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Mapping glacial lineaments from satellite imagery: an assessment of the problems and development of best procedure.

MIKE J. SMITH, CHRIS D. CLARK and STEVE M. WISE

Department of Geography, Sheffield University, Sheffield, S10 2TN, UK.

Abstract. Remotely sensed images are important tools in the mapping of glacial landforms and reconstruction of past glacial environments. However the quality of imagery can be highly variable, introducing random and selective bias into any landforms mapped from them. In this paper we illustrate the three main sources of bias and go onto provide a descriptive and analytical assessment of these bias. With a primary focus on visual and near infra-red sensors, we also illustrate the utility in using radar imagery, particularly as a supplemental data source. We conclude that low solar elevation is an important requirement, whilst an awareness of the selective bias introduced by solar azimuth is necessary. Landsat ETM+ imagery meets the requirements for glacial landform mapping and is our recommended data source.

Keywords: bias, mapping, satellite, imagery, glacial

Introduction

Remotely sensed images have been used for mapping glacial landforms since the widespread availability of aerial photography in the 1950's. The aerial view allows easy landform identification over large, often inaccessible, areas that would otherwise be difficult to map from field surveys. These analogue images were supplemented in the 1970's with the introduction of digital satellite imagery. The synoptic scale view (up to 180x180km per scene) and near-complete global coverage offered distinct advantages over traditional aerial photography.

Sugden (1979) first used Landsat Multi-Spectral Scanner (MSS) images to map glacial erosional landforms of the former Laurentide Ice Sheet. Since then, a variety of researchers have used images from different satellite sensors to map glacial landforms (e.g. Punkari, 1982, Boulton, 1990). Mapping has primarily been of ice-flow landforms, such as drumlins (i.e. glacial lineaments) which can then be generalised to help with the process of ice sheet reconstruction.

The use of remotely sensed imagery for glacial landform mapping is relatively new, having been developed from photointerpretive techniques applied to aerial photography and refined by different researchers over the past two decades. Clark (1997) provides a summary, from the acquisition of relevant imagery, to the production of a glacial reconstruction. During our current research into the reconstruction of the Irish ice sheet, it has become clear that the results obtained by mapping from remotely sensed imagery may vary according to the nature of the imagery used, and the skill and experience of the operator. If this method is to yield reliable results which are comparable between different areas, mapped by different researchers, then there needs to be a greater understanding of the sensitivity of the results to the exact methodology employed.

Clark's (1997) method involves two stages. The first stage is to map the individual glacial landforms from the imagery. The results from this stage will depend on the detectability of the landforms, a term which includes two elements: the degree to which the physical and spectral characteristics of the sensor allow the landforms to be distinguished from other features on the image and the success with which an observer can record these differences and thus map the landforms. The second stage involves summarising the landform information by grouping the individual landforms into sets of features which can be assumed to have been derived by a single glacial event. This is an entirely subjective process, which in many ways resembles the process by which cartographers generalise information from large scale maps to produce small scale ones. This paper is solely concerned with the first of these stages although work is also underway to provide a semi-quantitative approach to the second stage, allowing methodological checks to be implemented by the operator.

In the next section, we discuss the factors which affect the detectability of landforms on imagery. The effect of these factors has been tested in a series of experiments using multiple images of a series of test areas, and a Digital Terrain Model. The paper concludes with a discussion of the findings and some suggestions for good practice in the mapping of glacial features from remotely sensed imagery.

Landform Detectability

Central to the mapping of glacial landforms is the process of *landform detection*, which is dependent upon *landform representation* and *observer ability*. This section will discuss the factors that affect these two variables.

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Landform Representation

The representation of a landform upon an image depends upon the *characteristics of the sensor*, the *characteristics of the landform, the illumination conditions* and sometimes the *meteorological conditions prior to and during acquisition.* The interaction of these categories combine to produce the following variables:

1) **Relative size:** the relationship of *lineament length* to *sensor spatial resolution.* The higher the spatial resolution the greater the ability to resolve shorter lineaments.

2) **Azimuth Biasing:** a bias in landform detectability arising from the difference between the *lineament orientation* and the *illumination orientation* (azimuth angle). Landforms are known to appear differently when they have different solar illumination directions. For example, a drumlin viewed side-on will look like drumlin, but when viewed head-on can look like a circular hill (Aber *et al* (1993) and Lidmar-Bergström *et al* (1991)).

3) **Landform Signal Strength:** the degree to which the landform can be distinguished from other features by tonal and textural information in the image. These variations are caused by differences between the surface cover of a lineament and its surroundings, and the relief effect arising from slopes appearing lighter or darker depending upon the height of the sun in the sky (solar elevation). High illumination angles cause lee slopes to be illuminated (so reducing textural information), whilst low illumination obscures lee slope with shadow (also reducing textural information, but highlighting the presence of the lineament). Several authors have investigated the conditions through which high contrast images depicting lineaments are obtained (e.g. Slaney, 1981). In general they conclude that a low solar elevation produces ideal imaging conditions.

Synthetic aperture radar (SAR) imagery is also used for mapping landforms but here the controls on detectability are different because of the different viewing geometry. SAR imagery is good at detecting topographic variation due to the oblique viewing angle of the sensor, as opposed to the vertical viewing angle of VIR sensors. The oblique viewing angle not only produces little variation in landform signal strength (i.e. the angle is the same for every image), but also the same azimuth biasing for every image.

The greater the difference in reflectance properties of the surface cover of the lineament when compared to surrounding terrain and the greater the *relief effect* (for VIR imagery), the greater the tonal differentiation of the lineament on the image (see Clark, 1997 and Aber *et al*, 1993 for further discussion). As lineaments are often composed of the same material as the surrounding terrain, spectral differentiation is of limited use in these situations. However Punkari (1982) and Dongelmans (1996) have successfully used spectral differentiation by taking advantage of certain regions where drumlinised terrain enhances the collection of moisture in inter-drumlin areas. This variability in surface moisture affects surface cover (i.e. inter-drumlin regions become boggy) and allows drumlin identification.

In summary, there is a minimum resolvable landform size and a range of lineament orientations that an individual sensor will be able to represent. In addition, the *definition* of these landforms is dependent upon the surface cover and the strength of the relief effect.

Observer Ability

Image interpretation is the qualitative, manual, identification of features of interest within an image and an appraisal of their significance. The ability of an observer to interpret a remotely sensed image depends on their experience in using interpretive techniques and their level of specialist knowledge pertaining to the features being mapped. Inter-operator variability is a consequence of any interpretive technique and is known to be a specific problem in geological lineament mapping (e.g. Siegal, 1977).

In summary, landform detectability is dependent upon the representation of a surface by a satellite sensor and the ability of an observer to map those landforms. This raises the following questions:

- is the available imagery representing all, or a large proportion, of the landforms present?
- is the observer able to map these landforms or are errors of omission and commission present?

The latter question has been briefly touched upon above, but is yet to receive specific examination with respect to glacial landforms. Indeed, recent research (e.g. Vencatasawmy, 1997) looked at the ability to automate the process of lineament mapping.

This research is aimed at investigating the former question by using existing imagery to model the effects of the above variables on landform representation. Operator variability in mapping is minimised through the use of one operator.

