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The Use of Satellite Data for Monitoring Oil Spills in Canada

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THE USE OF SATELLITE DATA FOR MONITORING OIL SPILLS IN CANADA

by

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ABSTRACT

The use of satellite data for the surveillance and monitoring of oil spills is examined. The sensors aboard the Landsat and NOAA series (TIROS-N and GOES) satellites are described. In addition, a review of future satellite systems is presented. The various operational parameters including areal coverage, spatial resolution and spectral response are presented and used to analyze the applicability of the satellites to oil spill detection. Methods for the acquisition and use of these satellite data in a spill emergency are detailed.

It is concluded that current satellite systems are not configured to provide operational oil spill monitoring. Orbits, sensor parameters and coincidence of timing with cloud conditions are such that the probability of successfully imaging an oil spill at Canadian latitudes is low. If the parameters are such that spill detection is feasible, it may be possible to generate near-real time information. It is recommended that tests, both over real and experimental spills, be conducted to provide information and experience on the use of satellite data for oil spill detection.

RÉSUMÉ

Le but du présent document est d'examiner la possibilité d'utiliser les données obtenues par satellite pour la surveillance et le contrôle des déversements de pétrole. Il est question notamment des capteurs satelliportés Landsat et NOAA (TIROS-N et GOES) et des futurs systèmes à satellites. La possibilité de recourir aux satellites pour détecter des déversements de pétrole est analysée en fonction des divers paramètres des satellites comme leur aire de couverture, leur résolution spatiale et leur réponse spectrale. Enfin, les méthodes de saisie et d'utilisation des données transmises par satellite en cas de déversement de pétrole, sont décrites en détail.

On en arrive à la conclusion que les systèmes à satellites actuels ne conviennent pas pour surveiller des déversements de pétrole. Les orbites, les paramètres des capteurs et le masquage par la nébulosité diminuent la probabilité d'obtenir de bonnes images d'un déversement de pétrole aux latitudes canadiennes. Si les caractéristiques d'un satellite se prêtaient à la télédétection d'un déversement, il serait peut-être possible d'obtenir des informations presque en temps réel. On recommande donc de réaliser des essais à l'occasion de déversements accidentels et provoqués afin d'acquérir de l'expérience dans ce domaine.

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1 INTRODUCTION

In the event of a marine oil spill, the prerequisite to any corrective action is the acquisition of pertinent information about the spill (time, location, quantity and type of oil, etc.). Uncertainty on the location of the spill is acknowledged[1] to be the most critical detriment to responsive action. The KURDISTAN incident (Fingas et al., 1979b) demonstrated the problems and confusion that surround an unlocated oil spill.

Remote sensing from aircraft and satellite platforms offers a practical, effective mechanism for search and detection of oil spills. Airborne sensing is a very flexible and direct approach to this problem. A wide range of aircraft and sensor systems may be configured, and flight parameters may be chosen to suit a specific situation. Airborne data can provide information pertinent to detection and identification of oil, its physical dimensions, and basic categories of type (O'Neil et al., 1980a). The acquisition of useful oil spill information from aircraft is limited, however, by access time to remote spills, flying constraints of weather, and maximum available flight duration.

Sensing of oil spills by satellite presents a different set of opportunities and limits, and is the topic addressed herein. In this document, the state of the art in satellite remote sensing of marine oil spills (using the visible and infrared (IR) bands) is reviewed, and additional research on the IXTOC oil well blowout, the KURDISTAN spill incident, and the Scott Inlet oil seep is presented from Landsat imagery. Reception, preprocessing, formatting and analysis possibilities currently available for satellite imagery, and potential for new systems in the near future are investigated; detailed recommendations are made for prearrangements and procedures to follow for an oil spill emergency, as analyzed from satellite data. Finally, estimates of time and costs, associated with the scenarios proposed, offer a realistic outlook on the value of this information source.

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1 Ad Hoc Committee on Surveillance and Monitoring of Oil Spills Meeting, 21/1/82, Ottawa.

2 SURVEILLANCE OF OIL SPILLS FROM SATELLITES

2.1 Oil in the Marine Environment

As a target for remote sensing devices, an oil slick can present one of a wide variety of semblances. The nature of the oil and the environmental conditions on-site dictate the configuration of the oil slick and thus its spectral and radiometric properties. Oils and their derivatives can endure and be significant in the marine environment; they may sometimes be detected and measured easily using remote sensing devices. If an oil is emulsified with water, the slick becomes much more reflective in the visible and near infrared (VNIR) bands, a definite aid to detection. In many cases, however, the composition and characteristics of the oil are such that the oil offers to VNIR sensors a target even darker than typical water targets.

The interaction of an oil slick with its environment also influences its visibility to remote sensors. As the slick weathers, chemical and physical changes in the oil can produce dramatic alterations in the oil's appearance. Dissolution and/or evaporation of certain oil fractions, for instance, can reduce an extensive and highly visible slick to one which is less cohesive or perhaps submerged, and thus less detectable. An ice environment can partly or completely hide, or at least disguise, an oil slick from the view of a remote sensing device.

As a slick spreads and thins, its appearance changes. Radiometric properties are altered due to the reflectivity of different oil thicknesses and the oil layer's ability to transmit scattered light from the water below. In the thermal infrared (TIR) régime, emittance changes with oil thickness resulting in the apparent contrast between oil and water. Thin-film light interference phenomena further complicate the radiometric characterization of oil slicks. When an oil slick starts to break up, the non-contiguous oil surface presents mixed water and oil spectral signatures to an observer. This is of particular concern with satelliteborne sensors which suffer from inflexibility and poor spatial resolution and therefore from the "mixed pixel syndrome". (The pixel is akin to a "dot" on a photographic picture and is the smallest unit of resolution on an image.)

In summary, a simple definition of the visibility of oil slicks is prevented by the wealth of parameters that influence remote sensing detection and measurement of oil slicks in the visible and IR spectral regions. It is possible, however, to define general guidelines and to draw upon the experience provided by a few satellite-recorded oil spills.

Fingas et al. (1979a) offer a comprehensive review of marine oil spill characteristics and the methodologies available for cleanup.

2.2 Current Satellite Systems

The Landsat series of satellites is the first of the quasi-operational earth resource satellites. At the time of writing, these are still unique in this mandate. Several other satellites (Television and Infrared Observational Satellites/National Oceanic and Atmospheric Administration (TIROS-N/NOAA), and Geostationary Operational Environmental Satellite (GOES) series) are mentioned briefly. Although they are classified as meteorological satellites, they have previously been used to image oil slicks and could possibly be used in future.

2.2.1 Landsat[2].

Historical review. Three Landsat satellites have been launched to date by the National Aeronautics and Space Administration (NASA), U.S.A. The first was originally called Earth Resources Technology Satellite (ERTS) and is now called Landsat, to indicate that the primary areas of application are land-based resources. Table 1 lists the launch and retirement history for Landsat satellites 1, 2 and 3. All three have greatly exceeded the original design lifetime of 1 year per satellite. Currently, only Landsat 3 is functioning, albeit with some technical problems.

The Landsat satellite systems are built to provide high-resolution, quantitative and multispectral imagery of the Earth's surface. These data are also repetitive, synoptic and provide global coverage. Although Landsat was identified originally as a developmental engineering tool, many users of Landsat data have come to rely on these systems for operational or near-operational activities. The U.S. government has recognized that the research label for Landsat is no longer completely valid; consequently, the management of these systems is being reconfigured under more operations-oriented agencies.

Orbital characteristics. Each Landsat satellite follows a circular, near-polar orbit, which results in constant-scale imagery, oriented approximately north-south (along-track). The orbits are sun-synchronous and in westward precession, so that constant local (solar) time of overpass is maintained for any one latitude on all days. One complete orbit

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2 Technical details on Landsat are summarized from NASA (1976), USGS (1980-1982), and from information provided by the User Assistance and Marketing Unit of the Canada Centre for Remote Sensing.

of the earth takes 103 minutes; there are 14 such orbits per day, providing global coverage (excluding the poles) every 18 days. Each Landsat follows the same orbital path; however, whenever two are functioning at the same time (see Table 1), they are phased 9 days apart so that coverage of a point on the Earth's surface is repeated every 9 days.

TABLE 1 TIME SCALE OF EARTH RESOURCE SATELLITES (from Laurer, 1982)

Historical Overview		
Landsat 1	launched:	23/07/72
	retired:	06/01/78
Landsat 2	launched:	22/01/75
	inactivated:	05/11/79
	reactivated:	06/06/80
	retired:	25/02/82
Landsat 3	launched:	05/03/78
	inactivated:	/12/80
	reactivated:	/04/81
Future Systems		
Landsat D (USA)	launch:	30/07/82
Landsat D' (USA)	launch:	after failure of "D"
SPOT (France)	launch:	/84
MOS (Japan)	launch:	/85

As the orbits converge with increasing distance from the equator (north and south), sidelap of orbits from successive days also increases. Thus, in addition to the normal coverage repetition due to one or two active satellites, a latitude factor will further increase the frequency of imaging. Table 2 describes the relationship between latitude and image sidelap. For example, Lancaster Sound, which is a part of the Northwest Passage, is located at approximately 74°N latitude. Landsat 3 will pass over a particular spot in Lancaster Sound on 3 consecutive days; after 15 days' absence, it will provide 3 more days of coverage, etc.

EMR (1979) have published an index map which presents the orbital ground tracks for Landsats 1, 2 and 3. The orbits or paths are numbered from 1 (just east of

TABLE 2 LANDSAT SCENE SIDELAP AS A FUNCTION OF LATITUDE (ADAPTED FROM ORIGINAL TABLE IN NASA, 1976)

Latitude (Degrees)	Image Sidelap (Percent)	Redundancy Factor[a]
0 - 55	14 - 50	1
55 - 67	50 - 67	2
67 - 72	67 - 75	3
72 - 74	75 - 80	4
74 - 76	80 - 85	5
76 - 82	85	6

[a] Number of adjoining ground tracks which provide coverage for a given location.

St. John's, Newfoundland) to 251, with path number 76 just touching the northernmost tip of the Yukon Territories. These paths are the descending (north to south) orbits on the sunlit side of the earth, and are followed as orbit adjustments permit. During the lifetime of any one Landsat satellite, across-track imagery drift is constrained to 37 km.

Sensor description - RBV. On Landsats 1 and 2, three return-beam vidicon (RBV) cameras recorded high-resolution multispectral scenes of 185 km each side. These instruments have been described in detail in NASA (1976), but will not be dealt with here since they are inoperative.

Landsat 3 carries a two-camera RBV system in which the cameras provide side-by-side (across-track) images of 98 km on a side; the marginal sidelap results in a total imaged swath width of 183 km. Both RBVs have a panchromatic sensitivity from 505 to 750 nm (yellow to near IR). Highlight irradiance is 2.013 mW/cm^2/sr, with a peak signal/rms noise of 33 dB. Spatial resolution on the Earth's surface is approximately 40 m.

Sensor description - MSS. The multispectral scanner (MSS) on each of Landsats 1, 2 and 3 would generate a continuous swath of multispectral imagery at high resolution. On Landsats 1 and 2, a four-channel MSS recorded reflected radiation in the VNIR portions of the spectrum: band 4, 0.5-0.6 μm (green); band 5, 0.6-0.7 μm (red); band 6, 0.7-0.8 μm (IR); band 7, 0.8-1.1 μm (IR). Landsat 3 had an additional TIR (Thermal Infrared) band (10.4-12.6 μm) which however became inoperative soon after launch.

The swath width (or field of view (FOV)) of the MSS is 185 km across-track; the continuous imagery is usually broken into lengths of 185 km along-track to produce (near) square images. The footprint of the instantaneous field of view (IFOV) on the Earth's surface, known as a pixel, is 57 by 79 m.

On-board calibration sources permit precise radiometric calibration of the multispectral data. The MSS analogue signal is digitized on-board the satellite into a 6-bit (0 to 63) range which represents radiance values (specific to each Landsat satellite, the MSS band and the processing options chosen by the data user). In Table 3 the radiometric scale is presented for Landsat 3 MSS bands, as offered by Canadian processing options. The mean level of noise is approximately one digital level on a scale of 64. Details on the radiometric correction and calibration for Landsat MSS digital scenes processed in Canada are described by Ahern and Murphy (1978). Format and specifications of the digital scenes on computer-compatible tapes (CCTs) are presented by Strome et al. (1975) and Murphy (1981).

TABLE 3 LANDSAT 3 RADIOMETRIC SENSITIVITY SCALES (AS PRESCRIBED BY CANADIAN CCT PREPROCESSING OPTIONS) (from Ahern and Murphy, 1978)

MSS Band	8-Bit Digital Value	Radiance Equivalent ($mW/cm^2/sr$)	
		Option "2"	Option "3"
4	0	0.04	0.00
	255	2.50	2.50
5	0	0.03	0.00
	255	2.00	2.00
6	0	0.03	0.00
	255	1.65	1.75
7	0	0.03	0.00
	255	4.50	4.00

For MSS bands 4 and 5, there is an alternate sensitivity, called "high-gain" mode, which is ground-commanded. When this option is activated, a 3X amplification is applied to the detected signal before analogue-to-digital conversion. Thus, the 6-bit digital scale now represents the lowest third of the original range of radiance that would have been recorded in low-gain mode. The result of this signal amplification is a 3X improvement in radiometric resolution of dark targets. In addition, the saturation level is reduced by a factor of three. The significance of using high-gain MSS data in the Canadian environment is discussed by Alfoldi et al. (1978).

Data telemetry and recording. Both the RBV and the MSS data are downlinked to ground stations in the line of sight of the satellite. The telemetry of these data normally is simultaneous via two S-band links. All ancillary and navigational data, as well as the video signal, are recorded onto magnetic tape.

In Canada, the primary ground station is located near Prince Albert, Saskatchewan, and is referred to as the "Prince Albert Satellite Station" (PASS). A secondary ground station, just outside St. John's, Newfoundland, is called "Shoe Cove Satellite Station" (SCSS). Both stations are operated by the Canada Centre for Remote Sensing (CCRS) of the Department of Energy, Mines and Resources. The reception circles of these two stations for Landsats 1, 2 and 3 are indicated on the map published by EMR (1979). Current expectations are that SCSS will be closed down imminently, and that a new antenna will be positioned more centrally (east of PASS), to cover most Canadian land masses from a single location.

Prediction tables for Landsat 3 overpasses of Canadian territories have been prepared for 1982 and 1983, and are presented in Tables 4 and 5, respectively. The track numbers correspond to the path or orbit numbering in orbital path maps published by Energy, Mines and Resources Canada (EMR, 1979). With the orbit map and the prediction tables, the dates of Landsat coverage of any point in Canada or in adjacent water bodies can be determined.

Also pertinent to Canadian coverage are the three American Landsat receiving stations located in Fairbanks, Alaska; Goldstone, California; and Greenbelt, Maryland. Their respective reception coverages are shown in Figure 1 (published by the EROS Data Center, U.S.A.), along with reception circles for all other Landsat ground stations around the world. The Goldstone station offers some coverage of the Pacific Ocean near the British Columbia coast; Fairbanks gives extensive coverage of the northern Pacific Ocean and all of the western (Canadian) Arctic; and Greenbelt provides access to the Atlantic provinces and the nearby Atlantic Ocean. The redundant coverage of U.S. and Canadian stations is an additional ensurance of data reception if technical or logistic problems prevent suitable data recording at any ground station.

Processing and data products. RBV image products are available primarily in photographic form. The original videotape recording is displayed and exposed on black-

TABLE 4 LANDSAT 3 - TIMETABLE FOR 1982

Day	7	8	9	10	11	12	13	14	15	16	17	18	1	2	3	4	5	6
Track Nos.	17	18	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	35	36	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	53	54	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
	71	72	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	250	251	73	74	75	76	77	78	79	80	81	82	83	84	85	247	248	249
Cycle								Day/Month										
78			1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	10/1	11/1	12/1	13/1	14/1	15/1	16/1
79	17/1	18/1	19/1	20/1	21/1	22/1	23/1	24/1	25/1	26/1	27/1	28/1	29/1	30/1	31/1	1/2	2/2	3/2
80	4/2	5/2	6/2	7/2	8/2	9/2	10/2	11/2	12/2	13/2	14/2	15/2	16/2	17/2	18/2	19/2	20/2	21/2
81	22/2	23/2	24/2	25/2	26/2	27/2	28/2	1/3	2/3	3/3	4/3	5/3	6/3	7/3	8/3	9/3	10/3	11/3
82	12/3	13/3	14/3	15/3	16/3	17/3	18/3	19/3	20/3	21/3	22/3	23/3	24/3	25/3	26/3	27/3	28/3	29/3
83	30/3	31/3	1/4	2/4	3/4	4/4	5/4	6/4	7/4	8/4	9/4	10/4	11/4	12/4	13/4	14/4	15/4	16/4
84	17/4	18/4	19/4	20/4	21/4	22/4	23/4	24/4	25/4	26/4	27/4	28/4	29/4	30/4	1/5	2/5	3/5	4/5
85	5/5	6/5	7/5	8/5	9/5	10/5	11/5	12/5	13/5	14/5	15/5	16/5	17/5	18/5	19/5	20/5	21/5	22/5
86	23/5	24/5	25/5	26/5	27/5	28/5	29/5	30/5	31/5	1/6	2/6	3/6	4/6	5/6	6/6	7/6	8/6	9/6
87	10/6	11/6	12/6	13/6	14/6	15/6	16/6	17/6	18/6	19/6	20/6	21/6	22/6	23/6	24/6	25/6	26/6	27/6
88	28/6	29/6	30/6	1/7	2/7	3/7	4/7	5/7	6/7	7/7	8/7	9/7	10/7	11/7	12/7	13/7	14/7	15/7
89	16/7	17/7	18/7	19/7	20/7	21/7	22/7	23/7	24/7	25/7	26/7	27/7	28/7	29/7	30/7	31/7	1/8	2/8
90	3/8	4/8	5/8	6/8	7/8	8/8	9/8	10/8	11/8	12/8	13/8	14/8	15/8	16/8	17/8	18/8	19/8	20/8
91	21/8	22/8	23/8	24/8	25/8	26/8	27/8	28/8	29/8	30/8	31/8	1/9	2/9	3/9	4/9	5/9	6/9	7/9
92	8/9	9/9	10/9	11/9	12/9	13/9	14/9	15/9	16/9	17/9	18/9	19/9	20/9	21/9	22/9	23/9	24/9	25/9
93	26/9	27/9	28/9	29/9	30/9	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	10/10	11/10	12/10	13/10
94	14/10	15/10	16/10	17/10	18/10	19/10	20/10	21/10	22/10	23/10	24/10	25/10	26/10	27/10	28/10	29/10	30/10	31/10
95	1/11	2/11	3/11	4/11	5/11	6/11	7/11	8/11	9/11	10/11	11/11	12/11	13/11	14/11	15/11	16/11	17/11	18/11
96	19/11	20/11	21/11	22/11	23/11	24/11	25/11	26/11	27/11	28/11	29/11	30/11	1/12	2/12	3/12	4/12	5/12	6/12
97	7/12	8/12	9/12	10/12	11/12	12/12	13/12	14/12	15/12	16/12	17/12	18/12	19/12	20/12	21/12	22/12	23/12	24/12
98	25/12	26/12	27/12	28/12	29/12	30/12	31/12											

