E7.6-10277.
CR-146647

THE IDENTIFICATION OF CLOUD TYPES IN LANDSAT MSS IMAGES.

ERTS Follow-on Programme Study No. 2962A

Second Quarterly Report on
Mesoscale Assessments of Cloud and Rainfall
over the British Isles.

By

Eric C. Barrett
M.Sc., Ph.D., F.R.G.S., F.R.Met.S., F.B.I.S.,

and

Colin K. Grant
B.Sc.

(E76-10277) THE IDENTIFICATION OF CLOUD TYPES IN LANDSAT MSS IMAGES Quarterly Report (Department of Industry) 46 p HC $4.00 CSCL 04B
N76-21644
Unclas
G3/43 00277

Supported by the U.K. Department of Industry,
Monsanto House, 10-18, Victoria Street, London, SW1H ONQ

March, 1976.

THE IDENTIFICATION OF CLOUD TYPES

IN LANDSAT MSS IMAGES.

ERTS Follow-on Programme Study No. 2962A

Second Quarterly Report on

Mesoscale Assessments of Cloud and Rainfall

over the British Isles.

By

Eric C. Barrett
M.Sc., Ph.D., F.R.G.S., F.R.Met.S., F.B.I.S.,

and

Colin K. Grant
B.Sc.

Supported by the U.K. Department of Industry,
Monsanto House, 10-18, Victoria Street, London, SW1H ONQ

March, 1976.

I. INTRODUCTION

The First Quarterly Report (Barrett and Grant, 1975) stated that, in the early stages of this Study, attention was to be focussed on the analysis of Landsat imagery cloud contents, and that consideration of rainfall questions was to be left until later. Consequently, this Second Quarterly Report is concerned with the identification and description of clouds appearing in Landsat images of the British region. Although much detailed attention has been given to the identification and description of clouds portrayed by meteorological satellites (e.g. Anderson et al., 1974, Barrett, 1974, Conover, 1962 and 1963, Hopkins, 1967, Lee and Taggart, 1969), the present authors are unaware of any similar analyses of Landsat MSS data. The tabulation of criteria characterizing a reasonable range of cloud types therefore constituted a necessary task in advance of, and in preparation for, the comparing of Landsat and conventional weather observations. In view of the lack of any earlier schemes, we feel that our efforts in that direction properly constitute "significant results", and should be of interest and use to many investigators whose objectives in any way involve cloud cover.

II. TECHNIQUES

In selecting "classic" examples of different cloud types for consideration in the compilation of the Landsat Cloud Photointerpretation key, the following steps were taken:

(a) Numbers of Landsat 2 70mm positive transparencies were laid out on large light tables, and separated into sets on the basis of their dominant cloud contents. The categories used here were those commonly employed in meteorological satellite nephanalysis procedures (see Harris and Barrett, 1975), namely cumulonimbiform, cumuliform, stratiform, cirriform and stratocumuliform families.

(b) The initial sets were examined separately so that a small number of images containing type examples of those different cloud families could be identified.

Table 1

Landsat 2 coverage of the British Isles:

Tabulation of individual frames

(see also Table 2 in Barrett & Grant, 1975)

DAY since launch	DATE 1975	ORBIT NUMBER	FRAME NUMBERS 4 / 6	FRAME NUMBERS 5 / 7	TIME H : M : S	CO-ORDS OF CENTRE LATITUDE	CO-ORDS OF CENTRE LONGITUDE
2146	17 JUNE	2032	281 / 313	297 / 329	11:23:50	N59:45	W012:26
"	"	"	282 / 314	298 / 330	11:24:10	N58:23	W013:23
2150	21 JUNE	2087	103 / 153	128 / 178	11:05:30	N52:54	E003:27
"	"	"	104 / 154	129 / 179	11:06:00	N51:30	E002:45
"	"	"	001 / 065	— / 097	11:06:50	N48:41	E001:26
2155	26 JUNE	2157	017 / 087	052 / 122	10:33:00	N57:09	W001:20
"	"	"	018 / 088	053 / 123	10:33:20	N55:45	W002:11
"	"	"	019 / 089	054 / 124	10:33:50	N54:21	W002:59
"	"	"	020 / 090	055 / 125	10:34:10	N52:58	W003:43
"	"	"	021 / 091	056 / 126	10:34:40	N51:33	W004:26
"	"	"	022 / 092	057 / 127	10:35:00	N50:09	W005:06
"	"	"	023 / 093	058 / 128	10:35:30	N48:44	W005:44
2161	2 JULY	2241	105 / 143	124 / 162	11:06:30	N59:57	W008:01
"	"	"	106 / 144	125 / 163	11:07:00	N58:34	W008:59
"	"	"	107 / 145	126 / 164	11:07:20	N57:11	W009:54
"	"	"	109 / 147	128 / 166	11:08:10	N54:23	W011:32
"	"	"	110 / 148	129 / 167	11:08:40	N53:00	W012:17
"	"	"	111 / 149	130 / 168	11:09:00	N51:35	W013:00
2188	29 JULY	2617	249 / 289	269 / 309	10:16:50	N51:46	E000:04
"	"	"	250 / 290	270 / 310	10:17:20	N50:22	W000:37
2189	30 JULY	2631	161 / 223	192 / 254	10:21:20	N55:58	E000:52
"	"	"	162 / 224	193 / 255	10:21:50	N54:34	E000:04
"	"	"	163 / 225	194 / 256	10:22:10	N53:10	W000:41

DAY since launch	DATE 1975	ORBIT NUMBER	FRAME NUMBERS 4 6	5 7	TIME H : M : S	CO-ORDS OF CENTRE LATITUDE	LONGITUDE
2189	30 JULY	2631	164 226	195 257	10:22:40	N51:46	W001:24
"	"	"	165 227	196 258	10:23:00	N50:21	W002:05
"	"	"	166 228	197 259	10:23:30	N48:56	W002:43
2190	31 JULY	2645	145 183	164 202	10:25:50	N60:07	E002:11
"	"	"	146 184	165 203	10:26:20	N58:44	E001:12
"	"	"	147 185	166 204	10:26:40	N57:21	E000:17
"	"	"	148 186	167 205	10:27:10	N55:57	W000:34
"	"	"	149 187	168 206	10:27:30	N54:33	W001:22
"	"	"	150 188	169 207	10:28:00	N53:09	W002:07
"	"	"	151 189	170 208	10:28:20	N51:44	W002:45
"	"	"	152 190	171 209	10:28:50	N50:20	W003:31
"	"	"	153 191	172 210	10:29:10	N48:55	W004:10
2191	1 AUGUST	2659	018 058	038 078	10:31:30	N60:06	E000:44
2194	4 AUGUST	2701	009 065	037 093	10:48:40	N60:06	W003:32
"	"	"	010 066	038 094	10:49:10	N58:43	W004:30
2196	6 AUGUST	2729	109 143	126 160	11:00:10	N60:06	W006:23
2206	16 AUGUST	2868	123 159	141 177	10:16:20	N51:44	E000:04
2207	17 AUGUST	2882	214 248	231 265	10:22:30	N50:20	W001:59
2208	18 AUGUST	2896	111 145	128 162	10:25:20	N60:07	E002:19
2209	19 AUGUST	2910	099 131	115 147	10:31:10	N60:03	E000:49

DAY since launch	DATE 1975	ORBIT NUMBER	FRAME NUMBERS 4 6	5 7	TIME H : M : S	CO-ORDS OF CENTRE LATITUDE	LONGITUDE
2213	23 AUGUST	2966	090 128	109 147	10:53:50	N60:07	W004:52
2222	1 SEPTEMBER	3091	126 152	139 165	10:05:10	N50:12	E002:16
"	"	"	127 153	140 166	10:05:30	N48:48	E001:37
2225	4 SEPTEMBER	3133	221 247	234 260	10:22:20	N50:12	W002:02
2233	12 SEPTEMBER	3245	075 129	102 156	11:05:20	N59:54	W007:55
"	"	"	076 130	103 157	11:05:40	N58:32	W008:53
"	"	"	061 115	088 142	11:06:10	N57:08	W009:47
"	"	"	062 116	089 143	11:06:30	N55:45	W010:38
"	"	"	063 117	090 144	11:07:00	N54:21	W011:25
"	"	"	064 118	091 145	11:07:20	N52:57	W012:11
"	"	"	065 119	092 146	11:07:50	N51:32	W012:54
2235	14 SEPTEMBER	3273	005 065	035 095	11:16:40	N59:57	W010:44
"	"	"	006 066	036 096	11:17:10	N58:34	W011:43
"	"	"	007 067	037 097	11:17:30	N57:11	W012:37
"	"	"	008 068	038 098	11:18:00	N55:47	W013:28
2236	15 SEPTEMBER	3287	190 254	222 286	11:22:30	N59:55	W012:13
2239	18 SEPTEMBER	3328	001 065	033 097	09:59:20	N50:05	E003:38
"	"	"	002 066	034 098	09:59:40	N48:41	E003:00
2244	23 SEPTEMBER	3398	013 085	049 121	10:28:20	N48:44	W004:11
2259	8 OCTOBER	3607	009 071	040 102	10:10:10	N51:27	E001:24
"	"	"	010 072	041 103	10:10:40	N50:03	E000:44

DAY since launch	DATE 1975	ORBIT NUMBER	FRAME NUMBERS 4 6	5 7	TIME H : M : S	CO-ORDS OF CENTRE LATITUDE	LONGITUDE
2259	8 OCTOBER	3607	011 073	042 104	10:11:00	N48:39	E000:06
2276	25 OCTOBER	3844	100 156	128 184	10:04:20	N51:34	E002:52
"	"	"	101 157	129 185	10:04:40	N50:09	E002:11
"	"	"	102 158	130 186	10:05:10	N48:45	E001:32
2279	28 OCTOBER	3886	008 074	041 107	10:21:50	N50:09	W002:07
"	"	"	009 075	042 108	10:22:20	N48:45	W002:45
2280	29 OCTOBER	3900	136 168	152 184	10:28:00	N48:47	W004:10