Methodology

We needed to select suitable images from a range of earth resources satellites for areas that contained enough lineaments to be statistically viable. We selected the region around Lough Gara, County Roscommon, Ireland ($1539 km^2$), bounded by the Ox Mountains on the west and the town of Sligo to the north. There is complete coverage from the four of the five main earth resources sensors; Landsat MSS, Landsat TM, SPOT Panchromatic and ERS-1 Synthetic Aperture Radar (SAR). Unfortunately there were no suitable cloud free scenes from Landsat ETM+ available for this study area, so a second area on the Kola Peninsula ($1183 km^2$), Russia, has been used to supplement our results.

In order to assess the accuracy with which landforms can be mapped from each type of imagery it is necessary to have some information on the landforms which are known to be present in the test area. For this purpose we used a high resolution DEM to create a morphological map for a subset of the area (587km^2), as complete DEM coverage was not available. Hill shading is an effective way of identifying landforms on a DEM, although this suffers from the same azimuth biasing as satellite imagery. Therefore the morphological map was produced through full break-of-slope mapping using multiple illumination azimuths. The DEM was produced by the Irish Ordnance Survey from 1:40000 stereoscopic aerial photography at a spatial resolution of 50m, using a digital analytical plotter. The spatial resolution of the DEM is therefore similar to that of the imagery, but because the landform mapping is based upon stereoscopy rather than photo interpretation, and because the original photographs are at a higher resolution than the satellite imagery, the morphological map produced from the DEM will be at a higher level of accuracy than is possible using satellite imagery. A comparison of the morphological map derived from the DEM with a selection of the original stereoscopic aerial photography confirmed the accuracy of the morphological map, which was able to resolve individual drumlins, although cross-cutting patterns and smaller forms could not be distinguished.

Table 1 Satellite image meta-data used in this study (D=descending, A=Ascending).

Satellite Images	Spatial Resolution (m)	Date	Lat/Long (°)	Illumination Elevation (°)	Illumination Azimuth (°)
Lough Gara					
ERS-1 SAR	25	04/08/92	54:14N 8:53W	23.1	104D
ERS-1 SAR	25	02/03/93	54:19N 8:51W	23.1	104D
Landsat TM	30	10/12/	53:39N 7:43W	11.2	160
Landsat TM	30	06/05/89	54:51N 7:58W	48.3	147
Landsat MSS	80	06/01/83	54:51N 7:45W	10.1	157
SPOT Panchromatic	10	28/11/92	53:39N 8:20W	14.3	167
SPOT Panchromatic	10	28/11/92	54:07N 8:10W	13.9	168
Strangford Lough					
ERS-1 SAR	25	30/06/93	54:28N 6:00W	23.1	256A
Landsat TM	30	03/11/90	54:31N 4:28W	18.1	158
Kola Peninsular					
Landsat ETM+	15/30	17/07/99	66:57N 32:24E	43.8	166

Given the differences between the SAR and VIR sensors, it is not appropriate to directly compare their imagery. As a result these sensors are treated separately through a case study. Our SAR case study area (110km^2) lies west of Strangford Lough, County Down, Ireland, bordered on the south by Dundrum Bay.

Experiments

1) **Landform Signal Strength** – In order to assess the effect of varying solar elevations on landform representation, ideally we would obtain images acquired at the same time but with different solar elevations. As this was not possible, we illustrate this experiment using images with variable solar elevations.

It was also hoped to use the DEM to model the effects of landform signal strength by simulating different solar elevations through the use hill shading. However hill shading is unable to effectively model these variations and so this was not pursued.

2) **Azimuth Biasing Effect** – In order to assess the biasing effect we used an image with varying lineament orientations. A relative comparison was then performed between the image and the morphological map.

A further experiment was also performed using the DEM to investigate azimuth biasing more objectively by simulating different azimuth angles through the use of hill shading. All lineaments were mapped and then compared to the morphological map.

3) **Relative size** – In order to assess the effect of image spatial resolution on landform representation we acquired Landsat ETM+ data, which is ideally suited to this task, as the high resolution panchromatic band (15m) and lower resolution multispectral bands (30m) are acquired at the same time. We selected Band 2 to compare against the Panchromatic band, as a greyscale image was appropriate and they both record an overlapping part of the EM spectrum.

SPOT Panchromatic, Landsat TM Band 5 and Landsat MSS Band 4 were used for all lineament mapping (Table 1). The Landsat TM and MSS bands were chosen as the near-IR enhances any moisture variations (Clark, 1997), whilst tonal variations are more efficiently detected by the human eye from a greyscale image. Where appropriate all images had pre-processing techniques applied to them following the guidelines of Clark (1997). All mapping was performed by one observer.

Results

This section presents the results of interimage comparisons and our analysis of the controls on detectability. The first section provides a description both of the images and of the landforms mapped from them, whilst the second section presents summary statistics for each experiment.

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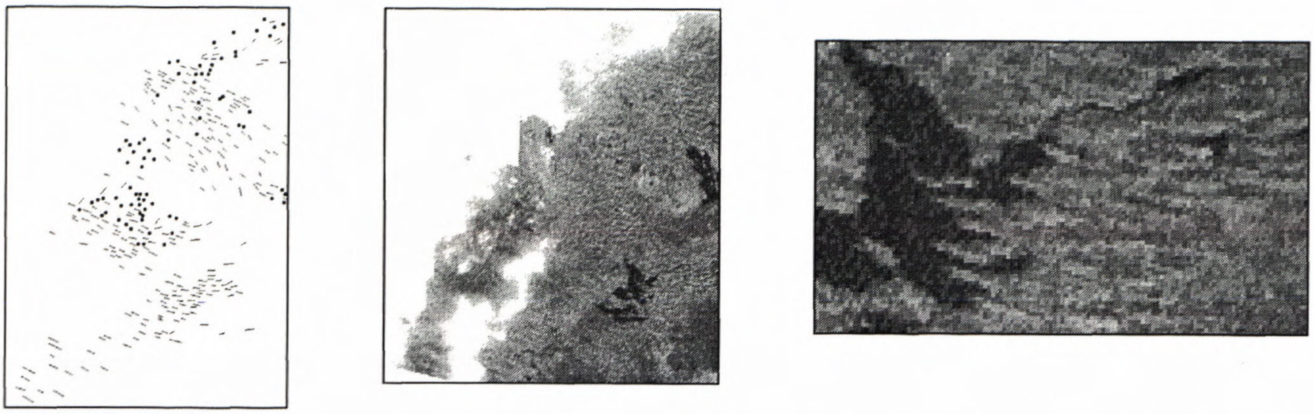


Figure 1a, b and c Landsat MSS glacial landform mapping (left), image (centre) and zoomed region (right) for Lough Gara, Ireland. The landform map shows lineaments (lines) and hillocks (points).

