strip and area detectors. The suitability of CCD detectors for sensing and mapping jobs is assessed. Specifically, the differences between strip and area detectors for the mentioned tasks are shown. Finally, the VOS60 electro-optical camera system from Carl Zeiss for the Open Skies program for verifying international disarmament agreements is described.

1. DIFFERENCES BETWEEN FILM AND ELECTRO-OPTICAL CAMERAS

Today's mapping cameras perform their surveying and sensing tasks, e. g. environmental monitoring, very reliably, with the utmost geometrical precision, and an excellent production rate.
Even so the question arises if electro-optical cameras with CCD strip or area detectors, which today provide a geometrical resolution comparable to that of mapping cameras, might also be used for these jobs because they provide the following additional advantages over mapping cameras:

- The surveyed terrain can be viewed immediately and online on a monitor.
- The image material is directly available for automated processing without the digitization required with photographic film.

Mapping cameras feature a very large field of view and a very high geometrical resolution. As a rule, modern mapping cameras with FMC and stabilization across the flying direction cover about 220 mm in the image plane and achieve a geometrical resolution of about 65 lp/mm. This corresponds to a pixel size of about 7.7 µm. If the image information stored in the film is digitized with this pixel size, a data volume of $(30k)^2$ pixels or 0.9 gigabytes is obtained.
Because of their useful length or area, currently available CCD strip or area detectors capture lesser dimensions in the image plane than mapping cameras. This is why, at a comparable geometrical resolution of mapping cameras and electro-optical cameras of about 8 µm, the latter capture smaller terrain strips than mapping cameras.
However, electro-optical cameras feature novel characteristics that mapping cameras do not offer. As mentioned above, this includes the option to view the terrain online on a monitor and to assess, e. g., the image quality or the navigation precision, and to apply immediate corrections. Also, digital image data is much easier to preprocess than photographic film, e.g. by manipulating the image brightness or the contrast digitally and online. These illustrative features of electro-optical cameras will influence and change future procedures of image taking and mapping. It may well be that the demand that electro-optical cameras have not only the same geometrical resolution as mapping cameras but also the same field of view will become of minor or no importance.
During photogrammetric plotting of the taken aerial images, certain processing steps can be automated already today if the image data is available in digital or digitized form. While the digital image data from an electro-optical camera is directly available for further processing, the image information stored in photographic film has first to be subjected to a delaying scan before it can be plotted.
The procedural steps which can be automated already today include, for example, interior orientation, digital aerotriangulation, image rectification, the generation of orthophotos and digital terrain models,

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image and map superimposition, and updating comparisons. Future automation of further steps, e.g. the automatic extraction of buildings, will further increase the need for digital image data and thus for electro-optical cameras.
Electro-optical cameras differ considerably depending on whether a strip detector or an area detector is being used. A CCD area detector places the same demands on stabilization, for example, but covers less ground than a mapping camera. Because of their length, CCD strip detectors offer better ground coverage than area detectors but require much better stabilization than a mapping camera or an electro-optical area detector camera.

2. REQUIREMENTS FOR SENSING AND MAPPING

For the following, sensing is defined as the interpretation of the image content, e.g. terrain overgrowth, changes compared to older, existing images, or environmental monitoring. Geometrical mapping of the image content is to play a minor role.
Mapping tasks, on the other hand, evaluate the image material geometrically, e. g. by coordinates and distances, and possibly require the superimposition of the image to be plotted with other images or maps. They may in addition include the above-mentioned sensing tasks.
Since mapping includes sensing, it is more complex and places higher demands on taking and plotting than sensing. Photogrammetric image plotting is included in mapping as defined above.
Strip and area detector cameras are differently suited for these tasks.
Generally speaking it may be said that, for mapping tasks, a stable geometry is mandatory in the recorded images. Area detectors are therefore better suited for this task than strip detectors because, in an image created by a CCD area detector, the geometric relationshis are constant (e. g. rotations) or change linearly (e.g. scale). The geometric relationships can change only during the short period of exposure, which can be avoided by powerful stabilization. Thus, the performance of a mapping camera is similar to that of an electro-optical camera with area detector except for the smaller ground coverage.
When a strip detector is used, however, the geometric relationships can change in the recorded image strip from one line to the next due to the influence of plane movements. This means that a strip detector has to be stabilized online precisely and continually over the whole length of the image strip, or that the plane movements have to be recorded precisely in digital form and have to be compensated offline during image plotting.
The stabilization quality requirements are identical for area and strip detectors. A major difference is that with an area detector, the stabilization precision is required only during the moment of exposure and that the drift of the gyroscope required for stabilization plays a minor role, while it plays a much greater role with strip detectors.
CCD strips therefore are better suited for sensing than for mapping because they would have to be stabilized very precisely for the latter. For the interpretation tasks that are generally performed within the scope of sensing, the geometric imprecisions from one line to the next are easier to tolerate than for mapping tasks.
To precisely stablize to one detector element with a detector element size of 8 µm and a 300 mm lens, a stabilization quality of 0.03 mrad is required. This required stabilization quality is at least 2 times higher than the best that has been achieved in our company.