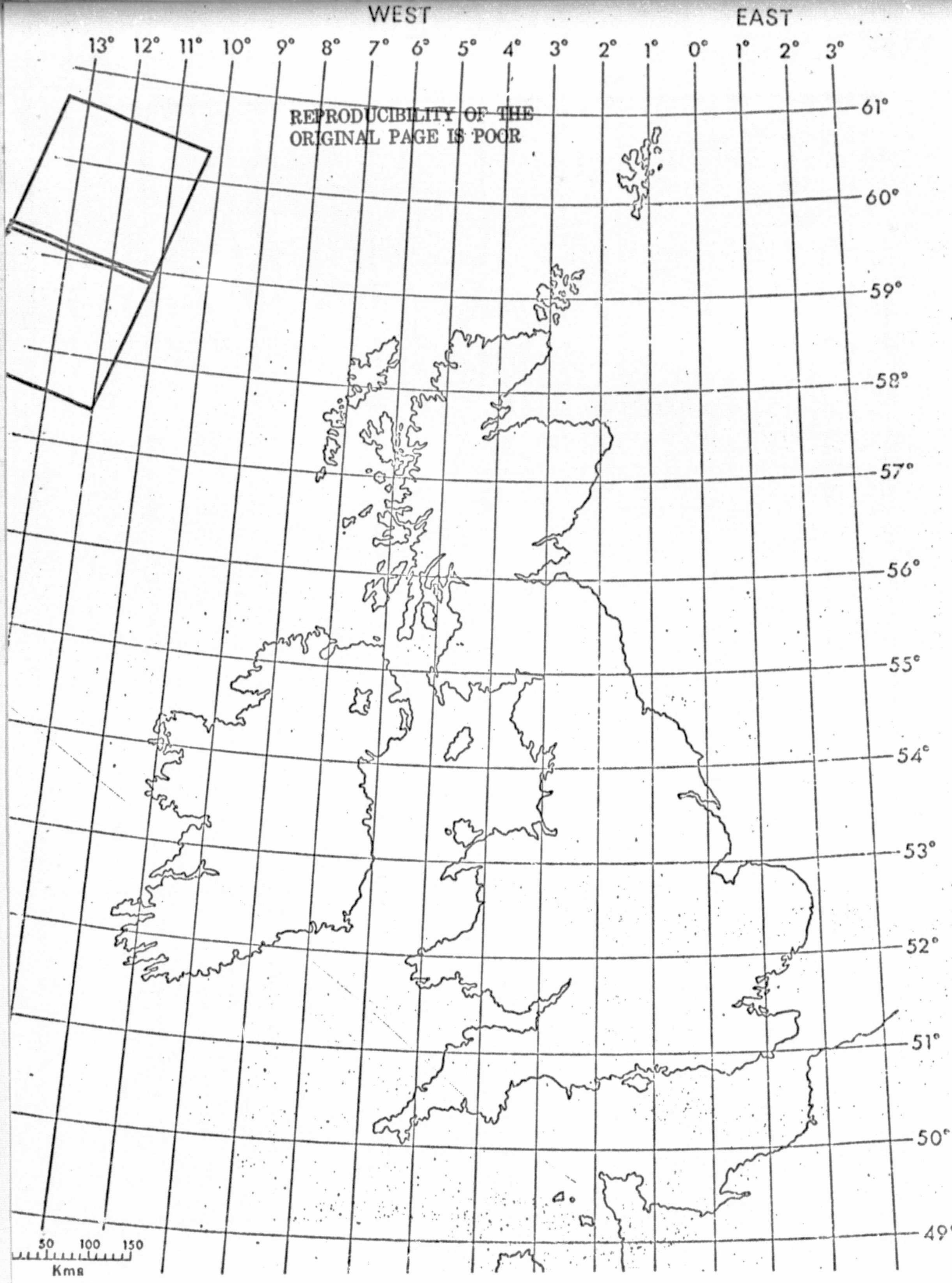


Fig. 1(a): Additional Landsat coverage of the British Isles, Cycle 7, 2 June - 19 June, 1975.

1E

Fig. 1(b): Additional Landsat coverage of the British Isles, Cycle 8, 20 June - 7 July, 1975.

1F

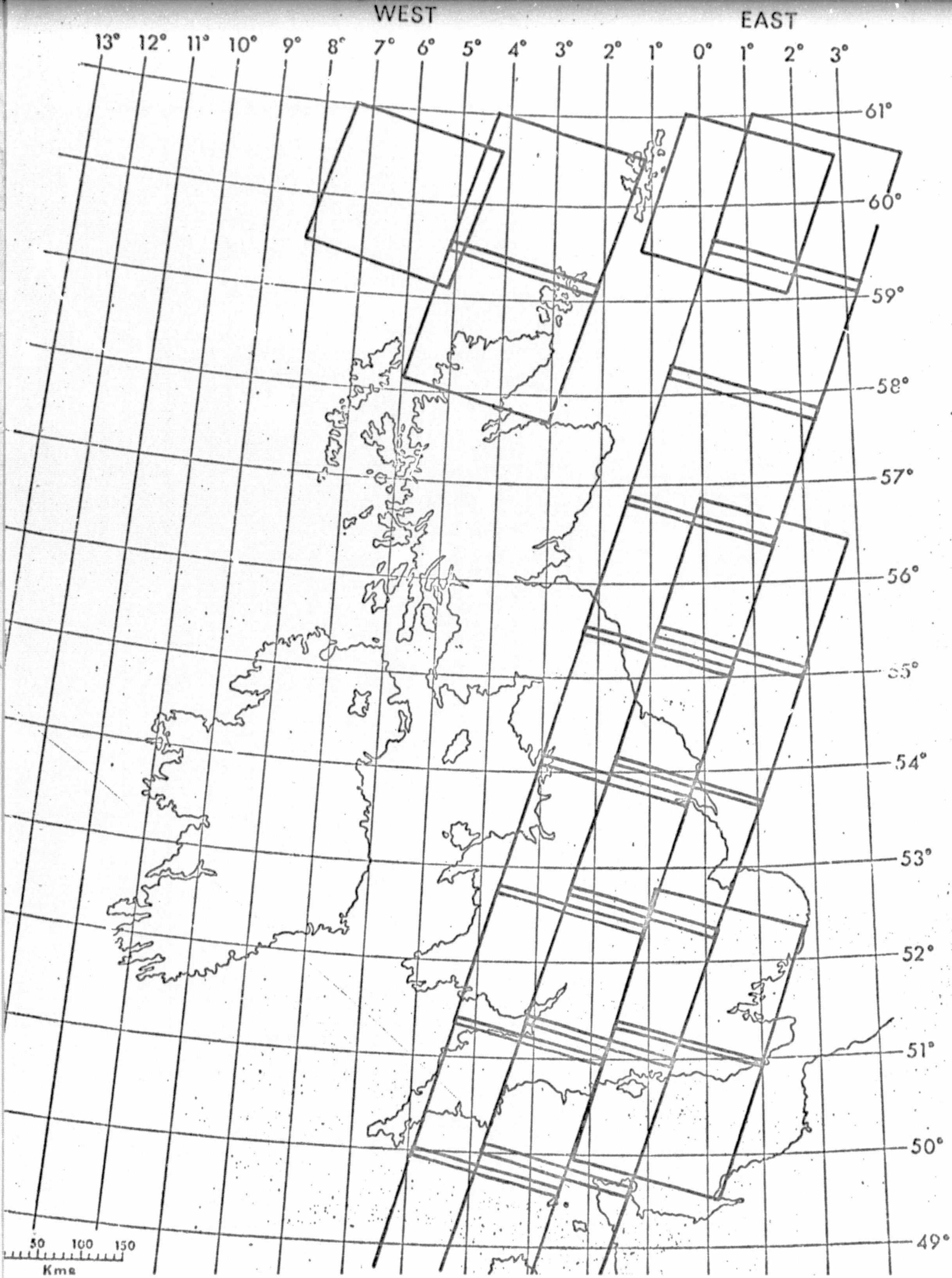


Fig. 1(c): Additional Landsat coverage of the British Isles, Cycle 10, 26 July - 12 Aug., 1975.

10

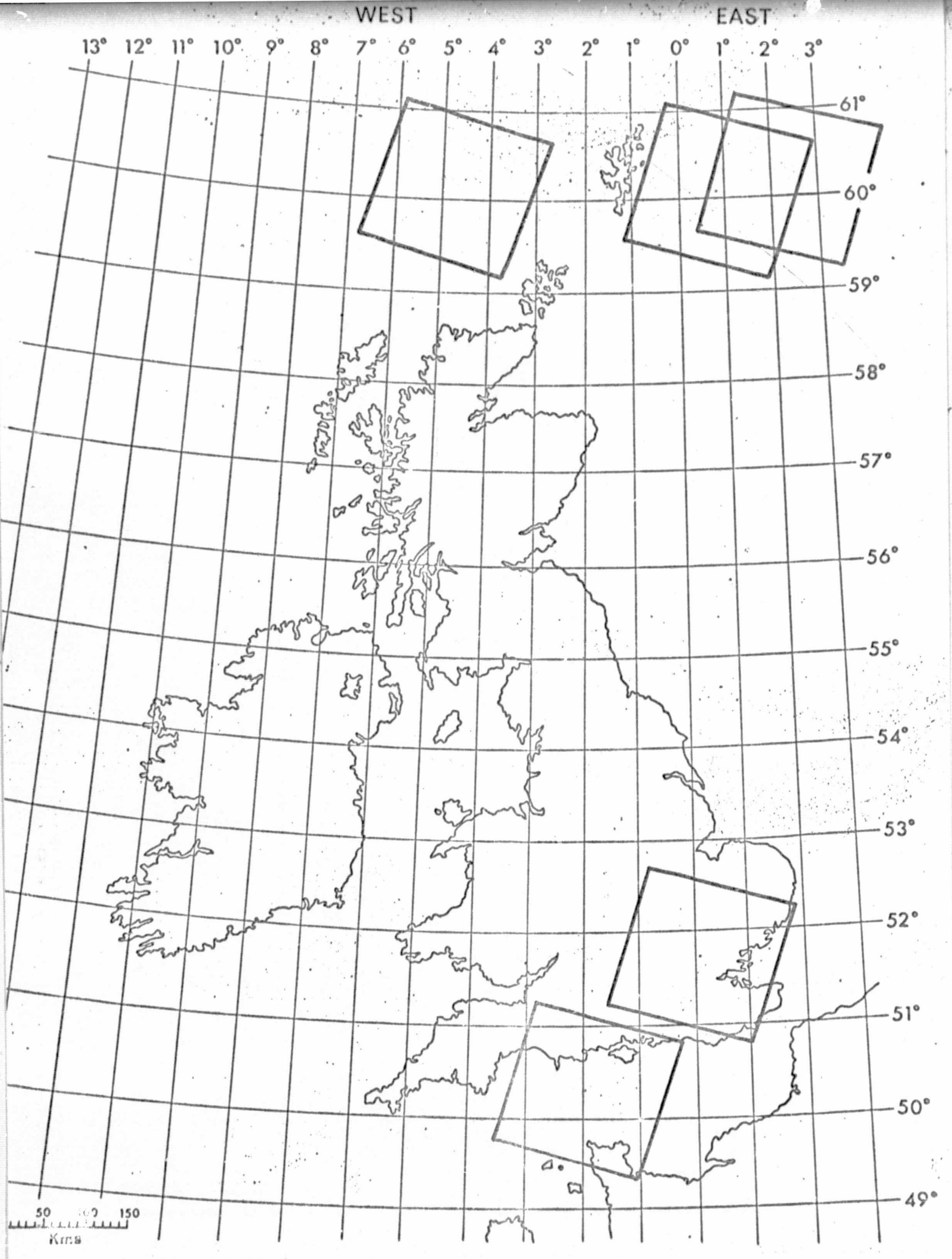


Fig. 1(d): Landsat coverage of the British Isles, Cycle 11,
13 Aug. - 30 Aug., 1975.

