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Airborne video as a remote sensor for environmental monitoring of linear infrastructure: a case study and review

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ABSTRACT

At present, environmental monitoring of linear infrastructure is based mainly on field sampling. The 'integrated mapping' approach has received only limited attention from field scientists. The increased environmental regulation of corridor targets has required remote sensing research to develop a sensor or technique for targets ranging from 15 m to 100 m in swath width. In an attempt to identify the optimal remote sensing system for linear targets, an overview is provided of the application requirements and the technology currently available. The relative limitation of traditional remote sensing systems in such a linear application is briefly discussed. It is noted that airborne video could provide, in a cost-effective manner, information required for a very narrow and long strip target utilising the narrow view angle and dynamic stereo coverage. The value of this paper is warranted in proposing a new concept of video infrastructure monitoring as a future research direction in the recognition of sensor characteristics and limitations.

Keywords : linear infrastructure, airborne video, environmental monitoring

요 약

도로, 철도, 송전선 등 선형개발 사업에 대한 환경평가과정은 몇 군데의 샘플 조사 결과에 의거하여 전체 대상지역의 실태를 유추하는 현지조사에 의존하는 것이 일반적으로 정착된 방법이다. 현지조사와 원격탐사를 연계한 통합적인 접근에 의거하여 환경감시를 수행하는 사례를 실무에서 찾아보기 어렵다. 선형개발사업은 산지, 습지, 하천 등 자연환경에서 보전우선순위가 높은 지역을 통과하여 인간 생활권을 연결하는 경향이 있어 통상의 면형개발사업 (예: 공단건설)보다 자연환경에 광역적이고 부정적인

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영향을 미치기 때문에 각국 정부가 선형개발 사업에 대하여 환경규제를 보다 강화하고 있는 추세가 두드러지고 있다. 지형적으로 길고(수백 킬로미터) 폭이 좁은(수십~수백 미터) 특징을 지닌 선형개발사업의 환경감시를 위한 최적의 원격센서를 개발하는 것이 시급하게 요청되고 있다. 본 연구에서는 실제 선형개발 사업에서 현지조사를 통해 수집되는 데이터를 분석하고 상응한 정보를 취득할 수 있는 최적의 원격센서를 평가하고자 하였다. 항공 비디오가 저렴한 경비로 실시간 동영상을 제공하고 협각조망 때문에 선형개발 사업에 최적의 센서로 평가된다. 특별히 본 논문은 센서의 장단점을 확실히 규명하고 미래의 연구방향에 있어 “비디오 선형 모니터링”이라는 새로운 개념을 제시하였다는 데 그 가치를 지닌다고 하겠다. 궁극적으로 본 논문에서 제안이 비디오 선형모니터링의 가능성에 대해 새로운 전기를 마련할 수 있을 것으로 기대된다.

주요어 : 선행개발사업, 항공비디오, 환경감시

1. Introduction

Environmental monitoring of sites affected by the construction of power plants, transmission lines, gas lines, utility roads and other related linear facilities is essential as it is required by regulatory agencies (Chan, 1984). Utility companies are actively involved in monitoring natural landscape areas which have been disturbed by linear development. Environmental monitoring of 'corridor-based' facilities is different from the traditional targets of 'area-based' mapping such as industrial complexes, city development, etc. The corridor itself is linear and generally very long (hundreds or thousands of kilometres) yet very narrow (10-100 metres). The types of facilities which fit these criteria include cross-country pipelines, electric transmission lines and overhead cables, but also include railways, roads, highways, rivers and coastlines. Railways and transmission lines or pipelines as well as fibre optic cables are physically quite dissimilar. These facilities do, however, fit the same corridor target for purposes of environmental monitoring. Such corridor-based facilities have a number of characteristics in common: they are expensive to build, expensive to maintain and are subject to strict environmental regulation. All of these facilities do, however, fit the description of a 'corridor' target for purposes of environmental monitoring.

In general, current monitoring programmes for disturbed corridor sites have been based on the attributes of an area at one point in time, reflecting the emphasis on the small number of in-situ data (British Gas, 1988; Ritchie et al., 1988; Ritchie et al., 1990; Gimingham et al., 1991; Environmental Consultants (Alta.) Ltd., 1996; Calvert-Hayes, 1996; Chambers Group Inc., 1997). One of the major disadvantages of traditional field monitoring is that it is costly, laborious and time consuming due to the large number of samples required. Nevertheless, sampling errors can be quite large, especially where the ground vegetation is not uniformly distributed in the field. Furthermore, point observations have the disadvantage that they provide only limited information on historical trends and spatial distribution of the vegetation recovery, which is possible through a comparison of scenes of different dates. Until recently, the investigations of a shifting mosaic and patch dynamics in linear projects remained largely theoretical because the current field survey technique has difficulty in assembling multi-temporal images simultaneously. Present ground-based regular inventories are not practical in terms of either cost or scientific reliability (Um, 1997).

