The utility of SKYLAB photo-interpreted earth resources data in studies of marine geology and coastal processes in Puerto Rico and the Virgin Islands

by
James V. A. Trumbull

1975

Original photography may be purchased from:
EROS Data Center
10th and Dakota Avenue
Sioux Falls, SD 57198

ERRATUM SHEET

For the Final Report under Skylab EREP Project 409, NASA P. O. Number T-4658B, titled "The utility of SKYLAB photo-interpreted earth resources data in studies of marine geology and coastal processes in Puerto Rico and the Virgin Islands." Prinicipal Investigator, James V. A. Trumbull, U. S. Geological Survey, Box 5917, Pta. de Tierra Station, San Juan, Puerto Rico 00906

Title page. -- Add "1975".

Page 4. -- Add at bottom of page "A log of all field operations is given in Appendix A."

Page 5, PP2, line 5. -- Change "234 kilometers (126 nautical miles)" to "234 nautical miles (432 kilometers)".

Page 6. -- Change "frequencies" to "wavelength" in PP1 line 7, and change "Frequency" to "wavelength" in PP2 line 4 and in the table heading.

Page 7. -- At top of page, change "frequency" to "wavelength".

Page 13, PP2, next-to-last line, change "does" to "is".

Page 18, PP1, line 2, third word, change "bathymetry" to "turbidity".

Page 21, last line, change "quality" to "qualify".

Page 23, third line from bottom, change "Pass 85" to "Pass 54".

Page 24, PP2, lines 1, 7 and 9, change "0.6-0.7" to "0.7-0.8".

Page 36, PP3, lines 5 and 6, change "herringbone" to "instrumentally-caused ".

Figure 14 title, following page 40, PP2 line 2, change "62,00" to "62,000".

Page 41. Please unbind the report, discard page 41, and replace it with the new page 41 attached to this list.

Figure 15 title, following page 44, check that line 2 of text begins with "62,000".

Figure 17 title, following page 48, last PP, line 2, change "images" to "image".

Page 50, PP2 line 8, change "longer" to "shorter".

Page 55, PP2 line 7, insert the numerals "53" between "(following page" and the close-parentheses mark.

Page 56, PP1 line 4, change "northeastward-trending" to "northwestward-trending".

Page 61, PP3 line 2, change "west" to "coast".

Appendix page A-2, last PP line 2, change "is" to "in".

-0-

COVER PAGE

Title of investigation: Determination of marine and coastal processes on the Puerto Rico - Virgin Islands Platform.

Title of final report: The utility of SKYLAB photo-interpreted earth resources data in studies of marine geology and coastal processes in Puerto Rico and the Virgin Islands.

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Investigation of SKYLAB EREP data

The utility of SKYLAB photo-interpreted earth resources data in studies of marine geology and coastal processes in Puerto Rico and the Virgin Islands

by
James V. A. Trumbull

Final report under EREP Project 409, NASA P.O. Number T-4658B

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THE UTILITY OF SKYLAB PHOTO-INTERPRETED
EARTH RESOURCES DATA IN STUDIES OF
MARINE GEOLOGY AND COASTAL PROCESSES
IN PUERTO RICO AND THE VIRGIN ISLANDS

ABSTRACT

Three Skylab earth-resources passes over Puerto Rico and St. Croix on 6 June and 30 November 1973 and 18 January 1974 resulted in color photography (Earth Terrain Camera) and multispectral photography and scanner imagery that contains a wealth of data useful in a number of fields of study. Bathymetric detail to a limiting depth of 84 feet (26 meters) is well-shown in clear-water areas and could be used to make contoured charts by means of image-enhancement techniques and some field control. Bathymetric and turbid-water features are differentiable by use of the multispectral data. The photography allows mapping of coral reefs, offshore sand deposits, areas of coastal erosion, and patterns of sediment transport. Bottom-sediment types could not be differentiated. Patterns of bottom-dwelling biologic communities are well portrayed but are difficult to differentiate from bathymetric detail.

Much detailed information on patterns of coastal surface water currents can be readily extracted from images taken at times of high water turbidity. Anomalous large-scale offshore-oriented plumes undetected by other means appear on the photography.

Effluent discharges and oil slicks are readily detected and are differentiated from other phenomena by the persistance of their images into the longer-wavelength multispectral bands. Light aircraft used for observation and photography are judged more cost-effective than high-

altitude aerial photography as an aid in interpreting orbital imagery. The Skylab data make up a valuable benchmark inventory of a variety of coastal conditions that will be of great future value in the study of slowly time-variant phenomena.

More rapidly time-repetitive orbital-height photography of Skylab quality is urgently needed for a wide variety of studies. Information that can be derived from Skylab-quality orbital-height photography could be of great value in scientific and in more immediately practical studies of the coastlines of the less-developed areas of the earth.

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INTRODUCTION

The advent of earth-orbital satellites creates the responsibility to investigate by all available means the uses to which orbital earth-sensing data can be put. Only through the application of a broad spectrum of investigative techniques can the sensor design and output utilization of earth-sensing systems be optimized.

This report describes and evaluates the utility of Skylab photography (S190A and S190B cameras) and multispectral scanner imagery (S192) in marine and coastal studies in a clear-water tropical area.

The report is predominantly concerned with Puerto Rico. This is because orbital tracks and sensor acceptance angles were such that of the Virgin Islands, only the western part of St. Croix was imaged, and that only by the S190A multispectral cameras. Fortunately, however, all of Puerto Rico was photographed by both the S190A multispectral cameras and the S190B earth terrain camera. The island is about 178 kilometers (96 nautical miles) long, but the swath-width of the narrower-angle camera, the S190B earth terrain camera, is only 109 kilometers (59 nautical miles). Complete photographic coverage of Puerto Rico came about because during Skylab-2 photography the satellite was some 135 kilometers (73 nautical miles) west of its nominal fixed track, but later during Skylab-4 photography the satellite was on its nominal track. The fortuitously complete coverage of Puerto

Rico came about also because the Skylab's track azimuth was about 137 degrees true, or southeastward, over an island oriented east-west. Thus the image of the island lies diagonally across the image format.

Puerto Rico is big enough (3435 square statute miles) and high enough (maximum elevation 1338 meters, or 4390 feet) to have considerable precipitation and river runoff. Thus river-mouth plumes and coastal zones of sediment-laden water prevail, and they are conspicious on the satellite imagery. They have considerable potential as indicators of near-shore coastal currents, knowledge of which has considerable practical importances in matters of coastal erosion and effluent dispersal. Repetitive coverage closely spaced in time would be necessary for their detailed study, however.

Puerto Rico is surrounded and connected to the northern Virgin Islands by an insular shallow-water shelf much of which is less than 30 meters deep. The predominantly coralline sand on the shelf, especially east, south, and west of the island, has high light reflectance. A wide variety of shoals, sand waves, and other features of bottom topography is thus prominent in the images made by light of wavelengths that penetrate water.

The coastal environment of Puerto Rico is highly stressed. The island is heavily populated and heavily industrialized. Most bulk cargoes are moved by sea, and considerable dredging of channels and harbors has been done. Coastal erosion is a severe problem. The resolution of Skylab's imagery is inadequate for direct studies of coastal erosion, but a number of what seem clearly to be oil slicks were detected, and the imagery is of great value as a benchmark record of the coastal status of the entire island.