1H

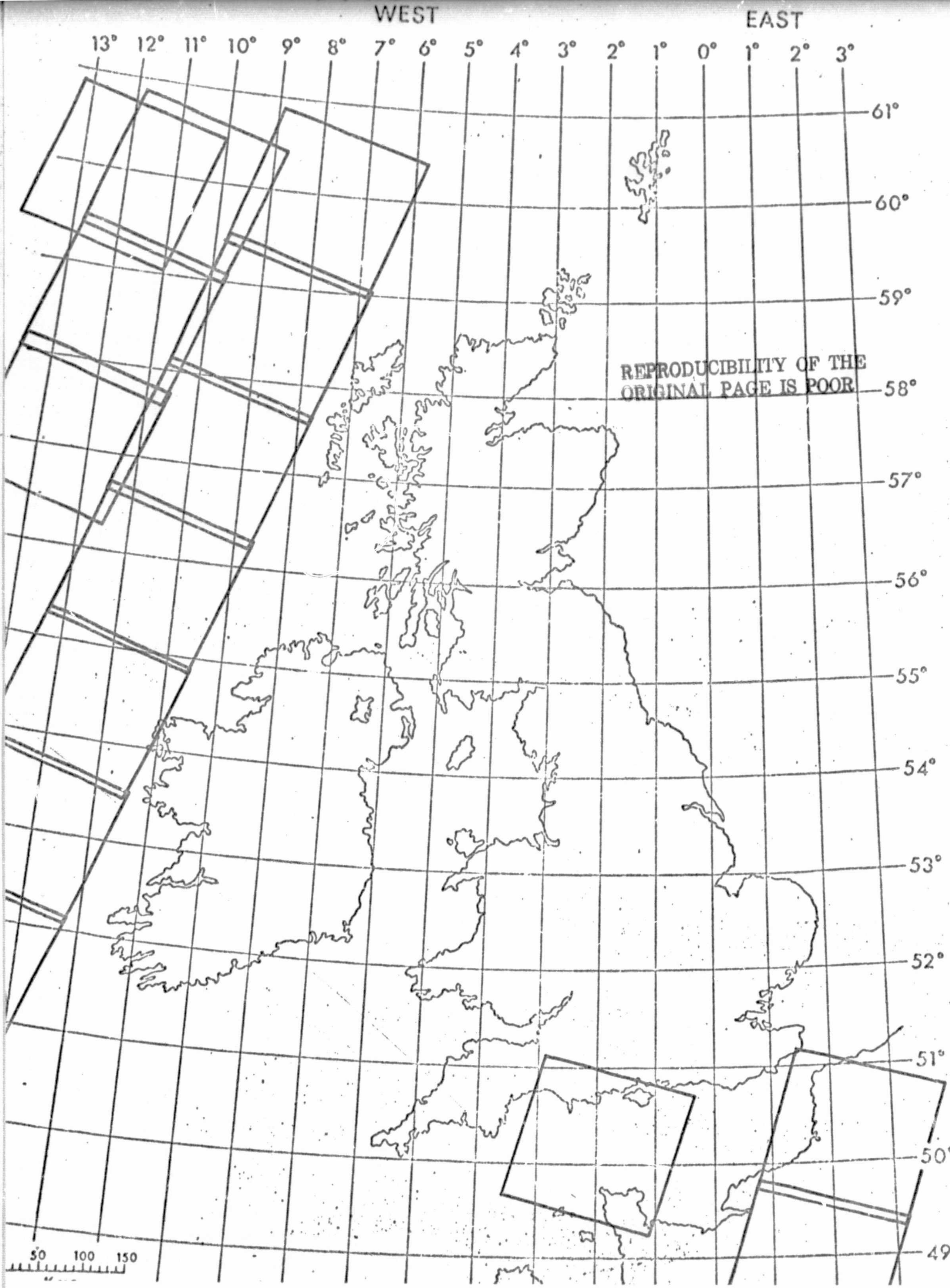


Fig. 1(e): Landsat coverage of the British Isles, Cycle 12,
31 Aug. - 17 Sept., 1975.

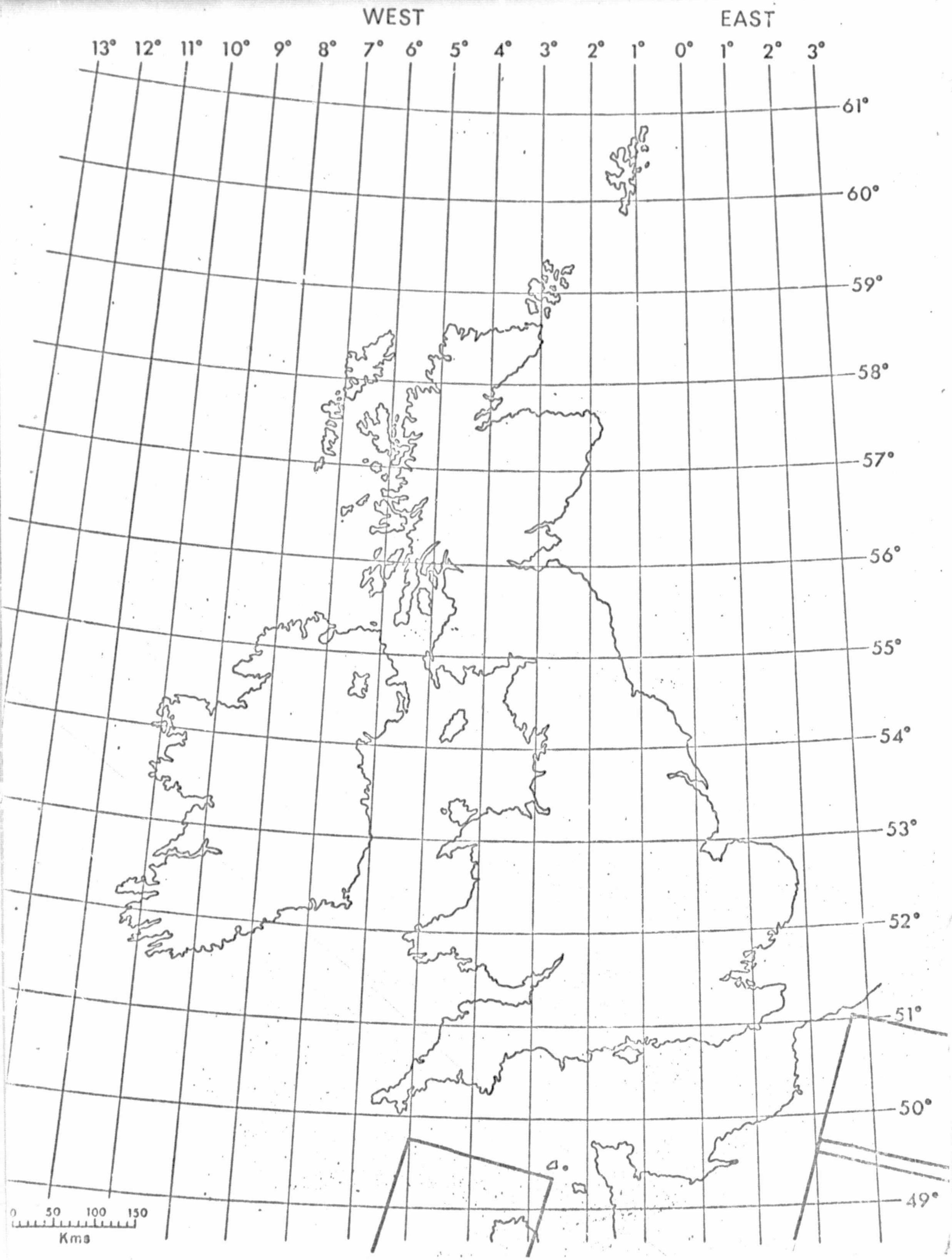


Fig. 1(f): Landsat coverage of the British Isles, Cycle 13,
18 Sept. - 5 Oct., 1975.

1-5

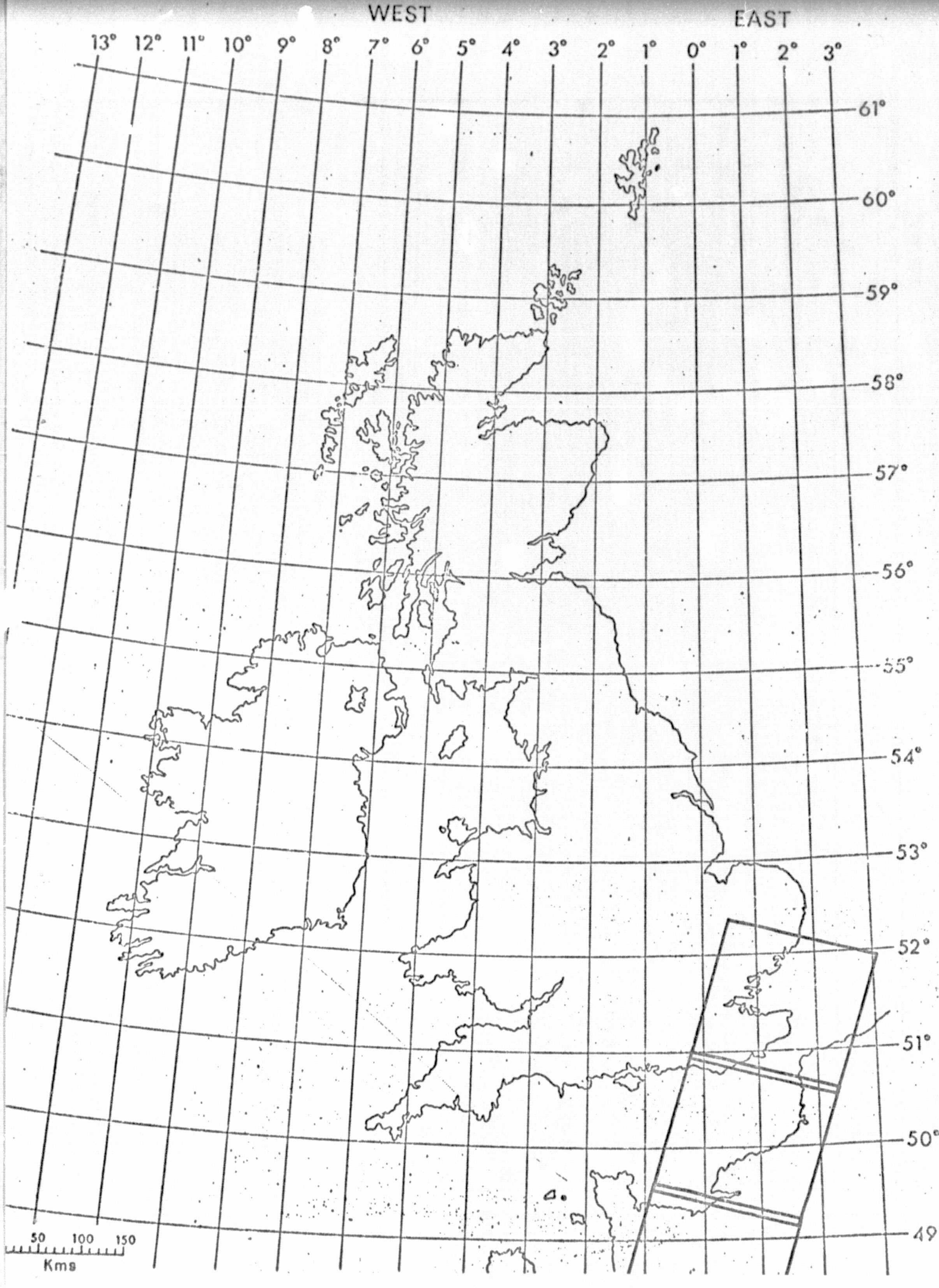


Fig. 1(g): Landsat coverage of the British Isles, Cycle 14,
6 Oct. - 23 Oct., 1975.