Over the last 20 years, remote sensing research has been primarily used to support global, national or large area applications(Cherrill et al., 1994; Mumby et al., 1999). As a consequence, those charged with more site-specific responsibilities such as the environmental monitoring of a linear development facility have benefited far less from the fruits of that research. It is important to identify an optimal remote sensor best suited to the characteristics of the ground target. Remote sensing techniques, in order to be practical, must be part of a methodology that delivers the most useful information at as low a cost as possible to the potential user. For the requirements of corridor monitoring, various sensors can be deployed from satellite or aircraft (i.e. from photographic cameras to scanners and complex imaging spectrometers). Satellite image resolution is currently limited to a minimum mapping unit of 1 m per picture elements (pixels). It would still not be possible to extract detailed information on a 10 m or so wide Right-of-Way (ROW). For this type of narrow target, it will still be necessary to use aerial photography to get fine details at larger scales.

Aerial photography is one of the oldest and most widely applied sensors, capable of recording information in visible and near-infrared wavebands onto photographic film. Large-scale photography has often been used for this type of application to investigate detailed ground features (Hoover, 1974; Aird, 1980; Ellis et al., 1984; Jadkowski et al., 1994). However, many inconveniences involved in the collection and processing of data, as well as the cost, have proven to be a barrier to its widespread use for this type of application. If digital remote sensing techniques are applied, the film image and hard copy must be digitized into machine-readable pixels and stored on computer-compatible media such as tape or disks. The cost of scanning conventional aerial photography is prohibitively expensive for a long linear target. Furthermore, manual handling of hundreds or thousands of hard-copy aerial photographs may prove to be unmanageable.

Traditional sensors are essentially designed for site-by-site assessment of a specific ground target. They do little to address the overall impact of such linear developments on the landscape. Moreover, if large areas are to be covered to detect sufficient ground detail, the cost disadvantage will apply to the whole coverage. To fulfill the data requirements of corridor monitoring, it is sufficient to have information along a line in the vicinity of the corridor disturbed. Traditional remote sensing systems have many inherent drawbacks when incorporated within a monitoring programme for a long narrow target. Needless much recording of redundant information in linear applications occurs when using traditional area-based sensors. Clearly, economic factors hinder the use of standard area-based remote sensors in this type of application. This is one reason why most of the information for strip features at lower levels is currently gathered from ground surveys. Corridor monitoring represents a potential application for remote sensing which is largely unfulfilled (Um, 1997).

For environmental monitoring of linear targets using remote sensing techniques, it is necessary to acquire detailed aerial survey data for a narrow corridor regularly to keep the ecological monitoring process at a relatively low cost. Depending upon the width and length of the corridor, the facility operator should maintain a ROW of 10-100 metres wide and should assess the environmental impact along the route. The ROW managers are continually being faced with the challenge of monitoring the ROW with reduced budgets and personnel. It is certain that more linear projects will be implemented in many places in the near future and it is also apparent from recent global trends that concern about the environmental impact of such linear development may be of world-wide importance.

There is, therefore, an imperative need to identify an appropriate practical technique to monitor the environmental impact along routes. Consequently, major research questions investigated in this paper focused on identifying the optimal remote sensors for environmental monitoring of linear projects. This is to overcome the apparent scientific gaps that exist between field scientists such as ecologists and the remote sensing experts and to share common interests between the two groups.

2. Environmental significance of linear development projects

The number of linear development projects has increased substantially in the last few decades. The standard sequence of linear development projects starts with the preparation of the working width to limit the contractor's movement. The working width is prepared to facilitate easy passage of equipment with top soil removed to one side (Figure 1). Disturbance of the ground during construction usually results in a change from the previously vegetated area to bare ground. The stark linear boundaries of ROW have the effect of breaking up the natural habitat visually, immediately after the disturbance (British Gas, 1988). Because of this, Ritchie (1989) noted that "the public's suspicion for a new corridor magnifies itself in the appearance of the bare ground shortly after the development projects" (Figure 2). The assessment of landscape impact by linear projects involves the consideration of numerous habitat types. For example, a pipeline trench may have to be dug through agricultural land, woodland and moorland as well as traverse streams and rivers (Ryder et al., 1989). In particular, linear developments (including roads, railways, pipelines, canals and overhead transmission lines) tend to occupy the most convenient and short routes between centres of population or sources of supply and demand. Such a prominent impact has made environmentalists more eager to protect all natural ecosystems, which may be disturbed.