Methods of interpretation have been those of classical direct photo-interpretation. In general, third-generation transparencies were studied through a wide-field microscope at 10 diameters magnification. Enhancement of photographic images by such techniques as density slicing, microdensitometry, and the use of additive viewers has not been done. Applications of such techniques to this imagery would result in further information extraction, particularly by comparing line microdensitometry profiles with bathymetric profiles as an aid in differentiating bathymetric and turbid-water images, and in comparing density-sliced images showing bathymetric detail with actual contours of bottom topography. It is hoped that such work can be done when time allows. Computer ratioing of various bands of the multispectral scanner (S192) imagery in this area to compare with known bathymetry is being done by Fabian C. Polcyn of the Environmental Research Institute of Michigan.

A copy of National Ocean Survey nautical chart No. 920[1/] covering Puerto Rico and the Virgin Islands is to be found in the pocket at the end of this report. It is for use in locating place-names and giving an overall concept of the extent of shallow-water areas around Puerto Rico and the Virgin Islands.

1/ Recently renumbered to No. 25640

DATA SOURCES

The Skylab Earth Resources Experiment Package (EREP) made data passes over the Puerto Rico - Virgin Islands area three times, as follows:

	Pass	Date	Local time
Skylab 2	6	9 June 73	1116
Skylab 4	54	30 Nov 73	1243
Skylab 4	85	18 Jan 74	1649

Puerto Rico's skies are only infrequently wholly clear of clouds, and partial cloud cover prevails. We were fortunate that of the three Skylab passes that imaged Puerto Rico, only 15 percent of the coastline was obscured by clouds and shadows on 9 June 1973, and 35 percent was obscured both on 30 November 1973 and on 18 January 1974.

Other data sources were 1) Multispectral photography by a NASA WB57F aircraft at a nominal radar-determined flight height of 62,000 feet (18,900 meters) of all Puerto Rican (excepting the Isla de Mona) and nearly all Virgin Islands coasts; 2) Light-plane flights at altitude ranging from 1500 to 12,000 feet (457 to 3660 meters) of all the Puerto Rican and St. Croix coast for visual observation and photography by 35-mm hand-held cameras; and 3) ship-bourne measurement of color, transparency and temperature, and sampling for laboratory determination of salinity and amount of suspended sediment of coastal and oceanic waters near Puerto Rico. In addition, all Earthsat-1 images of Puerto Rico were on hand, as was an extensive collection of bathymetric data on the Puerto Rico and Virgin Islands shelf.
A log of all field operations is given in Appendix-A

EREP sensors used were the S190A Multispectral Photographic Camera, the S190B Earth Terrain Camera, and the S192 Multispectral Scanner. Brief technical descriptions of them follow. More detailed information on Skylab instrumentation may be found in two reports by NASA (1972, 1973), and on the RB57F instrumentation in another NASA report (1971).

The Multispectral Photographic Camera (S190A) is an array of six boresighted high-precision cameras with matched f/2.8 lenses of 6-inch focal length and an angular field of view of 21.2°. The cameras use 70-mm film with an image size of 2-1/4 inches. From the Skylab orbital height of 234 nautical miles (432 kilometers) the images cover a square on the earth's surface 88 nautical miles (137 kilometers) on a side. Nominal original scale of the photographs is 1:2,860,000. Film-filter combinations and resulting pass-bands of the six cameras were as shown in the following table (wavelengths in micrometers). Design resolution ranged from 78 to 223 feet depending on light frequency and image contrast.

Camera Station	Film	Filter Transmittance	Pass-band	Color
1	EK2424	0.7-0.8	0.7-0.8	IR B-W
2	EK2424	0.8---	0.8-0.9	IR B-W
3	EK2443	0.5---	0.5-0.88	IR Color
4	SO356	0.4---	0.4-0.7	Color
5	SO022	0.6---	0.6-0.7	Green-yellow
6	SO022	0.5-0.6	0.5-0.6	Visible red

The Earth Terrain Camera (S190B) is a single camera approximately boresighted with the S190A cameras. The lens is f/4 and has a focal length of 18 inches; the angular field of view is 14.24°. The camera uses 5-inch film and has an image size of 4-1/2 inches square. The image covers a square on the earth's surface 59 nautical miles (109 kilometers) on a side. Film used was S0242 high-resolution color film and the wavelength from 0.4 to 0.7 micrometers were recorded. The design resolution of roughly 15 meters for that film was achieved on at least the original transparencies; the resolution of succeeding generations was degraded. Transparencies used in this study were third generation.

The Multispectral Scanner (S192) generated line-scan images formed by reflected and emitted radiation in 13 discrete spectral intervals of the visible, near-infrared, and thermal-infrared frequencies. The wavelength (in micrometer) of each recorded spectral interval was as follows:

Band	Wavelength
1	0.41 to 0.46
2	0.46 to 0.51
3	0.52 to 0.56
4	0.56 to 0.61
5	0.62 to 0.67
6	0.68 to 0.76
7	0.78 to 0.88
8	0.98 to 1.08
9	1.09 to 1.19

Band	Wavelength
10	1.20 to 1.30
11	1.55 to 1.75
12	2.10 to 2.35
13	10.20 to 12.5

Recordings were made from the forward 110° portion of a conical scan with a rate of 94.79 scans per second. The width of the instantaneous field of view on the ground was 260 feet (79 meters). Swath width was about 39 nautical miles (72 kilometers). Single-band black and white reconstructed imagery was used in this study.

The high-altitude aircraft support operation flown at 62,000 feet (18,960 meters) as flights 5 and 6 of Mission 260 by a WB57F (NASA 925) on 16 and 17 January 1974 employed a Wild-Heerbrugg RC-8 metric mapping camera with a lens of 6-inch focal length and 9-inch square-format color film (SO397) with a spectral coverage of 0.4 to 0.9 micrometers; a Zeiss aerial mapping camera with a 12-inch lens using 9-inch color infrared film (EK 2443) with a spectral coverage of 0.4 to 0.72 micrometers; and a multispectral array of six Hasselblad 500EL cameras of which five were equipped with 80-mm focal-length lenses. The sixth Hasselblad had a 40-mm lens and the film from it was for the use of the Mission Manager in determining navigational accuracy and cloud cover. Film-filter combinations in the 5 Hasselblads and the resulting frequency pass-bands were as follows:

Camera	Film	Filter	Pass-band	Color
1	EK2402 1/	25	0.6---	Red
2	EK2402	57	0.48-0.58	Green
3	EK2424	89B	0.7-0.89	Infrared
4	EK2402	21+59	0.54-0.6	Green-orange
5	EK2402	12+57	0.52-0.58	Green

1/ Plus-X Aerographic film

The RB57F was also fitted with a Texas Instruments RS-7 single-channel infrared scanner sensing wavelengths from 0.7 to 14 micrometers, but the resulting film was too dark and had streaking, banding, and static; it was not used in preparing this report.

Light-plane observation and photography from altitudes between 1500 and 12,000 feet (457 and 3660 meters) resulted in notes and sketches of observed features on a variety of base maps, mostly nautical charts, and in Kodachrome-X oblique color transparencies taken with 35-mm hand-held cameras with wide-angle (29mm and 35mm focal length) lenses.