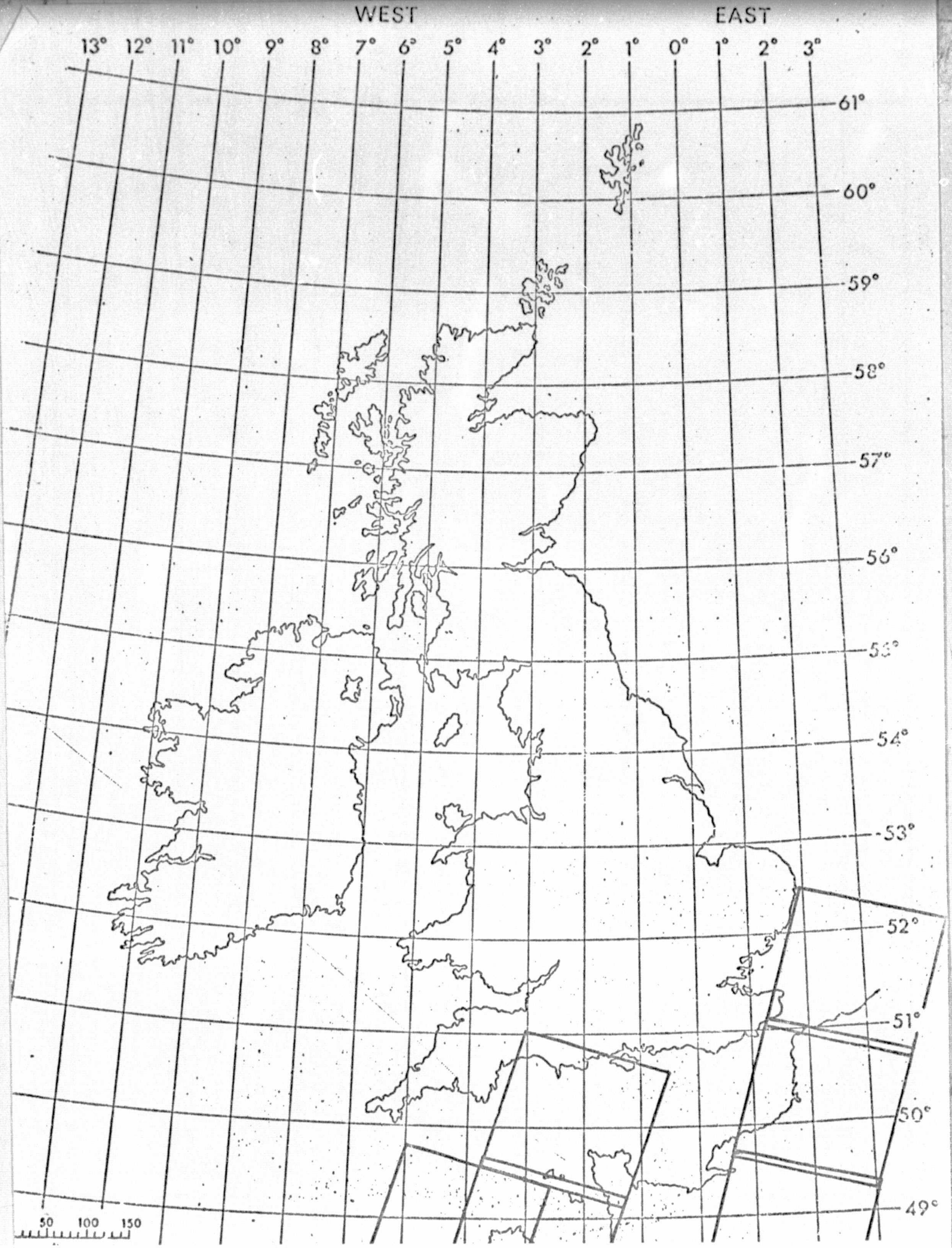


Fig. 1(h): Landsat coverage of the British Isles, Cycle 15, 24 Oct. - 10 Nov., 1975.

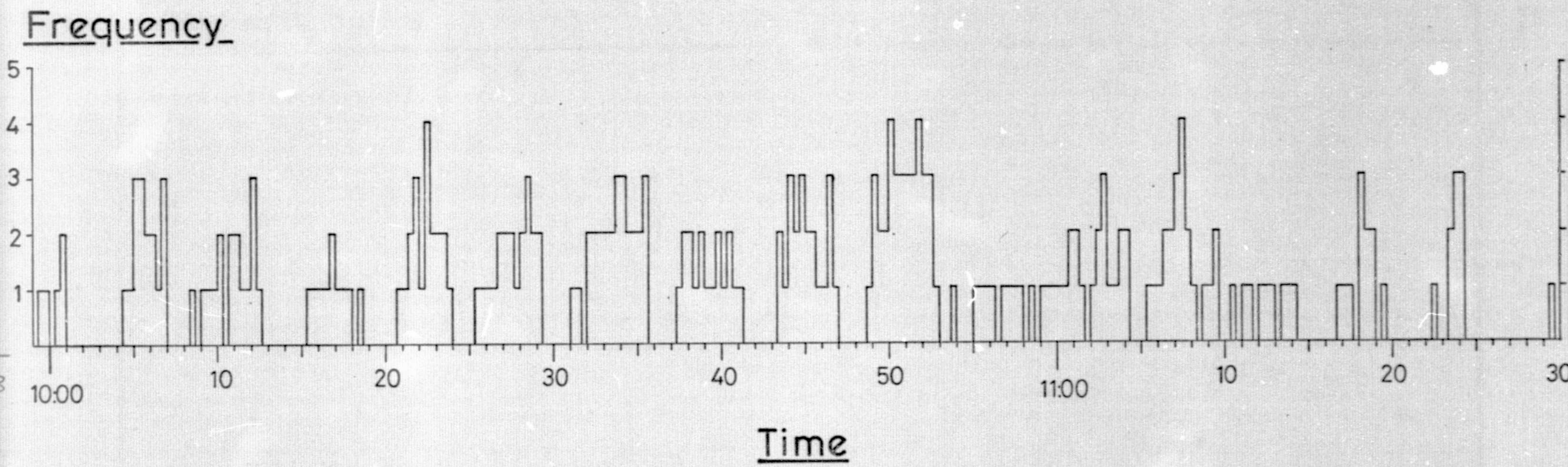


Fig. 2 Distribution of the imagery through time

(c) The sets of type examples were viewed on a microfilm reader (E. Marshall Smith Ltd., Bournemouth), with X14 and X25 magnification in order that the finer details of the five basic cloud families might be examined closely and noted.

(d) Representative examples of the five cloud families, and their more important members evident in the Landsat imagery, were selected for incorporation in the photo-key.

At each stage in this procedure there was dependence upon previously-gained experience in cloud recognition on meteorological satellite imagery, and a knowledge and understanding of the principles upon which commonly-accepted cloud classifications from ground viewing positions are based.

III. ACCOMPLISHMENTS

The chief accomplishment during the second quarter was the compilation of a cloud interpretation key for use with Landsat imagery. Table 2 compares the resolution of Landsat imagery with that obtained from other current satellite platforms.

TABLE 2.

A comparison of the satellite systems viewing the U.K. in the visible waveband in 1975-6.

Satellite	Sensor	Sub-satellite resolution	Frequency of coverage
Landsat	Multispectral scanner (MSS)	c.80m	18-daily
DMSP	Scanning Radiometer, Very High Resolution (SR-VHR)	0.6km	Daily
Noaa	Very High Resolution Radiometer (VHRR)	0.9km	Daily
DMSP	Scanning Radiometer, High Resolution (SR-HR)	3.6km	Daily
Noaa	Scanning Radiometer (SR)	4.5km	Daily

Since the Landsat data afford a much more detailed view of cloudiness than the other satellite systems whose data are readily available to the scientific community, the cloud contents evident in Landsat images are of considerable interest and importance to several groups of workers, including the following:

(a) Atmospheric scientists, interested in the correct analysis of meteorological satellite data (with which the Landsat data can be compared), and in assessing the potential benefits which might accrue were extremely high resolution images available more frequently than from Landsat 1 and 2;

(b) Earth scientists, concerned with the influence of aggregations of water droplets in the atmosphere upon the measured radiances from various Earth surface features, and the development of techniques to avoid interpretation problems caused by cloud cover (whether opaque or transparent, continuous or discontinuous) and associated shadow effects;

(c) Operational remote sensing teams, especially those using airborne platforms, and requiring certain sky conditions in order to commence specific missions.

The first requirement in most cases is a recognition of the types of clouds present over a given area on a particular occasion. The complex Landsat Cloud Photointerpretation Key which follows in Section IV is designed for use by any scientists concerned with cloud identification, whether they are professional meteorologists or not. It does not presume that other data are available to assist or confirm the Landsat indications. Thus it will be possible later in the present study to use this Key in comparison with other satellite keys and/or ground observations of sky conditions.

The Landsat Cloud Photointerpretation Key is structured for maximum flexibility in its application and use. Following American Society of Photogrammetry (1975) it is clear that the suggested scheme may be described in several ways. In terms of its scope, it may be described as a joint <u>Subject/Analagous Area Key</u>, dealing as it does with specified categories of clouds in a mid-latitudinal zone including oceanic and island or fringe-continental areas; in terms of its treatment, it is a Semi-technical and Direct key involving a necessary minimum of technical meteorological terms to characterise features immediately obvious in much of the Landsat imagery; in terms of its organisation, it may be described as a Selective Key, arranged as it is so that the interpreter simply selects that example corresponding to the feature he is attempting to identify, with both Essay Key and Photo-index Key components.

The Key is comprised of three separate, yet inter-related parts, namely:-

a) The Short Description Key;

b) The Detailed Description Key; and

c) The Photo-index Key.

The Short Description Key, for general use, is comprised of brief notes concerning the five basic cloud families and their more important members (most frequent/most widespread/most readily recognized on Landsat imagery in mid-latitude continental fringe regions). The notes are basically descriptive, but brief comments on cloud genesis and synoptic context are also included.

The Detailed Description Key, for more specialized use, is structured on the recognition that there are two basically different ways in which satellite-viewed cloudiness may be described. Although visible imagery from meteorological satellites might, with profit, be approached similarly, the following scheme has been developed to exploit the special characteristics of the Landsat cloud representation, especially its unsurpassed detail. The scheme differentiates between primary and secondary cloud features, namely:

a) Broadscale features of masses and/or aggregates of clouds, i.e. cloud fields; and

b) Smaller scale features of masses and/or aggregates of clouds, i.e. structural elements of cloud fields.

Although it has been widely recognised that some clouds (notably those of the cumulnimbus and cumuliform families) can be described in terms of their individual clouds (or "cells"), problems have arisen in other cases (notably stratiform types) where the search for individual cloud elements is inappropriate. We feel that our differentiation between cloud fields and the structural elements apparent within them is an advance over earlier thinking since it permits all cloud families to be treated alike. In cumuliform cloud fields, for example, the structural elements may be individual cloud cells and/or clusters thereof, and/or organizations of the same; in stratiform cloud fields the identifiable structural elements might be streaks, mottlings or bandings which are evidences of the meso- and/or sub-synoptic scale factors which sculpture the outlines and surfaces of those cloud types which own a dominantly sheet-like appearance in plan.

The Photo-index key illustrates classic examples of the identified cloud families and their significant members or sub-groups.

IV. SIGNIFICANT RESULTS

The Landsat Cloud Photointerpretation Key for Middle Latitudes

INTRODUCTION

Satellite:- LANDSAT 2; launched January 22, 1975.

Sensor:- Multispectral Scanner Subsystem (MSS). This gathers data by imaging the surface of the Earth in 4 spectral bands simultaneously through the same optical system. The spectral bands are numbered from 4 to 7 inclusive.

BAND No.	WAVELENGTH (µm)
4	0.5 - 0.6
5	0.6 - 0.7
6	0.7 - 0.8
7	0.8 - 1.1

Bands 4, 5 and 6 use photomultiplier tubes as detectors; band 7 uses silicon photodiodes.