TABLE 5 LANDSAT 3 - TIMETABLE FOR 1983

Day	7	8	9	10	11	12	13	14	15	16	17	18	1	2	3	4	5	6
Track Nos.	17	18	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	35	36	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	53	54	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
	71	72	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	250	251	73	74	75	76	77	78	79	80	81	82	83	84	85	247	248	249
Cycle								Day/Month										
98								1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	10/1	11/1
99	12/1	13/1	14/1	15/1	16/1	17/1	18/1	19/1	20/1	21/1	22/1	23/1	24/1	25/1	26/1	27/1	28/1	29/1
100	30/1	31/1	1/2	2/2	3/2	4/2	5/2	6/2	7/2	8/2	9/2	10/2	11/2	12/2	13/2	14/2	15/2	16/2
101	17/2	18/2	19/2	20/2	21/2	22/2	23/2	24/2	25/2	26/2	27/2	28/2	1/3	2/3	3/3	4/3	5/3	6/3
102	7/3	8/3	9/3	10/3	11/3	12/3	13/3	14/3	15/3	16/3	17/3	18/3	19/3	20/3	21/3	22/3	23/3	24/3
103	25/3	26/3	27/3	28/3	29/3	30/3	31/3	1/4	2/4	3/4	4/4	5/4	6/4	7/4	8/4	9/4	10/4	11/4
104	12/4	13/4	14/4	15/4	16/4	17/4	18/4	19/4	20/4	21/4	22/4	23/4	24/4	25/4	26/4	27/4	28/4	29/4
105	30/4	1/5	2/5	3/5	4/5	5/5	6/5	7/5	8/5	9/5	10/5	11/5	12/5	13/5	14/5	15/5	16/5	17/5
106	18/5	19/5	20/5	21/5	22/5	23/5	24/5	25/5	26/5	27/5	28/5	29/5	30/5	31/5	1/6	2/6	3/6	4/6
107	5/6	6/6	7/6	8/6	9/6	10/6	11/6	12/6	13/6	14/6	15/6	16/6	17/6	18/6	19/6	20/6	21/6	22/6
108	23/6	24/6	25/6	26/6	27/6	28/6	29/6	30/6	1/7	2/7	3/7	4/7	5/7	6/7	7/7	8/7	9/7	10/7
109	11/7	12/7	13/7	14/7	15/7	16/7	17/7	18/7	19/7	20/7	21/7	22/7	23/7	24/7	25/7	26/7	27/7	28/7
110	29/7	30/7	31/7	1/8	2/8	3/8	4/8	5/8	6/8	7/8	8/8	9/8	10/8	11/8	12/8	13/8	14/8	15/8
111	16/8	17/8	18/8	19/8	20/8	21/8	22/8	23/8	24/8	25/8	26/8	27/8	28/8	29/8	30/8	31/8	1/9	2/9
112	3/9	4/9	5/9	6/9	7/9	8/9	9/9	10/9	11/9	12/9	13/9	14/9	15/9	16/9	17/9	18/9	19/9	20/9
113	21/9	22/9	23/9	24/9	25/9	26/9	27/9	28/9	29/9	30/9	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10
114	9/10	10/10	11/10	12/10	13/10	14/10	15/10	16/10	17/10	18/10	19/10	20/10	21/10	22/10	23/10	24/10	25/10	26/10
115	27/10	28/10	29/10	30/10	31/10	1/11	2/11	3/11	4/11	5/11	6/11	7/11	8/11	9/11	10/11	11/11	12/11	13/11
116	14/11	15/11	16/11	17/11	18/11	19/11	20/11	21/11	22/11	23/11	24/11	25/11	26/11	27/11	28/11	29/11	30/11	1/12
117	2/12	3/12	4/12	5/12	6/12	7/12	8/12	9/12	10/12	11/12	12/12	13/12	14/12	15/12	16/12	17/12	18/12	19/12
118	20/12	21/12	22/12	23/12	24/12	25/12	26/12	27/12	28/12	29/12	30/12	31/12						

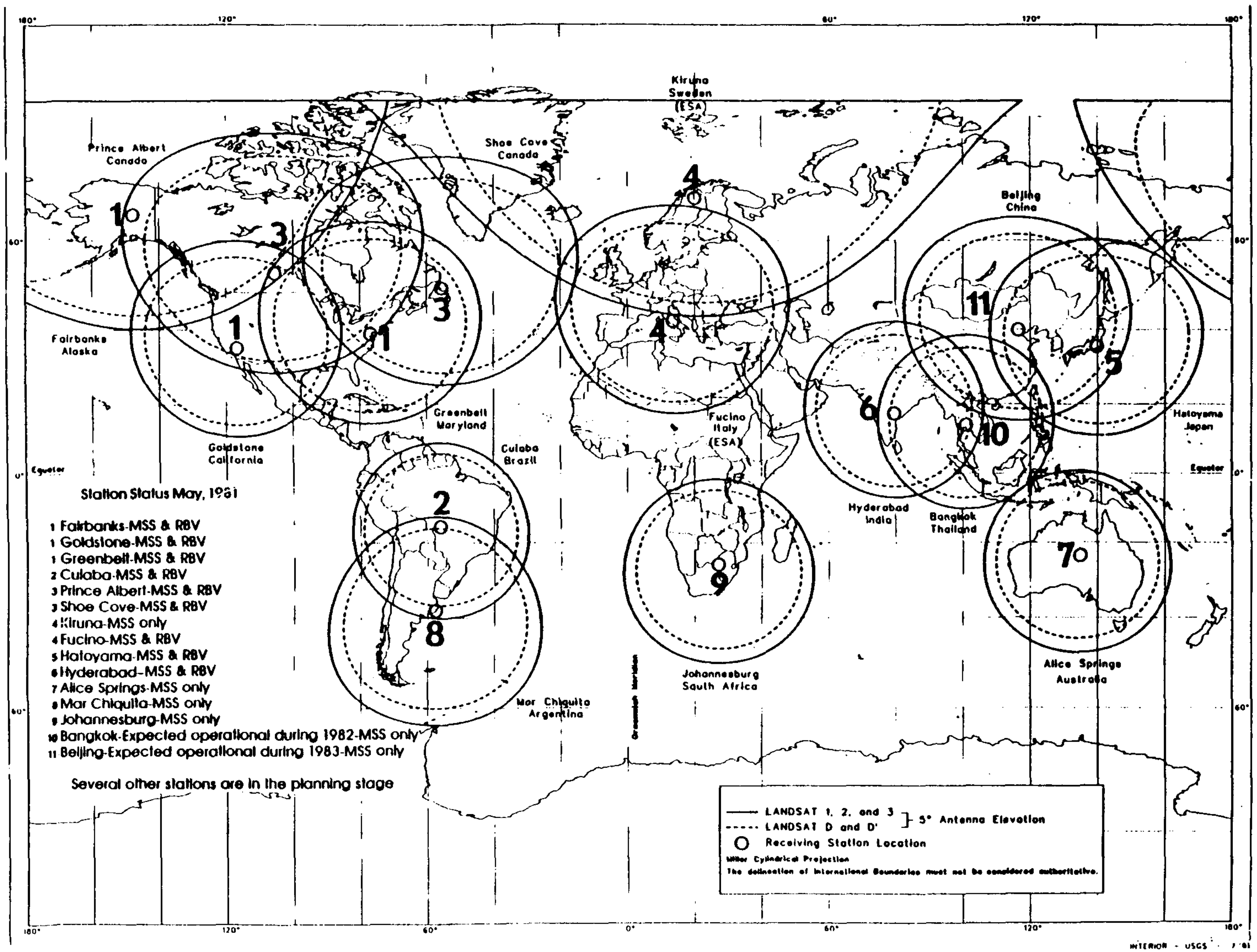

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FIGURE 1 LANDSAT RECEIVING STATION COVERAGE (WORLDWIDE) and-white 70 mm film. Copies and enlargements can be made thereafter. Landsat 3 RBV scenes are received only at PASS, not at SCSS. In Canada, the only method employed so far to produce digital RBV images is the scanning of a photographic image by a microdensitometer. This method limits both the spatial and radiometric resolution of the final digital image to that of the photographic resolutions, with further degradation due to the analogue-to-digital process.

MSS scenes are received and stored originally in digital format, retaining maximum data fidelity. From the high-density digital tapes (HDDTs) which are the original recording medium, both photographic and digital products are produced at PASS. (Only PASS production features are described here, for SCSS will probably be inoperative for Landsat data by April.) A full range of photographic products is produced, including transparencies and paper copies: 70 mm, 9-in and larger copies; black-and-white and colour composites.

Digital data are produced in the form of Computer-Compatible Tapes (CCTs), raw or "system-corrected". System-corrected scenes have radiometric and some basic geometric corrections applied. Digital data received since 1 March 1978 are archived at PASS. In addition, PASS communications systems include: telephone, Telex, TWX and facsimile transmission.

2.2.2 **NOAA Satellite Series**[3]. A series of 27 operational environmental satellites providing meteorological, hydrologic and oceanographic data have been put into orbit since the 1960s, when the Applications Technology Satellites of NASA were first introduced (Table 6). These satellites are operated by the National Environmental Satellite Service (NESS) of NOAA. Currently there are two distinct series, with two satellites each, operating at any one time (i.e. four in all)[4] to ensure timely and complete coverage. These are the TIROS-N/NOAA and the GOES.

The data from these satellites are used on an operational basis in Canada (and North America) for meteorological and hydrologic applications (particularly weather forecasting and snow mapping). They have only briefly been referred to in the literature

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3 This section contains much unpublished material, provided through personal communication with B. Goodison and P. King of AES, Downsview, Ontario; J. Bulas of AES, Edmonton, Alberta; and A. Collins of CCRS, Ottawa, Ontario.

4 TIROS-N/NOAA was reduced to one satellite in March 1982. More detail can be found in the following paragraphs.

TABLE 6 NOAA/NESS SATELLITE SERIES

Satellites	Dates of Operation
TIROS	1960 - 1966
ESSA	1966 - 1980
ITOS/NOAA	1970 - 1978
SMS/GOES	1974 -
TIROS-N (NOAA)	1978 -

on oil spill detection and monitoring (Hayes, 1980; Dawe et al., 1981). Study of the IXTOC spill in Campeche Bay indicated promising results for the detection of large, widespread spills when alignment of target, satellite viewing angle and illumination are appropriate. The KURDISTAN study, however, did not offer conclusive results; the spill size was very small, relative to satellite spatial resolution, and location of the spill was also questionable.

The limited number of applications to oil spill detection and monitoring would suggest that more study of such phenomena from these satellites should be initiated, but realistically keeping in mind the limitations (particularly spatial) of these satellites. The characteristics of these satellites have evolved from the earlier prototypes and are described in the following sections.

TIROS-N/NOAA systems. The TIROS-N series became operational with the launch of TIROS-N in October 1978 and its twin, NOAA-6, in June 1979 (Table 6). The series has been operated in satellite pairs to provide complete and frequent coverage from their sun-synchronous orbits. These satellites have a life expectancy of about 2 years; replacements are launched when one of the satellites stops functioning.

NOAA-7 has replaced TIROS-N as of June 1981; both NOAA-6 and 7 have been recording data after that date. At the time of this writing, however, NOAA/NESS programs have been reduced, thereby changing this scenario drastically (NOAA/NESS, 1982). In future, only one satellite from this series will be operational at any one time, thus reducing the synoptic overview and revisit frequency offered by multiple satellites. Questions have also been raised on whether the back-up satellite will be in orbit or not; gaps will occur in coverage if a launch is required before the back-up is in place and functioning. More recently (i.e. subsequent to the announcement), NOAA-6 has experienced

TABLE 7 TIROS-N/NOAA CHARACTERISTICS

Nominal Altitude	835 ± 18 km
Orbit	Near-polar, sun-synchronous
Passes Tracked	five per station, per satellite in Canada
Swath Width	2 700 km (AVHRR)
Sensors/Systems	AVHRR TOVS DCS SEM

Instrumentation on board includes four main systems:

1. AVHRR, which provides visible and IR imagery for mapping of clouds and the surface, surface water delineation, and determining sea surface temperature.

2. TIROS Operational Vertical Sounders (TOVS), comprising three sensors, sensitive to emissions in different parts of the spectrum:
   a. High-resolution Infrared Radiation Scanner (HIRS/2);
   b. Stratospheric Sounding Unit (SSU);
   c. Microwave Sounding Unit (MSU).

3. ARGOS Data-collection System (DCS) is a platform locator, and receives, processes and stores data from various platforms.

4. Space Environment Monitor (SEM) continuously measures solar proton flux, alpha particle and electron flux density, and total particulate energy disposition into the Earth's upper atmosphere.

failures such that the Advanced, Very High Resolution Radiometer (AVHRR; see Table 7) data are not available; coverage is thereby reduced to that of NOAA-7.

Data telemetry and recording. Primary stations in the U.S.A. (satellite command and data acquisition) for NOAA satellites are located at Fairbanks, Alaska and Wallops Station, Virginia. These sites can transmit commands to the satellite, and receive and record environmental and engineering data from the satellite.

In Canada, NOAA data are received directly from the satellite by the Department of Energy, Mines and Resources at ground receiving stations in Shoe Cove, Newfoundland and Prince Albert, Saskatchewan, and by the Atmospheric Environment Service (AES) of Environment Canada at Downsview (Toronto), Ontario and Edmonton, Alberta.

Currently, these agencies archive digital NOAA data for only 3 to 7 days, and printed images for approximately 2 years. The data at Shoe Cove are recorded onto both magnetic tape and photographic film, and may be viewed in near-real time; at PASS, however, data are recorded directly on film; they are recorded on tape only as an interim measure until they can be recorded on film. A similar approach is taken at the AES Satellite Data Labs in Toronto and in Edmonton. These two locations track, receive and record more passes per day than either PASS or SCSS. For each AES station, data can be recorded for nine to ten passes (four to five per NOAA satellite) per day. Six to eight images can be recorded per hour, and all five channels can be recorded if special arrangements are made; however, because of the volume of data and the data rate, one AES station usually records only three of the five channels at any one time. The full contact sources for these stations and agencies are listed in Appendix B.

Sensor description - AVHRR. The sensor on board TIROS-N/NOAA of primary interest to oil spill studies is the AVHRR which, on current NOAA satellites, is a five-channel sensor:

Channel	Spectral Range (μm)
1	0.58 - 0.68
2	0.73 - 1.00
3	10.30 - 11.30
4	3.55 - 3.93
5	11.50 - 12.50

(TIR resolution is about 1.5°C absolute, and 0.5° relative.)

The VNIR channels provide data during daylight hours only because they record solar-reflected radiation. The TIR channels can record night and day, for they sense emitted radiation. Peak surface emissions with less ambient noise can be observed during nighttime passes.

The radiometric data from the AVHRR are 10-bit resolution digital data which are processed on board the spacecraft to produce four data-transmission types. These AVHRR data are:

a) high-resolution picture transmission (HRPT), 1 km resolution;

b) automatic picture transmission (APT), 4 km resolution;

c) global area coverage (GAC), 4 km resolution;

d) local area coverage (LAC), 1 km resolution.

Of these data transmissions, HRPT output is the most relevant to disaster monitoring because of its spatial resolution, data flow rate and wide coverage. The 10-bit data are transmitted from the satellite in real time by an S-band transmitter and are received at Canadian ground stations with a reduction to 8-bit data.

Data processing and products. Currently, HRPT data are received at Canadian stations in digital format, stored on CCTs, and produced as hard copy, 10-in by 10-in imagery. The digital data are full-resolution, 2 048 pixels by 2 600 lines. Although all five channels can be received, operational limitations restrict recording to three channels.

The recorded data are integers in the range of 0 to 255, and can be represented as grey levels. A response function is provided for the TIR bands (3 and 4) (Figure 2). The digital data, therefore, can be used to produce an analogue image which reduces the data in a step-wedge fashion to 17 levels of grey. The TIR data represent brightness temperature; however, the relationship between temperature and grey shade is not linear. Therefore, calibration curves are used to relate temperature and integer values or grey shade (Figure 3). It is important to note that for the TIR data to be useful the thermal differences between oil and water must be greater than the system noise; this thermal difference must extend over a very large area because of the 1 km resolution of the AVHRR sensor.

Prior to producing the imagery, a computer algorithm is applied to the data to accentuate a certain range of data (e.g. AES is interested in a range of cloud brightness and temperatures for meteorological applications). This is referred to as "contrast-stretching". The algorithm may be altered to enhance any subset of the total radiance range - for instance the temperature range at which the ocean/oil contrast is prevalent - or in terms of visible wavelengths, on the sunglint patterns on the water surface, rather than clouds. Data to be used in oil spill studies should be analyzed in digital form to maintain high spatial and radiometric resolution and to permit maximum data manipulation.

The hard-copy imagery, produced as a 10-in (25.4 cm) photograph, covers a ground area of 2 700 by 3 300 km for a full frame. Imagery of portions of this full frame is produced as two 4-in by 8-in (10 cm x 20 cm) enlargements; however, resolution is still only 1 km. Images are relayed via facsimile to main weather centres (i.e. from Toronto, Ontario, these images are relayed to Halifax, Nova Scotia; Montreal, Quebec; and Winnipeg, Manitoba).