Ground-truth was gathered from the 65-foot (20-meter) research vessel "Jean A", owned and operated by the Department of Natural Resources of the Commonwealth of Puerto Rico. The cooperation of the vessel's operators and crew is gratefully acknowledged.

At each water station, water color was measured on the Forel scale, transparency was measured by Secchi disc, and bucket temperature was measured by thermometer. Samples were taken for later laboratory measurement of salinity (kindly provided by the Oceanographic

Studies Program of the Puerto Rico Department of Natural Resources) and of amount of suspended sediment. Analyses of amount of suspended sediment were by standard methods (Manheim etal., 1970), and yielded results in milligrams of suspended material per liter of sea water.

SKYLAB EREP DATA EVALUATION

Multispectral Photographic Camera (S190A)

Pass 6, 9 June 73.-- S190A image coverage for this pass is shown in figure 1, and the images are reproduced in figure 2. On the color infrared film the open ocean shows linear streaks probably caused by near-surface Langmuir cells that are parallel to the local winds, which were from about 080° on the north side of Puerto Rico and 120° on the south side. On frame 180, the Isla Desecheo (see NOS Chart 920, infolded in pocket, for location of all geographic names) shows a prominent down-wind wake about 8 nautical miles (15 kilometers) long. The wind velocity there at the time was probably in the range 15-20 knots. It may be assumed from the wind-parallel orientation of the wake, the fairly high wind velocity, and the lack of parallelism between the wake and the prevailing currents in the area that the wake was caused by the wind, not currents.

A boundary between waters of different reflectance characteristics shows as a sharp demarcation line oriented east-west to the west of the Punta Cadena, near the western tip of Puerto Rico. Its shoreward end is roughly 4 nautical miles (6 kilometers) west of Punta Cadena, and it extends westward about 25 nautical miles (46 kilometers), passing about 5 nautical miles (9 kilometers) south of the Isla Desecheo. At its western end its identity is lost in a confused pattern of water-mass boundaries. The apparent color of the water-mass north of the demarcation line is lighter than that to the south, and is similar to that south of Puerto Rico. This albedo difference is probably not caused

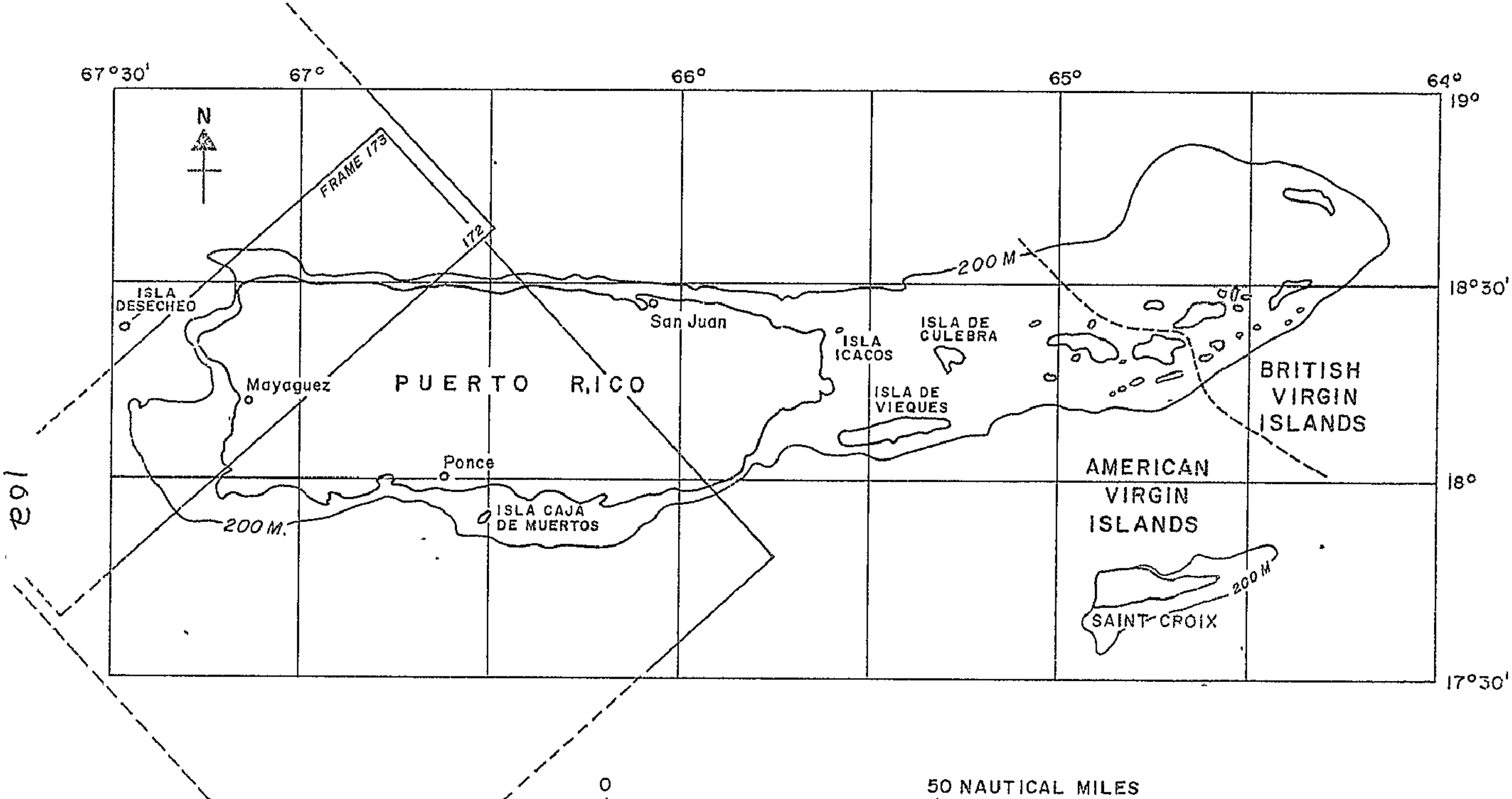


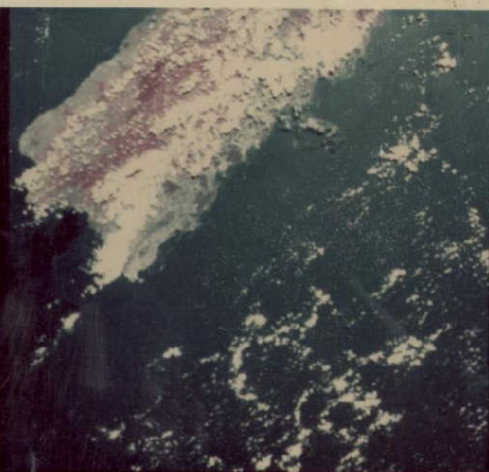
FIGURE 1 COVERAGE DIAGRAM, S190A, SL-2, PASS 6.