3. COMPARISON OF CCD STRIP AND AREA DETECTORS

As already mentioned, either a CCD strip or an area detector can be used in an electro-optical camera for the above tasks. They differ fundamentally and have advantages and disadvantages. The suitability of strip and area detectors for sensing and mapping is discussed in the following.

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3.1 Available Strip and Area Detectors

Both strip and area detectors have to meet the requirement of a very large useful area for a small detector element size. While large strip detectors achieve up to 96 mm in one dimension in the image plane, area detectors cover a maximum area of 61 x 61 mm^2 in the image plane. However, the DALSA detector that achieves this is not readily available and extremely expensive. Thus the area coverage achievable in the image plane with currently available area detectors can typically be assumed to be 30 x 30 mm^2. In addition, the maximum data transfer rate is also a major performance feature. With a strip detector, it determines the maximum number of lines per second, and with an area detector the maximum number of images per second. The line rate and the flying speed together determine the maximum ground sampled distance in the flying direction for the strip detector resp. the maximum number of frames per second for the area detector, which decides whether bridging or even the image overlapping required for stereoscopic image pairs is possible with a given flying speed.
The following tables survey the available strip and area detectors.

Detector	Manufacturer	Pixel Number	Pixel Size	Dynamic Range	Color	Data Rate	Line Rate	Length
KLI-6003A	Kodak	3*6000	12x12•m•	4000:1	y	30Mhz	1600Hz	72mm
KLI-8003A	Kodak	3*8000	9x9•m•	4000:1	y	30Mhz	1250Hz	72mm
THX7821B	Thomson	3*8000	7x7•m•	15000:1	y	5MHz	192Hz	60mm
CCD11-80	EEV	1*8000	8x8•m•	8000:1	b/w	28 Mhz	3500Hz	96mm
CCD21-40	EEV	1*12000	8x8•m•	8000:1	b/w	28 Mhz	2300Hz	96mm
THX7834A	Thomson	1*12000	6,5x6,5•m•	6000:1	b/w	20MHz	1600Hz	78mm

Table 1: Long CCD strip detectors with small detector element size.

Detector	Manufacturer	Pixel Number	Pixel Size	Dynamic Range	Color	Data Rate	Frames/s	Size
IA-D9-2048	DALSA	2048•	12x12•m•	3000:1	b/w	60MHz	14	24,5x24,5mm•
RA2000J	RETICON	2048•	13,5x13,5•m•	20000:1	b/w	4MHz	1	27,6x27,6mm•
THX7897M	Thomson	2048•	15x15•m•	32000:1	b/w	4MHz	1	30,7x30,7mm•
KAF-4200	Kodak	2048•	9x9•m•	4000:1	b/w	40MHz	9	18,4x18,4mm•
KAF-6300	Kodak	3072*2048	9x9•m•	4000:1	b/w	20MHz	3	27,6x18,4mm•
IA-D9-5000	DALSA	5120•	12x12•m•	1600:1	b/w	60MHz	2	61,4x61,4mm•

Table 2: CCD area detectors with small detector element size.

To multiply the line length, several lines can be joind by optical butting. This is also possible with area detectors. In both cases the hardware requirement and, worse, the data volume generated by butted detectors multiplies. If the maximum data rate of a single EEV strip is 220 megabits per second (MBPS), it increases to 440 MBPS for 2 butted lines. This applies similarly to the Kodak detector with 2048^2 elements. If a single Kodak detector generates up to 302 MBPS, the data rate of a detector butted from 2 such single detectors increases to 604 MBPS. Such immense data volumes cannot be stored with a single digital recorder but would have to be reduced to 240 MBPS by means of a data compression method. This is the maximum data rate that a modern digital recorder from AMPEX or Schlumberger can record in the form of digial image data. Another drawback is that this very large data volume has to be viewed on the monitor in a window with a size of 1K × 1K and then has to be plotted manually or semi-automatically.