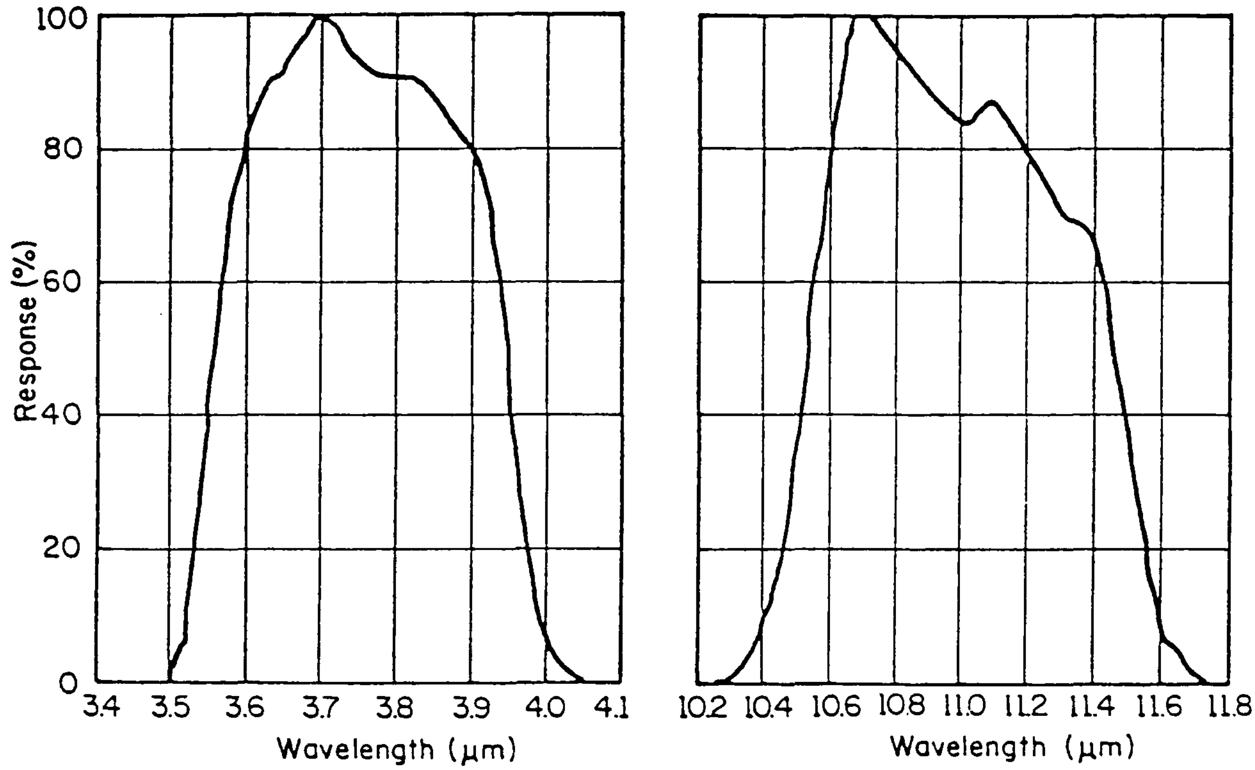


FIGURE 2 RELATIVE SPECTRAL RESPONSE FUNCTIONS (PERCENT) FOR CHANNELS 3 (LEFT) AND 4 (RIGHT) OF THE NOAA-6 SATELLITE

2.2.3 GOES.

Historical review. The GOES satellites have evolved from the series of Applications Technology Satellites (ATS). The first two of these were entitled Synchronous Meteorological Satellites (SMS), and a third was called GOES, which became the current name for this series. The first GOES (as SMS) was launched to support the Global Atmospheric Research Program (GARP), Atlantic Tropical Experiment (GATE), and located above the equator at 45°W; after that project, however, it was moved to 75°W to provide better coverage of the Eastern Seaboard and Atlantic Ocean. This satellite location has been retained as GOES-EAST. A second satellite was launched and moved into a position above the equator at 135°W (GOES-WEST) to provide coverage over the Pacific and Western Seaboard. (As a readily available replacement, a third satellite is maintained in orbit at 105°W so that it can be moved over to either GOES-EAST or -WEST in the event of satellite failure at one of these locations.)

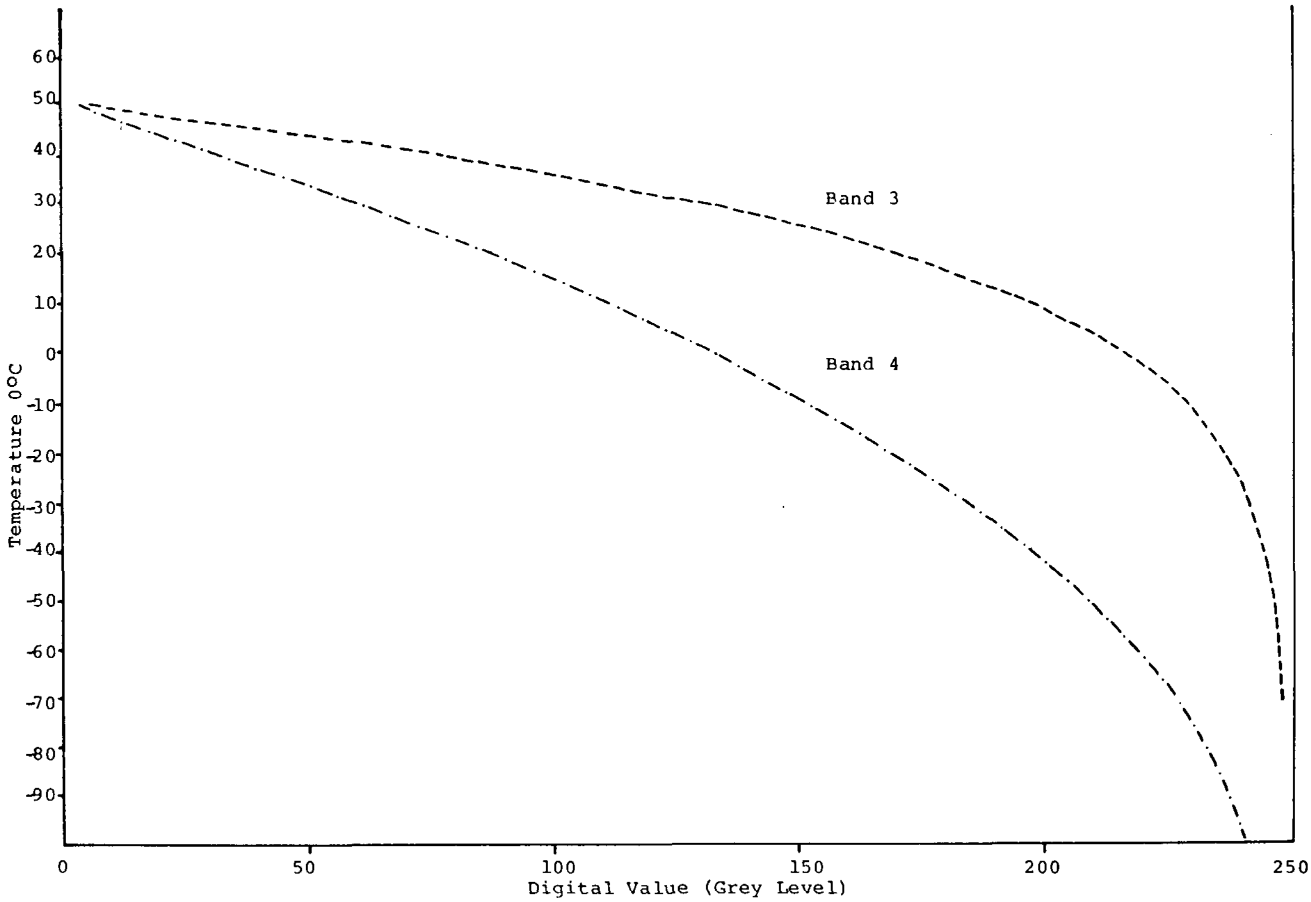


FIGURE 3 NOAA-6, 7: TEMPERATURE CALIBRATION CURVES

Orbital characteristics. Although it has a circular orbit, GOES is termed geostationary, or earth-synchronous; it is always above the same location on the equator. This is because, at an altitude of 35 800 km and speed of 11 000 km per hour, the satellite on an equatorial plane turns through the same arc distance as the earth, with a 24-hour orbit.

The area within the GOES FOV covers about one-quarter of the Earth's surface, from approximately 60°N to 60°S. The regions of coverage for GOES-EAST and -WEST are illustrated in Figure 4. These regions are imaged every 30 minutes, the time required as the sensors perform successive scans from north to south.

As a result of this type of orbit, resolution is highest for areas beneath the satellite where the view is directly downward, and deteriorates with distance away from this sub-point as the viewing angle becomes more oblique. Thus, coverage of Canada is from a more oblique perspective than the U.S.; resolution is much lower than satellite sub-points (approximately 2-8 cm); and geometric distortion is great.

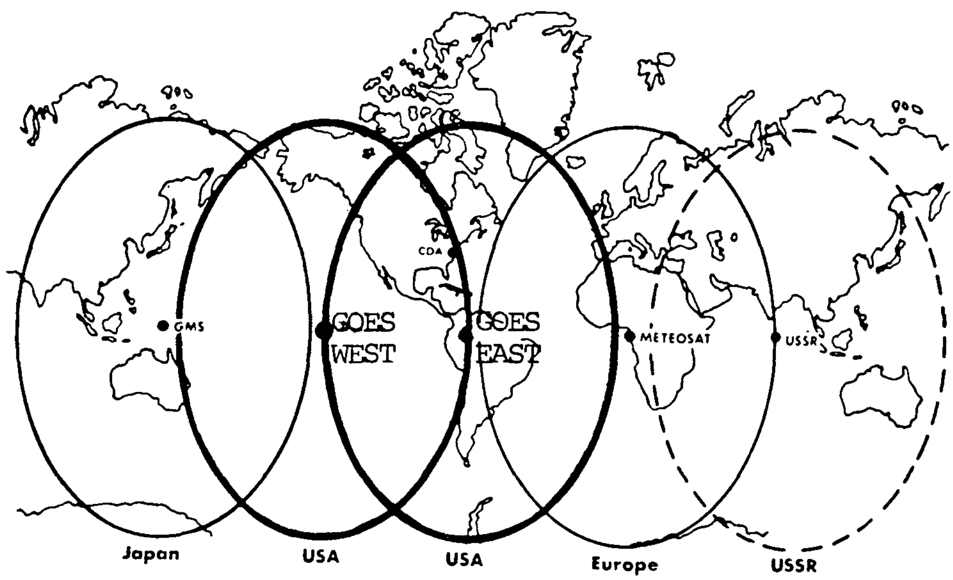


FIGURE 4 GOES COVERAGE

Sensor description - VISSR. The payloads on board GOES include the following sensors and subsystems:

a) Visible and Infrared Spin Scan Radiometer (VISSR):
   - eight identical visible channels (0.55-0.70 µm);
   - two redundant TIR channels (10.5-12.6 µm).

b) Space Environment Monitor (SEM):
   - magnetometer;
   - solar X-ray telescope;
   - energetic particle monitor.

c) Telemetry, Tracking and Command (TTC):
   - S-band transmitter;
   - UHF transmitter;
   - VHF transmitter.

The imagery of interest in this study is the VISSR. The scanning mirror scans from west to east and requires 1 821 successive scans to complete north-south coverage. For the visible wavelength, therefore, the eight sensors record 14 568 lines of data, whereas 1 821 lines of data are recorded for the TIR band. Raw data are transmitted to the S-band frequencies.

Data reception. VISSR data are transmitted to Wallops Island, Virginia, where they are processed, reduced and transmitted back to the satellites. This reduced band width or "stretched" data is then telemetered to ground stations. Canada currently has two GOES receiving stations: AES in Downsview, Ontario, for GOES-EAST, and AES in Vancouver, British Columbia, for GOES-WEST. These data can then be relayed via facsimile to various stations across Canada; four different images are sent at any one time in degraded resolution (2 to 8 km). For instance, data are transmitted to Gander, Newfoundland; Halifax, Nova Scotia; Montreal, Quebec; and Winnipeg, Manitoba, from the Downsview Satellite Data Lab of AES.

Data processing and products. In Canada, the data are recorded on digital tape and stored only for 3 days (unless a special request is made). The data are also reproduced as hard-copy images. Similar to NOAA data, GOES VIS and TIR data can be contrast-stretched to enhance features of certain grey levels; however, the spatial resolution of the data at Canadian latitudes is only approximately 4 km or less for the east and west coasts. This poor resolution (2 to 8 km, depending on location and data format) and the high geometric distortion for Canadian coverage reduce the potential of this data source for application to the detection of oil spills.

2.3 Future Satellite Systems

Of the many satellites to be launched in the next few years, Landsat D (and D') and Système probatoire d'observation de la terre (SPOT) will be most useful and, probably, accessible to potential Canadian users. Negotiations are proceeding between the Canadian government and the U.S. (Landsat), and French (SPOT) governments for defining the agreements under which the data from these satellites will be received and distributed in Canada.

2.3.1 Landsat D and D'. The launch of Landsat D is anticipated for 30 July 1982. Landsat D', an identical platform/sensor system, will be ready 12 to 15 months later and will be launched when Landsat D fails. The design lifetime of each satellite is 3 years. NASA will develop and launch these satellites; NOAA will be the managing agency after operational status is achieved.

Reception and orbits. The orbit of Landsat D will be near-polar and sun-synchronous, as for the previous Landsats. The (circular) orbit altitude, however, will be lower (705 km), reducing the direct (line-of-sight) reception circle for all ground stations. NASA will use its regular ground stations for direct reception of MSS-D data, but will configure only Goddard Space Flight Center, Greenbelt, Maryland, for direct reception of the other sensor on Landsat D, the thematic mapper (TM). Within a year of the launch of Landsat D, NASA will also launch two tracking and data-relay satellite systems (TDRSS) into geostationary orbit, positioning them to be able to acquire worldwide Landsat D reception.

Canadian reception arrangements are as yet imprecise. The most current scenario (personal communication, Art Collins, Data Processing Division, CCRS, 5 January and 17 February 1982) calls for a single reception (antenna) location, central to the Canadian land mass. Substantial charges for Landsat reception rights will be levied by NASA on each receiving station; therefore, CCRS will most probably choose SCSS for Landsat recording. The reception circles, as anticipated for Landsat D MSS and TM for the PASS antenna location, are shown in Figure 5; the same reception from a potential antenna location at Churchill, Manitoba is described in Figure 6. The Churchill antenna location still would require data processing at PASS. Transfer of the raw data in HDDT format to PASS requires commercial air transportation (via Winnipeg), which would add several days to the delay between satellite imaging time and user access to the data. It would be technically feasible to retransmit the data in digital format from Churchill to PASS via communications satellites, and thus reduce access time to hours; however, user demand would determine the economic feasibility.

The orbital paths for Landsat D will differ from those of previous Landsats. The new orbit configuration for Canadian territorial coverage is to be published in 1982. Landsat D will have a 16-day revisit (to any one location) frequency, but its precession will be seven paths per day. Thus, adjacent orbits on the Earth's surface will be imaged 2 days apart. Sidelap between adjacent orbits will be similar to that of Landsat 3; consequently, this will increase the frequency of coverage for high latitudes. The descending (sunlit) equatorial crossing will be at about 9:30 to 10:00 a.m. local (sun) time.

Multispectral scanner. The MSS on Landsat D will be the same as that on Landsat 3. Assuming that the MSS TIR band will be operational, it will not only open the use of thermal emission signatures for target detection but will also make practical use of nighttime (ascending) passes. The lower altitude of Landsat D, along with maintenance of the same swath width (FOV) of the MSS, dictate a larger range of look-angles for the sensors on this satellite. This parameter will degrade to some extent the detectability of targets imaged on the edge of the swath, due to greater atmospheric path length.