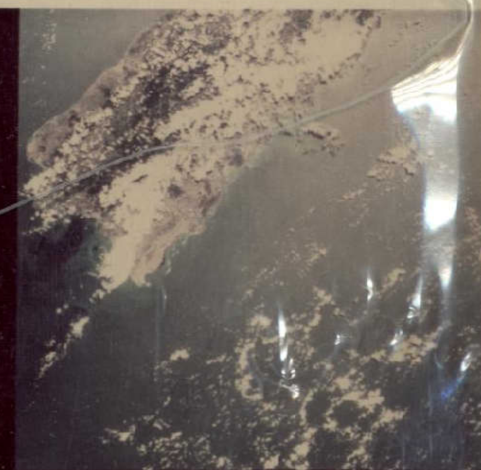
Note that frame numbers for color IR and color are not those shown here. Their correct frame numbers may be determined by adding 8 to the frame number shown

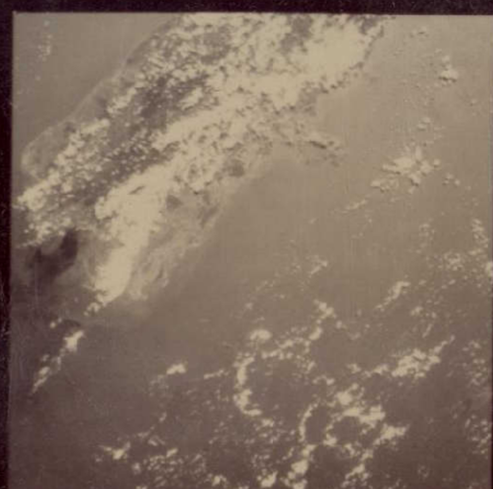
Example: 172 + 8 = 180

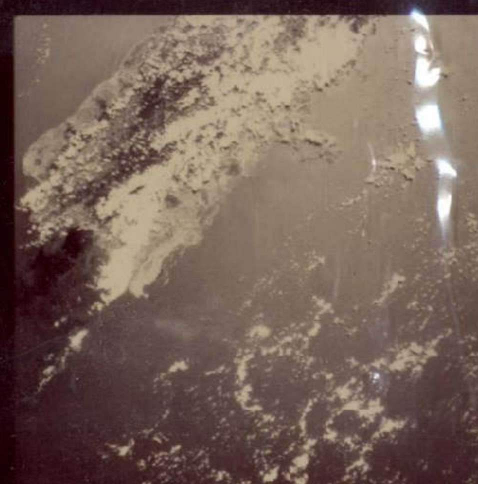
Figure 2 (following page).-- S190A multispectral camera imagery from frame 173 (frame 181 of color and color infrared), Pass 6.

North is to the upper left in each photograph. The upper left image is color infrared and shows the effluent area called the great blue anomaly well, turbid water less well, and bathymetry rather poorly. Water penetration depth is about 50 feet (15 meters). The upper right image is plain color, and shows considerably more turbid-water and bathymetric detail than the color infrared; water penetration is 60 to 65 feet (18 to 20 meters). The center left image is the 0.5-0.6 micrometer band and shows water penetration of 60 to 65 feet (18 to 20 meters). The center right image is the 0.6-0.7 micrometer band; it is superior to the preceding bands in rendition of the effluent area. The lower left image is the 0.7-0.8 micrometer infrared band. In this reproduction differentiation only between land and water is seen, but on the original transparency the great blue anomaly is clearly seen. The lower right image is the 0.8-0.9 micrometer infrared band, which shows shoreline details less well than the preceding band, but which on the original transparency also shows the great blue anomaly.









10c

by a higher sea state north and south of Puerto Rico, though the fetch is much greater there than in the wind-shadow west of the island. A boundary caused by sea-state differences would not be so sharp. Nor is the albedo difference likely to be caused by differences in suspended sediment, for suspended-sediment values (measured on three cruises some months later but with consistent results) are as low in the vicinity of the Isla de Mona, in the darker-colored area, as they are in the open sea north of Puerto Rico away from the influence of land, where the color is lighter.

It is thought most likely that the darker color generally downwind of Puerto Rico is caused by a diffusion of small amount of oils from industrial and domestic wastes that are discharged into the Bahia de Mayaguez.

In the Bahia de Mayaguez itself is the most striking features on any of the Skylab images. An intensely dark blue, almost black, area occupies much of the Bahia. It is most strongly developed just offshore from the city of Mayaguez, in and downwind of an area of known discharge of oily waste water from tuna-packing plants and other industries. The boundary of the deep blue-colored area on the south is exactly at the location of a reef edge: depths in the lighter-colored area to the south are generally in the range 15 to 25 feet (5 to 8 meters), while depths in the deepest blue area are on the general order of 600 feet (183 meters). The depth and intensity of blue in the dark blue area is clearly not a simple function of depth, however, for nearby areas of far deeper water are not at all such a deep blue color, and the waters of the Bahia de Mayaguez were highly polluted that day.

The deep blue area is bounded and intruded on the north by extremely light-colored water, and the nature of the boundary between them in interdigitating. This light-blue area seems clearly to be a sediment plume from the Rio Grande de Añasco, for it is centered on it, extends downwind from it, and was photographed from low altitude on the same day. It had rained heavily in its valley prior to the Skylab pass - as it had not, incidentally, along Puerto Rico's north and south coasts, where only small river-sediment plumes were visible.

It seems clear that the anomalously deep blue area is caused by some effluent on the surface of the water that changes the water's spectral reflectance. This is substantiated by the presence in shoal-water light-colored areas nearby to the south of long, narrow lineations that also register as dark blue. They are distinctive in form and are generally known as oil slicks, though it is not known whether they are of direct organic origin, or pollution. They are commonly seen in the Bahia de Mayaguez, and were observed there earlier on the same day the Skylab images were made. Numerous dark blue patches and streaks close to the city of Mayaguez are also probably oil slicks; many were observed in that area earlier in the day.

Color variations within the light-blue area south of the anomalous dark blue area and north of the prominant cloud mass that obscures some of the western coastline compares fairly well with the known bathymetry of the area, but the details are sharper and the correspondence between image color and actual depth is closer on both the S190A and the S190B color images than on the color infrared image. This substantiates the general finding (Lukens, 1968; Helgeson, 1970; Kelly and Castiglione, 1970; Berryhill, 1969, and others) that color photographs result in better water penetration because wavelengths below 0.5 micrometers, in the spectral region where water penetration is greatest, do not appear on the color infrared images.

A linear light-colored zone oriented about 100° true just northwest of the cloud mass that obscures the coastline extends across a bathymetrically flat area. It was not observed during light-plane flights earlier in the day. It is neither a ship's wake nor a plume phenomenon, and it is not aligned with local surface winds. Its origin is unknown.

The outer edge of the insular shelf shows clearly through the arc from northwest to south of Cabo Rojo (the southwestern corner of Puerto Rico). The color contrast is strongest in the arc from northwest to west of Cabo Rojo, and becomes progressively weaker to the southwest and south. This corresponds to the bathymetry, for prevailing minimum shelf-edge depths are in the general range 35 to 40 feet in the sector northwest to west of Cabo Rojo, but are generally somewhat deeper southwest and south of Cabo Rojo. This area may be used to establish the maximum penetration depth of S190A color infrared photography in relatively clear water at about 50 feet (15 meters). In all depths the detail and resolution of underwater features on color infrared images is clearly inferior to that on the high-resolution color images.