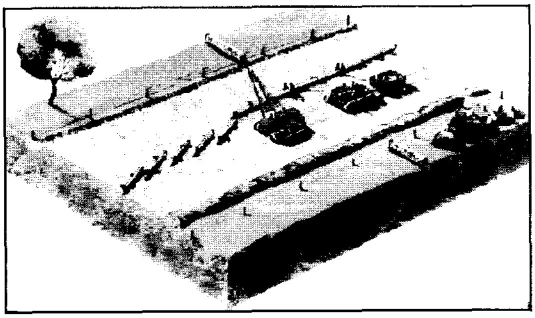


Figure 1. A typical linear development site

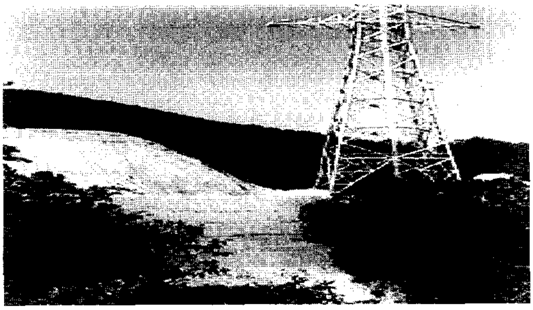


Figure 2. A typical scene shortly after the linear development projects

Therefore, one of the critical issues influencing the approval of linear development projects by government agencies is a demonstration of how the environmental impact will be evaluated. Recently, there has been a trend toward the strict enforcement of government regulations concerning the environmental impact of linear development projects. In particular, during the past twenty years or so, much public interest has focused on disturbance caused by linear projects. After World War II, rapid economic development provided many advanced countries with extensive linear projects in a comparatively short time. Due to the increased density of linear projects, many of them require EIA by the planning authorities. In fact, 70% of projects subject to Environmental Impact Assessment (EIA) are classified as linear development (Um, 1997).

For example, under the Electricity and Pipeline Works Regulations (1990) of the UK, cross-country pipelines for the transmission of hazardous materials, when over 16 km in length, require an EIA for Construction Authorization from the Secretary of State for Energy. It is now standard practice to include provisions for the restoration and monitoring of pipeline routes at the initial planning stage within the legal framework of the UK. In addition, in accordance with such a legally binding agreement being included at the planning stage, subsequent monitoring procedures should be carried out to ensure the restoration of pipeline routes after pipeline construction.

When granting Pipeline Construction Authorization (PCA), the Secretary of State requires the developer to agree with the method statement with the relevant local planning authority over environmentally sensitive crossings such as moorlands. The method statement specifies the methods of reinstatement and also the requirements for subsequent environmental monitoring. Based on this statement, the developer undertakes the monitoring of all the environmental effects of the projects and provides the relevant local planning authorities and nature conservation bodies with the monitoring results. Many other countries throughout the world have similar regulations for the restoration monitoring of pipeline routes. For example, in the case of the USA, Calvert-Hayes (1996) states "Our monitoring follows the strict guidelines of the Federal Energy Regulatory Commission (FERC) Upland Erosion Control, Revegetation, and Maintenance Plan and the Wetland and Waterbody Construction and Mitigation Procedures. Both the Plan and Procedures become conditions of approval for the permit to construct issued by the FERC".

3. Present monitoring practice for the disturbed corridor

Traditional methods for environmental monitoring of linear projects can be exemplified by current practice in relation to the Shell North West Ethylene Pipeline (NWEP), which was constructed in 1992. The NWEP consists of approximately 411 kilometres of 25-cm diameter pipeline. There are several stages of monitoring for reinstatement of a pipeline route, before and after pipeline construction. The method of monitoring varies depending on the degree of disturbance by pipeline construction and the environmental significance of the site. The Pipeline Construction Authorization (PCA) of the UK requires the monitoring of all environmentally sensitive sites. Shell monitored the success of reinstatement over the 5-year period following construction. It also made the results of the monitoring available to the relevant local planning authorities and to the statutory nature conservation organizations: English Nature and Scottish Natural Heritage (RSK Environment Ltd., 1995).

Before the pipeline construction, a series of progressively detailed field surveys were carried out and detailed qualitative ecological data were collected along the pipeline route. These were to be used as a baseline against which the success of reinstatement could be measured along the route and to determine any short or long-term disturbance effects (Shell Chemicals UK Limited, 1992). After the pipeline construction, an annual field survey was carried out in the summer. The results were compiled, with maps drawn to indicate position and extent of the communities. An overall estimate for the revegetation was made by a subjective visual assessment (by percentage). At certain ecologically important sites, transects were recorded across the pipeline. These were marked out with one or more wooden stakes, so that recording may be repeated along a similar line in future years. The transects are generally 40 m in length, with the vegetation recorded at 2 m intervals. Records were also made by percentage of cover, in 1 m by 1 m quadrats.

Figure 3. Photograph which shows scene to locate the existing field transect and the following quadrat recordings of vegetation recovery

Figure 3 is a photograph, which shows the scene to locate an existing field transect, followed by quadrat recordings of vegetation recovery at the Carnwath Moss during the 1995 annual field survey for the NWEP. Information from the vegetation transect recordings was used to compile a set of histograms for vegetation recovery between the disturbed ROW and surrounding undisturbed areas. The survey results are followed by general comments on the state of the vegetation both inside (20 m) and outside the spread (RSK Environment Ltd., 1995).