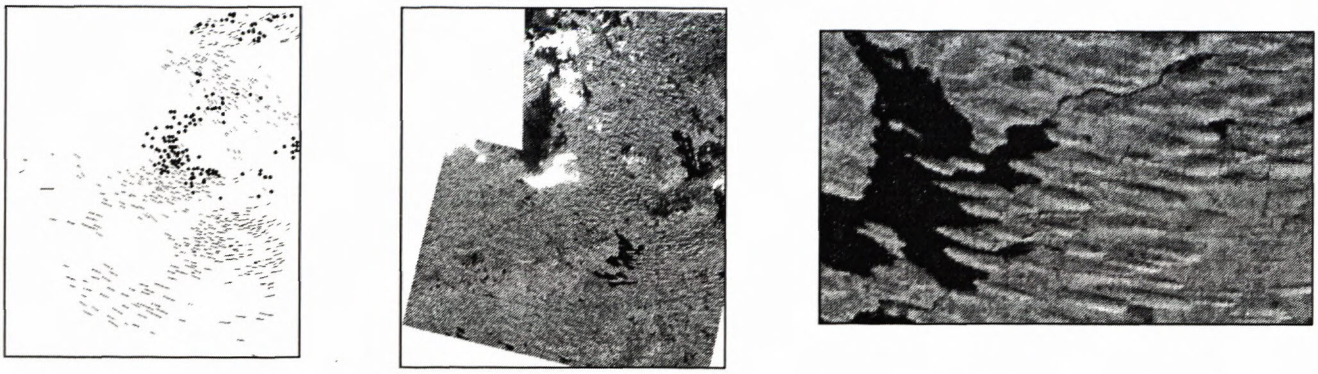


Figure 2a, b and c Landsat TM glacial landform mapping (left), image (centre) and zoomed region (right) for Lough Gara, Ireland. The landform map shows lineaments (lines) and hillocks (points).

Interimage Comparisons

Morphological Map

Figure 5 shows a map of all detectable lineaments produced from the DEM for a subset of the Lough Gara study area (approximately the southern half of the Lough Gara satellite images). There is a strong trend of lineaments oriented NW-SE, with longer lineaments in the southern area. A random spread of lineaments oriented E-W is also noticeable. There is a strong concentration of hummocky terrain in the northerly part of the map, with few hummocky forms elsewhere. The northern half of the map also contains transverse ridges, often with lineaments overlying them.

Landsat MSS Image

The low contrast and poor detectability of lineaments within the image (Figure 1b) is readily apparent. Although the southern portion of the image depicts E-W trending lineaments, curving to the NE, this is not clear and is barely detectable in many parts. The presence of hummocky terrain in the central portion is clearer, whilst the northern area depicts clearly detectable lineaments although their trend is not so obvious. The forms in the south, whilst less detectable, appear wider and longer. The overall impression is one of an ability to see lineaments, but not identify and map them precisely.

Figure 1a shows the lineaments that have been mapped from this image. There is a strong lineament orientation of NW-SE, with some lineaments in the east trending W-E and some in the north trending SW-NE. The central area has a greater abundance of hummocky terrain, with further hummocks in the northern area. In general there are far less lineaments mapped in comparison to the morphological map, however the main general trends are readily apparent, although no transverse ridges have been identified.

Landsat TM Image

The topographic shadows increase the amount of contrast present, producing a high quality image (Figure 2b) and allowing the easy recognition of landforms.

In the southern portion of the image long, broad lineaments are visible in the west (trending east-west), becoming more apparent in the east whilst curving towards the NE. The central region shows hummocky terrain, comprised of many small circular hills. In the northern part of the image there is a clear orientation NW-SE, although in the extreme NE corner lineaments are again trending E-W.

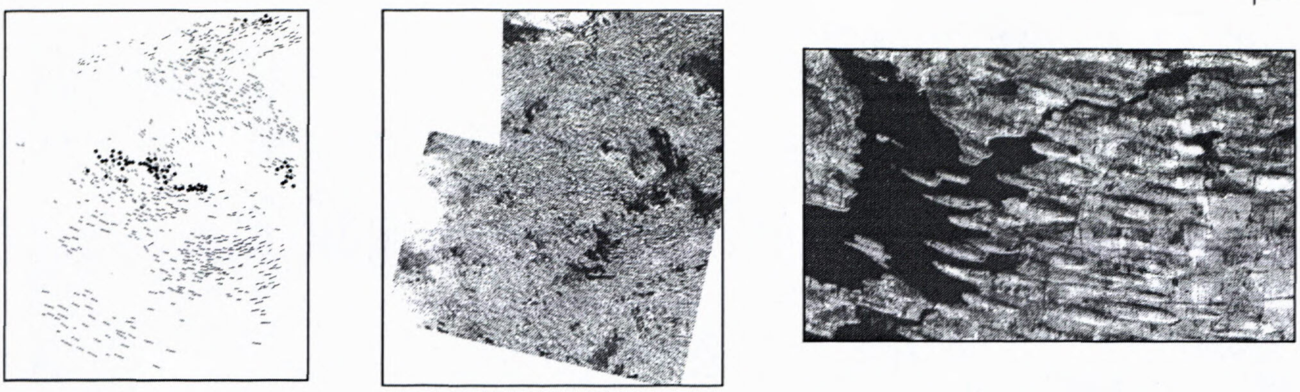


Figure 3a, b and c SPOT glacial landform mapping (left), image (centre) and zoomed region (right) for Lough Gara, Ireland. The landform map shows lineaments (lines) and hillocks (points).

In contrast to the MSS mapped data, Figure 2a shows a greater number of lineaments mapped, although still less than for the morphological map. The same general pattern is visible between all three maps. In comparison to the MSS mapped data, the eastern area shows a clear transition in lineament orientation from NW-SE to NE-SW. In addition, the northern area shows some lineaments cross-cutting one another.

SPOT Image

Simple contrast enhancements were necessary in order to make the best use of this image (Figure 3a). Initial assessment of the amount of contrast available for lineament mapping suggests a high quality image, although closer inspection reveals that the contrasts are more subdued and, although landforms are clearly visible, their representation is not as good as with the TM image. However the high spatial resolution allows detailed landform mapping, clearly showing areas of intersection between E-W and NW-SE trending lineaments in the northern region. The southern region shows longer lineaments in the W trending NW-SE, curving towards the NE-SW in the eastern area. The central region appears as a more complicated area of „hummocky" terrain, with elongate and ovoid forms present.

Like the morphological map, TM and MSS mapped data, the SPOT data again shows the same general trends (Figure 3b). There are even more lineaments mapped than in either of the previous two images (Table 2), although less than the morphological map. There are noticeably fewer hummocks than the Landsat MSS and TM images and a greater incidence of crossing lineaments in the northern portion of the image.

Landsat ETM+ Image

Panchromatic

Simple contrast enhancements were again employed to prepare the image. The high contrast within the image is mainly manifested through spectral differentiation (Figure 4a). Non-vegetated regions appear as dark areas and typically mark lineament ridges, which are often offset from elongated lakes. The high spatial resolution of the image allows clear identification of lineaments as short as 80m in length.

The mapped lineaments show a strong orientation of SW to NE, ranging up to 4km in length. The larger lineaments are clearly detectable, although they are sometimes composed of several, smaller, lineaments.

Multi-spectral (Band 2)

The multi-spectral image (Figure 4b) also allows lineament detection through spectral differentiation. The effect of decreased resolution is clearly apparent through the higher proportion of longer lineaments mapped. For example, where many individual lineaments might have been mapped on the panchromatic image, the multi-spectral image often shows a single, larger, lineament. The mapped lineaments range from 280m to 4km in length, with a strong SW to NE orientation.