Along the south coast of Puerto Rico the S190A color infrared images shows little turbidity or bathymetric detail. Coastal waters are prevailing somewhat turbid there, though at the time of Pass 6 the turbidity was at a minimum. Still, much near-shore turbidity as well as bathymetry is visible in the S190A and S190B color images. Maximum water penetration on the color-infrared image was on the order of 20 feet (6 meters) along the south coast.

In the Bahia de Ponce on the color infrared as well as the color images, linear light-color areas oriented northwest-southeast appear. They have no relation to the trend of the bathymetry, and they lie about parallel to the local surface wind. They are most strongly developed and touch land only in the vicinity of the tuna-canning plants and other industrial operations at Playa de Ponce. They are probably oil slicks from that source, even though they photographed lighter than the water whereas somewhat similar slicks near Mayaguez photographed darker than the water. Light-plane low-altitude observations substantiate their suggested origin.

What appear on the images to be dark oil slicks inshore southeast of the Playa de Ponce and south of Punta Cuchara (west of the Playa de Ponce) are in reality shadows of diffuse clouds.

The S190A color film has both higher resolution and better water penetration than the color infrared. The open-ocean streaks thought to be langmuir cells are more readily visible, boat wakes are sharper, and both bathymetry and coastal turbidity are far better shown.

On the north coast, the small sediment plume from the Rio Grande de Arecibo, only faintly detectable on color infrared, is well shown on the color film, including an offshore development of the plume that shows by its sharp western and diffuse eastern boundaries (as well as by its general shape) that it is wind-driven to the westward. Submarine sandspits that extend westward from the west side of rocky spurs and the east side of concavities in the shoreline prove that longshore drift is westward, and represent potential sources of sand for industrial use. These sandspits are also only faintly visible on the color infrared.

Near Aguadilla the color image shows both minor sediment plumes and minor oil slicks driven offshore from the west coast by the northeast wind. The oil slicks are slightly less than a mile long and are judged (by comparison with the runway width of the nearby airport, previously Ramey Air Force Base) to be well under 100 meters wide. These slicks are well above the size detection limit for S190A photography, thus proving the utility of such orbital photography for detection of slicks of small dimensions under favorable illumination circumstances.

This particular area demonstrates the importance of sun azimuth from the photo center in the detection of sediment plumes and especially of oil slicks. On frame 180 (see figure 1 for frame coverage) the Aguadilla area is in the northeastern part of the image, and the sun's azimuth from the photo center is also northeastward, as shown clearly by cloud-cloud shadow relations. Thus the Aguadilla area is up-sun from the photo center,-- and the plumes are hardly visible and the slicks are invisible. On frame 181, on the other hand, the azimuth of the Aguadilla area from the photo center is northwestward, and the sun's azimuth is of course still northeastward; the two frames were exposed only 18 seconds apart. Thus on frame 181 the Aguadilla area is in a cross-sun direction, and the plumes and slicks are well shown. We can thus draw the general conclusion that in orbital as well as aerial photography, plume and especially slick detection efficiency is a direct function of the relation between sun azimuth and target-area azimuth from the photo center.

In the Bahia de Mayaguez, all features described above in the color infrared discussion - the deep blue area, sediment plumes, bathymetry, and oil slicks - are better shown and have increased resolution on the color film. A critical difference is that the depth of near-surface bathymetric features is shown by apparent color variation on the color film -- the shallowest features become increasingly light green --, whereas on the infrared film the depth of near-surface bathymetric features is shown only by variation in intensity of blue. The difference is striking, and the color film is far more useful in delineating details of shallow bathymetric features,-- in addition to which, its penetration is appreciably greater.

Estimated maximum penetration depth (based on the depth of the point on a sloping sea floor at which the sea-floor image becomes undetectable) is 60 to 65 feet (18 to 20 meters). Details of bottom topography are splendidly shown in depths up to about 40 feet (12 meters) in the Cabo Rojo area. It is to be noted, however, that this penetration depth 1) may be limited by slightly turbid water -- suspended sediment and transparency measurements are lacking in the area--, and 2) is in an area whose azimuth from the photo center is much more than ninety degrees from the azimuth to the sun. Eastward along the south coast, penetration is markedly degraded because that direction is more toward the sun's azimuth.

In general the S190A 0.5 to 0.6 micrometer imagery shows all features observed on the S190A color photography, but the resolution of details is distinctly poorer and the film appears grainy under only 10x magnification. A subjectively-judged similar degree of graininess does not appear on the color film until a magnification of at least about 16x is reached. Maximum light penetration is judged about the same (60-65 feet, 18-20 meters) as on the color film, or very slightly less, but fine detail in bottom topography is not so well rendered. Sediment plumes are definitely less well rendered on the 0.5-0.6 micrometer imagery than on the color, and oil slicks are slightly less well rendered. The 0.5-0.6 micrometer imagery appears to have no point of superiority over the high-resolution color imagery for direct photo interpretation except when compared with images from other wavelengths.

S190A 0.6-0.7 micrometer imagery is superior to the 0.5-0.6 micrometer imagery in rendition of oil slicks and turbid water, and appears to be slightly superior to the color imagery in resolution of details of oil slicks, but slightly inferior in sediment-plume rendition.

The 0.6-0.7 micrometer imagery is of course markedly inferior to the 0.5-0.6 micrometer imagery in water penetration due to the higher extinction coefficient for longer wavelengths in water. Maximum penetration is estimated at 10 feet (3 meters). But this becomes a virtue when the otherwise difficult differentiation of the signatures of bathymetry and TURBIDITY is desired. To a close approximation the 0.6-0.7 micrometer imagery shows only water turbidity (except in very shallow areas), while the 0.5-0.6 micrometer and the color imagery with their greater water penetrability show both turbidity and bathymetry rather well. Hence turbidity and bathymetric features, once detected on 0.5-0.6 micrometer or color imagery, can in general be identified by their presence or absence on the 0.6-0.7 imagery.

In summary, the 0.6-0.7 micrometer imagery is superior to color infrared, color, and 0.5-0.6 micrometer images for detection and definition of oil slicks, and is very useful in conjunction with the more water-penetrative wavelengths in differentiating turbidity and bathymetric signatures.

The S190A 0.7-0.8 and 0.8-0.9 micrometer imagery, being in the deepest red and the near infrared respectively, show absolutely no bathymetry, though as is well known they portray the actual shoreline with great clarity because of the extremely low water penetrability of those wavelengths. Highly turbid water cannot be differentiated from clear ocean water.

But these wavelengths, particularly the 0.7-0.8 micrometer deepest red band, have the valuable property of differentiating oil slicks from all other observed water phenomena. Resolution of detail of long narrow slicks is poor, but identification as oil slicks of such suspected oil slick areas as the great anomalous (deep blue on color film) area in the Bahia de Mayaguez and the light-colored slicks near the Playa de

Ponce is absolute because they, and they alone (excepting cloud shadows), appear in the water-covered areas on the 0.7-0.8 micrometer imagery. They can also be detected, but much more poorly, on the 0.8-0.9 micrometer imagery. The ability of the 0.7-0.8 micrometer image as a detector of oil slicks makes possible the identification as an oil slick of a previously unmentioned dark pattern in the nearshore waters directly south of the town of Jobos. A tanker unloading terminal and an oil refinery are located in this area.