Imagery:- Although the sensor's output is initially in the form of continuous strips, NASA process the imagery into more manageable output products. This study uses MSS bulk processed, 70mm positives. The image area on this type of product is:-

cross track - 55 mm

in track - 53 mm

This gives a ground cover for each frame of approx. 185 - 176 kilometres.

The scale of these products is 1:3,369,000.

The resolution is approx. 80m on the ground.

Cloud Families:- 5 general families of clouds are considered, namely:-

1. Cumulonimbiform
2. Cumuliform
3. Stratiform

4. Stratocumuliform

5. Cirriform.

Four members of this five-fold primary division of clouds are further divided into a number of members or sub-groups. Some of these sub-groups, for example altostratus and altocumulus, are generally regarded as cloud genera in their own right. However, for most purposes, it is more convenient to regard them as sub-groups of the 5 cloud families. Sub-groupings are shown below, together with the appropriate illustration numbers.

Family	Sub-Groups		Illustratioh Numbers
1.	(i)	Cumulonimbus	Plates 1 (a) & (b)
	(ii)	Cumulonimbus with Cirrus	Plates 1 (c) & (d)
2.	(i)	Cumulus humilis and Cumulus mediocris	Plates 2(a),(b) & (c)
	(ii)	Cumulus congestus	Plate 2 (d)
	(iii)	Altocumulus	Plates 2 (e) & (f)
3.	(i)	Stratus	Plates 3 (a) & (b)
	(ii)	Layered stratiform (incl. Nimbostratus)	Plate 3 (c)
	(iii)	Altostratus	Plate 3 (d)
4.	(i)	Stratocumulus	Plates 4 (a) to (f)
5.	(i)	Cirrus fibratus	Plate 5 (a)
	(ii)	Cirrus spissatus	Plate 5 (b)
	(iii)	Cirrostratus	Plate 5 (c)
	(iv)	Cirrocumulus	Plate 5 (d)
	(v)	Condensation trails	Plates 5 (e) & (f)

Band Differences:-

As has been noted above, the MSS observes and records Earth radiation in 4 different wavebands. Two of these bands (4 and 5) image in the visible portion of the electromagnetic spectrum, while the others (6 and 7) image in the short-wave portion, or just into the infra-red. However, all four bands are imaging reflected solar radiation only.

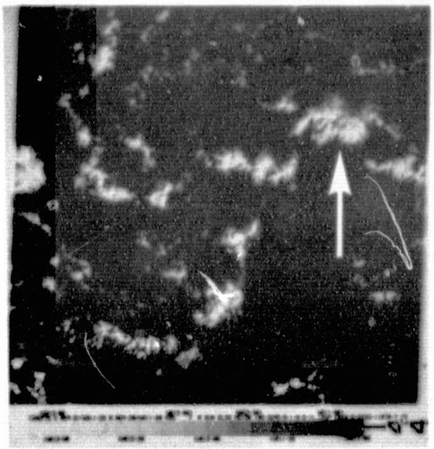
The main differences between the appearances of clouds in the four wavebands are related to the background brightnesses of land and sea surfaces. In bands 4 and 5 both land and sea appear dark grey. Often, there is no clear distinction between land and sea where both occur in a particular image, and the coastline is difficult to distinguish. In bands 6 and 7, the sea appears black, whereas land surfaces appear much lighter (mid-grey to pale-grey tones).

Such differences are significant for the distinguishing of cloud types over land and sea surfaces. As a general rule, bands 6 and 7 seem to be the more useful for identifying clouds over the sea, and bands 4 and 5 for clouds over land. However, where extensive cloud fields occur over land (which is consequently hidden) band 7 is usually the best as textural characteristics tend to be enhanced herein.

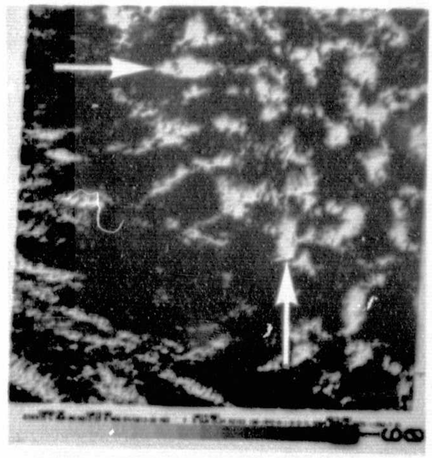
In the "band differences" section of the detailed description key below, the use of the term "LAND/SEA" indicates that these considerations apply.

Plate 1: Cumulonimbiform

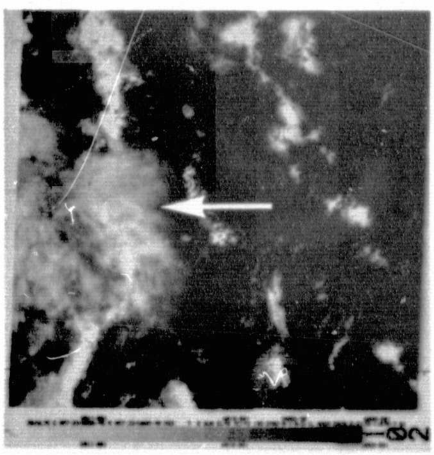
(a) Cumulonimbus



(b) Cumulonimbus



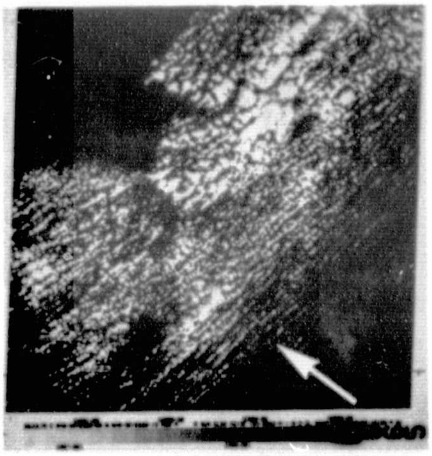
(c) Cumulonimbus with Cirrus



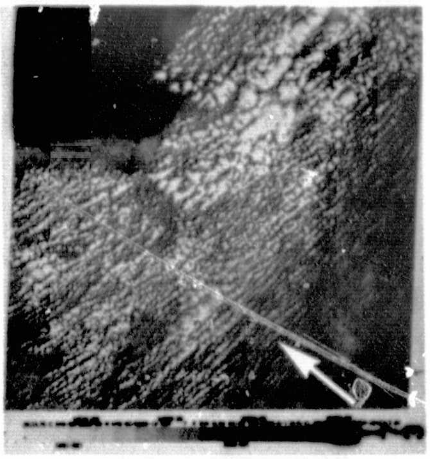
(d) Cumulonimbus with Cirrus

Plate 2: Cumuliform

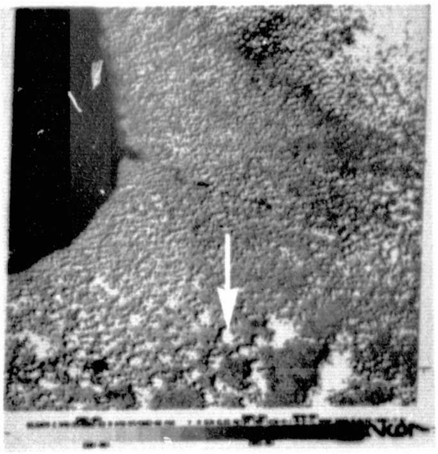
(a) Cumulus humilis (band 4)



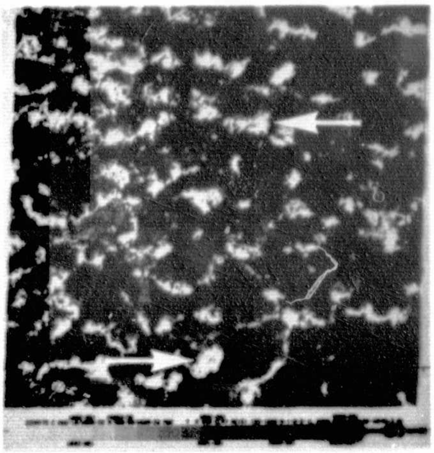
(b) Cumulus humilis (band 7)



(c) Cumulus mediocris



(d) Cumulus congestus



(e) Altocumulus

(f) Altocumulus waves

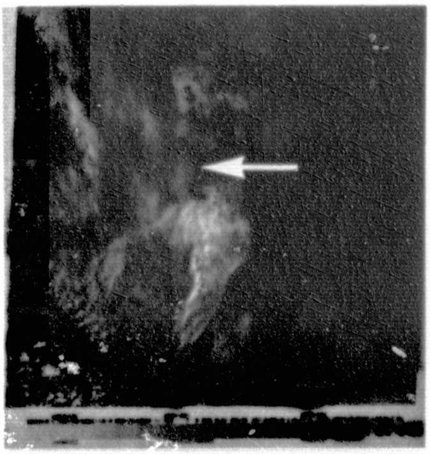
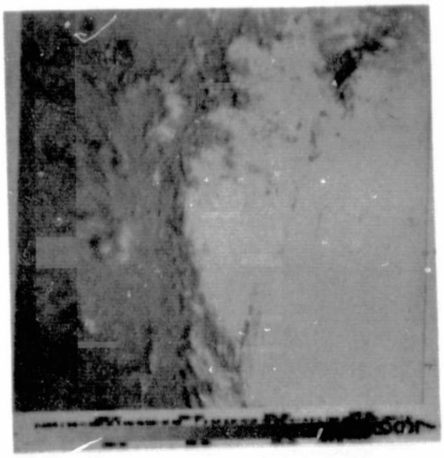
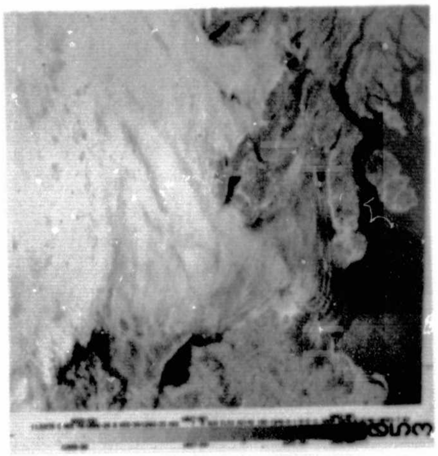