Many other countries have similar practices for restoration monitoring of a pipeline route. In the case of the USA, Calvert-Hayes (1996) states "Our firm monitors the restoration of pipelines during and after construction. Our monitoring is based on field surveys conducted during construction, just after the completion of construction, and yearly". An Interim Resource Management Plan for the San Joaquin Hills Transportation prepared by Chambers Group Inc. (1997) specifies subsequent monitoring of restoration efforts. Plant mixes for revegetating approximately 155 acres of coastal sage scrub were developed from baseline data obtained from transects through representative scrub in the project ROW. In addition, they were supplemented by several non-invasive native pioneer species to assure coverage in the first years of revegetation to aid in soil development and provide erosion control. More than 600 Coast live oak trees in the construction path and the ROW were tagged, measured (diameter at breast height [dbh], height, canopy), and assessed for health, aesthetic value and potential for relocation (Chambers Group Inc., 1997).

As an example from Canada, the Environmental Protection Plan (EPP) for Banff Natural Gas pipeline construction states "Canadian Western Natural Gas Company Limited (CWNG) monitors the pipeline following construction to assess revegetation, erosion and trench subsidence. Particular attention is being paid after heavy rains or winds and the first spring after construction. Weed growth is monitored and corrected, if required. Touch up reclamation is being undertaken on an 'as needed' basis, depending on the problem with touch up seeding where plant establishment has failed. A rare and endangered plant survey is being undertaken"(Environmental Consultants, Alta Ltd., 1996).

4. On-site observation for the field survey

On-site observation for monitoring methods described in the previous section was carried out. The field work was started with a community-based survey. First, the surveyor looked at the entire vegetation cover at the edge of the survey site by walking around the site. The survey result was recorded based on the surveyor's personal impression from such a community overview and observations from walking over the ROW. The observer could locate himself at any direction or point to get an overall view. Different directions, heights and positions may produce different results for vegetation recovery. The observer could also start to survey, to get an overall view, in a different direction from the previous year. Furthermore, the surveyor could walk over a well-reinstated site and a badly-recovered site, depending on his mood. It was suspected that the field survey identified the ground condition reliably in that the ability to perceive visual change is strongly influenced by location of survey points and personal subjectivity.

Following the community-based survey, a transect recording was carried out for the site. It was difficult to locate exactly the same transect line as the previous year (despite the presence of a bare wood stake mark) since the ground is not always flat and recovered vegetation (height of heather: around 30-40 cm) seriously interrupted an accurate measurement of the straight transect stretches. It was noticed that it is easy for whole 40-m transect stretches of 1-m width to be displaced differently leftward or rightward, further or back and forth from the straight line due to vegetation growth and topographic condition change. If the initial transect location is different from the previous year by about 10 to 20cm, then the succeeding quadrats will be placed in the wrong position. It was very difficult to locate the same 1 m by 1 m quadrat in the same place as the previous year. If the initial quadrat begins from a 10-cm displacement, then subsequent quadrats and the entire transect will show totally misleading results for the ROW recovery. If twenty quadrats per transect are considered, then it would be impractical to carry out reliable measurements of vegetation recovery.

It is also desirable that the transect should be designed to be representative of vegetation recovery at the survey site. In the field, there were many places where the fixed transect had not properly represented the vegetation recovery of the sites to be surveyed. The surveyor usually relies on the previous year's record and tries to increase the percentage recovery from the previous survey. If the first year survey is not well recorded, then the next survey (which is usually based on the previous one) will give a totally misleading result. Consequently, the results of recovery monitoring mostly show an annual increase according to the RSK ecological survey report. Generally, such an approach is really not comprehensible in the eye of a remote sensing practitioner. Although the experienced surveyor may have spent a full working day for two communities and three transect recordings at the Carnwath Moss site of the NWEP, it could be argued that this is a waste of time and money.

Ground-based surveys designed to regularly document the size, shape and location of recovered vegetation are not economically feasible. Environmental monitoring of a corridor target first requires clear identification of the level of information necessary to solve the specific field problem. In practice, the most feasible remedial measures based on the field survey results are drainage restoration in waterlogged areas as well as reseeding and spading of bare soil sites, as described in the field ecological monitoring result (RSK Environment Ltd., 1995). Practically, it is very difficult to implement any better means to assist ROW recovery. To meet such requirements for the remedial measures, it is possible that overview monitoring using remote sensing could be successfully designed to show the feasibility of much more cost-effective and reliable information than that of the field survey. To show annual change of the ROW site recovery, the monitoring result should be able to generate a recovery inventory for the ROW site. It is sufficient for remedial measures in ROW site reinstatement if the inventory includes very simple thematic ground classes such as 'vegetated area/non-vegetated area' and 'waterlogged area'. Such an inventory will easily show inadequately recovered areas which are not well adapted to the surrounding disturbed site and require ROW maintenance.

Based on this, the ROW manager could produce a landscape replanting programme over the ROW. In particular, in 1997 the environmental manager of the NWEP pipeline route (Dr. S. Rapson) showed keen interest to know whether the airborne video could show the percentages of bare ground and biomass as useful indicators of the success of the restoration (which is, in essence, the basic information acquired by statistical classification of digitized video). However, for certain cases, to meet the interests of the ecologist and environmentalist, the inventory would require some more detailed ground classes: recovered heather, moss, revegetated grass and unvegetated peat, bare soil and waterlogged area (Harwood, 1997).