3.2 Advantages and Drawbacks of the Two Detector Types

Both the strip detector and the area detector have specific advantages and drawbacks that make them suitable or less suitable for sensing and mapping tasks.

3.2.1 Strip Detector

Due to its larger size, a strip detector generally captures a wider ground strip than an area detector. If one compares the 12 000-element strip detector from EEV with the Kodak area detector (3072×2048 detector elements), the ground coverage of the strip detector is 3.5 times better than that of the area detector.
An EO strip camera pointing down vertically reproduces the terrain in central perspective across the flying direction and in parallel perspective in the flying direction.
However, in contrast to an area detector, a strip detector does not allow forward motion compensation (FMC), and the exposure time cannot be extended beyond the set line rate. Plane movements causing the geometric relationships to change from line to line have to be compensated by continual and precise stabilization on a pixel basis. If a strip detector requires stabilization over, for example, 5 000 lines, this corresponds to 10 sec. with a line rate of 500 Hz. With an area detector with also 5 000 lines, the required stabilization time is reduced to the exposure time per frame of about 1/500 sec. However, the stabilization time for a strip detector may reach up to one hour.
To achieve ground pixels with the same dimension in and across the flying direction, the line rate has to be matched taking into account the flying height and the flying speed, which presupposes a precise knowledge of the flying height and speed. Stereoscopic surveys can be made only with a multi-strip array or with gaps if a single strip detector and a mirror in front of the EO camera lens is used.
In contrast to area detectors, color strip detectors are available whose 3 individual strips are arranged one behind the other in the flying direction. For geometrically correct superimposition of the three color lines, which take the surveyed terrain at different times, the variations of the flying speed, roll, pitch and yaw and the line rate have to be known.
The work involved in superimposing the taken image with another aerial image or a map decreases with the stabilization precision achieved during taking. For pixel-precise stabilization it can currently even be less for a strip detector than for an area detector because the bridging effort is not required.

3.2.2 Area Detector

At the same exposure time of, e. g. 1/2300 sec. (corresponding to a line rate of 2.3 kHz), an area detector exposes up to 25 million and a strip detector only up to 12 000 detector elements. This means that the ground strip surveyed per exposure is narrower but several times longer than with a strip detector. If electro-mechanical or electronic FMC is used, the CCD area detector allows not only the exposure time to be extended in case of bad lighting conditions, but also a larger v/h to be used. If one compares the 12 000-element strip detector with the DALSA area detector (2048^2 elements and 14 frames per second corresponding to about 28 700 lines in the flying direction), one obtains a factor of 12 in favor of the area detector. In addition, the stable geometrical relationships within the image generated by an area detector, the effort required for superimposition with other images or maps corresponds to that required for the superimposition of photographic films.
Ground coverage across the flying direction is about 1.6 to 5.3 times less with an area detector than with a strip detector. The cost of an area detector is about 3.2 times (Kodak with 2048^2 elements) or

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even 16 times (DALSA area with 5 120^2 elements) higher than that of the 12 000-element EEV strip. These cost factors apply to area detectors in the highest quality range, i. e. those with the minimum number of defective detector elements.

3.2.3 Assessment of Strip and Area Detectors

If the small field of view across the flying direction can be tolerated for a given application, an EO camera with area detector should be used. Compared to a strip detector, the area detector offers the following additional advantages already listed in section 3.2.2, e. g. FMC, longer exposure times and a higher v/h.
If the ground coverage across the flying direction has to be very large, optical butting of CCD strip or area detectors may be considered. The data rates that have to be handled by the hardware and the software during taking, storage, displaying and mapping multiply in both cases, however. The strip detector in addition requires highly precise, i. e. pixel-precise stabilization for geometrical plotting.
In conclusion it may be said that, whenever the application permits, an area detector should be used.