Plate 3: Stratiform

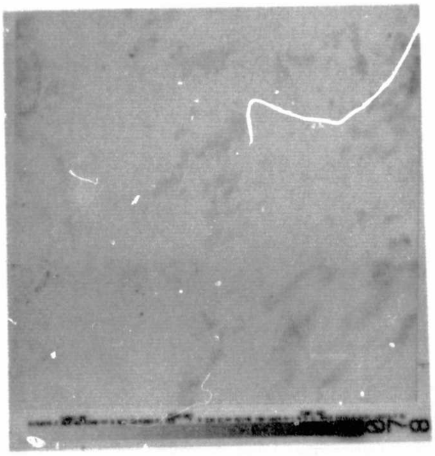
(a) Stratus



(b) Stratus



(c) Layered Stratiform



(d) Altostratus

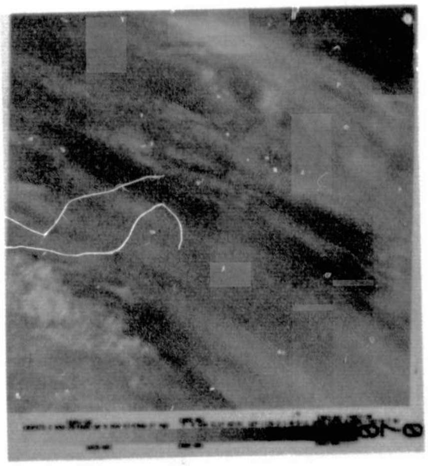
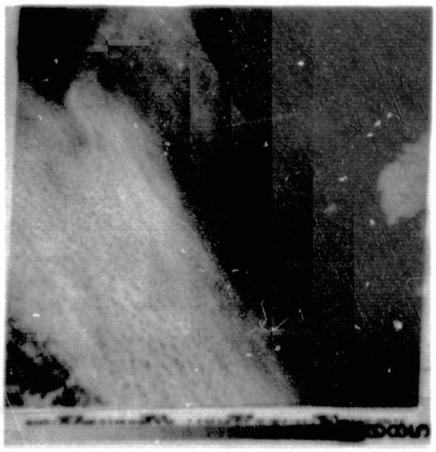
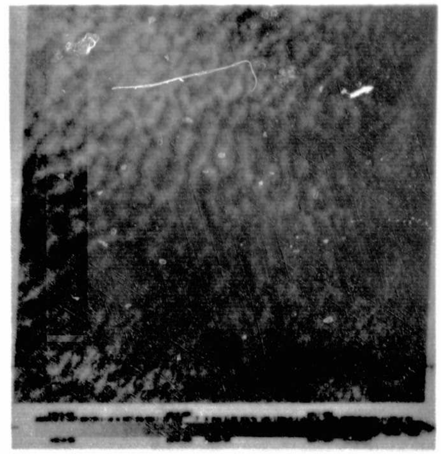


Plate 4: Stratocumuliform

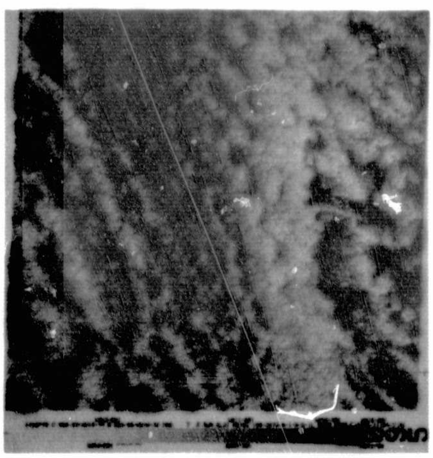
(a) Cells



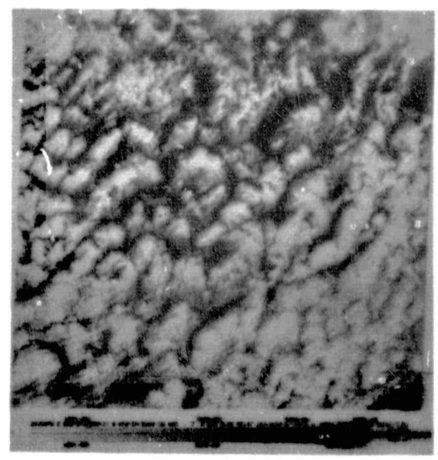
(b) Ripples



(c) Bands



(d) Scallops



(e) Waves

(f) Scallops and waves

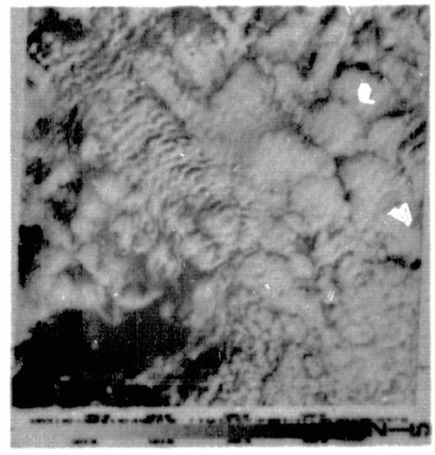
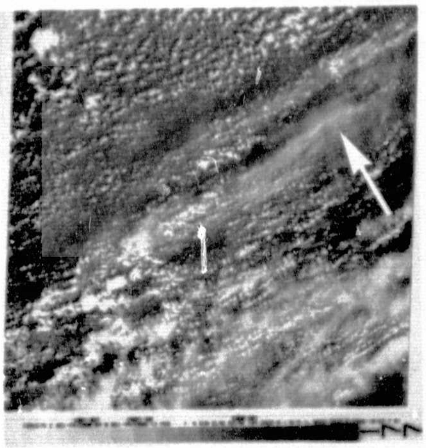
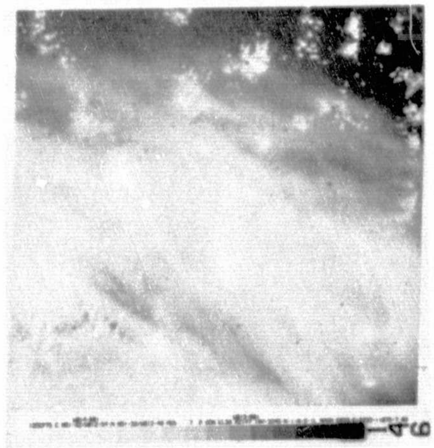


Plate 5: Cirriform

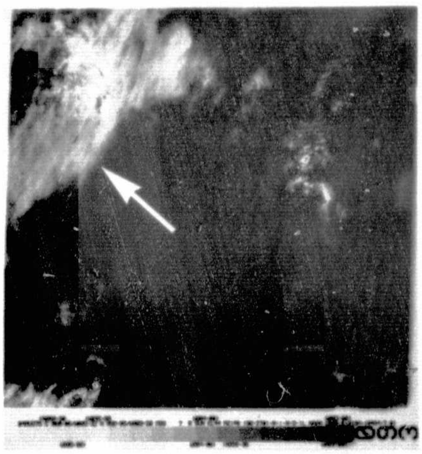
(a) Cirrus fibratus



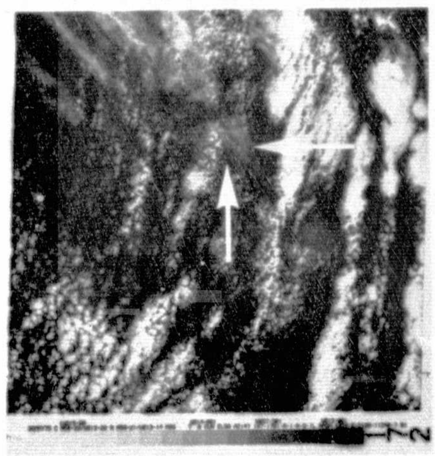
(b) Cirrus spissatus



(c) Cirrostratus

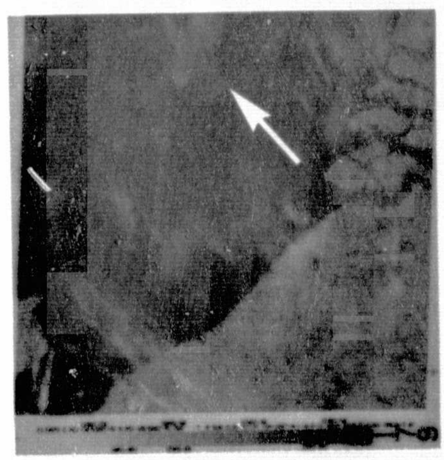


(d) Cirrocumulus



(e) Condensation trails (band 4)

(f) Condensation trails (band 7)



8E

THE SHORT DESCRIPTION KEY

1. Cumulonimbiform

(i) Cumulonimbus

These appear as large, very bright cloud elements whose shape varies from subcircular to irregular. Cloud edges are usually sharply defined, often emphasized by shadows cast by these tall, towering clouds or cloud masses. Fields of cumulonimbus, and the included open spaces, may extend over broad areas with individual clouds organised into lines, closed clusters and more or less regularly patterned open convective cells or honeycombs. Sometimes the cloud masses are chaotically distributed. They form preferentially over relatively warm surfaces and/or where the air is markedly unstable.

(ii) Cumulonimbus with Cirrus

Very bright cumulonimbus clouds are here covered wholly or in part by cirrus which appears greyer and often has a fibrous texture. Where cirrus is present (indicating upper level conditions not conducive to a continuation of vertical cloud growth) the summits are indistinct and margins are ill-defined e.g. where vertical wind-shear causes cirrus plumes to extend beyond the cumulonimbus towers. Fields of cumulonimbus with cirrus are often extensive especially where merging of cirrus anvils occurs, with little cloud-free space between. Strong instability is indicated, often on exposed slopes where orographic and meteorologic factors enhance each other, or along powerful cold fronts or squall lines.

2. Cumuliform

(i) Cumulus humilis and Cumulus mediocris

These involve small cloud elements, generally bright to very bright in tone. These may be circular, sub-circular or irregular in shape. They often occur in fields of irregularly spaced elements, but may be organized, characteristically into open convective cells or streets. The edges of the fields often indicate distributions of surface heating patterns, e.g. in summer, when these are fair weather clouds over land.

(ii) Cumulus congestus

These somewhat larger cumulus clouds are frequently found in conjunction with cumulus humilis and cumulus mediocris, where tower cloud growth is locally more advanced. They are very bright, due to their greater depth. The edges of the elements are sharply defined and shadows from these clouds are often visible over land surfaces where the background is of light to medium tone.

(iii) Altocumulus

Being somewhat higher clouds than those of types (i) or (ii), the small grey elements which are characteristic of this generally shallow cloud type are often seen overlying lower cloud masses. They occur either in irregular fields or organized into narrow, parallel bands transverse to the wind flow. The latter organisation produces "waves" when viewed on the Landsat imagery - these are often orographically induced lee wave clouds.

3. Stratiform

(i) Stratus

This forms generally extensive cloud sheets possessing little or no internal organization visible on the Landsat imagery. The fields are usually bright, though edges of sheets may show tonal variations. They indicate moist layers of air at or near the Earth's surface and may conform more or less closely with topography or coastlines (lowland, valley and coastal fog).

(ii) Layered Stratiform

A generally bright or very bright cloud field, consisting of a number of layers which usually form continuous sheets when viewed on Landsat imagery. Usually frontal in origin and often extending over wide areas. Some texture is visible as a result of changes in thickness and/or shadows cast by higher structural elements. The latter may include stratus, nimbo-stratus and altostratus.

(iii) Altostratus

This occurs characteristically as extensive bands or sheets. Bright appearances prevail but small tonal variations are common, related to changes in thickness of the cloud field which is more usually translucent than transparent. The texture may be smooth or fibrous. Altostratus indicates widespread uplift of moist air, e.g. along warm fronts.

4. Stratocumuliform

These form extensive sheets or bands with characteristic cellular and/or sub-linear sub-structures, although a wide variety of etchings occur related to turbulent processes. Brightness is variable, from medium to bright. These clouds are anticyclonic, forming when low-level convection is over-ruled by widespread subsidence.

5. Cirriform

Usually a "thin" dull cloud, this often overlies lower cloud formations which are visible when the overlying cirrus is translucent. There are several distinct varieties.

(i) Cirrus fibratus

This is a thin, grey cloud, typically showing a fibrous texture; it is often found in association with Cumulonimbus towers, and along the leading edges of warm and occluding frontal bands of cloud.

(ii) Cirrus spissatus

This may form extensive sheets or bands. Often opaque and white in appearance, its texture is comparatively smooth. It may be found at or near the leading edge of a warm or occluding frontal band of cloud.