Field monitoring may be conducted just because it is a legal requirement and to demonstrate the environmental conservation will of the oil company for the ecologist and environmentalist. Detailed documentation of the ROW recovery status may also create a good impression with the regulatory agencies. The funding and number of personnel that were available to do ground monitoring 10 years ago are now a thing of the past. On the other hand, the cost of remote sensing data is getting much cheaper and it is more powerful in terms of information content than before. The collection of field data via remote sensing is, therefore, proposed as a practical alternative. Such an aerial survey should be conducted regularly as an integral part of the ecological monitoring process. However, even using a remote sensing method for hundreds or thousands of kilometres of pipeline, such monitoring could be quite a costly activity. Consequently, it is necessary to identify an optimal sensor to solve the field data problem in the most cost-effective manner.

5. Limitations of traditional remote sensing techniques in a linear application

The characteristics of linear ground targets are considerably different from the conventional target on which traditional remote sensing has focused. It is necessary to acquire the remotely sensed image from an extremely low altitude, with a narrow angle of view, along a long corridor. It will generally be necessary to acquire imagery with a ground field-of-view (swath width) of less than 100 m for several hundreds of kilometres. To identify an optimal sensor for this target, four typical airborne sensors have been compared in consideration of the imaging requirement, based on target characteristics (as presented in Table 1). Satellite remote sensing is ruled out since the ground resolution is too coarse for the task being considered in the corridor target.

The most critical requirement for any remote sensing system is cost-effectiveness. The cost of inventory mapping with aerial photography is a good standard against which other sensors can be readily compared. To monitor the 400-km length of the corridor with aerial photography (in the case of 36-mm format) of a 100-m swath, the number of photographs required is estimated at 10,000 frames (as shown below*). For multi-year monitoring, the cost would increase several times. It is considered too expensive to monitor a long narrow corridor frequently by aerial photography. Due to such limitations, corridor monitoring using aerial photography has not achieved operational status, although a few previous attempts have been reported (Hoover, 1974; Aird, 1980; Ellis et al., 1984; Jadkowski et al., 1994).

*NOTE : Estimation of the number of photos required for a 60% stereo overlap

- Estimation of along-track ground coverage = along-track format size of small format photographic camera (36 mm) * flying height (300 m)/focal length (106 mm) = 100 m
- Net gain = along-track ground coverage (100 m) * 4/10 (standard forward overlap 60%) = 40 m

The number of photographs required for stereo-cover = 400km/40m = 10,000 exposures

Table 1. Comparison of sensor characteristics

	The Daedalus 1268 ATM[1]	Airborne Imaging spectrometer (CASI)[1]	Photography[2]	Video[2]
Cost	hardware purchase cost: £1M	Hardware purchase cost: £0.25M	hardware purchase cost: 35mm camera:(£300-400) 70mm camera (£1,000-3,000)	hardware purchase cost: Digital video camera (£1,500), £10 for one hour tape
field of view	73°-90°	42° across track (90° is available)	24°-130°[3]	5°-44°[3]
operational diagonal ground swath achievable[4]	443 m-600 m	230 m-600 m	127.5 m-1286 m	26 m-242 m
Number of bands	11 (71 available)	spatial mode:18 spectral mode:288	3	3 or 4
wavelength (m)	0.42-13 (visible, near, shortwave, thermal infrared)	0.4-0.915 (visible, near-infrared)	0.4-0.8 (visible near-infrared): wideband with spectral overlap	0.4-10 (visible near-infrared, mid-infrared, thermal)
radiometric quantisation	16bit	10-12bit	usually 8bit[5]	usually 8bit[5]
real-time imaging	No	No	No	Yes
dynamic stereo coverage	No	No	No	Yes
user friendliness	No	No	Yes	Yes
Sensor	array of silicon detectors	CCD	Film	CCD
image motion tolerability	No	Yes	No	Yes
low-light tolerance	No	Yes	No	Yes

1. For the line scanner and imaging spectrometer, ATM and CASI have been used as examples, which the Natural Environment Research Council in the UK presently uses to provide airborne remotely sensed data for research by environmental scientists (Wilson, 1995).
2. The purchase cost of the photographic camera and video camera were estimated based on the current price of professional grade digital camera.
3. A field of view was estimated by assuming a 10 mm-100 mm focal length for 36 mm by 24 mm film sensor and 6.4 mm by 4.8 mm video sensor. [Field of view ((θ) is given by tan (θ/2 = half diagonal length of sensor format/focal length]
4. A diagonal swath width was estimated by assuming a 300-m flying height from the above range of Field of View (FOV). [Diagonal swath width = 2 * flying height * tan (θ/2 ((: Field of view)]
5. Video and photo images have their own grey levels under analogue imaging conditions. In a digital environment, it all depends on the digitizing device.