4. EO SENSORS FROM CARL ZEISS FOR OPEN SKIES

4.1 Open Skies

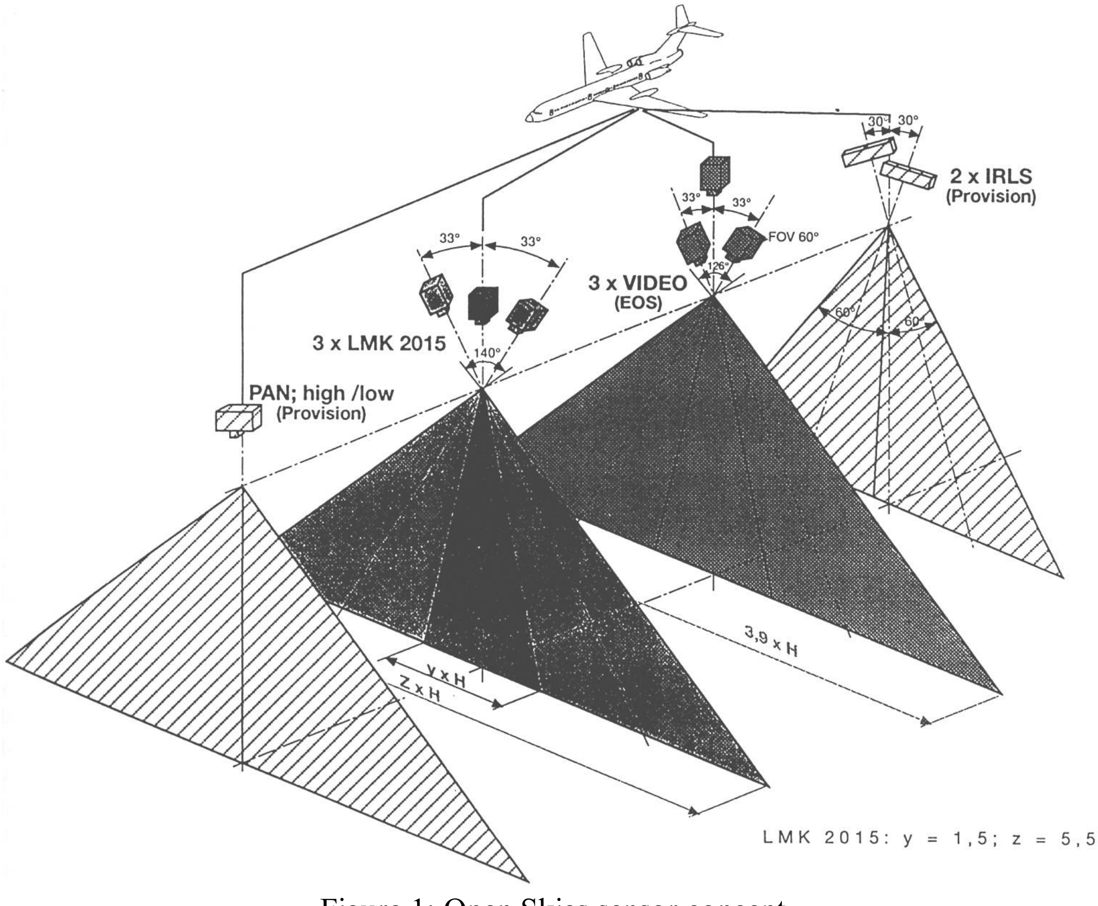

Figure 1: Open Skies sensor concept.

Open Skies is an international program for verifying the disarmament measures agreed upon at Vienna from the air according to specific rules by flying across the territory of the treaty states.The Open Skies treaty was signed on March 24, 1992, by 9 countries from the former Warsaw Pact and by 16 NATO countries with a view to:

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- implementing the obligations entered into at the Conference on Security and Cooperation in Europe (CSCE) to promote the openness and transparency of military activities,
- increasing the security by confidence- and security-enhancing measures,
- facilitating the monitoring of disarmament verification agreements,
- conflict avoidance and crisis management,
- improving environmental protection.

Further countries have since joined this convention. The above objectives are to be implemented in an Open Sky by observation flights of the contracting states over the territory of other treaty states.
Within the scope of this verification, digital images are to be interpreted but not mapped. This is why a strip detector is suited for this sensing task as described above and is used in the VOS60.
Germany, which participates in Open Skies, is equipping a TU-154M plane with appropriate sensors for this task. The sensor equipment is being installed in two phases. In the first "initial capability" phase, which ends 3 years after the signing of the treaty, the following sensors have been installed: 3 LMK2015 mapping cameras from Carl Zeiss Jena GmbH and 3 high-resolution VOS60 electro-optical cameras from Carl Zeiss Oberkochen. In the second "real concept" phase, this sensor equipment is to be complemented by further sensors, e.g. a panoramic camera, 2 infrared line scanners, and a synthetic aperture radar (SAR).
During these international observation flights for verifying the disarmament agreements, guarantees have to be given that the ground sampled distance (GSD) specified for each sensor type (which corresponds to the projection of a detector element on the ground) is not exceeded. The agreed maximum GSD is 30 cm for optical and optronic sensors, 50 cm for the infrared line scanner, and 300 cm for the SAR. This sensor concept is illustrated in Fig. 1, for which we thank Fa. Dornier, Deutsche Aerospace.