Pass 54, 30 November 1973.-- Areas covered by the S190A multispectral camera on Pass 54 are shown in figure 3. All six rolls from Pass 54 were inadvertantly exposed without filters but this seems to have had little effect on the three rolls that were examined for this study, which contain the color, 0.5-0.6 micrometer, and 0.8-0.9 micrometer images. The 0.5-0.6 micrometer imagery is somewnat thin and lacking in contrast but is fully usable.

As in the Pass 6 photography, the color image is excellent in portraying both bathymetry and turbidity. On the north coast of Puerto Rico west of the San Juan area the coast is almost wholly cloud-free but little bathymetric or turbidity detail is apparent. This is due simply to the facts that little rain had fallen prior to Pass 54, and that coast has few offshore shallow areas. In the Bahia de Aguadilla the small discharge plume of the Rio Culebrinas is shown clearly as flowing northeastward along the coast, in an upwind direction, proving that coastal currents and therefore sediment transport on at least that day were northeastward. As so often, here again one feels strongly

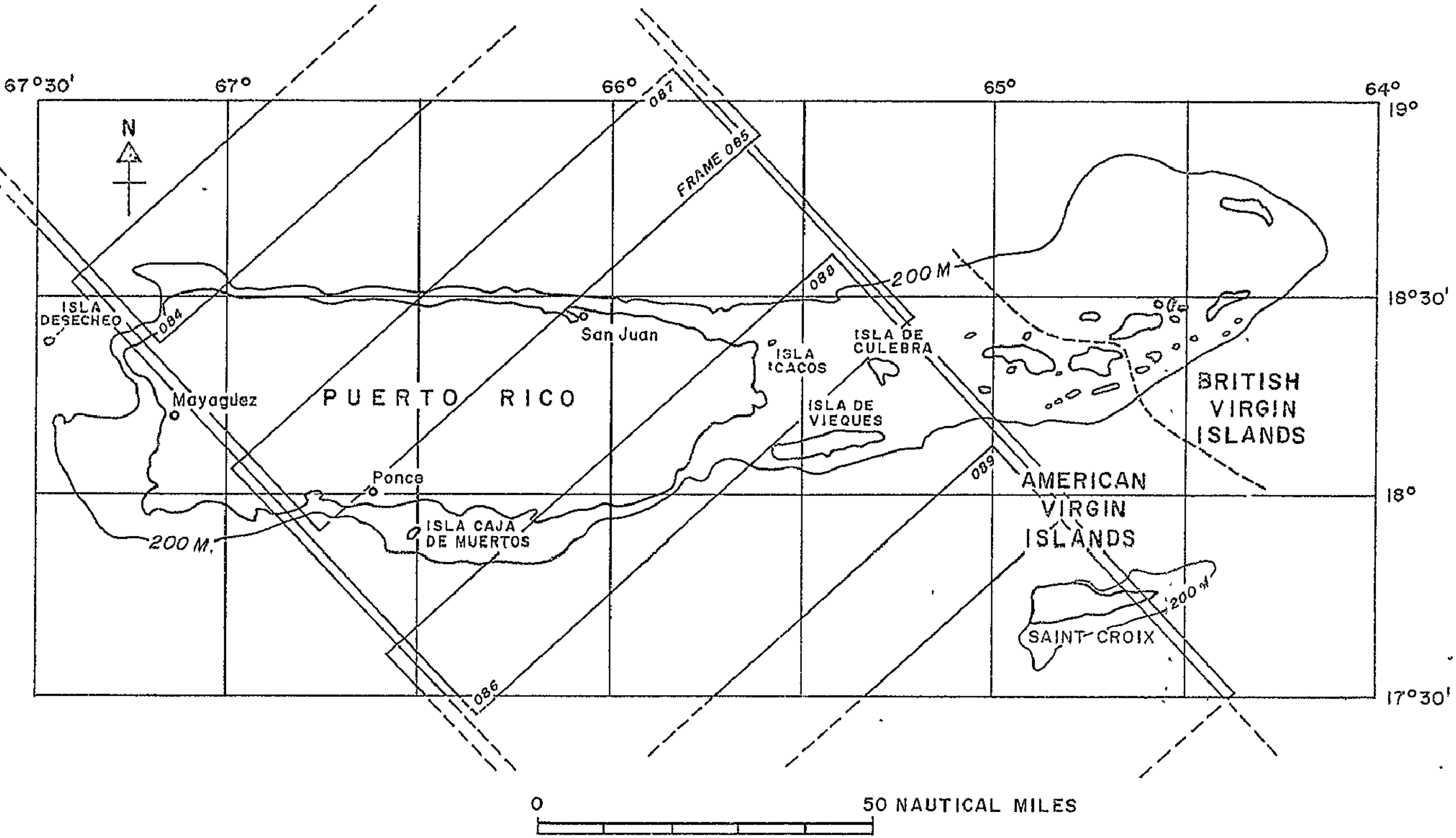


FIGURE 3. COVERAGE DIAGRAM, S190A, SL-4, PASS 54.

the need of closely time-repetitive coverage of at least this quality.

In the San Juan area both turbidity and bathymetric details are visible on the color film, but the two cannot be differentiated except by reference to other imagery. Examination by stereoscope of both the S190A and S190B color images does not provide sufficient apparent relief to differentiate turbidity and bathymetry.

East of San Juan and down the east coast of Puerto Rico bathymetric detail is well shown. Maximum penetration depth on the color image in the clear oceanic waters west of the Isla de Vieques is about 66 feet (20 meters).

Along the south coast of Puerto Rico the S190A color imagery shows both bathymetry and an intermittent coastal belt of water turbidity. The outlines of turbid water areas show the longshore drift to be westward except within the Bahia de Ponce, where an apparent clockwise current gyre shows northeastward coastal currents over a distance of about 3 nautical miles (6 kilometers).

At the northwestern tip of the Isla de Vieques a pointed northwestern-trending shoal is prominant in the color imagery, for it is made of white coralline debris and depths over it are only about 20 feet (6 meters). Megaripples on its crest are well delineated, as is a long field of submarine sand waves along the western half of the north coast of the Isla de Vieques.

The coastlines of St. Croix were almost totally obscured by clouds at the time of Pass 54.

No oil slicks were detected on the S190A color imagery.

The Pass 54 S190A 0.5-0.6 micrometer imagery is far inferior to the S190A color imagery in revealing and resolving details of turbid water and bathymetry signatures, as was described in more detail in the preceding Pass 6 discussion. Maximum water penetration at 0.5-0.6 micrometers is only about 53 feet (16 meters).

The 0.8-0.9 micrometer image contains a surprise: a faint image of the prominent northwestward-oriented shoal at the northwestern corner of the Isla de Vieques appears. Least water depths on that shoal are about 13 feet (4 meters), and though it is a high-reflectance target in clear water, that depth of penetration at such long wavelength is not to be expected (Sherman, 1971; Yost and Wenderoth, 1972).

Pass 85, 18 January 1974.-- Areas covered by the S190A multispectral camera on Pass 85 are shown on figure 4 (following page).