The use of scanner and imaging spectrometer is more costly and complex (complicated equipment and time-consuming analysis procedure) than photography. White (1998) states that "the approximate cost for a new Airborne Thematic Mapper (ATM) is £1M, and for the Compact Airborne Spectrographic Imager (CASI), £0.25M. For maintenance, roughly 10% of the initial system purchase cost per annum is required". The hardware cost of the ATM is 666 times that of the digital video camera (if it is assumed as £1,500). The initial purchase cost of the ATM and CASI are too prohibitively expensive and further maintenance costs are also quite costly because, unlike video and small format photography, there is no large market for the ATM and CASI sensors. In the context of optimizing cost-effectiveness for this type of application, it is clear that video and small-format photography have decided advantages. [For this type of project, these would not be purchased. The daily or weekly 'hire cost' is more realistic.]

Another important element is the optimal swath width. Field of View (FOV) differences provided by various remote sensing sensors will find application at different scales. The view-angle of the imaging device must be carefully considered when trying to obtain remotely sensed data of a long, narrow target. Wide-angle imagery, such as line scanner and photography, generally covers a larger area of land surface than a smaller format system operated at the same altitude and with the same focal length lens as shown in Figure 4.

For example, as presented in Table 1,

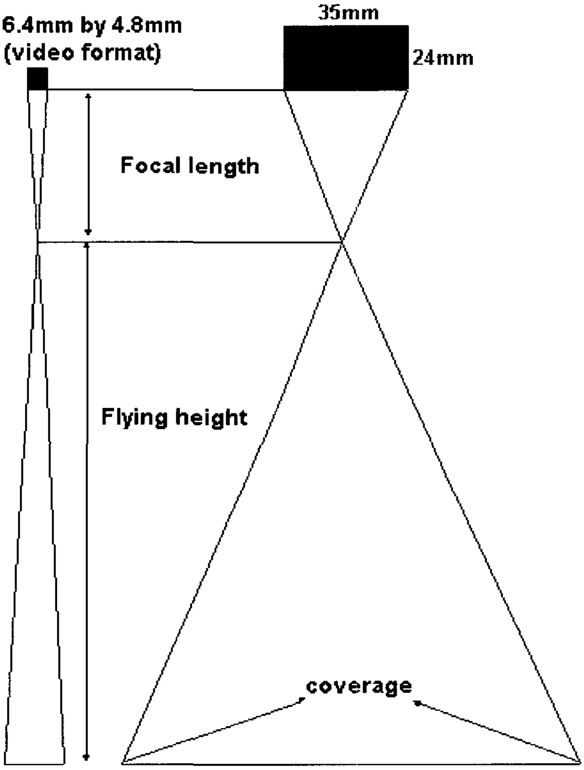


Figure 4. The relationship in ground coverage between a video sensor and photographic film (small format) at the same altitude and with the same focal lens

under the same flight specifications (300 m flying height, 10 mm-100 mm focal length range), a diagonal swath width (127.5 m-1286 m) of 35mm photography is much wider than that of video (26 m-242 m). Any single-scene image collected via such systems covers a wide area of surrounding features in addition to the strip. Such an image will, therefore, include a considerable redundancy of information which is not needed for corridor monitoring. Such wide-area coverage also disturbs the information content of the image by increasing spectral variance, through displaying unnecessary thematic ground classes. This can complicate analysis when doing digital image processing at a later stage (Um and Wright, 2000).

In many instances, the two digital sensors and aerial photography are neither technically nor economically feasible for corridor monitoring and cannot provide the needed information in a cost-effective manner. Optimal sensor selection suggests the use of lower-cost systems to fully realize the potential of airborne remotely sensed data in a cost-effective application of corridor monitoring.

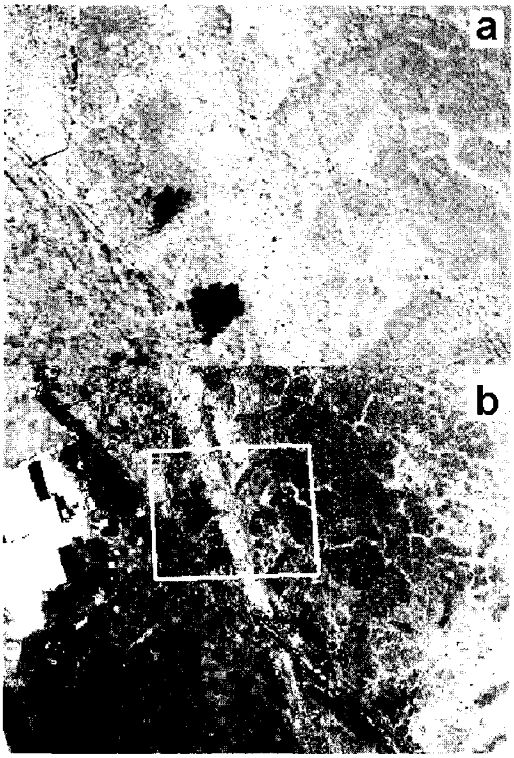
6. Value of video as a corridor sensor

The cheapest data among presently available remote sensors are generated from video, with a large amount of frames within a second (operational rate of 25 frames/s in the European PAL television system and 30 frames/s in the American NTSC system). Video is also ideally suited to continuous data acquisition along long/narrow corridors. Airborne video remote sensing, with a narrow angular view, can be applied in a fairly cost-effective manner to linear feature monitoring (requiring a narrow swath) by imaging the necessary ground target efficiently. For this particular application, the limitation of a narrow view becomes a positive advantage and makes video particularly cost-effective (Um, 1997).