Analysis of Controls on Detectability

1) Landform Signal Strength

We acquired low (11.2°) and high (48.3°) solar elevation images for our test areas, shown respectively in Figure 2b and 6a. These show the dramatic impact solar elevation has on lineament representation. The high solar elevation provides very little tonal and textural variation, whilst the lack of surface cover variation means that the lineaments are very difficult to identify.

2) Azimuth Biasing Effect

Although it is possible for the azimuth angle to vary from due east to due west, testing its effect on landform detectability is difficult as it is not possible to hold other factors, such as solar elevation, constant. As a result it is not possible to test variations in the azimuth angle using different imagery. Consequently, the effect of varying lineament orientations was used to test the azimuth biasing effect. This was achieved through the use of one image (Landsat TM) with a variety of alternately oriented lineaments. This was then compared to the morphological map derived from the DEM.

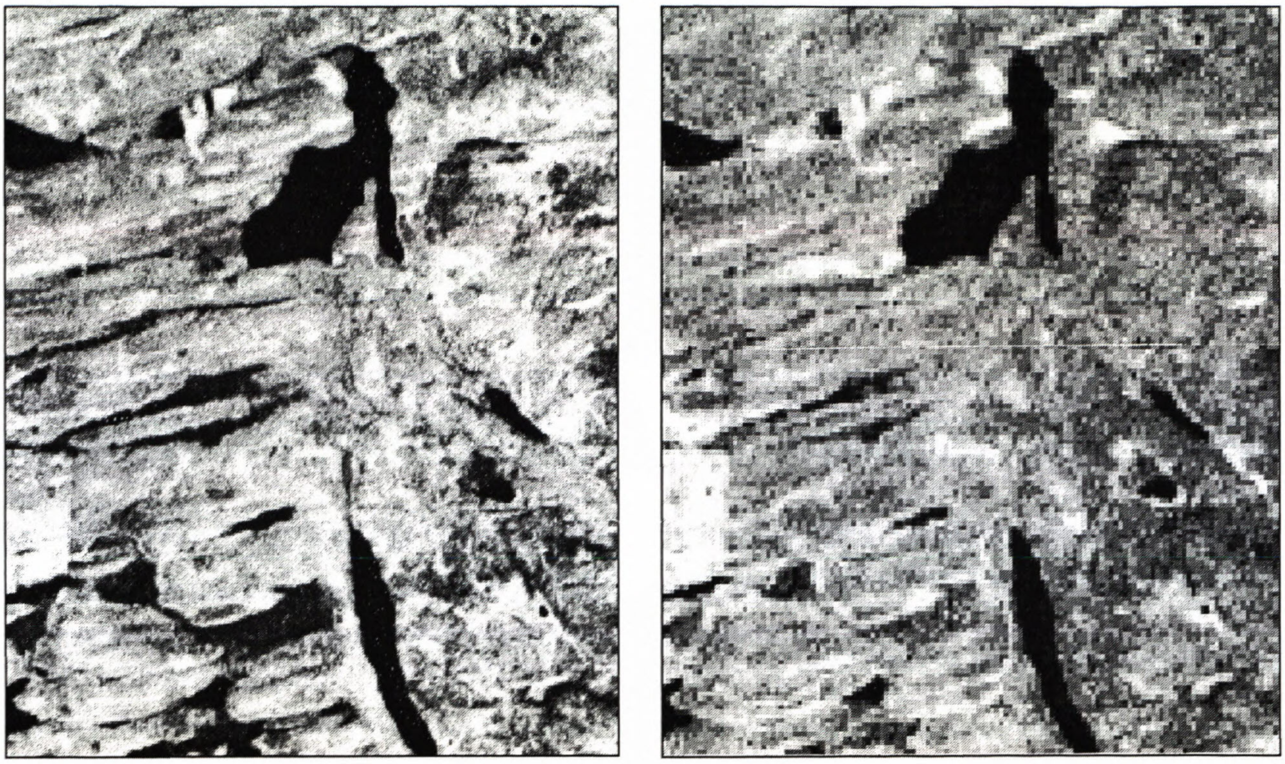


Figure 4a and b Landsat ETM+ Panchromatic (left) and Multispectral (right) images (Kola Peninsular, Russia) showing the effect of sensor spatial resolution (15m and 30m respectively) on lineament detection

Table 2 Total number of lineaments and hillocks mapped from the Landsat MSS, Landsat TM and SPOT imagery for the Lough Gara region.

Landform	*SPOT*	*Landsat MSS*	*Landsat TM*	*Landsat EMT+ Pan*	*Landsat EMT+ XS*
Lineament	576	245	394	813	473
Hillock	59	78	132	-	-

The Landsat TM image has an azimuth angle of 159.7°; so we would expect lineaments oriented in this direction to be selectively „hidden." Lineaments which have an orientation close to 160° on the morphological map (Figure 5) are often not present on the map produced from the Landsat TM image (Figure 2a). There is also a clear difference in the descriptive statistics for the two sets of lineaments (Figure 7, Table 3) caused by the omission of the lineaments parallel to the azimuth direction.

Table 3 Descriptive statistics of lineament orientation for the DEM and Landsat TM data. The higher maximum and mean for the DEM data support the selective „hiding" of lineaments oriented parallel to the illumination azimuth.

Lineament Orientation	***DEM***	***Landsat TM***
Mean *(°)*	109	106
Min *(°)*	40	24
Max *(°)*	161	135
Number	377	271

In order to explore this effect more fully, the DEM of the Lough Gara region was hill shaded with illumination orientations parallel, orthogonal and intermediate to the principal lineament direction. Figures 8a and b show the DEM hill shaded using an illumination orientation parallel and orthogonal directions. The difference between the two images is striking, showing not only the complete disappearance of lineaments (not visible in *parallel* that

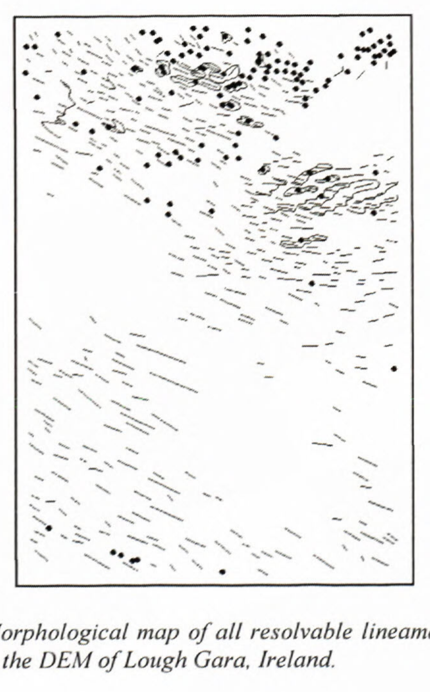


Figure 5 Morphological map of all resolvable lineaments produced from the DEM of Lough Gara, Ireland.