While only 35 percent of the coastline was obscured by clouds during Pass 85, the same figure as for Pass 54, widely scattered small clouds and cloud fragments and wisps prevailed. This combined with an extremely low sun elevation angle of about 18° during Pass 85 resulted in serious degradation in the utility of the imagery from that pass. The considerable horizontal displacement between any cloud or cloud fragment and its shadow prevents tracing a shadow back to the cloud that caused it, and as a result numerous patterns in water-covered areas cannot be ascribed to a definite source except through knowledge of the features of the area gained from other passes. The shadows of large cloud masses are displaced from the image of the cloud masses themselves and totally obscure significant image detail in areas that qualify as not covered by cloud.

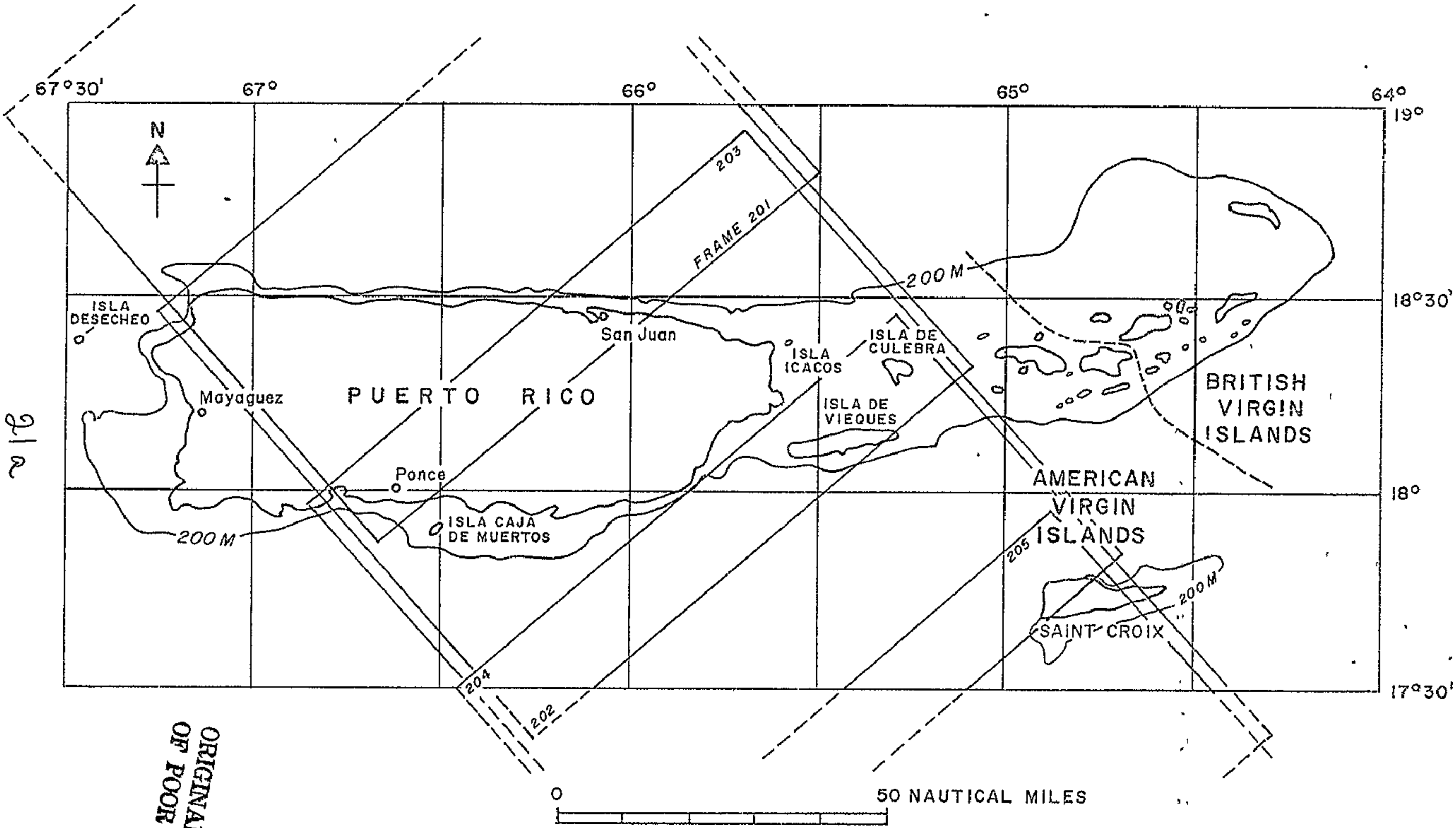


FIGURE 4 COVERAGE DIAGRAM, S190A, SL-4, PASS 85

More rain had fallen on Puerto Rico in the few days before Pass 85 than before Pass 54, and the waters adjacent to nearly all the island's coasts that can be seen have a broad zone of high turbidity.

The rapid overall rate of flushing and exchange of Puerto Rico's coastal waters is demonstrated by the low values for suspended sediment in them that were measured on several cruises between 4 and 12 days after Pass 85 along the north coast and west of the island.

The prevailing coastal zone of turbid water masks many bathymetric features visible in the same imagery from other passes. Furthermore the low sun angle severely decreased water penetration in clear-water area. On the S190A color infrared image, penetration in the clear-water around the west end of the Isla de Vieques is only something on the order of 20 feet (6 meters), and on the color image it is only on the order of 33 feet (10 meters).

Again on the Pass 85 images the overall superiority of color over color infrared imagery in water-covered areas is clearly demonstrated, particularly in resolution and detail of bathymetry and coastal turbidity. One notices on the color film (but not on the color infrared film) that the low sun angle of Pass 85 aids in differentiating between the signatures of turbid water and bathymetric features. This is because the low sun angle limits water penetrability but has little or no apparent effect on the rendition of turbid water.

An unusual turbidity phenomenon near the east end of the south coast is best shown on the color film. Just off the prominent point (unnamed on Chart 920, in pocket) southeast of the town of Jobos a a sediment plume extends at least 5 nautical miles (9 kilometers) directly seaward. Only 16 nautical miles (27 kilometers) along the coast to the east, in the vicinity of Punta Tuna, turbidity patterns clearly reveal that coastal currents are strong and are moving southwestward parallel to the shore. The fact that the sediment plume off the unnamed point goes directly seaward proves that the longshore current changes direction off the unnamed point and turns seaward.

Here we have a direct application of the utility of orbital high-resolution photography for the detection of an anomalous situation in the pattern of coastal currents. One wishes so that rapidly time-repetitive photography of this quality were available, for detecting the presence of such an anomalous situation would be truly impossible with conventional ship-bourne or even aerial photography unless from great altitude with wide-angle lenses. Even once detected, measuring the extent and the time history of one single such current anomaly would be a formidable and extremely expensive job for a well-equipped research vessel.

Previous comments to the effect that 0.5-0.6 micrometer imagery shows everything the color imagery shows, but not so well, remain mostly true for the Pass 85 images. Rendition of the presence and details of water turbidity are very nearly as good on the 0.5-0.6 micrometer images as on the color, however. The only factor that is known to have changed from Pass 54 is sun angle, and we may tentatively suggest that low sun angle has acted somewhat to improve the rendition of turbidity in the 0.5-0.6 micrometer band.