To achieve a narrow ground swath, it is necessary to fly at a very low altitude with a longer focal length. This specification requires the use of very fast shutter speed, such as 1/2000s, to avoid image motion. The Charge Coupled Device (CCD) sensor, with greater light sensitivity than standard film, allows the use of faster exposure times than are typically used with photography. Thus, low-altitude imaging with a narrow swath can be conducted without noticeable image motion effects during sensor exposure (King, 1995). For example, with the popular video CCD size of 6.4 mm by 4.8 mm, it is possible to cover a 40-m swath from a 600-m (2000 feet) flying height at a 97.5-mm focal length setting, without any difficulties in terms of image motion and flight regulation. As a result, the use of airborne video data would fill an existing gap with its ability to gather image information of a land surface area quickly and under conditions of weather and time that would render aerial photography inadvisable. This is a very important attribute of video for low-level applications.

To visibly demonstrate the effect of coverage-angle differences, full coverage of the aerial photograph is presented in Figure 5.b. The larger format of aerial photography has covered a larger area of land surface and provides the user with more reference points for geographic orientation than the smaller format of video operated at the same altitude and with a shorter focal length lens. The visible scars of the access road during pipeline construction are distinctively represented. There is also a clear distinction between the vegetated area and the non-vegetated area.

It is difficult, however, to see the necessary information for the ROW site when compared to the 64-m swath video (Figure 5.a). The waterlogged area is completely lost on the aerial photograph. The ROW site (15 m



(a) video frame (300 m flight height, 30 mm focal length and 64 m swath);
(b) aerial photograph (300 m flight height, 80 mm focal length and 206 m swath), with video coverage marked as a rectangle

Figure 5. Comparison of information content according to different view angles: [The original color image in this paper is presented here in black and white.]

wide) occupies only 7.28% of the total photograph (206 m ground width) while the ROW site occupies 23.43% of the video frame (64-m ground width). The wide-angle of coverage of aerial photography does not include much of the necessary information for the ROW site. The vital features of interest are buried in a mass of extraneous information and there is also serious redundancy of information. The theoretical disadvantage of the wide-angle of coverage for a linear target is clearly demonstrated in Figure 5.b.

To ameliorate the problem of 'too-wide' coverage with medium format photography, the smallest photographic format available (36 mm by 24 mm) could be considered. It would be possible to cover a 72-m ground swath to monitor a 15-m pipeline ROW when a 300-m flying height and 100-mm focal length are applied, as shown below*.

*Estimation of ground swath = format size of photographic film (24 mm: long axis) x flying height (300 m)/focal length (100 mm) = 72 m

Such specifications may cause many problems in terms of flight regulation and image motion. For instance, in the UK, according to the Pipeline Inspection Notification System (PINS) of the Aviation Law, a fixed wing pipeline surveillance aircraft would not be allowed to fly lower than 150 m (500 feet) above rural areas and not less than 450 m (1500 feet) above built-up areas. This means that such a low-level flight with a small photographic format could violate the regulation. Low-level flights also cause serious image motion and should be compensated for a faster shutter speed in very bright light conditions. Practically, it would be very difficult to use a small format photographic sensor for this type of narrow target (Um et al., 2000).

To cover such a narrow swath, the camera should use a zoom lens, which causes some deterioration in photo image quality. Even if it is available, it is not an easy matter to change the focal lengths of a photographic camera while in-flight. On the other hand, a video camera is almost invariably fitted with a zoom lens and, in the context of swath/ coverage angle, this offers a greater possibility of selecting swath and changing it in-flight if required. This observation demonstrates that airborne video remote sensing with such narrow angular coverage is a system which can be applied in a fairly cost-effective manner to corridor site monitoring (requiring a narrow swath), by covering the necessary ground target precisely. Furthermore, to use wide ground coverage data (film photography) for a corridor target, the film first has to be developed. Digitizing of the interested portion from the photograph is required, which involves additional time-consuming processing.

The most frequently quoted shortcoming of existing video systems is the relatively coarse spatial resolution. The resolution in video systems is commonly measured as a horizontal by vertical resolution. Horizontal resolution is the number of black and white vertical lines which can be detected at the centre of the video picture while vertical resolution is examined by checking how many black and white bars can be distinguished vertically through the middle of the picture. However, the performance of a video system can also be evaluated according to the line-pairs per mm convention of photographic systems, via an empirical resolving power test such as the Kell conversion factor [one optical line pair $=2\sqrt{2}$ TV lines (Jensen, 1986)]. According to an empirical experiment by King (1995), S-VHS video recorders have an image resolution equivalent to 25 line-pairs/mm across the format field in comparison to the potentially more than 80 line-pairs/mm resolution of 35-mm (small-format) film.