(iii) Cirrostratus

Typically forming bright sheets or bands of clouds, with a fibrous texture, this is often associated with advancing warm or occluded fronts.

(iv) Cirrocumulus

Rarely seen; cirrocumulus is composed of tiny, dull, translucent cloud elements which give the cloud field a finely mottled appearance.

(v) Condensation Trails

These appear as thin, dull grey, straight lines or bands, usually of considerable length. They often form criss-cross patterns when numerous trails are present, indicating considerable moisture through depth in the middle and/or upper troposphere.

DETAILED DESCRIPTION KEY

1. CUMULONIMBIFORM

(i) Cumulonimbus

Structural Elements

Nature : Individual cumulonimbus cells

Size : 10 - 20km. across longest dimension.

Form : Subcircular generally, some elongated into oval shapes. Well defined margins.

Brightness : Generally very bright. Occasionally the structure of individual elements causes shadows to be cast down onto lower portions of these tall towering clouds. In these instances the shading of portions of individual elements helps to enhance their towering appearance.

Texture of Each Element : Uniformly smooth; some texture seen when shadows cast - as noted above.

Organisation of Elements : Individual elements may be organised into closed clusters, with overlapping margins (which may cover extensive areas), or open, cellular patterns. These patterns may be honeycombs or lines (where the cells are more regularly spaced), or chaotic distributions (where the cells are less regularly spaced).

Band Differences : 4,5,6 very similar; 7 shows more shadow which enhances cloud structures.

Cloud Fields

Size : May be 150 km. or more across.

Form : Fields of cumulonimbus are often related to relatively warm surfaces, these prompting convective instability under appropriate vertical profile conditions; in such cases the fields may be dominantly over land (summer) or sea (winter). When related to the state of the atmosphere alone they are characteristically elongated (fronts and/or squall lines) or irregularly-shaped (e.g. trailing cold sectors of depressions).

Brightness : Field brightness depends on the organisation of the individual elements. Generally, the closer the spacing of the cells, the brighter the field, as a whole, appears.

Texture : Similarly depends on organisation; and may vary from a smooth, extensive cloud mass to a mottled, open texture.

Band Differences : LAND/SEA

(ii) Cumulonimbus with Cirrus

Structural Elements

Nature : Individual cumulonimbus cells, with cirrus plumes.

Size : 10 - 30 km. across longest dimension.

Form : Subcircular generally; margins ill defined, especially where the cirrus is dense and blown out from the top of the cumulonimbus tower. This leaves an indistinct, diffuse edge.

Brightness : Very bright. Cirrus, where extending beyond the individual cumulonimbus towers, may appear duller. Individual towers are often seen as brighter elements through the duller, translucent cirrus.

Texture : Little structure is seen in individual elements, which appear smooth. Cirrus plumes may have a fibrous texture.

Organisation of Elements : Often organised into closed clusters, which may cover extensive areas especially where cirrus plumes from individual towers merge to form one cirrus sheet.

Band Differences : Band 7 shows greater texture and structure in the cirrus elements.

Cloud Fields

Size : Very extensive, may be 150 km. or more across.

Form : Cumulonimbus with cirrus anvils normally evolve out of cumulonimbus clouds by a continuous process of transformation. Conditions under which these clouds occur are therefore similar to those which are favourable for the development of Cumulonimbus.

Brightness : Very bright.

Texture : Smooth. Cirrus plumes, where merging, may be diffuse and show a fibrous texture.

Band Differences : Band 7 shows greater texture and structure in the cirrus elements.

2. CUMULIFORM

(i) Cumulus humilis and Cumulus mediocris

Structural Elements

Nature : Individual cumulus cells.

Size : Generally 1 to 5 km. across the longest dimension, some humulis cells may be smaller, down to the limits of the Landsat resolution.

Form : Varied; may be circular, sub-circular or irregular. Edges are generally sharply defined. There may be some small shadows cast onto the ground if vertical development is locally accentuated.

Brightness : Bright to very bright; the cloud edge on the side away from the sun is often marked by ground shadow (if over land), which contrasts strongly with the cloud itself.

Texture : Generally no texture is seen in individual elements, which appear smooth. If vertical development is marked, as in some larger clouds, then shadows caused by higher portions of a cloud are seen on lower portions. This gives a faintly mottled appearance to these clouds.

Organisation of Elements : Commonly occur in irregularly organised fields, individual or parallel lines, or uniform, open cellular patterns.

Lines consist of individual Cumulus humilis and mediocris elements. (They may also contain Cumulus congestus). A field may contain 50 to 100 lines, with the spacing between the lines varying, but generally it is similar in magnitude to the width of the cloud lines, or slightly larger. The lines may be straight, or gently curved, and may occur over either land or sea surfaces.

Open, cellular patterns are formed from various Cumulus subgroups which cluster together to form honeycomb patterns often covering extensive areas.

Band Differences : LAND/SEA - very marked.

Cloud Fields.

Size : Lines may be 100 km. or more in length, and one field may consist of numerous (50+) lines. Open cellular patterns and chaotic distributions may cover wide areas, often the whole of a single image.

Form : Convection processes are responsible for their formation, individual cells forming in the thermals associated with instability in the lower troposphere. This instability may be due to surface receipt of solar radiation, and/or warming of the base of a cold air mass by passage over a relatively warm surface. Therefore, the margins of cumulus fields are closely related to surface heating patterns.

Brightness : Varies, depending on the spacing of the cloud lines or cellular patterns and also the background (land or sea). Generally, the closer the elements, the brighter the field.

Texture : Non-uniform, an alternating pattern of white and black or dark-grey; regularly repeated in the case of lines, irregular mottling in the case of open cells.

Band Differences : LAND/SEA - marked.

(ii) Cumulus congestus

Structural Elements.

Nature : Individual congestus cells.

Size : 10-20 km. across longest dimension.

Form : Varied: may be circular, sub-circular or irregular. Edges are sharply defined and shadows cast on side away from the sun.

Brightness : Usually very bright, may be some shadows cast on lower portions of an element if vertical development is marked, hence darker tones occur.

Texture : Little on individual elements which appear uniformly smooth except where shadows are cast.

Organisation of Elements : Commonly found in association with other cumulus subgroups. May occur in lines or open cells, marking locations of locally enhanced vertical development.

Band Differences : LAND/SEA. Bands 6 and 7 show more marked shadows on individual clouds than bands 4 and 5. Shadows cast over land by individual clouds are more marked in bands 6 and 7 than bands 4 and 5.

Cloud Fields.

Size : Variable, usually congestus elements are constituents of large cumuliform fields (containing humilis, mediocris and sometimes cumulonimbus clouds) which may cover extensive areas.

Form : Normally found in association with other cumuliform and cumulonimbiform varieties, being an intermediate form between the less well developed cumulus varieties, and the more advanced development of cumulonimbus. They are, therefore, similarly associated with surface heating patterns.

Brightness : Very bright to bright, depending on the spacing of elements in the cloud field.

Texture : Irregular mottling prevails; when elements are arranged linearly, bands or stripes occur.

Band Differences : LAND/SEA.

(iii) Altocumulus

Structural Elements.

Size : Individual elements difficult to distinguish; generally small - 1km. or less.

Form : Generally irregular, edges may be diffuse with cirrus smudging common.

Brightness : Generally grey; may be white where thin cirrus is above.

Texture : Not distinguishable.

Organisation of Elements : Either irregularly spaced, or found in narrow parallel bands which are often sinuous, and generally perpendicular to the direction of wind flow at the cloud level. There may be 10 or 15 bands in a space of 30 km., with uniform spacing.

Band Differences : LAND/SEA. Band 7 tends to show organisations of elements better than bands 4 and 5, especially where thin cirrus overlies the altocumulus.

Cloud Fields

Size : Irregularly spaced elements may form fairly extensive fields, covering an area with the longest dimension approx. 50km. Parallel bands may be 100 km. or more in length (in the direction parallel to the bands) and the distance across the bands may be 30km.

Form : Fields of altocumulus indicate unstable air in the middle troposphere. Often the fields are closely related to topography, being visible evidence of orographic waves. These are triggered by local orographic lifting. The cloud waves generally lie transverse to the wind direction, and may extend considerable distances downwind, forming extensive fields.

Brightness : Generally grey-white where overlain by cirrus.

Texture : Where elements are irregularly spaced they give a "lumpy" appearance. When in bands, they appear as smooth waves or ripples.

Band Differences : LAND/SEA.

3. STRATIFORM

(i) Stratus

Structural Elements

Nature : Streaks, mottles, bands.

Size : Variable, from small, irregular mottled areas, to extensive streaks or bands which may be 100 km. or more in length, and bands may be 50km. or more wide.

Form : Variable; mottles may be subcircular or irregular in shape, streaks are normally long and thin and bands are often long and broad.

Brightness : Bright, usually white. Occasionally grey if the elements are thin.

Texture : Only slight tonal variations are visible and usually the elements are rather indistinct.

Organisation of Elements : Stratus fields are generally amorphous sheets with little or no internal organisation. They may be comprised of very few elements, or a great number, e.g. a large sheet may contain a few bands or many streaks.

Band Differences : Individual elements are seen more easily in band 7 than the other bands.

Cloud Fields.

Size : May cover a whole frame or more.

Form : The development of stratus fields is a result of cooling in the lower troposphere, and the shape of the fields may be more or less strongly influenced by topography, coast-lines and wind direction, for example, valley or lowland fog, or fog formed over the sea and advected over the coast by an onshore wind.

Brightness : Usually bright; edges of a sheet may show varied tones where the elements become thinner.

Texture : Usually relatively smooth.

Band Differences : Difference of tones enhanced in band 7.

(ii) Layered Stratiform

Structural Elements

Nature : Streaks, mottles, bands.

Size : Variable, from small mottles to long streaks and wide bands.

Form : Mottles may be subcircular or irregular; bands are generally wide and straight with streaks being long and thin, gently curved or straight.

Brightness : Very bright.

Texture : Irregular texture may occur due to the casting of shadows by some elements at higher altitudes.

Organisation of Elements : A variety of elements at different altitudes are characteristic of this cloud type. The elements may include bands and/or mottles of stratus and nimbostratus (where rain is falling) with streaks of altostratus above.

Band Differences : Band 7 provides greater detail of individual elements.

Cloud Fields.

Size : Generally extensive - 100km. or more across, even 1000 km. in length.

Form : Usually frontal in origin; therefore the shapes of the cloud fields are related to synoptic-scale weather development rather than more localised factors, and are characteristically broad, more or less curvilinear bands where fronts are active; broken, discontinuous and/or amorphous patterns where fronts are dissipating.

Brightness : Bright to very bright.

Texture : Irregular, due to changes in thickness and casting of shadows.

Band Differences : Band 7 reveals textural differences more clearly.

(iii) Altostratus

Structural Elements

Nature : Streaks and/or bands.

Size : Generally extensive.

Form : Streaks or bands may be in straight lines or gently curved.

Brightness : Bright.

Texture : Smooth, or fibrous.

Organisation of Elements : Generally form extensive sheets or bands.

Band Differences : Band 7 shows slightly more texture (if present).

Cloud Fields

Size : Very Extensive - may cover a complete frame.

Form : Usually related to synoptic-scale weather factors; a major causation is the slow ascent of extensive layers of air to sufficiently high levels for condensation to occur. This frequently happens along warm and/or occluding frontal planes.