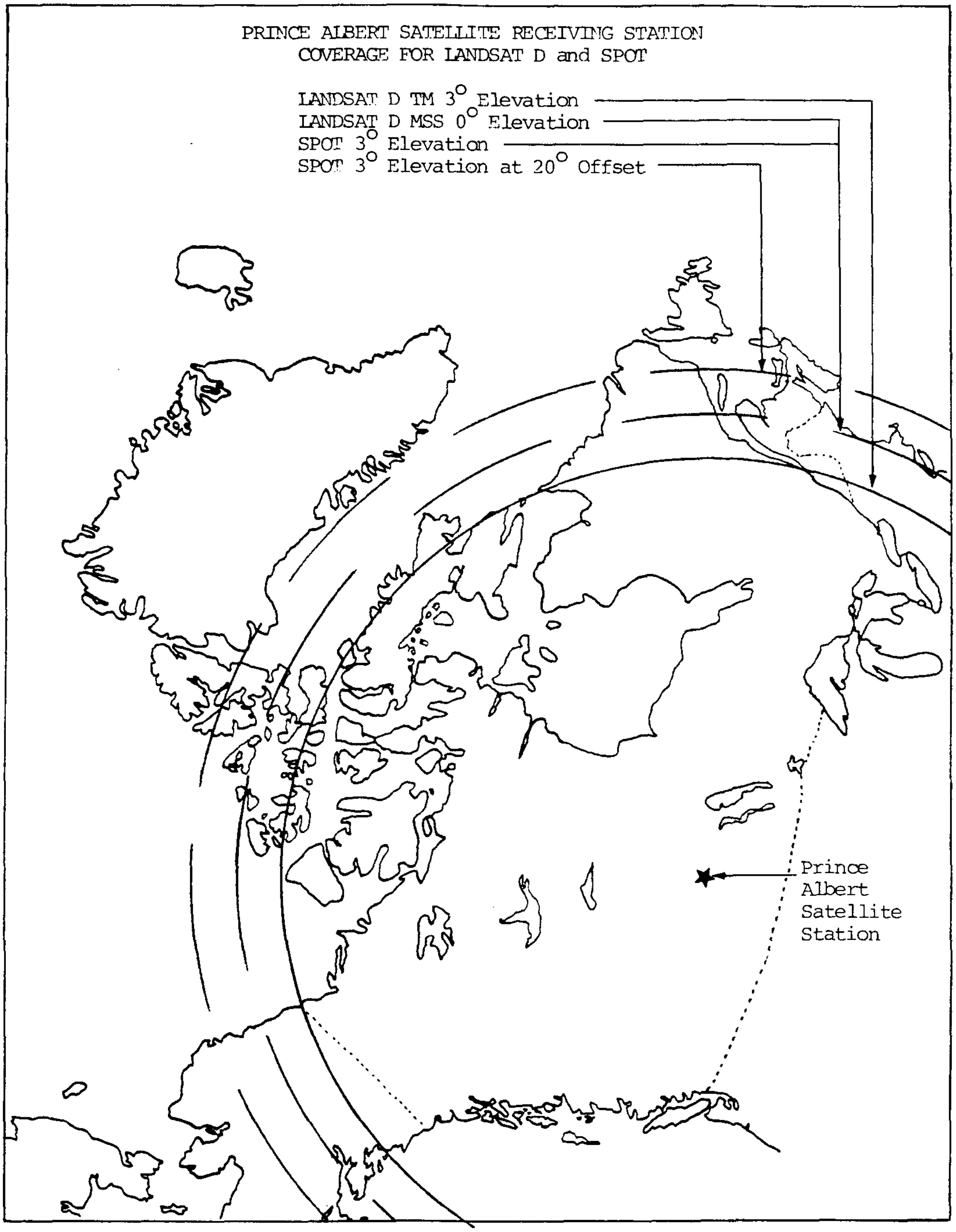


FIGURE 5 PRINCE ALBERT RECEIVING COVERAGE FOR LANDSAT D AND SPOT

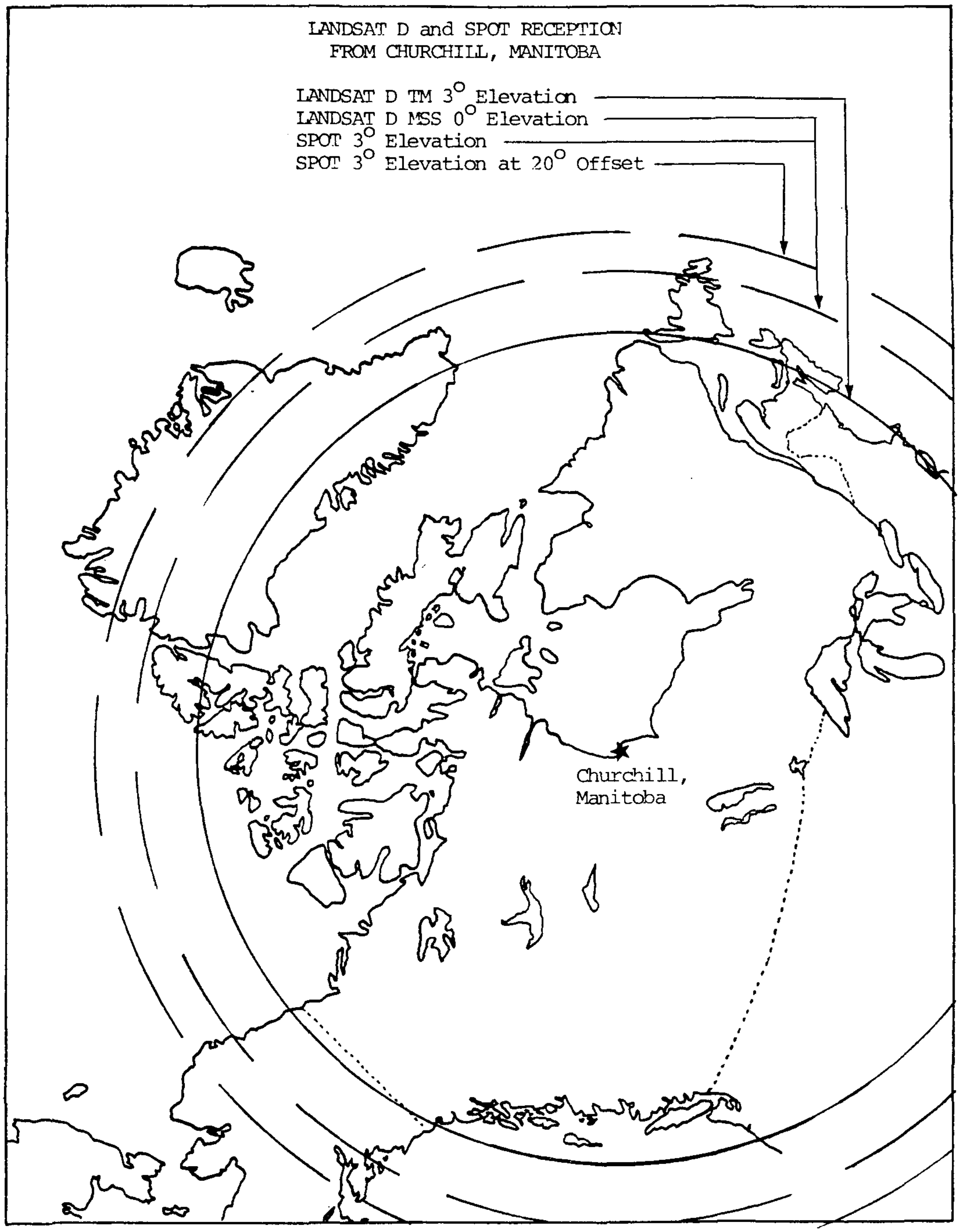


FIGURE 6 CHURCHILL RECEIVING COVERAGE FOR LANDSAT D AND SPOT

The Landsat D MSS will be the primary sensor for all earth science applications demanding high-resolution data, for a year or more after the launch of the Landsat D satellite. The Landsat 3 MSS is experiencing several problems, one of which results in a loss of 30% of the west side of each scene; the Landsat D TM will not be available for regular use for at least a year after launch. Thus, the MSS on Landsat D will be the primary or only source of high-resolution multispectral data from mid-1982 until late 1983 (at least).

Thematic mapper. The TM is an advanced version of the now familiar MSS, with substantial improvements in several areas. One improvement is the increased spatial resolution of 30 m. The significance of having an IFOV of 30 m for marine oil spill targets is: a) better detection of small or discontinuous oil slicks; b) improved areal measurement of slicks; and c) the probable detection of large ships.

The spectral (and other) characteristics of the TM are listed in Table 8. In the listing of the spectral sensitivities of the seven bands one can observe that: a) there are more bands than on the MSS; b) the bands are narrower; and c) the spectral sensitivity extends further into the shorter and longer wavelength regions. In addition, a 4X improvement in radiometric resolution is implemented, with an expected similar improvement in signal-to-noise ratio (S/N). These spectral and radiometric improvements will permit better detection (and identification) of oil slicks, in terms of oil-to-water contrast.

TABLE 8 LANDSAT D THEMATIC MAPPER SPECIFICATIONS

Ground Coverage (FOV)		(approximately 185 km)
IFOV		30 m (TIR: 120 m)
Radiometric Sensitivity Range		approximately same as MSS
Radiometric Digitization		8-bit (0 to 255)
Spectral Sensitivity:		
Band	Micrometres	
1	0.45 - 0.52	blue-green
2	0.52 - 0.60	green-yellow
3	0.63 - 0.69	orange-red
4	0.76 - 0.90	IR
5	1.55 - 1.75	IR
6	10.4 - 12.5	TIR
7	2.08 - 2.35	IR

2.3.2 SPOT. The French remote sensing satellite, SPOT, is scheduled for launch in 1984 by the French Space Agency, Centre National d'Études Spatiales (CNES). The data from this satellite will be made available to Canadian users through a government agreement, to be negotiated soon. This satellite is of interest to Canadian users because of unique features of flexibility and sensors.

Reception and orbits. The telemetry and reception of SPOT data have been designed to be compatible with those ground stations configured for Landsat D TM recording. The altitude (832 km) will be higher than that of Landsat D; therefore, the reception circle for each ground station will also be greater. Figures 5 and 6 show the potential coverage by SPOT for receiving antennas at PASS and Churchill, respectively.

As with the Landsat series, the orbits are circular, sun-synchronous and near-polar, with an equatorial crossing time of approximately 10:30 a.m. local (sun) time for descending (sunlit) orbits. The pattern of orbit ground tracks is to be repeated in 26-day cycles, with an accuracy of ± 5 km.

Sensors. A matched pair of sensors, termed haute résolution visible (HRV), will operate in either of two modes. The multispectral mode offers three bands in the VNIR at 20 m IFOV, while the panchromatic mode (integrating the green and red portions of the spectrum) is designed for 10 m IFOV. The sensor specifications are listed in Table 9. The HRV is a "push-broom" type of instrument requiring no scanning but using a multi-thousand array of charge-coupled devices as detectors.

TABLE 9 SPOT-HRV SENSOR SPECIFICATIONS (from CNES, 1981)

Sensor Features	Multispectral Mode	Panchromatic Mode
Spectral Bands	0.50 - 0.59 μm 0.61 - 0.68 μm 0.79 - 0.89 μm	0.51 - 0.73 μm
FOV	4.13°	4.13°
Ground Sampling Interval at Nadir	20 m	10 m
Number of Pixels per Line	3 000	6 000
Ground Swath Width Nadir-looking	60 km	60 km
Radiometric Digitizing	3 x 8 bits	6 bits

A movable mirror points the optical path of the sensor Earthward; this off-nadir viewing capability (which is ground-commanded) permits reviewing of the same point on the Earth's surface more frequently than the 26-day orbit cycle. At 45°N latitude, for example, it is possible to view a given location 11 times in 26 days, using the tilting mirror system. For nadir viewing, the swath width is 60 km and the sensor look-angle is ±27°. Depending on the sun/target/sensor geometry, the varying look-angle feature could positively or adversely affect the detectability of oil slicks.

2.3.3 NOAA Satellites. The U.S. meteorological satellite series will continue to be supported into 1992. Other countries also have launched similar platforms (e.g. Japan). As mentioned previously, the U.S program is currently in flux; however, coverage of at least a single polar-orbiting satellite of the NOAA type is ensured. The basic orbit characteristics and sensor performance of current systems will be continued.

2.4 Detection of Marine Oil Spills

Why should the possibility of using satellite platforms for detecting marine oil spills be considered when a variety of technical and logistical hurdles is involved? Current remote sensing satellites are not configured for oil spill applications, and past incidents in which oil slicks have been imaged from satellite can be called serendipity. The answer to the question is a combination of financial considerations and an overwhelming requirement for timely, useful information.

In an oil spill emergency for which the location and spatial extent of lost oil are unknown, the whole oil recovery and cleanup operation is impeded. Whereas airborne platforms are used as the primary search-and-detect vehicles, they also are subject to several logistical and technical constraints. Satellite data are easily acquired and relatively inexpensive. They offer synoptic views, even of very large targets, and image large areas of the Earth's surface with each orbit. The data are not dependent on subjective interpretation, but are objective and quantitative, permitting any analyst to extract particular, desired information in various ways. Acquisition of satellite data does not require the mobilization of special equipment or people. Satellite images may be obtained without visiting the spill site, which may be inaccessible or hazardous.

If conditions are such that the detection of an oil slick from a satelliteborne sensor is marginal or better, then it is a worthwhile exercise to acquire, process and interpret the satellite scenes. Satellite images of an oil spill site may provide information on the precise location of a slick, its spatial distribution, and the nature of the environment in the vicinity. If multiple images are available with some time interval separating them, then oil slick dynamics (and other related environmental changes) may be deduced. The effectiveness of cleanup operations can be interpreted if the imaging takes place during or after such activities. Environmental impact assessment is another application for satellite imaging whenever land or shallow water areas are in the path of an oil slick. The use of satellite monitoring can also be considered complementary to aircraft remote sensing; satellite scenes can minimize flying time by guiding aircraft searches, and can extend aircraft-detected oil targets to a larger area than is covered by the aircraft.

2.4.1 Sensing Parameters. The technical considerations involving the ability of satellites to detect marine oil slicks fall into four basic categories; these are: temporal, spatial, spectral and radiometric.

Temporal resolution. The trade-off applicable to current satellite systems is between spatial resolution and revisit frequency. Those satellites providing frequent (once or more per day) coverage of the Earth's surface are typically meteorological in nature, such as the GOES and TIROS-N/NOAA series and as such do not require high spatial resolution. Furthermore, these satellites generate a large quantity of data due to their high temporal resolution; a further increase in data quantity by increasing the spatial resolution would be logistically prohibitive.

Non-meteorological (earth resources) satellites, which require high spatial resolution due to the fine detail of their targets of interest, are typically located at lower orbital altitudes to achieve that fine resolution. The low orbit forces a narrow swath of coverage (FOV), because sensor look-angle is limited by increasingly severe atmospheric attenuation as the look-angle further deviates from nadir. The narrow FOV, then, requires more orbits to complete global coverage; thus, overpass frequency for any one point is reduced proportionately.

In Canada, the areas of concern for marine oil spills are primarily in the Arctic and the east and west coasts. The high latitudes of these areas will provide high sidelap for satellites such as Landsat 3, Landsat D and SPOT, so that the coincidence probability of satellite overpass for an oil spill event is reasonably high. Given such a coincidence, one of the more significant limiting factors for <u>successfully</u> imaging a slick is the prevailing cloud cover over the oil slick site.

Figure 7 presents one means of assessing the mean cloud coverage over Canadian territories. In this figure, provided by the Data Processing Division of CCRS, Landsat orbit tracks and frame numbers correspond to the path and row numbering of the Landsat orbit map (EMR, 1979). If the numbers on this map are interpreted as the mean probability of cloud cover at that location, then it may be seen that the potential of imaging an oil slick is reduced by half or more, depending on location. The situation is actually more serious than this map indicates, for bad weather (and accompanying cloud cover) is often a precipitating factor in oil spill disasters.

Spatial resolution. The method by which a satelliteborne sensor characterizes the view of the surface of the Earth in the visible and IR bands is to average the reflected or emitted radiation from the IFOV of the light detector and to represent it as an arithmetic value. When the target is unhomogeneous or made up of more than one feature, then the resulting mean radiance in the IFOV is representative not of a single target but of the mixture. The resulting mixed pixel reduces the detectability of the desired target by the proportion of the target/background ratio.

Presumably, more serious oil spills involve large quantities of oil and hence spread to cover a larger surface area. Thus, the spatial resolution of the Landsat 3 MSS at approximately 80 m would be adequate to cover even smaller spills. The 30, 20 and 10 m pixels of the next few satellites will permit not only basic detection but very detailed delineation, even of small or discontinuous spills.

Unfortunately, meteorological satellites, especially those in geostationary orbit, have a very large IFOV. The greater the number of "pure" target pixels, the more confidence is to be had in identifying the target. Although there is no threshold level of pixels-on-target above which oil slick targets are identified (especially because of the many other technical and environmental parameters involved in determining oil-to-water contrast), experience dictates a requirement of at least 10 to 20 pixels. This number demands a very large, contiguous oil slick for useful imaging by satellite sensors in the 1-km IFOV category.

Spectral and radiometric resolution. The method of satellite-based detection of oil slicks in a water or ice background (using the visible and IR portion of the spectrum) is to detect a radiometric difference between target and background in one or more spectral bands. Many factors contribute to determining the magnitude of the target-to-background radiance contrast, and hence, to the probability of successful target detection. In the VNIR, (crude) oil is typically more reflective than water; however, the

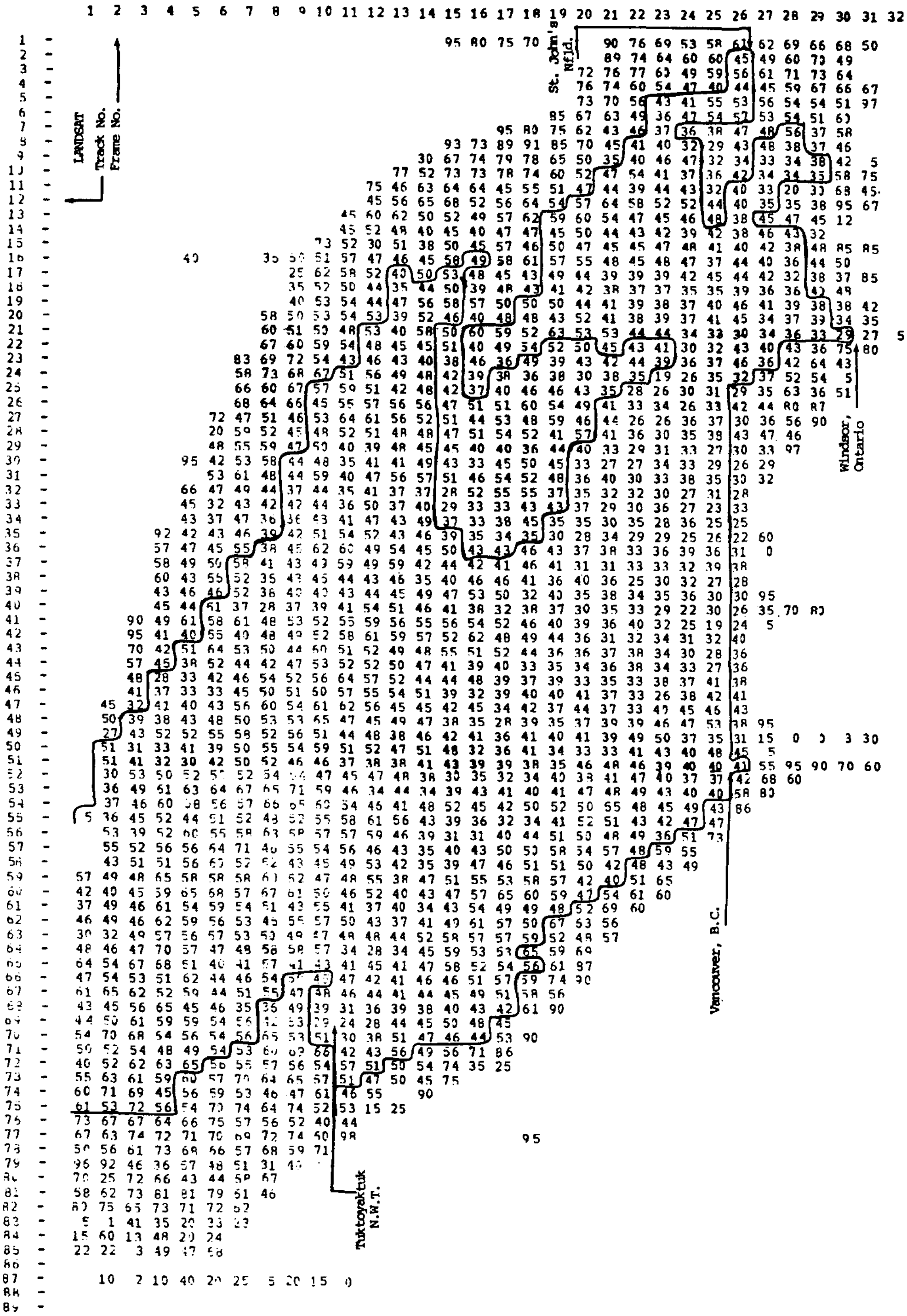


FIGURE 7 MEAN CLOUD COVER (PERCENTAGE) ON LANDSAT SCENES

specific conditions of atmospheric path and sky radiance, volume scattering of water, film thickness, and illumination angle will dictate the absolute oil/water contrast observed.

Path radiance is noise additional to the light reflected from the oil/water surface. For dark target scenes (such as water and oil) and satellite altitudes, the total radiance received at the sensor may be as much as 80% path radiance. The atmosphere also attenuates the light reflected from the target, in a wavelength-selective fashion. Lower wavelengths are attenuated most, which explains the frequent absence of bands in the ultraviolet and blue for satelliteborne sensors.