Such absolute values could be quite misleading if they were used as the practical capability of the sensor for imaging real ground targets. Consequently, an operational ground resolved distance is probably a more useful representation of ground resolution. The ground resolved distance (ground resolution) can be quite simply improved by reducing ground coverage (i.e. by using a longer focal length or by taking a lower level flight). In video, improving the ground resolved distance is simpler than with other airborne sensors by using the narrow angle-of-view and fast strobe shutter to avoid image motion. In fact, to ensure adequate ground coverage for a 20-m corridor, for example, the sensors with wide-angle FOV would require quite heavy optics in terms of focal length and exposure time and much lower altitude flight specifications than in the case of video.

In reality, typical photography, with poorer low-light sensitivity, can hardly accommodate the low-light conditions implied by using a longer focal length and fast shutter speed to avoid image motion. The reduced ground coverage would also increase the data acquisition cost proportionately for photography. Operational corridor inventories requiring hundreds or thousands of large-scale images would be much more expensive if using typical non-video airborne sensors. It is not feasible for other airborne sensors to be used practically for this type of application in terms of FOV, cost, and light sensitivity. Although film photography has better spatial resolution in terms of absolute value, it is unsuitable for this type of narrow target due to the inappropriateness of the imaging system in terms of wide angle-of-view, cost and low tolerance of image motion (Um, 1997; Dare et al., 2000).

Unlike with airborne scanners, imaging spectrometers or aerial photography, dynamic stereo coverage is achieved with airborne video in each single flight line by recording a very large number of individual frames within a very short time interval. Such dynamic stereo coverage allows approximately 99% overlap between sequential frames (Um et al., 1999b). Flexible overlap percentage can be selected after flight while others (e.g. photography) have a fixed overlap percentage at the moment of exposure.

Theoretically, there should be less geometric and radiometric difference between closely adjacent sequential frames since they have more similarity in terms of imaging conditions. As a result, mosaicking of video frames with abundant overlap could be a significant advantage since it would show better geometric and radiometric fidelity than with the standard 60% overlap in photography. Dynamic stereo coverage (achieved by high frame rates in analogue or digital-recorded video) is currently not possible with any other remote sensing system, including digital camera systems.

Historically, the invention of remote sensing technology was due to the human desire to present a pictorial view of the earth's surface. In reality, the use of remote sensing data to maintain a permanent visual record of a ground target was the most useful application for many different types of applications. People are likely to respond with "Just show me!" because they catch on more quickly when they can see how something is done rather than reading or listening to instruction. Likewise, many types of environmental information cannot be conveyed effectively with words alone. This information requires a much richer mode of communication that not only includes visual elements to enhance the spoken word, but also captures movement and visual expression. Experience has shown that a verbal or narrative record is inadequate, so it is much better to complement this with extensive videographic coverage.

In this context, a single aerial photograph presents a picture of a portion of the earth's surface. Because a single aerial photograph is limited in area, groups of photographs are combined into mosaics to provide aerial pictures of larger areas. The increased need for presenting a pictorial view of the earth's surface has led to the production of aerial mosaics to show a complete view of large areas. However, to achieve area-wide visualization, the human labor and costs required in the time-consuming mosaicking process are serious constraints. For long-narrow targets and large-area mapping, mosaics of multiple frames are required, which involve additional processing and the use of complicated geometric and radiometric matching routines (Um et al., 1999a).

Such dynamic stereo coverage makes video the best means of recording a large number of ground features over a given time interval, which is a main requirement in the case of monitoring a long river corridor. The video tape can be played back as often as required, stopped at a critical point or slowed down to capture a corridor target too fast for the eyes and brain. Visual interpretation of moving video, whether vertical or oblique, offers a perspective that can aid in understanding the spatial extent of features, which is difficult to achieve through other means.

In particular, video systems are fairly easy to handle, comparatively inexpensive and they satisfy most user requirements for corridor monitoring. Users do not need access to the sophisticated remote sensing skills needed to operate more complex imaging systems. In this regard, video is often referred to as do-it-yourself (DIY) remote sensing or a modern DIY data acquisition tool (Tarussov et al., 1996; Thomas, 1997).

7. Conclusions

A linear infrastructure monitoring represents a potential application for remote sensing which is largely unfulfilled. Aerial video is a technology that fills a niche that conventional aerial photographs cannot fulfill. Video remote sensing offers a number of unusual characteristics different from traditional sensors, which can be highly advantageous for imaging and monitoring of linear features. Many inventory and monitoring problems are not solved entirely by any one approach; no single data-acquisition methodology can satisfy all monitoring needs. Airborne video monitoring programmes, aided by the use of conventional sampling, can complement the present field survey in an optimal way. This method will provide information efficiently, which is both scientifically justifiable and practically understandable by the customer. However, it is important to fully understand the video medium in order to make the best use of its advantages. It is concluded that the postulated advantages of videography for 'corridor' application should be further tested through more rigorous experiments and assessment before widespread adoption of videography as a rapid, low-cost strip mapping method is employed.

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