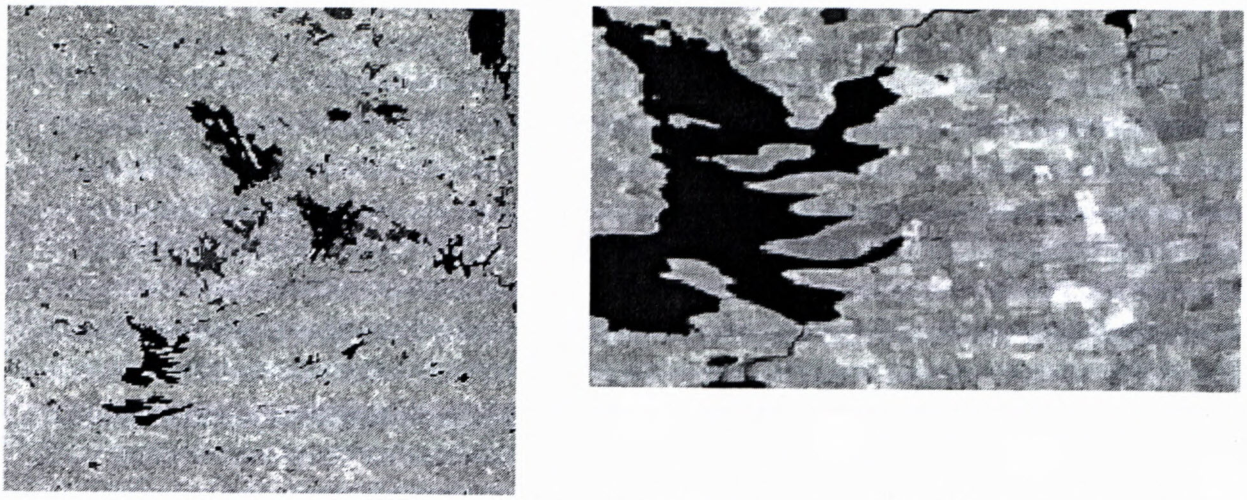


Figure 6 a and b Landsat TM image (left) of Lough Gara, Ireland, with zoomed region (right). This illustrates the low representation of lineaments as a result of the high solar elevation.

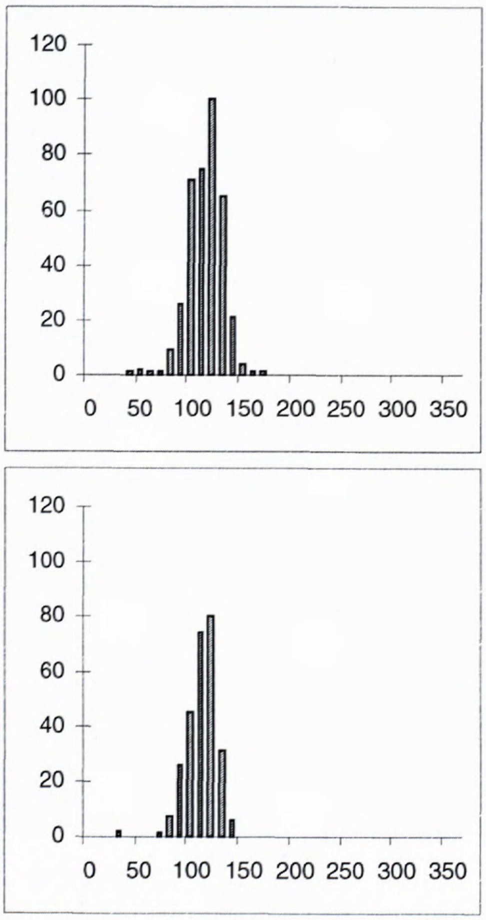


Figure 7a and b Frequency histograms of lineament orientation for the DEM (top) and Landsat TM (bottom) data. The Landsat TM shows a smaller upper tail, a result of azimuth biasing.

are visible in *orthogonal*), but also a change in the shape of other forms. This includes the appearance in *parallel* of transverse ridges, which have lineaments superimposed onto them.

The above description is supported by the statistics in Table 4. These show a dramatic reduction in the total number of lineaments mapped using a *parallel* illumination, when compared to the *orthogonal* and *intermediate* illuminations. It is also important to note that the *parallel* image identifies transverse ridges within the image and an increased number of hillocks. The transverse ridges were identified on the aerial photography, although their morphology is subdued due to their reorientation by the overlying lineaments. As a result the *parallel* image selectively enhances these, whilst the *orthogonal* image degrades them. The increase in the number of hillocks is probably due to the misrepresentation of lineaments as hillocks and consequently their misidentification.

Table 4 Total number of lineaments, hillocks and ridges mapped from the DEM for alternately hill shaded azimuth angles, illustrating the selective „hiding" of lineaments and enhancement of transverse ridges for those mapped from the parallel image.

Landform	*Orthogonal*	*Parallel*	*Intermediate*	*Complete*
Lineament	371	176	330	443
Hillock	101	120	75	109
Transverse Ridge	0	20	0	25

3) Relative Size

Intuitively we would expect that, as resolution increases, smaller lineaments become detectable and so more lineaments are mapped. As a result the value of the distribution peak of the frequency histogram for lineament length will decrease, gradually shifting in the direction of the origin.

Using the Landsat ETM+ Panchromatic (15m) image of the Kola Peninsula, 813 lineaments were mapped, compared to 473 lineaments for the multi-spectral (30m) image. This significant increase (170%) in lineaments can be attributed solely to the resolution of the sensor, as all other variables are fully controlled (e.g. solar elevation, azimuth angle). Table 5 presents descriptive statistics for these data.