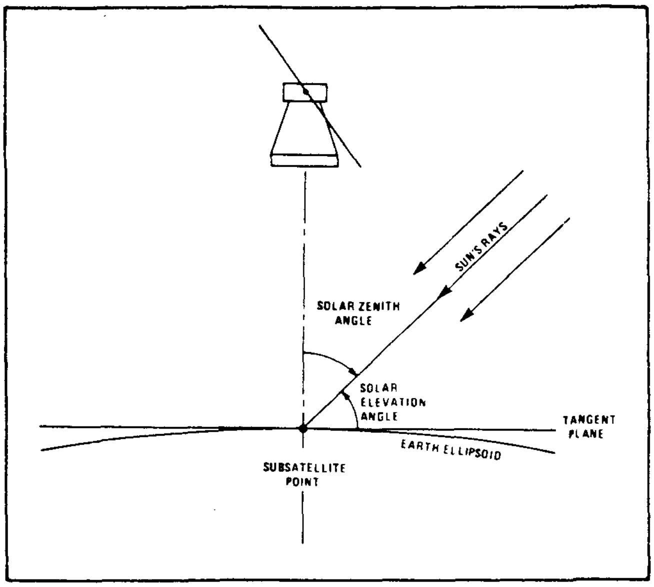
Sky radiance, predominant at lower wavelengths, is typically surface-reflected and controlled by the fraction of cloud cover on-site. Polarization of the incident and reflected sky light, which depends on look-angle and illumination-angle geometry, also affects the perceived oil-to-water contrast.

The reflectance properties of oil and water, and the influence of the above parameters on oil-to-water contrast are described in detail by O'Neil et al. (1980a) and Neville et al. (1979). The polarization effect is discussed by Thomson et al. (1979) and Millard and Arvesen (1973). With satelliteborne sensors, the user must deal with system inflexibility. It is useful to understand the electromagnetic structure of the satellite images, and essential to determine the system ability for detecting oil spills.

In the VNIR, one factor has an overwhelming influence on the success of imaging an oil slick from a satellite sensor. Given overpass coincidence and an absence of clouds over target, the intensity of illumination becomes the critical factor in adjusting the radiance difference between target (oil) and background (water/ice/snow) to the radiometric resolution of the sensor. Aside from the variable atmospheric capacity that may be encountered, the main controlling factor is the intensity of the incident illumination, which is dictated primarily by the solar elevation angle at the subsatellite point (Figure 8a). The angle is a function of latitude and season (Figure 8b).

The first-order calculation, which is wavelength-independent, for the impact of solar elevation changes is a simple, cosine factor to accommodate the illumination geometry. A second-order correction, influenced by spectral band selection, would be the increased atmospheric attenuation at lower sun angles, due to increasing path length through the atmosphere. The lower wavelength bands will be attenuated more, according to the Rayleigh criterion of scattering being proportional to λ^{-4}.

It is worthwhile to attempt a definition of the limits at which oil spill detection becomes possible in Canadian latitudes. The many variables influencing this a.



b.

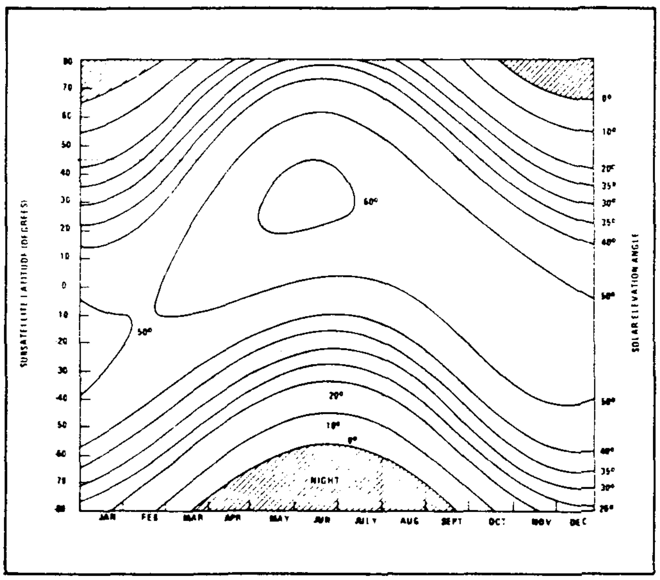


FIGURE 8 a. SOLAR ELEVATION ANGLE
b. SOLAR ELEVATION ANGLE HISTORY AS A FUNCTION OF SUBSATELLITE LATITUDE - DESCENDING NODE AT 9:30 a.m. (from NASA, 1976).

definition preclude an all-inclusive, rigorous treatment; however, the IXTOC spill of 1979 (see Appendix A) offers a unique data set and opportunity. This oil spill and its radiometric character are well defined, due to: a) extremely large areal extent; b) verification from other sources; and c) good solar illumination.

It is not claimed that an IXTOC-type spill is typical, nor that it will occur in Canadian waters. It is useful, however, to "transplant" this spill to Canadian latitudes in order to determine the ability to detect it and the seasonal limits of currently operating satellites.

The greatest difference achieved between the oil and water radiances at IXTOC was 6.0 for Landsat MSS band 4, and 3.9 for MSS band 5, using the original 6-bit radiometric resolution of the MSS. This difference, transposed to the site and date of the KURDISTAN spill by applying only the cosine correction for solar angle, would yield an oil/water radiance difference (6-bit scale) of 4.4. Considering the other factors of sensor noise and increased atmospheric path length at this site, it would appear that the spill would still have been (marginally) detectable from its background.

The latitude and time at which oil slick detection becomes feasible may be determined using a) the IXTOC spill radiometric characteristics, b) a first-order approximation for solar angle influences, and c) (an unverified rule requiring) a minimum of two (6-bit) digital levels of difference between mean radiances of oil and water. This scenario has been configured for a Landsat-type orbit and an MSS band 4 sensor. The oil-to-water brightness difference used is not that of the brightest, most emulsified oil found on the IXTOC scene (which would have limited temporal and spatial extent) but of an oil brightness régime more spatially extensive and hence more stable. The results are shown in Figure 9. The detection limits in this figure are a rough guide, for they are generalizations derived from a specific oil spill with unique environmental conditions. Nevertheless, this guide is a realistic decision-making tool.

Some of the radiometric resolution lost to digitization noise may be recovered by averaging over several or many pixels. This technique is useful for large oil spills and in data sets where "speckle" noise is apparent in the scene. Another detectability factor is that oil slicks have been found as the darker region in an area of specular reflection caused by the wave-damping of an oil layer (Deutsch et al., 1977). Since these instances have typically occurred on images with sun elevation angles greater that 40°, the detection limits shown in Figure 9 are still applicable.

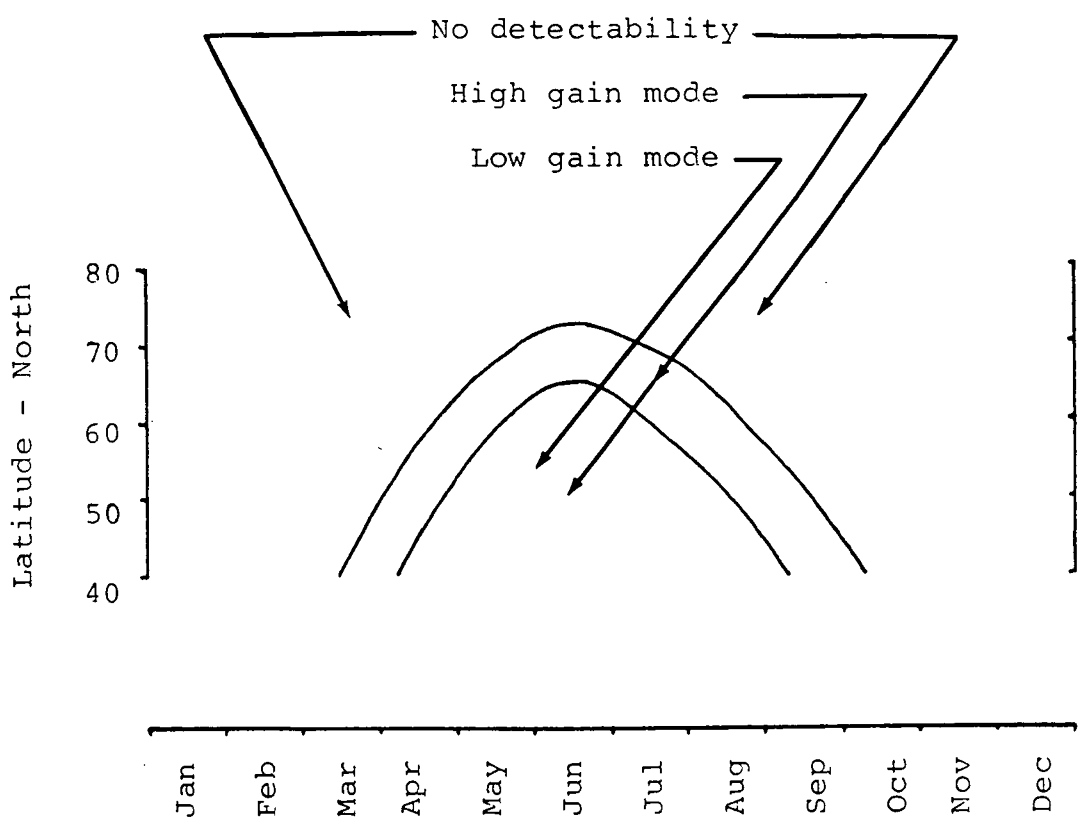


FIGURE 9 OIL SPILL DETECTION LIMITS FROM LANDSAT MSS 4

Less well known is the detection of oil slicks from satellite altitudes using the TIR portion of the spectrum. Much work on this topic has been done from airborne TIR sensors (O'Neil et al., 1980a; Neville et al., 1979) but the satellite approach has never been used.

It is very likely that the original temperature of the oil during a spill is higher than that of the receiving water body, and that this thermal difference is appreciably higher than the radiometric resolution of a satelliteborne TIR sensor. This original elevated oil temperature is very quickly reduced as the oil spreads, thereby reducing the probability of oil slick detection. In other words, while the thermal difference of oil from its background is sufficiently high for detection, the small areal extent prohibits detection, due to the poor spatial resolution of most satelliteborne TIR sensors. Also, when the slick has spread to cover several pixels, the temperature difference is probably below the radiometric resolution of the sensor.

Oil slick temperatures, especially of thicker slicks, are elevated as well by absorbed solar energy. This phenomenon is also subject to solar elevation angle changes and probably will not have sufficient impact to push the thermal contrast above the detection threshold. Despite pessimism here and in previously published literature on the use of the TIR band for oil detection, the TIR band of the Landsat D TM offers hope for the near future due to its unprecedented 120-m resolution.

2.4.2 Review of Past Experience. The very limited occasions upon which satellite coverage of oil slicks or spills has been available have retarded the development of this technology. Deutsch et al. (1979) list several observers who claim to have seen features which they interpret as oil slicks; the authors proffer several satellite scenes with features that are probable oil slicks.

Most effort to date has simply been detection of a potential slick, due to the very difficult target which pushes the satellite sensor systems and analysis methodologies to their limits. The primary use of satellite data for an oil spill emergency is to assist in locating and delineating a spill, but much work is required to characterize the radiometric properties of oil slicks so that an oil identification function can be added to the capabilities of satellite sensors.

O'Neil et al. (1980a) have exhaustively treated the topic of oil spill monitoring from remote sensing devices, yet abruptly dismiss the satellite approach. The satellite cannot yet be considered as an operational response platform.

Deutsch et al. (1980) list 185 Landsat satellite scenes of the IXTOC oil spill of 1979. They have examined many in photographic and digital forms, applying various enhancements. Almost no rigorous quantitative work is available on this spill, despite the fact that it is the only well-defined, corroborated, spatially and temporally extensive spill that has been imaged on numerous occasions by satellite.

An approach similar to that for the IXTOC spill was made by Deutsch and Estes (1980) in investigating the appearance of oil seeps off the coast of California. These authors tried numerous enhancement techniques to emphasize the visual appearance of oil targets in contrast to the water background on Landsat imagery.

Two studies have taken rigorous approaches to this topic. Dawe et al. (1981) studied the KURDISTAN spill off Nova Scotia and attempted to characterize the radiometric/spectral properties of oil/ice mixtures from Landsat. Kirby (1979) studied the Scott Inlet oil seep off Baffin Island, also from Landsat, using methods for defining the brightness and colour of potential targets. These studies had limited success due to the difficult nature of the features examined.

The most significant findings to date deal with the means of detecting oil slicks in the marine environment. It has been observed by Deutsch et al. (1979) that oil slicks may be detected due to the wave-damping influence of an oil film on the water surface, resulting in a suppression of the specular reflection from the coarse water surface. Wind speed and sensor/target/sun geometry have an influence here. Of the slicks detected by satellite so far, these authors also note that the sun elevation angle has been greater than 39°. A contribution is made herein (see Appendix) to the quantitative study of oil slicks from satellite, with particular emphasis on the IXTOC 1 oil well blowout of 1979.

3 CONTINGENCY PLAN - SATELLITE SURVEILLANCE

3.1 Procedures

The detailed history described below deals with an oil spill emergency in Canadian waters. It is presumed that through some prearrangements (see Section 3.2) a responsible individual can authorize commencement of satellite image analysis for the detection, location, mapping and monitoring of the oil slick in question. It is also assumed that an experienced individual, identified in advance, will receive and act on such a directive.

In the earliest stages of the oil spill scenario, when the oil slick is most confined and its location is perhaps not perfectly defined, Landsat MSS and RBV data with their high spatial resolution are the best satellite candidates for slick detection. NOAA data, with their high revisit frequency and lower spatial resolution, are the next most promising.

3.1.1 Input. The analyst will require some basic information for the logistics of acquiring and processing satellite data. Of primary importance is knowing the location of the oil spill as accurately as possible. Second, the date (and if possible the time) of the spill will establish the earliest useful imagery that may already have been recorded. Last, the destination of the satellite-derived information is a prerequisite. As many as possible of telephone, Telex and TWX numbers should be provided to the analyst.

Some other descriptions of the oil spill are useful, but not essential. These include: type of oil, quantity of oil, observed behaviour of the oil (breaking up, sinking, emulsifying, adhering to suspended sediment, interacting with ice, etc.), weather conditions on-site (wind, cloud, haze, fog, etc.), water conditions on-site (waves, current, ice, floes, etc.), the presence of large features (ships, drill rigs), and any other gross features (fire, smoke, etc.). Knowledge of these in situ conditions will assist in the identification of image artifacts and will help explain the appearance (or not) of the oil.

3.1.2 Logistics. Knowledge of only the approximate spill location and time will permit the definition of Landsat overpass coincidence. By referring to the Landsat orbit map (EMR, 1979), the Landsat picture centre co-ordinates for the oil spill location can be determined. Depending on sidelap, one or more orbital paths may be involved. Table 4 (for 1982, or use Table 5 for 1983) will thereafter specify the dates at which Landsat 3 will pass over that location. Figure 9 indicates the probability of oil detection at the specified latitude and date.

The analyst must activate some processes by which the data flow is ensured. There are many possible contacts and routes; the most efficient is the most direct. PASS is the best single contact for the Canadian situation, and operates about 16 hours per day, 6 to 7 days per week. PASS should be contacted (see Appendix B) and advised on the location and timing of the desired scene. Further, the analyst and the PASS station manager (or designate) should agree on the action that will be taken, namely:

a) PASS will notify NASA directly of the desired orbits and frames, to ensure that the Landsat sensors are active on the appropriate occasions.

b) PASS will request NASA to program the MSS for high-gain mode on MSS bands 4 and 5.

c) PASS will ensure that the appropriate scenes will be recorded at that station.

d) If there is overlap of the spill site by another ground station, PASS will ask that station to receive and record the scenes as a back-up for possible technical problems at PASS.

e) The analyst will identify expected arrival time at PASS, and will be advised of a contact person to seek upon arrival.

It is not guaranteed that NASA can or will respond to these requests. Published policy (NASA, 1980) expresses their strong interest in accommodating such user requests, but technical or time constraints influence their actions.

From the known dates of potentially useful Landsat scenes, the analyst can estimate the completion date of work at PASS. He/She should arrange for access to the CCRS Image Analysis System (CIAS) in Ottawa for the expected date of arrival in Ottawa from PASS. Several contacts for this purpose are listed in Appendix B, under the designation of "Fast Reaction Unit". This unit can provide machine time and assistance on the CIAS and expedite other CCRS services, such as the production of colour photography resulting from CIAS analysis. The fast reduction of basic data at PASS (and its transmission to the field) is expected to be followed by more detailed and retrospective analysis on the CIAS (see Section 3.1.5).

The analyst must collect all available maps and charts of the spill vicinity and take the earliest available transport to PASS. At PASS, he or she must notify the potential receivers of satellite data as to the nature and expected time of arrival of the data. This will be done through the channels intended for data transmission. Thus the channels will have been tested before transmission of the satellite data.

3.1.3 Analysis. If there is time prior to receiving the satellite scenes, the analyst and the appropriate PASS staff member should check the functioning of the digital processing system to be used for data reduction. As the target scene is being received from the satellite, the digital data are recorded on HDDT while a photographic version is produced in real time. The photograph of the scene is useful as a reference for initial image navigation. Latitude, longitude and scene orientation can be placed on this photograph; it can subsequently be released to the news media, if desired.

A system-corrected CCT is to be produced of the scene containing the potential oil slick target. Presuming that the primary digital processing system will be used for acquiring other satellite data on that day, the scene of interest should be shunted to the back-up (secondary) processing system for producing the system-corrected CCT. The corrected CCT will take about 1 hour to produce, and is more desirable than a "raw" scene. The corrections applied will reduce the sensor striping effect (due to variable gains of the MSS sensors) which interferes with the visual appreciation of subtle image features. As well, much of the geometric distortion will be removed, permitting greater accuracy in locating features.

A low-resolution version of the full scene should be called next to the 512 by 512 colour display, to check that the correct location/scene is available, and to assess the cloud cover over the target area and any other data problems (such as lost lines, noisy data, bit slips, etc.). From the full scene overview, a full-resolution subscene of 512 by 512 image pixels is chosen and called to the display. Histograms of each of the bands are collected, to find the most suitable range of digital values within which the oil/water contrast may be enhanced.

Based on the band intensity limits defined by the histograms, a look-up table file is constructed for transforming the scene. The look-up table is configured for linearly stretching a particular band, to provide maximum contrast between adjacent intensity levels. The subscene is then transformed by applying the look-up table to the brightness values. One or more iterations may be necessary at this stage to produce a suitable enhancement; a new subscene can be chosen once the analyst is satisfied that no oil spill features can be found on this subscene.

When a slick, or a feature that may be a slick, is found on the Landsat scene, its location and rough areal extent are sketched onto a map, chart or Landsat photograph. A photographic version of the enhanced subscene is made via the laser image recorder.