4.2 Electro-Optical VOS 60 Camera System for Open Skies

The high-resolution electro-optical camera system (airborne segment) supplied in August, 1994, by Carl Zeiss for this task consists of 3 VOS60 (Video Sensor Open Skies) color video sensors with a focal length of 60 mm and one each CCD color strip detector with 3×6,000 detector elements, control electronics, sensor control panels, Conrac monitors for online image display during the flight, and a laser altimeter for the overall system (see Fig. 2 which, for completeness, also shows the ground segment for image display and processing). The system further includes 3 AMPEX DCRsi digital recorders with a maximum data recording rate of 107 MBPS and the associated control panels. On the one hand the VOS60 electro-optical cameras are being used as viewfinders for the mapping cameras, i.e. the mapping cameras are turned on only when the ground information displayed on the VOS60 monitor indicates this. On the other hand, they can be used as primary sensors at low flying heights enforced, for example, by cloud covers, i. e. whenever the mapping cameras with their longer focal length would achieve a higher resolution than the agreed resolution of 300 mm and may therefore not be turned on. The terrain surveyed by each sensor is always shown online on the associated monitor. Regarding image display, the operator can choose between an overview mode and a window display mode. In the overview mode, the whole field of view of the camera lens is shown on the monitor, but of the 6 000 detector elements of the CCD strip, only every fifth detector element and thus a total of 1,200 detector elements are shown per monitor line. In the window mode, the operator can select any 1 280-element segment from the CCD strip for monitor display. At the lower monitor edge, a 48 pixel high data block is used to display the following additional information: flying height, flying speed, geographical longitude and latitude, date and time, aperture setting and the line rate. The operator can also select if the sensor-generated image lines are to be displayed continually in a so-called waterfall mode or - for more precise interpretation - as a full-screen still monitor image. Image display in color or monochrome is optional. The terrain taken by the electro-optical camera is always recorded by an

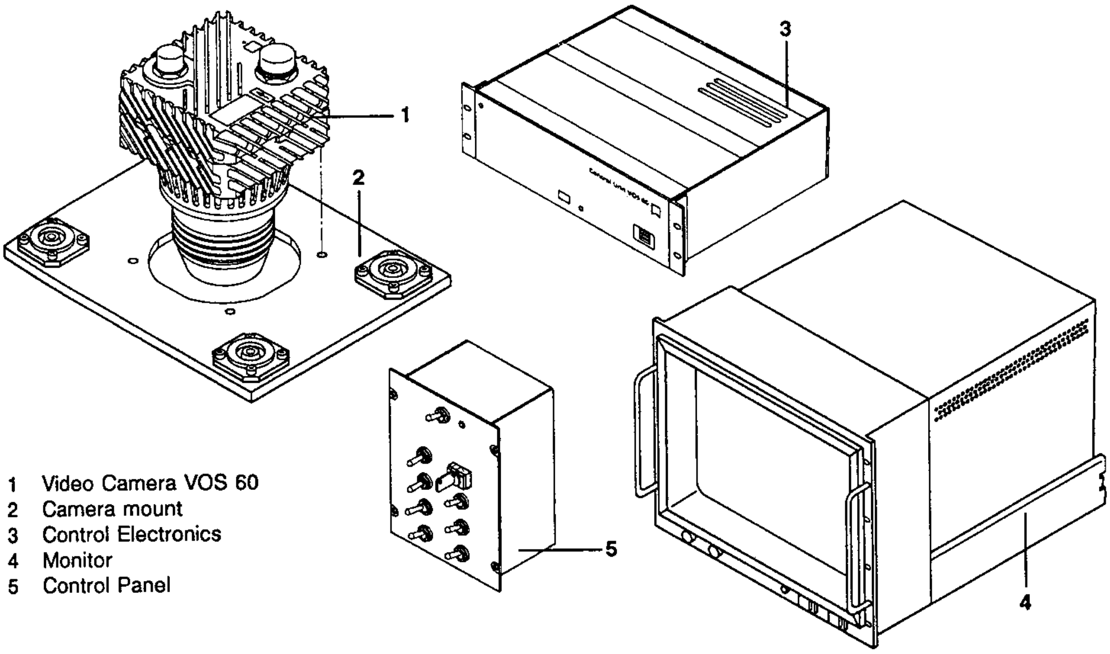

Figure 2: VOS60 sensor system.