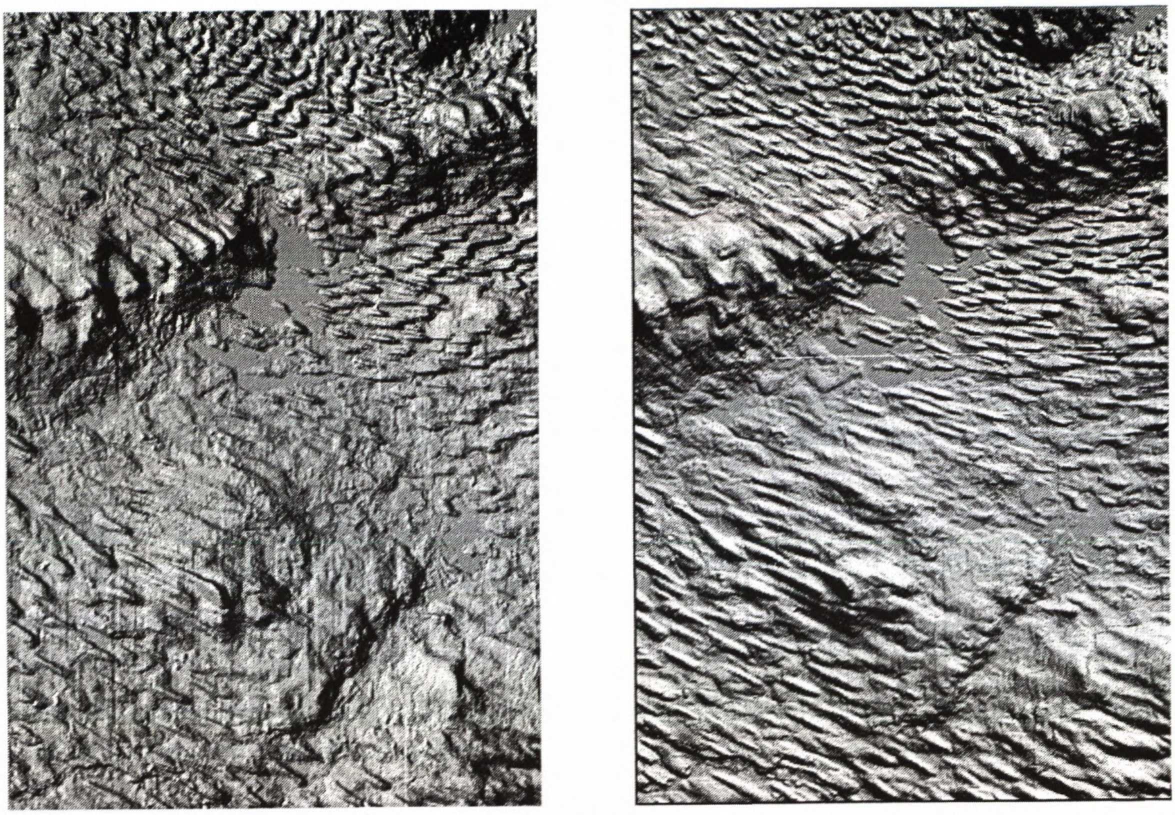


Figure 8a and b Hillshaded DEM of Lough Gara, Ireland, using an illumination azimuth parallel (left) and orthogonal (right) to the principal lineament orientation. Not the dramatic changes in lineament morphology, particularly above the centre of the image.

This shows that in addition to more lineaments being mapped, the panchromatic image represents not only shorter lineaments, but a greater number of them. This has the overall effect of reducing the mean (from 892m to 647m) and consequently shifting the histogram peak towards the origin (Figure 9a and b).

Table 5 Descriptive statistics of lineament orientation for the Landsat ETM+ Panchromatic and Multispectral data. These highlight the greater number of smaller lineaments mapped on the panchromatic image.

Lineament Orientation	*Panchromatic*	*Multispectral*
Mean (°)	647	892
Min (°)	81	282
Max (°)	3951	4040
Number	811	472

SAR Case Study

Although both Landsat TM and ERS-1 SAR have very similar spatial resolutions (and consequently relative size), it is not possible to control for the differences in landform signal strength or azimuth biasing. As a result this case study is designed to highlight the benefits in using SAR imagery to detect topographic landforms, as well as the differences with VIR imagery. In addition the active sensor operates in the microwave part of the EM spectrum which means that imagery can be obtained day or night, regardless of meteorological conditions.

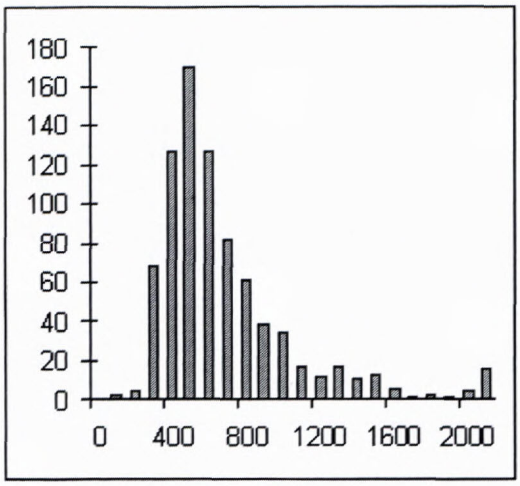
Our case study was located in the Strangford Lough region of eastern Ireland where we acquired a descending ERS-1 SAR image and a cloud free, winter, Landsat TM image. The images were geocorrected and then any detectable lineaments mapped.

Figure 10 (a and b) depicts a selected region from the SAR and TM images respectively; the dominant lineament directions for SAR (north-south) and TM (east-west) are striking, and are further illustrated by the frequency histograms of lineament orientation (Figure 11a and b). Table 6 also supports these results showing a much higher mean lineament orientation for the ERS-1 SAR data.

Table 6 Descriptive statistics of lineament orientation for ERS-1 SAR and Landsat TM data for the Strangford Lough region, highlighting the different populations of lineaments (with different orientations) mapped.

Lineament Orientation	*SAR*	*Landsat TM*
Mean (°)	139	96
Min (°)	0	3
Max (°)	179	167
Number	289	349

These results are principally explained by the difference in azimuth angle between SAR and VIR imagery. SAR imagery is obtained by active detection using an oblique sensor orthogonal to the satellite track. As the



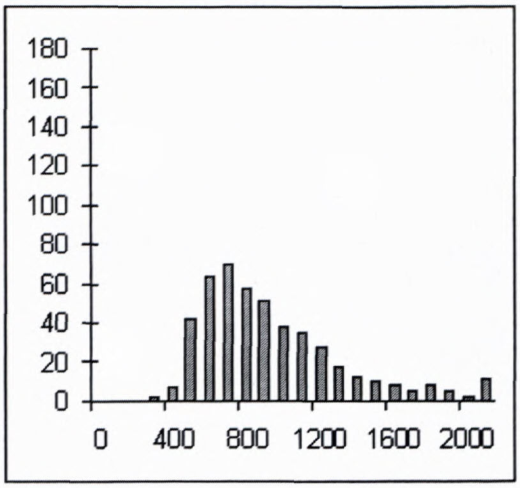


Figure 9a and b Frequency histograms of lineament length for the Landsat ETM+ Panchromatic (left) and Multispectral (right) data. These illustrate the increased number of smaller lineaments that were mapped from the panchromatic image..

satellite is polar-orbiting, this means that all images are sensed in an easterly or westerly direction depending on whether the satellite is in an ascending or descending orbit. Consequently all lineaments oriented approximately north-south are selectively enhanced, whilst those oriented approximately east-west are selectively degraded (Graham *et al* (1991).

VIR Case Study

The lineaments mapped from the Landsat MSS, Landsat TM and SPOT imagery for Lough Gara are now used to supplement the inter-image comparisons with quantitative data and so highlight the errors and bias often present within imagery acquired for landform mapping.

The solar elevation angles are so similar that we judge this to make little difference to the mapping. The effect of azimuth biasing can be significant, as illustrated by the SAR case study, although this is not the case for the Lough Gara area, because the lineaments are predominantly oriented in an east-west direction. The main difference in landform detectability between the images relates to **relative size** (i.e. resolution) where 245, 394 and 576 lineaments were mapped for Landsat MSS, Landsat TM and SPOT respectively. As resolution increases, there are more, shorter, lineaments detected. Figure 12 identifies histogram peaks at 600m, 450m and 350m respectively for Landsat MSS, Landsat TM and SPOT. This implies that the most common lineament lengths require 9, 15 and 35 pixels to identify lineaments on MSS, TM and SPOT for this region. If ~10-15 pixels are required to map a lineament, then the large number of pixels used to identify lineaments in the SPOT imagery suggests that the actual population peak has been mapped in this image, although this value will clearly vary for different regions with different lineament populations.

An important ancillary effect of being able to map smaller lineaments is the ability to be able to resolve cross-cutting patterns, which we demonstrate in the inter-image comparisons.