3.1.4 Output. Ideally, if the recipient of the information has facsimile communication capability a graphic version of the information, consisting of either a map or a photograph, can be sent. A hand-drawn oil slick on a map would be first available, while a photograph would take approximately an hour. For either case, the oil slick feature as well as any prominent landmarks should be emphasized with a pen, available latitude/longitude marks should be drawn in, and explanatory notes should be added. The resulting image should be binary, containing only black and white. This circumvents most grey-level resolution problems of facsimile machines as well as interpretation confusion.

If a facsimile machine is unavailable at the receiving end, then the pertinent information must be described verbally by telephone, Telex or TWX. It may be feasible to reduce and analyze one Landsat scene in the above manner within 3 to 5 hours from time of receipt.

3.1.5 Secondary Analysis. After the primary analysis at PASS is completed for all available overpasses of the target location, secondary analysis should be continued in Ottawa for those CCTs containing a visible oil slick. This analysis is best done on the CIAS, which is the best supported, most flexible and user-interactive system in Canada.

The purpose of the secondary analysis is threefold. First, the data reduction and interpretations completed at PASS may be confirmed and extended using the more sophisticated software packages available on the CIAS. Chromaticity analysis, for instance, may identify false oil slick targets such as fog, clouds or inorganic suspended sediment. Second, appropriate visual materials in paper and photographic form can be prepared easily and quickly for briefings, public relations, and as media handouts. Third, environmental analysis of land areas affected by the spill may be conducted by means of historical scenes which expose currently cloud- or snow-covered areas for a resource inventory. Alternately, if "before-and-after-spill" Landsat scenes are available, change detection methods can show the areas affected by oil deposition.

3.1.6 Alternate Landsat Sources. Figure 1 shows that much Canadian territory is covered redundantly, and some uniquely, by U.S. ground stations. Although the logistic implications are somewhat greater for access to data in the U.S., it is a very feasible route in the event of problems at PASS. The central distribution facility for Landsat data is the EROS Data Center in Sioux Falls, South Dakota (see Appendix B). The Center receives the preprocessed data from NASA in Greenbelt, Maryland, but has full reproduction, archiving and analysis facilities in Sioux Falls. The User Services section should be the primary contact point for U.S.-originated Landsat products and analysis services.

3.1.7 NOAA Data. The use of NOAA satellite data from the AVHRR sensor becomes feasible once the spill covers an area of 5 to 10 km^2 or more. NOAA data are received at PASS and at the AES installations in Edmonton and Toronto. The PASS location for NOAA recording is the most useful if an analyst is already there working with Landsat imagery. Otherwise, the most convenient of the other two locations can be chosen.

The analysis process should be conducted in a fashion similar to that for Landsat. A photographic version of the NOAA scene is useful for familiarization and orientation with the particular scene and for choosing the correct subscene. The full-resolution digital scene on magnetic tape is necessary for any analysis, for the data will probably be pushed to their maximum spatial and radiometric resolution. Once potential targets have been defined, the pertinent information can be sent by any communications medium. The AES stations are also equipped with facsimile-transmitting equipment. The contact points for access to AES services and products are listed in Appendix B.

3.2 Prearrangements

There are measures to be taken in advance of an oil spill emergency to ensure that a contingency plan for the use of satellite image analysis progresses as it should without serious breakdown. There are additional steps that can be taken to simplify, hasten or enhance the process whereby useful information is passed quickly to the appropriate decision-makers. The prearrangements described below are only those deemed essential to the course of the contingency plan, or which can be implemented with little effort yet yield significant benefits.

a) The individual, herein called the "analyst", must be identified clearly and assigned a mandate for oil spill detection. The analyst must have suitable experience, be able to respond to an oil spill emergency with minimum warning, and have a backup replacement for absences. If the analyst is a private contractor instead of a government employee, then appropriate contractual arrangements must be put in place to commit his/her time as needed.

b) A trial run of the contingency plan should be made at the first opportunity, then at (approximately) annual intervals. The trial is essential to test the system and expose any unforeseen barriers to the anticipated progress. The trials should be timed to coincide with the controlled oil spills conducted for testing dispersants, containment systems, cleanup operations, etc. Thus, the remote sensing exercise will have a true oil target; also, valuable research may be applied to understanding the mechanism of oil/light interaction.

c) The installation of interactive software at PASS for the creation and application of the look-up tables to digital images would greatly hasten the process of searching for oil spill features. Such software is simple, inexpensive, and already exists at the CCRS facilities in Ottawa.

d) Configuring a hard-copy device, such as a dot-matrix printer, on the data processing system at PASS would eliminate the need for manual sketching and the delays involved in processing photographs. The device would use paper as an output, which could then be used directly as the input to the facsimile device.

e) Installing the chromaticity software package at PASS would provide the means for identifying oil slicks and other features on Landsat MSS scenes. The number of false targets would be reduced and the interpretations would be made with much more confidence. This software is now operational on the CIAS in Ottawa.

4 TIME AND COST

To provide a realistic estimate of potential costs involved in following the plan of the previous section, a "typical" scenario for an oil spill emergency is given in Table 10. The scenario calls for an analyst, contracted from a private company, to travel from Ottawa to PASS, spend 4 days analyzing two Landsat scenes and four NOAA scenes, and then return. Costed separately is a single, 5-hour session on the CIAS during which various analyses are conducted, and map and photographic products are produced. Prices used will be in effect after 1 June 1982. Actual order forms and price lists for EDC and CCRS products are provided in Appendix C.

TABLE 10 ESTIMATED OIL SPILL EMERGENCY COSTS

Primary Analysis (PASS)	
Air Travel (Ottawa/Prince Albert/return)	$ 500.00
Ground Transport (taxis, car rental)	200.00
Accommodation and Meals (4 days)	300.00
Materials (maps, consumables)	50.00
Landsat Data (2 CCTs, 4 photographs)	1 600.00
NOAA Data (4 CCTs, 4 photographs)	500.00
Communications	200.00
Man-time	2 250.00
Overhead and Profit	400.00
Miscellaneous and Contingency	1 000.00
TOTAL	$7 000.00
Secondary Analysis (Ottawa)	
Ground Transport	$ 30.00
Materials (photographic output from CIAS)	300.00
Communications	20.00
Man-time	600.00
Overhead and Profit	100.00
Miscellaneous and Contingency	250.00
TOTAL	$1 300.00
GRAND TOTAL	$8 300.00

5 CONCLUSIONS

Current remote sensing satellite systems are not configured to provide operational oil spill disaster monitoring. Orbit and sensor parameters are such that the probability of successfully imaging an oil spill is very low especially at Canadian latitudes. Given the coincidence of proper timing and cloud-free site conditions, the sensors may still be inadequate for detecting oil in a marine environment.

If the environmental indications are such that spill detection is feasible, then the logistics for acquiring, formatting, and analyzing the necessary satellite data for generating near-real time information can be defined precisely. Such a contingency plan still needs to be put in place and tested.

Rigorous testing of any available satellite data of oil slicks is mandatory, to build up experience in dealing with such a difficult environmental feature. Past oil slick satellite scenes have not all been examined critically; controlled oil spills also have ignored satellite overpass timing.

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7 APPENDICES

7.1 Appendix A: Reinvestigations of Selected Oil Slick Events from Landsat Data

7.1.1 IXTOC Oil Well Blowout. The IXTOC 1 oil well blowout occurred on 3 June 1979, in the Bay of Campeche, Gulf of Mexico. This disastrous oil spill of tens of thousands of barrels per day for several months has offered a unique opportunity for satellite remote sensing research. For the first time, a large oil slick target was available for numerous overpasses even of satellites with infrequent revisit cycles (such as Landsat). The target location (blowout source) was well identified and optimum; high sun angles were available for some passes.

Hayes (1980) reported that Landsat imagery was on hand within 1 to 3 weeks of satellite overpass and that several mosaics of the satellite imagery were constructed from cloud-free scenes. Lack of real time processing has been identified as the reason for not using these data for tactical purposes by the U.S. Coast Guard. Hayes was able to define the oil slicks from two features: a dark area in a region of specular reflection (where the oil slick suppressed ocean waves), and light areas in a background of darker water (which he interpreted as a "chocolate mousse" oil emulsion).

Extensive analysis of Landsat MSS imagery by Deutsch et al. (1980) for monitoring the dynamics of the IXTOC oil spill interpreted oil-slick features on 185 scenes. Landsat MSS spatial resolution was found to be ideal for the "assessment of the synoptic distribution of oil". They found that MSS bands 5 and 6 showed oil-to-water contrast much better than did the panchromatic RBV images. Image enchancement, in the form of contrast-stretching, was applied to both photographic and digital data sets.

To take further advantage of this oil spill for investigating the physical process of remote sensing of marine oil slicks, one of the better Landsat MSS scenes of the IXTOC spill was analyzed quantitatively and in detail. The scene chosen was recorded over Campeche Bay on 16 August 1979. This scene contains on oil slick feature, which is a light tone in a darker water background. Thus, the oil-to-water contrast is achieved not through depression of waves (suppression of specular reflection) by the overlying oil but through a detectable difference in spectral reflectance between oil and water. The Landsat image identification number is: 2166715474, path 23, row 47, and frame centre is 18°42'N latitude, 92°28'W longitude. (During imaging by Landsat, the sun elevation was 54° at an azimuth of 092°.) Analysis was conducted on the CIAS.

An overview of the whole Landsat scene (185 by 185 km) is shown in Figure 10. A part of the southern shoreline of the Bay of Campeche is visible in this figure, as well as the oil slick emanating from the IXTOC 1 well site, under a scattered cloud cover. Seven sites are identified here and, with more precision, on two subscenes of the oil slick in Figures 11 (IXTOC well site and oil spill head) and 12 (part of the slick furthest from the head on this Landsat image).

Site 1 is near shore, at the mouth of a river that is discharging suspended sediment into the bay, under a clear sky. Sites 2, 3 and 4 are all near the oil source and are presumed to represent thick oil régimes. These three sites have been chosen carefully to avoid clouds or cloud shadows, and because their colorimetric appearance on a false-colour display (MSS bands 4, 5 and 6, coded as blue, green and red, respectively) has shown them to be mutually distinct. Site 5 is near the furthest region of oil from the head which could be accessed on this one Landsat scene. It is approximately 90 km from the well site and so may be assumed to be much thinner. Site 5W is a reference data point for non-oily water under a clear sky. Site 6 is of a homogeneous tract of clear water with varying cloud cover.

Data from sites 1 and 6 were taken to assess the probabilities of confusion for these two features (sediment and clouds), which can often be taken as false oil targets. To recover some of the radiometric resolution lost to quantization noise, 100 pixels were averaged for each of sites 2 to 5W. The mean digital values of the extracted data were converted to units of spectral radiance ($mW/m^2/sr/nm$) and are listed in Table 11 and graphically displayed in Figure 13.

The various surface features display reflectivity, consistently increasing through clear water, oil sites and high concentration of suspended sediment. It is expected that the varying appearance and reflectivities of the oil at sites 2, 3 and 4 are due to varying degrees of emulsification of the oil. Thus, the blue-grey oil with high reflectivity at site 3 is probably more completely emulsified than the oil at the neighbouring sites 2 and 4.

Oil-to-water (and sediment-to-water) contrast has been calculated using the formula: $(T-W)/(T+W)$, where T is the target (oil or sediment) spectral radiance, and W is the water spectral radiance on site 5W. The resulting contrast values per site per MSS band are also listed in Table 11.

As could be predicted, high sediment concentrations offer the best contrast to water; oil-to-water is second. In all cases, the contrast increases with wavelength; this

INTOC - GULF OF MEXICO HAFTON / CVF08A
VIDEO CHANNEL : 3 TOP LEFT (0, 0) BOTTOM RIGHT (511, 511) DATE: 28-JAN-82 TIME: 20:08:26
DISTRIBUTION : LINEAR INTENSITY INTENSITY LIMITS : 9 TO 42 DOT TEXTURE : COARSE
PIXEL SIZE : 59.00 BY 79.00 METRES SECTION : 1

1. Inorganic sediment discharge from river
2. Oil near source, brown colour[a]
3. Oil near source, blue-grey colour[a]
4. Oil near source, brown-blue colour[a]
5. Oil at slick tail, windrow appearance

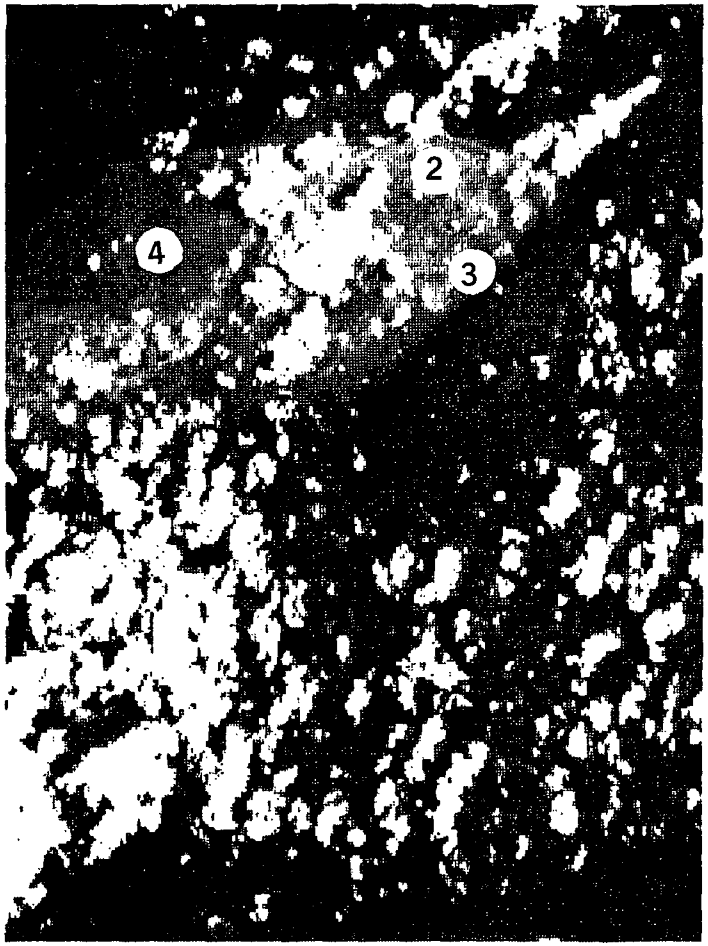
5W. Water outside of oil slick

6. Variable cloud over clear water

[a]Colour is defined from appearance on Landsat false-colour composite:
MSS bands 4, 5, 6 = blue, green, red

FIGURE 10 BAY OF CAMPECHE, GULF OF MEXICO - SITES FOR DATA EXTRACTION

IXTOC (HEAD) HAFTON / CVF03A
VIDEO CHANNEL : 3 TOP LEFT (0, 0) BOTTOM RIGHT (511, 511) DATE: 28-JAN-82 TIME: 21:21:47
DISTRIBUTION : LINEAR INTENSITY INTENSITY LIMITS : 9 TO 39 DOT TEXTURE : COARSE
SCALE 1 : 250000.00 PIXEL SIZE : 59.00 BY 79.00 METRES SECTION : 1

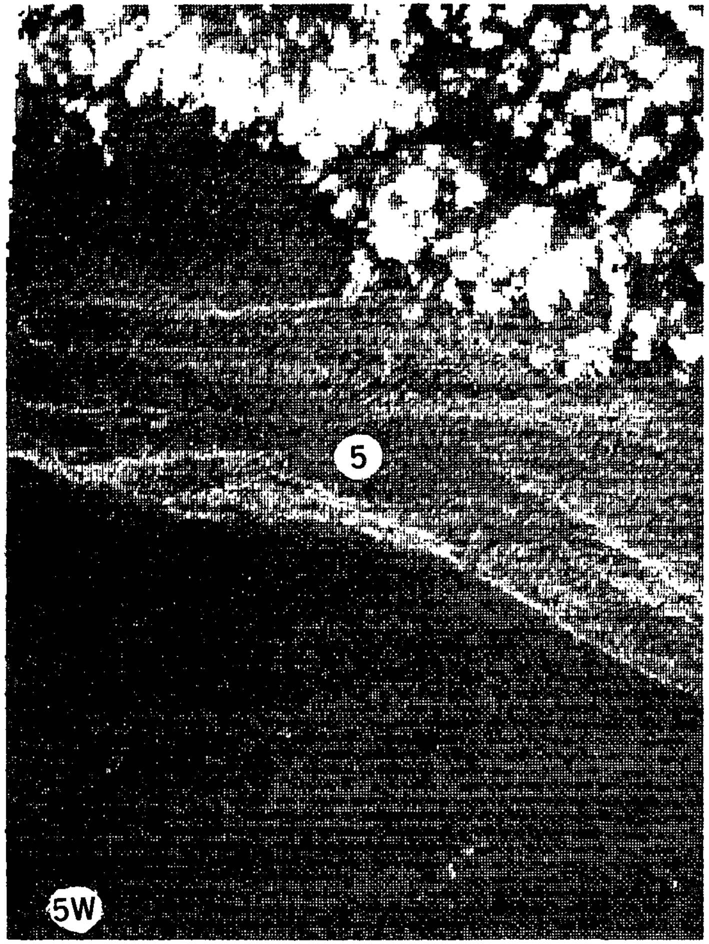


→ = Well site

2,3,4 = Data sites

FIGURE 11 SUBSCENE OF THE IXTOC WELL AND OIL SPILL HEAD

IXTOC (TAIL) HAFTON / CVF03A
VIDEO CHANNEL : 3 TOP LEFT (0, 0) BOTTOM RIGHT (511, 511) DATE: 28-JAN-82 TIME: 20:53:18
DISTRIBUTION : LINEAR INTENSITY INTENSITY LIMITS : 5 TO 18 DOT TEXTURE : COARSE
SCALE 1 : 250000.00 PIXEL SIZE : 59.00 BY 79.00 METRES SECTION : 1