Brightness : Bright, though may show tonal variations due to changes in thickness.

Texture : Fibrous generally.

Band Differences : Emphasis of texture in band 7.

4. STRATOCUMULIFORM

(i) Stratocumulus

Structural Elements

Nature : Mottles, streaks.

Size : Generally small. Mottles are usually 3-5km. across, though they are occasionally outside these limits. Streaks are usually narrow, less than 1 km. across, and may be a few kilometres in length.

Form : Mottles take a wide variety of shapes; they may be irregular, subcircular or circular. Streaks are straight or gently curved.

Brightness : Varies - from dull grey to bright, depending on the depth of the cloud and the sun elevation angle. As the latter increases, the brightness generally increases.

Texture : Streaks are usually smooth. Mottles may show some fine, irregular texture due to tonal variations caused by their uneven upper surfaces.

Organisation of Elements : Groupings of structural elements may be identified at two levels of aggregation. At the first level of aggregation, the formation of more or less closed clusters (consisting of perhaps 10 to 20 mottles or streaks) is common. These primary groupings are then further aggregated to form bands, sheets or scallop shapes, which may extend over large areas.

Band Differences : LAND/SEA; band 7 enables the texture and organisation of the elements to be seen more easily.

Cloud Fields

Size : Extensive - may cover a complete frame, or a number of consecutive frames.

Form : Fields of stratocumulus are associated with large scale subsidence to the level of the tops of the cloud fields under anticyclonic conditions. The cloud elements are formed by lower level convection and etched by turbulent processes. The different spatial organizations and textures so characteristic of this cloud family are not wholly understood at the present time, but are probably due to the interaction of particular synoptic and sub-synoptic scale factors.

Brightness : Medium to bright, depending on cloud thickness, organisation and sun elevation angle. Generally, thicker, more closely spaced fields appear brighter.

Texture : Cloud field textures are numerous - a result of the wide variety of element organisations at two levels of aggregation. They include more or less fine mottlings, scallops, "cauliflower"-like textures of certain closed cellular organisations and ripple-like textures when bands are arranged in rows.

Band Differences : Band 7 is again most useful in discerning textural and organisational characteristics within cloud fields.

5. CIRRIFORM

(i) Cirrus fibratus

Structural Elements

Nature : Streaks or fibres.

Size : Variable in length, from a few kilometres to 50 or 100 kms. Generally narrow in width, being a few kms. at most.

Form : Usually straight or gently curved.

Brightness : Dull grey and translucent; may be brighter, white tones if thicker and opaque.

Texture : Smooth.

Organisation of Elements : Numerous streaks or fibres may be organised into narrow or wide bands, and occasionally enough elements may be present to form an amorphous sheet. Thin streaks or filaments may sometimes be seen lying transverse to the major cloud axes.

Band Differences : LAND/SEA.

Cloud Fields

Size : May be extensive, occurring in diffuse sheets.

Form : Where blown from cumulonimbus towers, fields of cirrus fibratus will be related to the organisation of the towers and the direction of wind flow in the upper troposphere. If related to an advancing frontal system, the cloud field shape will be dependent on synoptic factors.

Brightness : Usually dull and translucent, revealing lower cloud formations, which appear as brighter patches in the cirrus field.

Texture : Commonly fibrous or banded.

Band Differences : LAND/SEA; in band 4, cirrus appears slightly brighter, especially where the cloud field is thicker.

(ii) Cirrus Spissatus

Note:

It ~~is~~ not possible on LANDSAT imagery to identify seperate structural elements and therefore the structural Element-Cloud Fields subdivision is not used.

Nature : Amorphous sheets or bands.

Size : Variable from small patches, to extensive sheets extending over a complete frame or a number of consecutive frames.

Form : In general, the comments applied to cirrus fibratus apply here also. If found chaotically distributed, this may be related to cumulonimbus towers which have now dissipated; here the field will bear some relation to previous cumulonimbus fields.

Brightness : Bright, usually white in appearance.

Texture : Smooth.

Band Differences : Band 7 shows slightly more texture in the cloud field, especially where the cloud may be thinner, and lower cloud layers may become visible.

(iii) Cirrostratus

Structural Elements

Nature : Streaks or bands.

Size : Variable - may be a few or many kilometres in length, but are usually narrow, being only a few kilometres wide.

Form : Straight or gently curged.

Brightness : Medium grey to white;usually opaque.

Texture : Rather smooth.

Organisation of Elements : The streaks or bands are usually closely arranged to form wide sheets or bands, with little or no space between the elements.

Band Differences : Somewhat brighter in band 4 than band 7.

Cloud Fields

Size : Variable, usually extensive.

Form : Usually frontal in origin, forming bands ahead of the surface positions of the frontal planes (behind cirrus fibratus, ahead of altostratus).

Brightness : Usually bright, pale grey to white tones. If thin, may be translucent revealing lower cloud as brighter patches.

Texture : Commonly fibrous, with thin bands or streaks.

Band Differences : Band 4 is generally brighter; band 7 reveals greater textural detail.

(iv) Cirrocumulus

Structural Elements

Nature : Small cells.

Size : 300 metres to 1 kilometre across.

Form : Each cell is circular or oval shaped.

Brightness : Dull grey, translucent.

Texture : Smooth.

Organisation of Elements : Closely spaced cells in an irregularly shaped field. May form bands with diffuse edges.

Band Differences : LAND/SEA; elements appear slightly brighter in band 4 than band 7.

Cloud Fields

Size : Field may be 50 km. or more across.

Form : Generally patches of restricted extent. Sometimes ahead of surface frontal positions in the cirriform zone. A rare cloud type.

Brightness : Dull grey and translucent. Lower cloud forms may be seen as brighter patches through the overlying cirrocumulus.

Texture : The field presents a dappled or rippled texture.

Band Differences : LAND/SEA - band 4 is brighter than band 7.

(v) Condensation Trails

Structural Elements

Nature : Streaks or bands

Size : Individual streaks may be 100 km. or more in length. They are usually very narrow, perhaps 1 or 2 km. wide at most. Bands may be of similar length, but are usually broader, perhaps 5-20 km. wide.

Form : Streaks are usually straight lines with sharp edges, this straightness being their most readily identifiable characteristic. Bands are usually streaks which have been drawn out by wind shear, and their margins are therefore not so sharply defined.

Brightness : Pale to medium grey tones.

Texture : Streaks are smooth; bands may show fibrous or feathery texture.

Organisation of Elements : When numerous trails are present, criss-cross patterns form which appear like irregularly spaced grids.

Band Differences : LAND/SEA; band 4 is slightly brighter.

Cloud Fields

Size : Fields of condensation trails may extend over considerable areas, but there are often extensive gaps between individual elements.

Form : Related to patterns of aircraft movement and wind patterns aloft when conditions are suitable for their formation.

Brightness : Usually dull grey, due to large spaces between individual elements.

Texture : Feathery or wispy appearance if bands are present; if streaks dominate then an irregular grid pattern occurs.

Band Differences : LAND/SEA - band 4 is usually slightly brighter.

V. PROBLEMS

In the First Quarterly Report it was observed that the Landsat 2 MSS coverage of the British Study Region as provided to the Principal Investigator compared badly with initial expectations in two ways. These may be summarized as follows:

(1) The coverage of the Study Region during the first ten Landsat cycles was very fragmentary and incomplete; and

(2) The coverage anticipated from a specific cycle was not known for any occasion in advance.

If anything, the data received for the next five cycles have been even less complete. Indeed, only 9 frames have been received by the time of writing for Landsat Cycles 13-15, covering the period from September 18th-November 10th 1975. It is to be hoped that this does not indicate a trend of diminishing returns.

On the other hand, we have received 39 additional frames for Landsat Cycles 7,8 and 10 bringing our total archive for the period from March 22nd - August 12th, 1975 to 219 from an estimated possible maximum of 560. Consequently, it is hoped that our current holding of 32 frames from an estimated maximum of 280 frames for Landsat Cycles 11-15 may be increased by late arrivals.

It is hoped that the problem of not knowing whether the taperecorder on the satellite is to be switched on for a given pass or not will be overcome for at least one or two future passes by prior arrangement with NASA. This will enable us to make plans for the acquisition of more sophisticated in situ measurements to aid our interpretation of the imagery. Such measurements would include weather radar observations from the Royal Radar Establishment at Malvern, Hereford and Worcester, and cloud droplet size spectra obtained by research aircraft attached to the British Meteorological Office. A formal request that such an arrangement might be made has been lodged by the Principal Investigator with his Technical Monitor.

VI. RECOMMENDATIONS AND CONCLUSIONS

The Landsat Cloud Photointerpretation Key presented in this report should be of immediate interest and use to the meteorological community and other Landsat investigators. However, it will be of significance also to those concerned with the planning of future satellite projects, most of which will almost certainly provide higher resolution data than their current counterparts or precursors. It seems to be accepted generally that resolutions of 1.0 - 2.5 km. are adequate for meteorological satellite operations in the foreseeable future; sensory systems on future polar-orbiting weather satellites like Tiros-N (1.0 km) and on geostationary weather satellites like Meteosat (2.5 km.) will have such capabilities. However, it is likely that other satellite systems under active consideration at the moment may be designed to give data of substantially higher resolution, e.g. MEOS (the geosynchronous Multidisciplinary Earth Observation Satellite presently under consideration by the European Space Agency (ESA)). The MEOS multispectral scanner may well provide data at least comparable with those of Landsat 1 and 2. Although MEOS satellites and others of the same generation (active from 1985 - 2000 A.D.) would have primary tasks to perform in monitoring rapid change on the surface of the Earth itself, they would inevitably provide extremely high resolution observations of the Earth's cloud cover also. It can only be helpful for those concerned with satellite design, and data utilization, in the future, to learn from existing spacecraft what the chief possibilities and problems of accommodating data of higher resolution and/or greater frequency than at present into operational programmes of work might be.

VII. REFERENCES

American Society of Photogrammetry (1975) : "Manual of remote sensing", Volume II, Chapter 14, "Fundamentals of Image Interpretation", American Society of Photogrammetry, Falls Church, Va., pp. 869 - 1072.

Anderson, R.K. et al., (1973) : "The use of satellite pictures in weather analysis and forecasting", W.M.O. Technical Note No.124, World Meteorological Organization, Geneva, 275pp.

Barrett, E.C. (1974) : "Climatology from satellites", Methuen, London, 418 pp.

Barrett, E.C., and Grant, C.K., (1975) : "Mesoscale assessments of cloud and rainfall over the British Isles", ERTS Follow-on Programme Study No.2962A, First Quarterly Report, 28pp.

Conover, J.H. (1962) : "Cloud interpretation from satellite altitudes", Research Note No.81, Air Force Cambridge Research Laboratories, Cambridge, Mass., 55pp.

Conover, J.H. (1963) : "Cloud interpretation from satellite altitudes", Research Note No.81, Supplement 1 Air Force Cambridge Research Laboratories, Cambridge, Mass., 18pp.

Harris, R. and Barrett, E.C., (1975) : "An improved satellite nephanalysis", Meteorological Magazine, 104, pp.9-16.

Hopkins, M.M. (1967) : "An approach to the classification of meteorological satellite data", Journal of Applied Meteorology, 6, pp. 164-78.

Lee, R., and Taggart, C.I., (1969) : "A procedure for satellite cloud photointerpretation, and Appearance of clouds from satellite altitudes", in Satellite Meteorology, Bureau of Meteorology, Melbourne, Australia, pp.17(e) - (f).