We also compared the coincidence of individual lineaments between images (Table 7). These show that Landsat MSS is highly coincident (~70%) with Landsat TM and SPOT, whilst Landsat TM and SPOT are poorly coincident with MSS and highly coincident with each other. These results reflect the fact that SPOT and Landsat TM have detected a greater number of lineaments which tend to be shorter, whilst MSS has detected fewer, longer, lineaments.

Table 7 Percentage coincidence of lineaments between the different satellite images and the morphological map. For example, 70% of lineaments on Landsat MSS are coincident with those on Landsat TM.

	Landsat MSS	Landsat TM	SPOT	Morphological Map Subset
Landsat MSS		50	40	19
LandsatTM	70		73	45
SPOT	78	82		49

Of further interest is the number of non-coincident lineaments. This is particularly interesting for MSS, where we expected to see high coincidence with the higher resolution imagery. Generally, this is correct, although ~30% remain non-coincident, comprising lineaments of varying orientation, length and locations. This apparent randomness in non-coincident lineaments probably relates to the mapping process. Errors in the geocorrection of the images, mapping of lineaments and visual lineament comparison can all cause errors of non-coincidence. Previous research (e.g. Siegal, 1977) suggests that inter-observation interpretation can be considerably varied, whilst geometry, mapping and comparison intra-observer variation can also occur.

In summary, for this particular case study, azimuth biasing and landform signal strength do not contribute major elements of bias. Relative size has the single largest

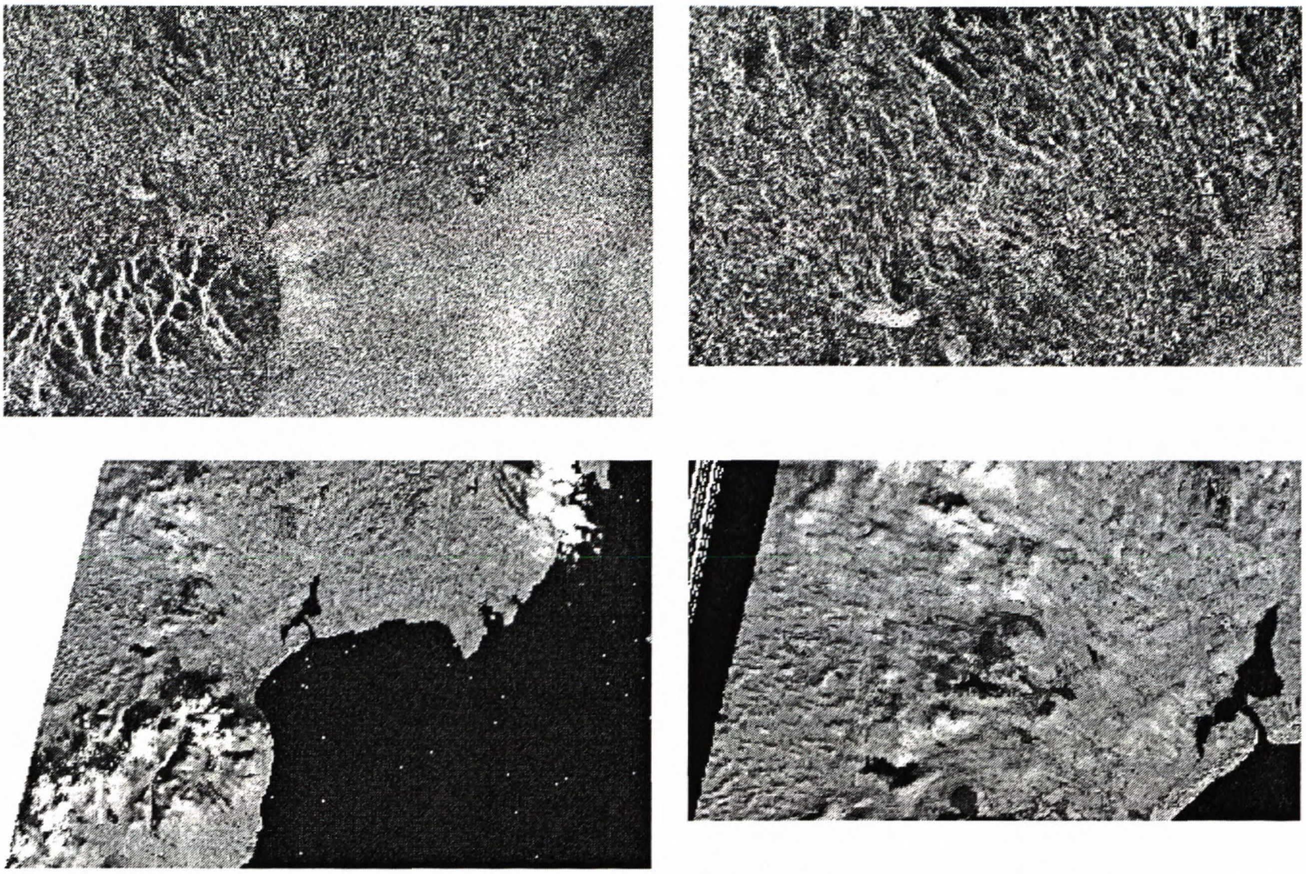


Figure 10a, b, c and d ERS-1 SAR (top left) and Landsat TM (bottom left) images (Strangford Lough, Ireland) highlighting the dramatic effect of the azimuth angle on lineament representation. Images c and d are zoomed regions. Note that the E-W trending lineaments on the Landsat TM image are not visible on the ERS-1 SAR image.

effect on mapped lineaments, whilst geocorrection, mapping and comparison errors probably account for the remaining variability.

Discussion and Recommendations

This paper has described some of benefits in using satellite imagery for glacial landform mapping. However these benefits have to weighed against weaknesses in its use. There are two main areas where error can be incorporated into a landform map (where there is a primary focus on lineament mapping). These are inherent bias within the imagery acquired and the ability of the observer to map the landforms. The latter has been touched upon by several authors whilst the former is the topic of this paper.

Image bias can occur from relative size, azimuth biasing and landform signal strength. We investigated the effect of each of these variables on lineament mapping for study areas in the Lough Gara region of western Ireland and the Kola Peninsula, Russia.

Our results suggest that low solar elevation is required (for VIR imagery) in order to selectively highlight topographic landforms (e.g. see Figures 3b and 7). From our experience we advise a solar elevation below ~20°, although <15° is desirable. Depending on latitude, solar elevations as low as 5° are possible. For Landsat ETM+, daylight imaging is not performed for solar elevations below 5°. Above 20° there is a gradual decrease in the relief effect and tonal variation to a point where lineaments are only detectable by surface cover variation. The availability of appropriate imagery from archive is variable, depending upon the latitude of the study area and the sensor desired. In mid-latitudes, winter scenes are necessary in order to acquire a low solar elevation and, coupled with the requirements for scenes to be snow and cloud free, makes suitable imagery difficult to acquire. In northerly latitudes, summer imagery is required in order acquire snow free scenes, although this is not necessarily ideal as solar elevation can be quite high (Table 1). Aber *et al* (1993) suggest that light snow cover, in association with a high relief effect, can increase detectability as tonal variation due to surface cover is effectively masked. This has to be weighed against the reduction in the relief effect with increased snow cover. Subtle topographic landforms can quickly become „hidden“ making mapping of features such as cross-cutting landforms difficult.