5, 5W = Data sites

FIGURE 12 SUBSCENE OF THE OIL SLICK, 90 km FROM THE WELL

TABLE 11 SPECTRAL RADIANCE AND CONTRAST OF FEATURES ON THE LANDSAT SCENE OF THE IXTOC OIL SPILL

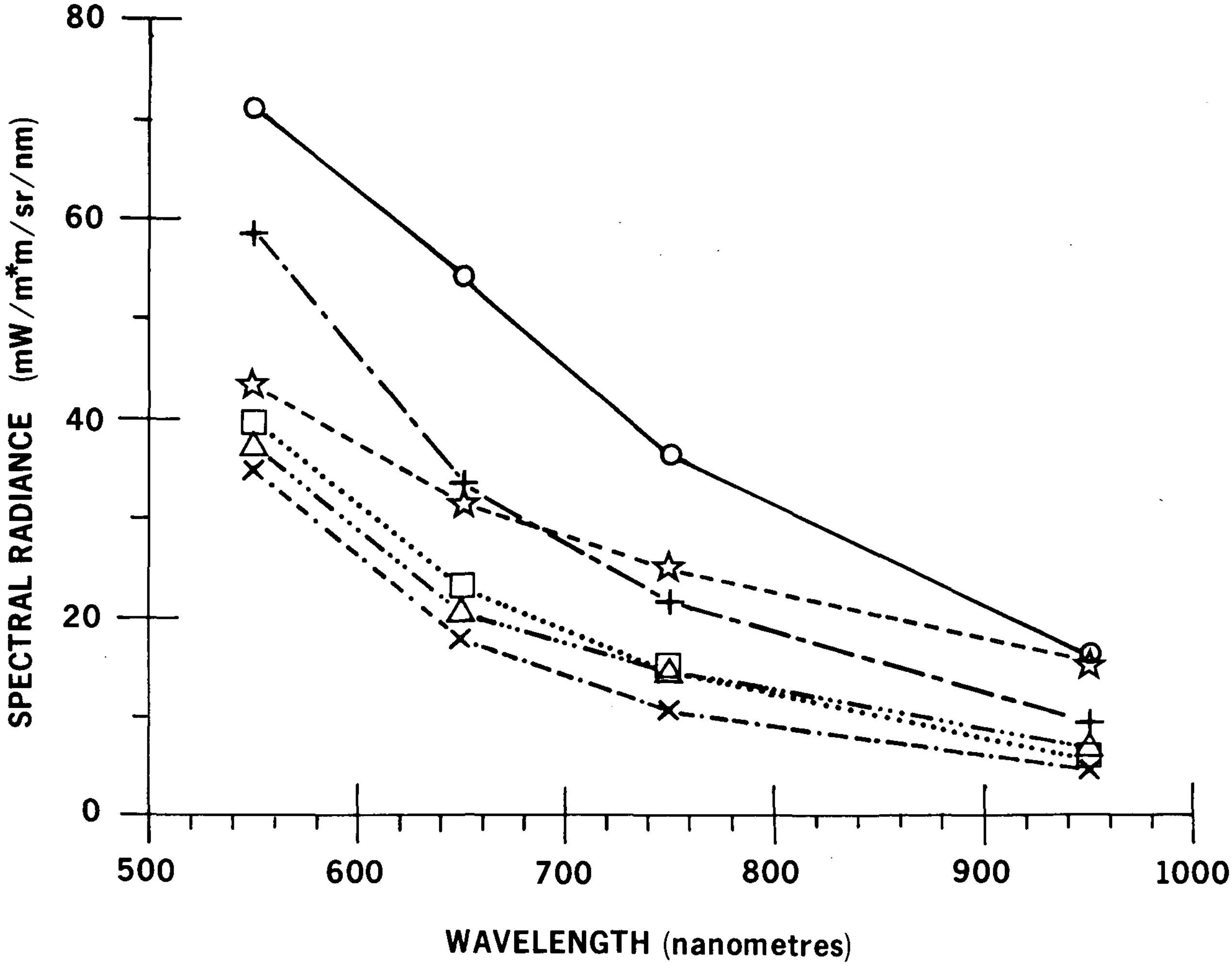
MSS band		4	5	6	7
mean wavelength (nm)		550	650	750	950
band width (nm)		100	100	100	300
Site 1: inorganic sediment discharge	R_λ	71.0	54.0	36.2	15.9
	SE	9.2	7.9	7.5	5.2
Site 2: oil near source, brown colour[a]	R_λ	43.4	31.4	24.6	15.1
	SE	9.6	7.1	7.1	5.3
Site 3: oil near source, blue-grey[a]	R_λ	58.8	33.3	21.4	9.1
	SE	11.5	7.7	7.7	5.0
Site 4: oil near source, brown-blue[a]	R_λ	39.5	22.8	14.4	5.4
	SE	9.7	6.9	7.0	4.5
Site 5: oil at slick tail, windrow appearance	R_λ	36.8	20.5	14.3	6.6
	SE	9.6	7.0	7.4	5.4
Site 5W: water outside of oil slick	R_λ	34.7	17.6	10.3	4.3
	SE	9.4	6.9	7.0	4.1
	Contrast[b]				
Site 1 (inorganics)		0.343	0.508	0.557	0.574
2 (oil)		0.111	0.282	0.410	0.557
3 (oil)		0.258	0.309	0.350	0.358
4 (oil)		0.065	0.129	0.166	0.113
5 (oil)		0.029	0.076	0.163	0.211

a Colour is defined from appearance on Landsat false-colour composite: MSS bands 4, 5, 6 = blue, green, red.

b Contrast is defined as: (T-W)/(T+W) where T is the spectral radiance of the target (inorganics or oil), and W is the spectral radiance of the water at site 5W.

R_λ = Spectral Radiance = $mW/m^2/sr/nm$.

SE = Standard error.



Site	Symbol	Feature
1.	○	Inorganic sediment discharge from river
2.	☆	Oil near source, brown colour *
3.	+	Oil near source, blue-grey colour *
4.	□	Oil near source, brown-blue colour *
5.	△	Oil at slick tail, windrow appearance
5W	×	Water, outside of oil slick

* Colour is defined from appearance on Landsat false-colour composite: MSS bands 4, 5, 6 = blue, green, red

FIGURE 13 FEATURES AT THE IXTOC SITE, FROM LANDSAT may be due, in part, to the decreased absorption of incident radiation by water. Therefore, at longer wavelengths the surface reflection component of the total radiation becomes more prominent with respect to the volume reflection component. Although the contrast appears to be greater at the longer wavelengths where there is also less atmospheric attenuation and path radiance, the data variability also increases. Table 11 shows that the standard error associated with each measure of spectral radiance increases consistently with wavelength. At lower intensities, the magnitude of the standard error approaches that of the mean radiance in the near-IR.

In Figure 13, the shapes of the spectral reflectance curves for all oil, water and sediment targets are very similar. The primary form of distinction is the curve amplitude, which is equivalent to total brightness; however, the sediment curve of site 1, for instance, represents a particular concentration (range) of suspended sediment. Lower concentrations decrease that curve amplitude, producing ambiguity with the curves representing oil targets. Confusion is greatest when any one MSS band is viewed or analyzed. Comparison among several MSS bands, however, allows the detection of small differences in the shape of the curves; this is a better identifying characteristic of targets than the simple measure of brightness in one or all bands, because total brightness is influenced more by factors such as atmospheric variation and illumination intensity than is proportional brightness among the bands.

The technique of examining the quantitive relationship of proportional brightness in a Landsat band, as normalized to total brightness, is called the chromaticity technique and is analogous to the examination of Landsat-derived "colour". Munday et al. (1979) have extensively used this technique for the quantitative measure of suspended sediment concentration from Landsat without need for repetitive in situ sampling. Intera (1981) have recently applied the technique to airborne MSS data of controlled oil spills to characterize the chromatic properties of oil slicks. Using spectral bands not identical to those of the Landsat MSS, variation in oil thickness was found to show no change in colour hue, but strictly in colour saturation (i.e. the "purity" or "whiteness" of the colour).

Following this finding, chromaticity analysis was applied to the IXTOC Landsat data. The chromaticity transform consists of the brightness normalization of MSS bands 4, 5 and 6 (omitting band 7, which contributes the least and contains the most relative noise) by:

$$X = R_4/(R_4+R_5+R_6)$$
$$Y = R_5/(R_4+R_5+R_6)$$

where X and Y are the chromaticity coordinates in the transformed space, and R_i (i = 4, 5, 6) is the (non-spectral) radiance in band "i".

A series of data points (each the average of 24 pixels) has been collected over a gradient of suspended sediment concentrations at site 1. The envelope enclosing the location of the transformed points is shown as locus 1 on Figure 14. The shape and location of this sediment locus well fits those of numerous other sediment loci collected by Munday et al. (1979). Loci for the data taken from the oil sites, as well as from the site of atmospheric variability (6), are also plotted on this figure.

The following may be observed:

a) The atmospheric variability (locus 6) conforms to that experienced by other investigators (Munday et al., 1979); the main axis of this locus is (near-) colinear with the achromatic point E at (0.333, 0.333).

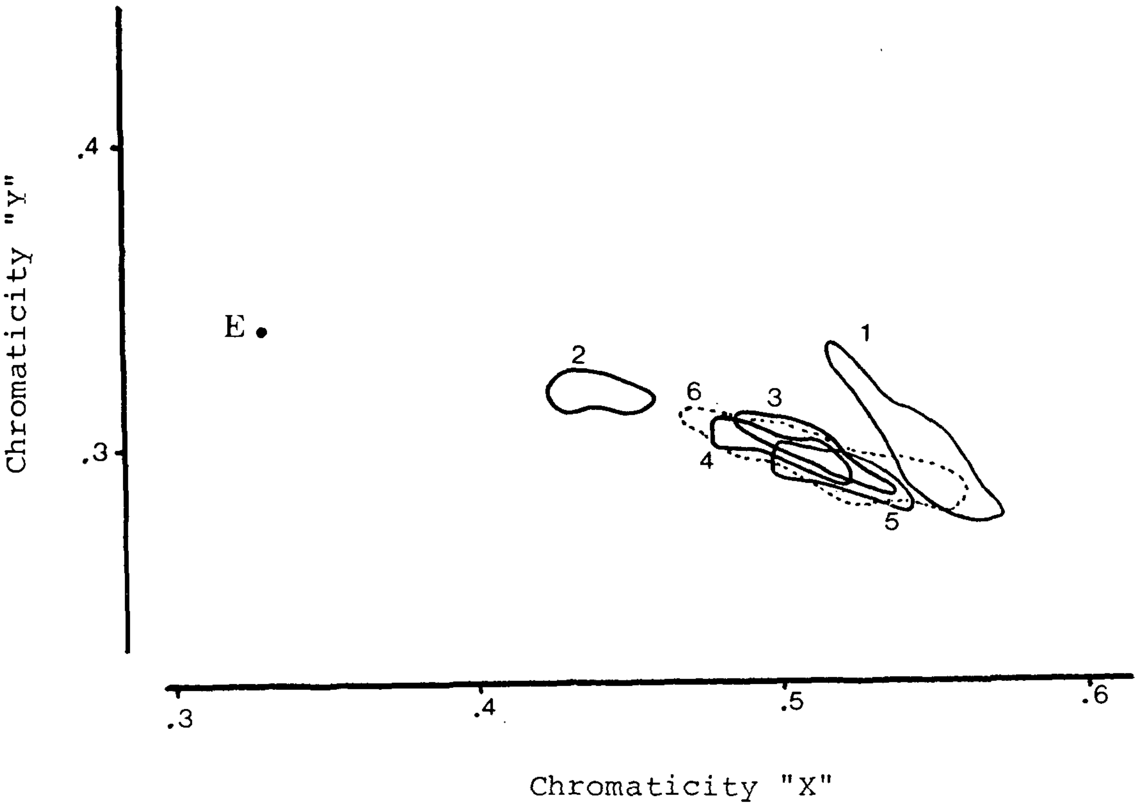
b) The main axis of the sediment locus (1) is parallel to the line on this graph, with a slope of -1.

c) The varying oil data sets completely overlap the variable-atmosphere locus and thus are also (near-) colinear with E.

d) The location at which the oil or atmosphere locus intersects the sediment locus (approximately 0.57, 0.27) is representative of the chromaticity of clear water with no oil, no sediment and minimum haze.

It appears from the above that the findings by Intera (1981) have been confirmed. Even more intriguing is that the chromaticity plane offers a mechanism for separating oil features from inorganic sediment features on Landsat (and similar) multispectral imagery. Thus, sediment plumes as false targets for oil slicks can be distinguished.

Using this method it was determined, for example, that in Figure 4 of Deutsch et al. (1980), which corresponds to the Landsat scene analyzed here, the "sediment" feature identified is actually a wispy cloud formation. To separate oil slicks from clouds, the investigator should not use chromaticity methods but rely on brightness, texture and shape information.



Feature	Description
1	Varying concentration of inorganic sediment
2	Oil near source, brown colour*
3	Oil near source, blue-grey colour*
4	Oil near source, brown-blue colour*
5	Oil at slick tail, windrow appearance
6	Varying atmospheric opacity over clear water

*Colour is defined from appearance on Landsat false-colour composite: MSS bands 4, 5, 6 = blue, green, red

E is the achromatic point (.333, .333)

FIGURE 14 CHROMATICITY REPRESENTATION OF FEATURES AT THE IXTOC SITE, FROM LANDSAT

7.1.2 The KURDISTAN Oil Spill. The oil tanker KURDISTAN suffered ice damage on 5 March 1979, off the coast of Cape Breton Island, Nova Scotia. It subsequently broke apart, spilling approximately 7 000 metric tons of Bunker "C" oil. CCRS flew several sorties with two aircraft and a large complement of sensors. The reports of the airborne remote sensing efforts to search for and map the oil spill are contained in reports by Fingas et al. (1979b) and O'Neil et al. (1980b).

Several satellite images were coincident with the time and location of the oil slick; of these, a few were cloud-free over the oil site. The analyses of these scenes are reported by Dawe et al. (1981). Of the appropriate Landsat images, two were critically analyzed in that report: a Sable Island scene of 25 February 1979, and a Cape Breton Island scene of 13 April 1979.

The Sable Island scene was analyzed by Dawe et al. using density-slicing, contrast-stretching and band-rationing techniques with no conclusive results on the existence of oil. In anticipation that the oil-to-water radiance difference would be no more than about one digital level (6-bit scale) due to the low sun elevation angle of 37°, Intera reanalyzed this Landsat scene (Figure 15), examining the spatial patterns of each digital level in the appropriate brightness range. All four MSS bands were thus examined. Only very vague spatial features, of the size and location to be anticipated in the oil slick, were noted in MSS bands 5 and 6. As found by Dawe et al., the noise in the low end of the brightness scale precluded any definite identification of oil features.

Figure 16 shows the Landsat scene of (a portion of) Cape Breton Island; the subscene of Gabarouse Bay, where the airborne sorties found oil in ice, is shown at full resolution in Figure 17. Dawe et al. (1981) constructed histograms and cluster diagrams for targets of open water, ice and ice/oil mixture. Pure oil spectra were unavailable. Enhancements and classification algorithms were also applied to this subscene, to depict the oil and ice environment. The spectral signatures obtained showed water to be the darkest target in all MSS bands, the oil-and-ice mixture to be brighter, and the pure ice to be the brightest. That is, the impact of the oil is to reduce the reflectivity of the ice.

The brightness domain for these targets had been examined; Intera therefore concentrated on colorimetric properties which are less influenced by solar elevation angle. Figure 17 shows the locations of five sites from which digital Landsat data were extracted. Sites 1 and 3 are of ice, with site 1 showing darker texture due to ice melting. Site 2 is the verified ice and oil mixture. Site 4 is clear water; site 5 is also clear water, but with a hazy cloud overhead.