AMPEX DCRsi digital recorder with a maximum data rate of 107 MBPS.

4.3 Results Obtained with the EO Camera System

The following images and results have been obtained with a precursor of the VOS 60 system. This system also has a color strip with 3×5 000 detector elements, a detector element size of 14 x 14 μm^2, and a focal length of 80 mm.

Figure 3: View of Nördlingen.

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Fig. 3 shows a 1:1 representation of a view taken of Nördlingen from an altitude of about 400 m. Fig. 4 shows a section of Fig. 3 enlarged 4 times. Fig. 5 shows a high-contrast resolution test taken at a flying height of 500 m. Such ground-installed resolution tests were used during an international resolution verification test at Shatalovo near Moscow in June, 1994, to determine a mean ground sampled distance of 34 line pairs at 36 theoretically possible line pairs with a detector element size of 14 µm.

Figure 4: Section of the Nördlingen view enlarged 4x.

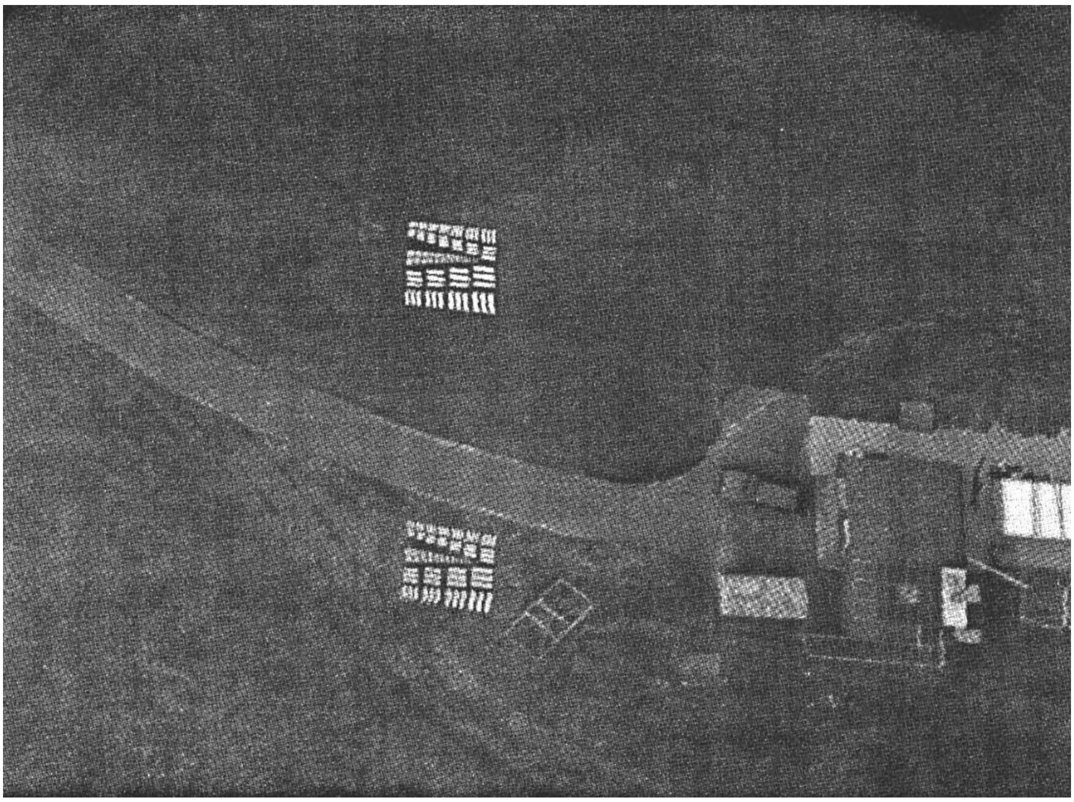

Figure 5: Resolution test.