Perhaps the single greatest bias over which the observer has little control is the azimuth biasing effect. Both the Landsat TM image for our study area and our DEM experiments suggest that large omissions can occur as a result of azimuth biasing. More particularly, the above constraints on acquisition dates for VIR imagery produce a small solar azimuth window through which images are available. As a consequence, lineaments oriented parallel to this direction are selectively diminished, such that they may change shape, appear as hillocks or completely dis-

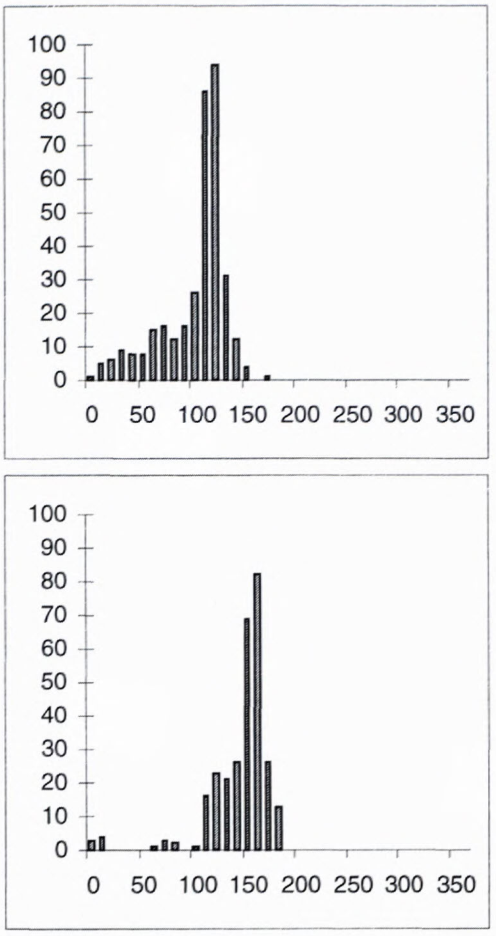
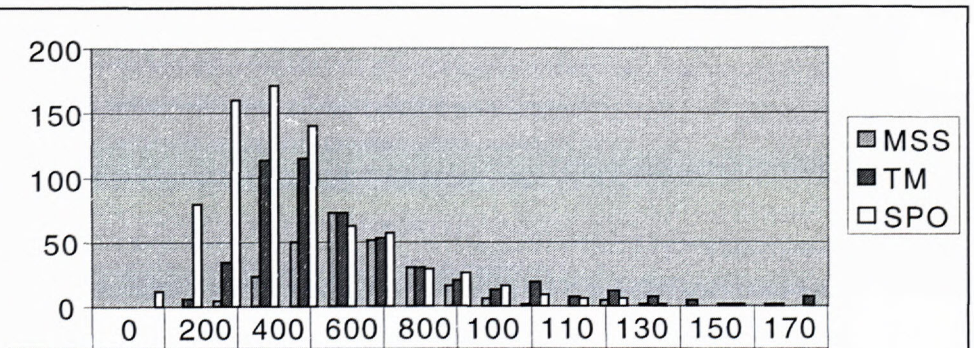


Figure 11a and b Frequency histograms of lineament orientation for Landsat TM (top) and ERS-1 SAR (bottom) data, illustrating the completely different populations of lineaments (with different orientations) mapped for exactly Strangford Lough, Ireland.

against this error. These sources include local mapping in the form of topographic maps, digital elevation models or field mapping. Where these are not available SAR imagery can be usefully used. Its alternative viewing geometry satisfactorily supplement VIR imagery, although users should not underestimate the experience required in its use (see Vencatasawmy *et al* 1998 for further discussion).

The final bias of relative size is familiar to most researchers. The higher the resolution of the satellite imagery, the greater the ability to map smaller landforms. The above results show a 170% increase in mapped lineaments by moving from 30m resolution data to 15m data. However higher precision data does not necessarily mean better quality results and it is important that researchers select imagery to match the requirements of their project. For ice sheet reconstruction, overall lineament trend is the single most important element. As a result, azimuth effects are the most serious problem since they can introduce a selective bias into the results. In contrast relative size and solar elevation are less important than azimuth bias here since the errors produced should be distributed randomly across lineaments of all orientations. From a more practical perspective, it is useful if the image coverage is as large (and cheap!) as possible. High resolution data are desirable if geomorphological or cross-cutting mapping are intended. Equally, multi-spectral data are very useful as they can be used to delimit lineaments through surface cover changes. These requirements point to Landsat ETM+ as the optimal images given the near-global coverage, large scene area (180x180km), high resolution (15m panchromatic) and multi-spectral facilities. In addition, the open access policy of NASA make the data very cheap. The disadvantage, in the short-term, is the short mission run-time which means, for mid-latitude regions, that suitable imagery may not be available.

Figure 12 Frequency histogram of lineament length for Landsat MSS, Landsat TM and SPOT for the Lough Gara region. This shows that as sensor spatial resolution increases, so the number of lineaments mapped increases, the size of lineaments decreases and the population peak shifts towards the origin.



	0	200	400	600	800	100	110	130	150	170
MSS	0	0	22	72	30	5	1	4	0	0
TM	0	5	113	73	30	13	18	12	4	1
SPO	0	80	172	62	29	16	9	5	0	1

appear. It is important to be familiar with a study area in order to be aware of this problem; for some areas no action may be necessary as lineaments may not be oriented in this direction. However other areas may require the acquisition of alternative data sources in order to mitigate

If Landsat ETM+ data are not available for a particular region, then the choice of imagery becomes more difficult. SPOT are available in both high resolution panchromatic and multi-spectral formats, but the scene coverage is small (60x60km) and relatively expensive.

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Landsat TM has had a longer mission time and so suitable imagery may be available that takes advantage of the larger areal coverage and multi-spectral format. Although cheaper than SPOT, Landsat TM is considerably more expensive than Landsat ETM+ and has a lower resolution (in equivalent panchromatic mode). Finally, Landsat MSS has had a very long mission time (and consequently large archive) and benefits from the areal coverage and multi-spectral format of the other Landsat missions. However it suffers from relatively poor spatial resolution.

As a result, our recommendation is to use Landsat ETM+ wherever suitable imagery is available. Otherwise, SPOT is desirable for geomorphological or cross-cutting mapping over small areas. If mapping glacial landforms over larger areas then Landsat TM is the best alternative, particularly where more detailed information on cross-cutting is required. Finally, Landsat MSS has great utility in the large archives and low cost that make it appropriate for small-scale mapping within tight budget constraints, or as a reconnaissance tool.

As a final note, users should be aware of the impending arrival of global DEM data generated by NASA from the Shuttle Radar Topography Mission (SRTM). Using SAR interferometry, a DEM covering all land masses between 60°N to 56°S will be generated at 90m and 30m spatial resolutions. The 90m data will be publicly available, whilst limited non-USA 30m data will be available to researchers upon application. This will clearly be a valuable resource for future glacial landform mapping, whilst placing new demands upon researchers in its use. There will, however, still be large previously glaciated regions that lie outside of the SRTM coverage area, making the continued use of satellite imagery necessary.

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