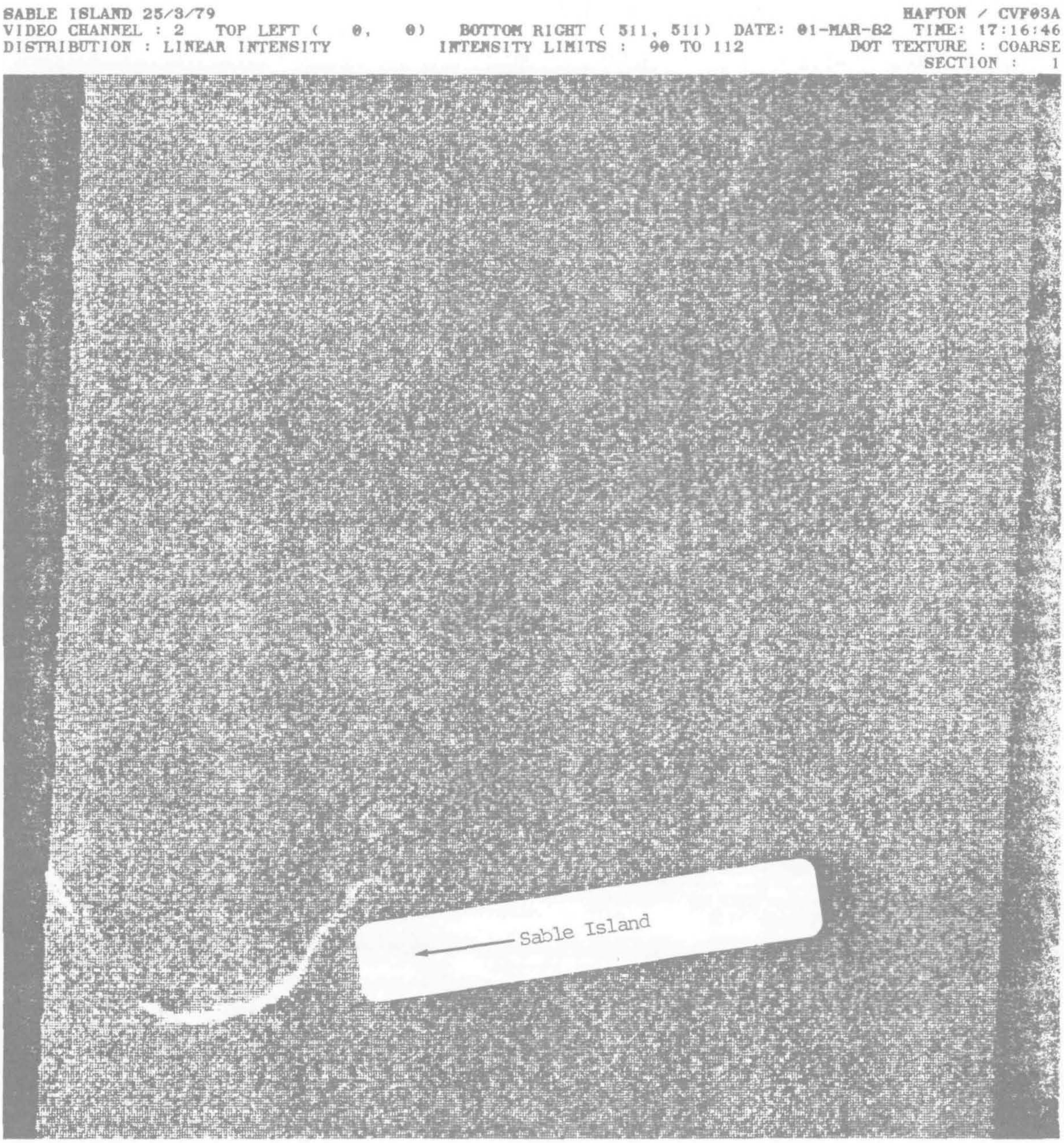


FIGURE 15 LANDSAT SCENE OF SABLE ISLAND, 25 MARCH 1979; MSS BAND 5

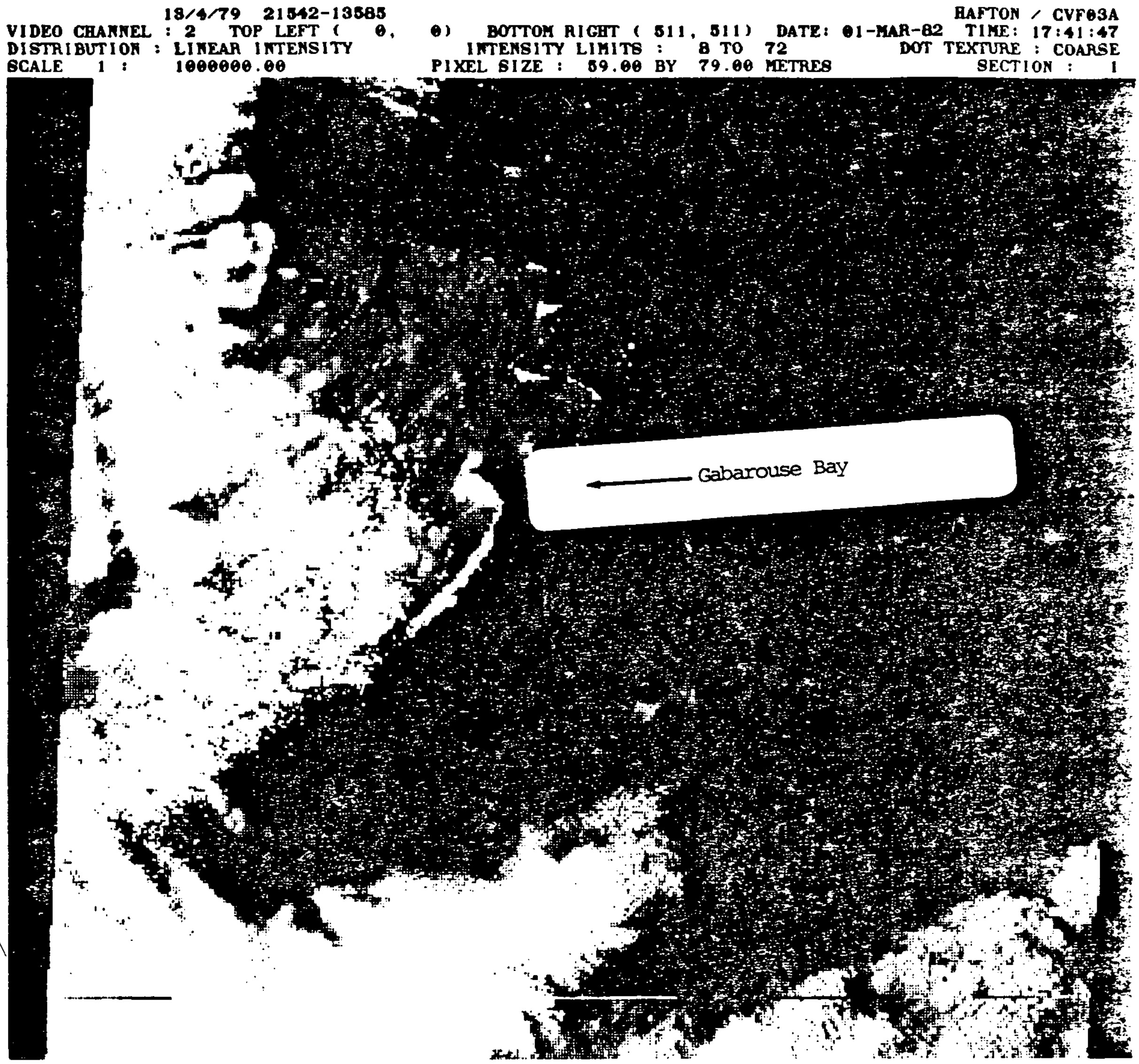
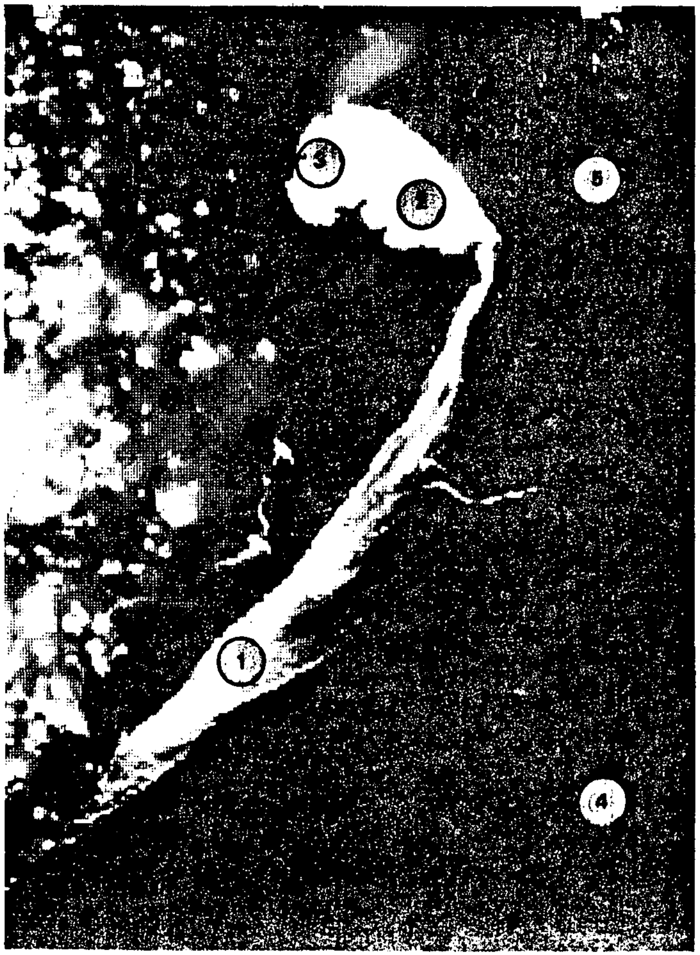


FIGURE 16 LANDSAT SCENE OF CAPE BRETON ISLAND, 13 APRIL 1979; MSS BAND 5

CAPE BRETON ISLAND 13/4/79 HAFTON / CVF03A
VIDEO CHANNEL : 2 TOP LEFT (0, 0) BOTTOM RIGHT (511, 511) DATE: 01-MAR-82 TIME: 17:53:11
DISTRIBUTION : LINEAR INTENSITY INTENSITY LIMITS : 23 TO 114 DOT TEXTURE : COARSE
SCALE 1 : 250000.00 PIXEL SIZE : 59.00 BY 79.00 METRES SECTION : 1



Sites for Data Analysis

1 ice
2 ice and oil mixture
3 ice
4 clear water
5 water and hazy cloud

FIGURE 17 LANDSAT SUBSCENE OF GABAROUSE BAY, CAPE BRETON ISLAND, 13 APRIL 1979

Several data samples were taken from each site, with some averaging performed for each to reduce noise. The digital data were converted to radiance values and then transformed to chromaticity space. The resulting plots in chromaticity space are shown in Figure 18 as envelopes surrounding the data spread for each site. The angular variation of the data about the point E indicates hue; the radial distance from E depicts colour saturation.

Atmospheric variability over a homogeneous water target is confirmed to be a radial (in the direction of E) change, as described by Munday et al. (1979), and also as found on the IXTOC scene analyzed in the previous section. The oil target seems to produce no change in hue from the pure water target, but desaturates (radial shift towards E) the colour designation of water. The same was found on the IXTOC scene. A slight hue change (angular shift about E) is indicated between the pure ice and the ice/oil targets, but this single data set is not sufficient to offer general comments about the possibility of ice and oil separation using chromaticity methodology. Without the verification of the existence and location of the oil by other means, neither the techniques used by Dawe et al. nor the chromaticity analysis used here would be sufficient to make positive identification of oil in this Landsat scene.

7.1.3 The Scott Inlet Oil Seep. The possible existence of a natural oil seep at the mouth of Scott Inlet on Baffin Island was reviewed and studied by Kirby (1979) on three Landsat scenes: 19 September 1977, 28 August 1976, and 14 August 1975. The two additional complicating factors for detecting oil slicks in the Arctic are the generally lower sun angles and the presence of ice.

Kirby found an "anomalous feature" at the mouth of Scott Inlet and examined it in detail, in both the brightness domain and chromaticity space. Due to the fact that the anomalous feature was defined by a single digital level (8-bit) and was distinct from the water background by a single digital level, the quantity of and confidence in the data were very limited. This resulted in very tentative speculations on the likelihood of hydrocarbons comprising the feature.

Kirby's work has been repeated here, to discern whether more detail or firmer conclusions can be generated. Of his three Landsat scenes, only that of 19 September 1977 contains this anomalous feature; therefore, this one scene (Figure 19) has been analyzed in greater detail. Data have been taken from the five locations shown in the figure. Site 1 contains the oval-shaped anomalous feature; site 2 is a cloud formation of

Site	Feature
1	ice
2	ice and oil
3	ice
4	clear water
5	water and hazy cloud

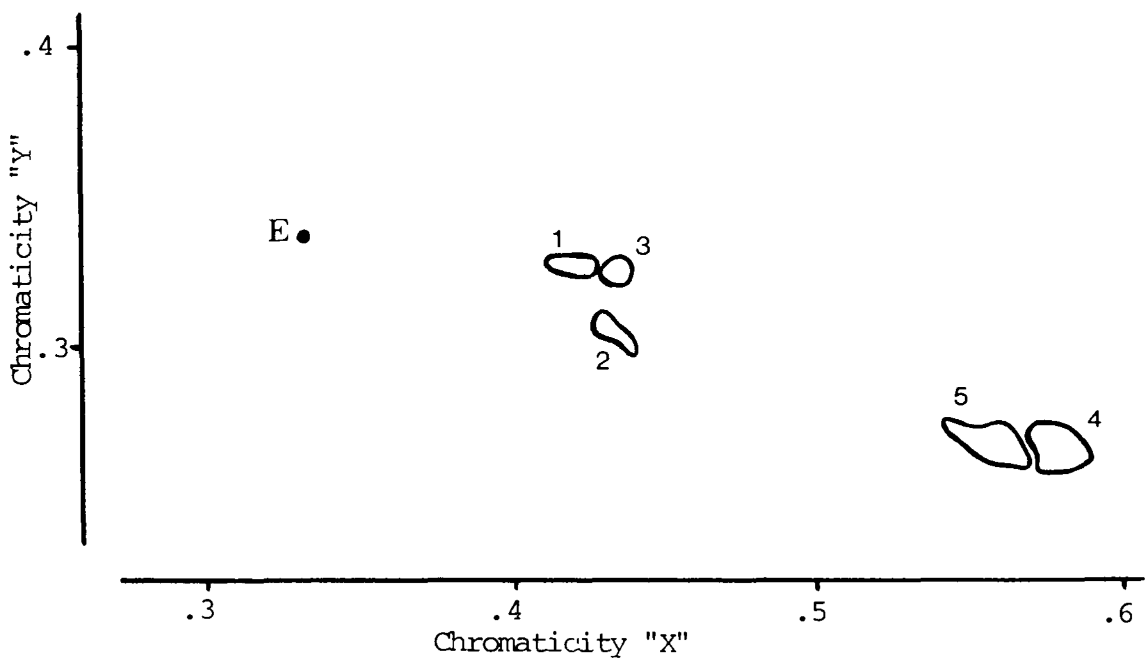
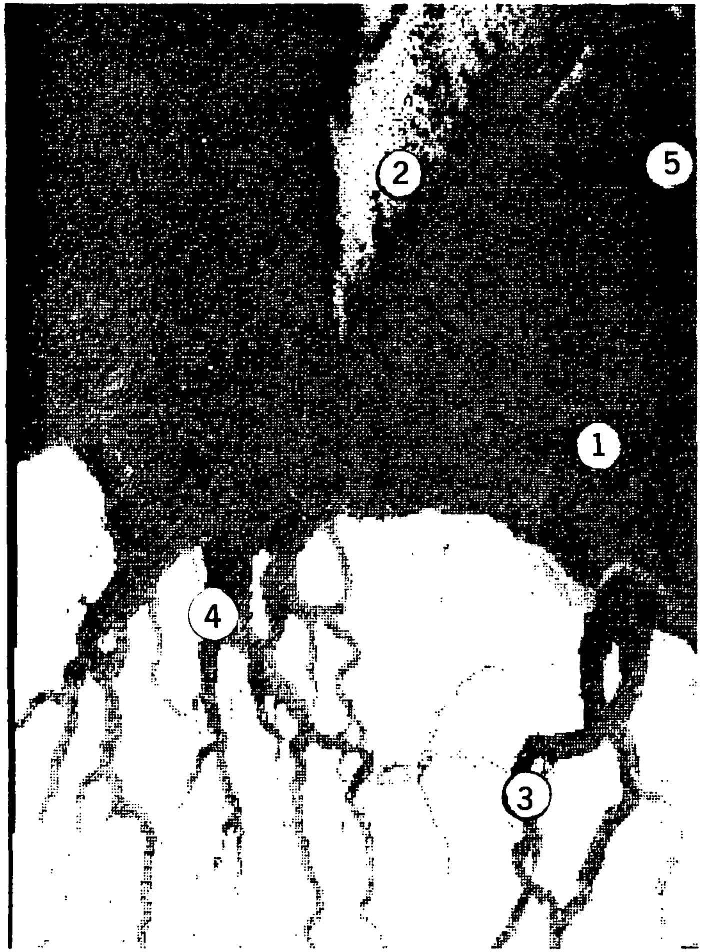


FIGURE 18 CHROMATICITY TRANSFORM OF LANDSAT RADIANCES OF SELECTED FEATURES IN THE GABAROUSE BAY SUBSCENE OF 13 APRIL 1979

SCOTT INLET 19/9/77
VIDEO CHANNEL : 1   TOP LEFT (0,   0)   BOTTOM RIGHT (511, 511) DATE: 28-JAN-82
DISTRIBUTION : LINEAR INTENSITY   INTENSITY LIMITS : 18 TO 23
PIXEL SIZE : 59.00 BY 79.00 METRES



Site	Feature
1	Anomalous feature
2	Variable opacity cloud
3	Inorganic suspended sediment
4	Inorganic suspended sediment
5	Clear water

FIGURE 19   LANDSAT SCENE OF SCOTT INLET, BAFFIN ISLAND; 19 SEPTEMBER 1979

variable opacity; sites 3 and 4 are inorganic sediment loads in nearby rivers (unconfirmed); and site 5 is of clear water.

The chromaticity technique depends on target variability to define a locus shape; therefore, the minimum data range offered by the anomalous target is not sufficient to produce confidence in the results. It has been observed that, whatever the nature of that target (site 1), it is: a) of low concentration; b) of low brightness range; c) of low colorimetric variability; and d) at least equally probable that it is inorganic sediment, as hydrocarbon in nature. The other two scenes of the two previous years provided no similar anomalous features, nor was there any target at the mouth of Scott Inlet other than water and inorganic sediment.

7.2 Appendix B: Analyst Contacts

Prince Albert Satellite Station (LANDSAT, NOAA)
P.O. Box 1150
Prince Albert, Saskatchewan
S6V 5S7
Telephone: (306) 764-3602, 764-4259
Telex: 074-2942 TWX: 610-751-1296

Fast Reaction Unit (CIAS)
Mr. Paul Hession
Mr. J.C. Henein
Canada Centre for Remote Sensing
2464 Sheffield Road
Ottawa, Ontario
K1A 0Y7
Telephone: (613) 993-0121
Telex: 053-3777

User Assistance and Marketing Unit (General)
Canada Centre for Remote Sensing
717 Belfast Road
Ottawa, Ontario
K1A 0Y7
Telephone: (613) 995-1210

Customer Relations (LANDSAT)
EROS Data Center
Sioux Falls, South Dakota 57198
Telephone: (605) 594-6511
TWX: 910-668-0310
Facsimile: (605) 594-6589

Satellite Data Laboratory and Aerospace (NOAA)
Meteorology
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
Telephone: (416) 667-4818

Satellite Specialists, Forecast Operations (NOAA)
Atmospheric Environment Service
Environment Canada
6325 - 103 Street
Edmonton, Alberta
T6H 5H6
Telephone: (403) 438-4356

7.3 Appendix C: Order Forms and Price Lists for Satellite Products

The following pages contain order forms and price lists for satellite products pertinent to surveillance and monitoring of oil spills in Canadian waters.

SATELLITE IMAGERY PRICE LIST (LANDSAT/NOAA/SEASAT SERIES)
Effective June 1, 1982

IAGE ZE	TYPE	SCALE	FORMAT	B&W	COLOR*
5mm	MSS	1:1,000,000	Paper	31.50	52.00
5mm	RBV	1:500,000	Paper	31.50	
5mm	NOAA/TIROS	Any	Paper	16.00	
5mm	NOAA/TIROS	Any	Film Pos.	19.00	
1mm	NOAA/TIROS	Any	Paper	26.00	
2mm	NOAA/TIROS	Any	Paper	45.00	
1mm	MSS	1:500,000	Paper	77.00	144.00
1mm	RBV	1:125,000	Paper	77.00	-
2mm	MSS	1:250,000	Paper	135.00	270.00
2mm	RBV	1:125,000	Paper	135.00	-
0mm	MSS	1:3,369,000	Film Pos.	66.00	
0mm	MSS	1:3,369,000	Film Neg.	99.00	
5mm	MSS	1:1,000,000	Film Pos.	38.00	85.00
5mm	RBV	1:500,000	Film Pos.	38.00	-
1mm	MSS	1:500,000	Film Pos.	96.00	173.00
1mm	RBV	1:250,000	Film Pos.	96.00	-

COMPUTER COMPATIBLE TAPES

PE	TRACKS	BPI	FORMAT	PRICE
Band MSS	9	1,600	Tape set	755.00
CS	9	1,600	Tape	755.00/475.00
AA (5 Bands)	9	1,600	Tape Set	100.00
ASAT	9	6250/1600	Tape Set	250.00

Microfiche

Yearly Subscription

Tracks	Price
1	60.00
10	500.00
20	850.00
50	1500.00
90	2200.00

Fax*

$ 32.00/Image
$ 120.00/Day (limit of 4 Images/day)
$ 3550.00/Month (up to 130 images)
$ 40,500.00/Year (up to 1500 images)

SPECIAL SERVICE CHARGES

*Colour Master Generation required if not in archive add $100.00
Handling charges: $15.00 per order

DELIVERY AND HANDLING

1. Postage extra to customers outside Canada
2. Registred mail and special delivery charged directly to customer.
3. Courier services charged directly to customer.

ders in escess of 1500 images are to be referred for pricing.
ease note: Prices are subject to change annually on 1 April.