On the 0.6-0.7 micrometer images, the low sun angle of Pass 85 has reduced water penetration in a clear-water area to only about 10 feet (3 meters) for the highest-contrast target available, the submarine point at the northwestern corner of the Isla de Vieques. Depth penetration for less splendid bathymetric targets is considerably less. As on the other passes, this makes the 0.6-0.7 micrometer imagery valuable for differentiating turbidity from bathymetry, though turbidity features are poorly rendered compared with color or 0.5-0.6 micrometer imagery.

The 0.7-0.8 micrometer Pass 85 images portray only the coastlines, there being no oil-slicks in the area. Near the south coast of St. Croix between Long Point and Southwest Cape the color and other short-wavelength images show very well the outline and fairly well some internal detail of a light-colored patch that corresponded only moderately well with the fairly good but old bathymetric data available for the area. Until consulting the 0.7-0.8 micrometer imagery it was an open question whether the light-colored area respresented bathymetry or an oil slick, but its absence on the 0.7-0.8 micrometer imagery clinches its identification as a bathymetric feature. Thus Skylab imagery is in this case yielding information on changes in bathymetry during the many years since the bathymetric survey was made.

The 0.8-0.9 micrometer imagery shows nothing but shoreline shape detail, though it does that well. In that band as well as in the 0.7-0.8 micrometer band, dense cloud shadows obscure the coastline as effectively as do the clouds themselves.

Earth Terrain Camera (S190B)

Pass 6, 9 June 1973.-- A mosaic of western Puerto Rico from frames 239 and 240 of the S190B Earth Terrain Camera is reproduced in figure 5, and the Pass 6 coverage diagram is shown in figure 6.

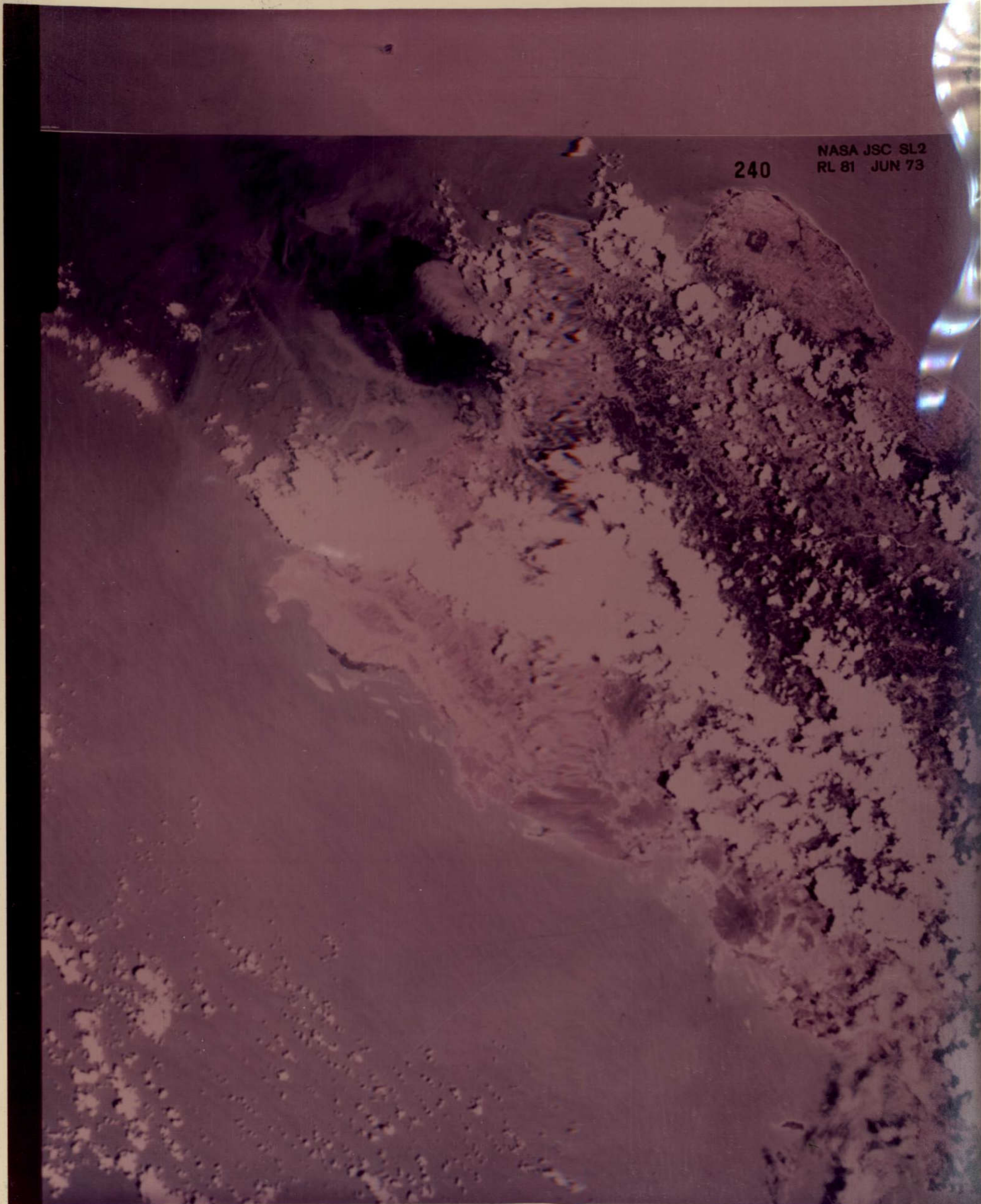
The S190B color image is of course similar to the S190A color image, but the resolution is considerable improved. Much more detail is revealed in the supremely complex patterns in the Bahia de Mayaguez in the vicinity of the great blue anomaly.

Somewhat surprisingly, color cannot be used to differentiate turbid water, which from low-altitude aircraft observation is somewhat brownish-gray, and bathymetric features, which from low-altitude aircraft appear as shades of blue lightening toward white.

The great blue anomaly is in general about 16 nautical miles (30 kilometers) long and 7 nautical miles (13 kilometers) wide. Aerial observations and photography on the same day from altitudes up to 12,000 feet of course showed many details of the complex overall situation in the area, but the perspective from that altitude was insufficient to get the overall picture in mind, or to photograph it. Even the RB57F photography (flown many months later) from 62,000 feet (18,900 meters) would not have had a wide enough swath-width to portray the overall situation. Thus orbital-height high-resolution photography has here again proved its unique synoptic ability. The presence and significance of the blue anomaly and the complex interplay between it, turbid-water plumes, bottom topography, and long narrow slicks simply

Figure 5 (following page).-- S190B Earth Terrain Camera imagery from frames 239 and 240, Pass 6.

North is to the upper right in this image, which shows the western half of Puerto Rico and the Isla Desecheo (small dark area at top). The "great blue anomaly" effluent area is very well portrayed. The ovate light-colored area protruding into it from the north is the turbid-water plume of the Rio Grande de Añasco. South of the great blue anomaly is a complex interplay of turbid water and bathymetric features, and in that area long narrow dark slicks thought to be of natural origin can be seen. The edge of the insular shelf is well portrayed offshore southwestward from Puerto Rico; maximum water penetration is about 72 feet (22 meters). The faint pattern in the open ocean north and south of Puerto Rico is thought to be caused by Langmuir cells. Note that they indicate different wind directions on the two sides of the island. The wake that extends downwind (southwestward) from the Isla Desecheo is clearly visible at the top of the image.



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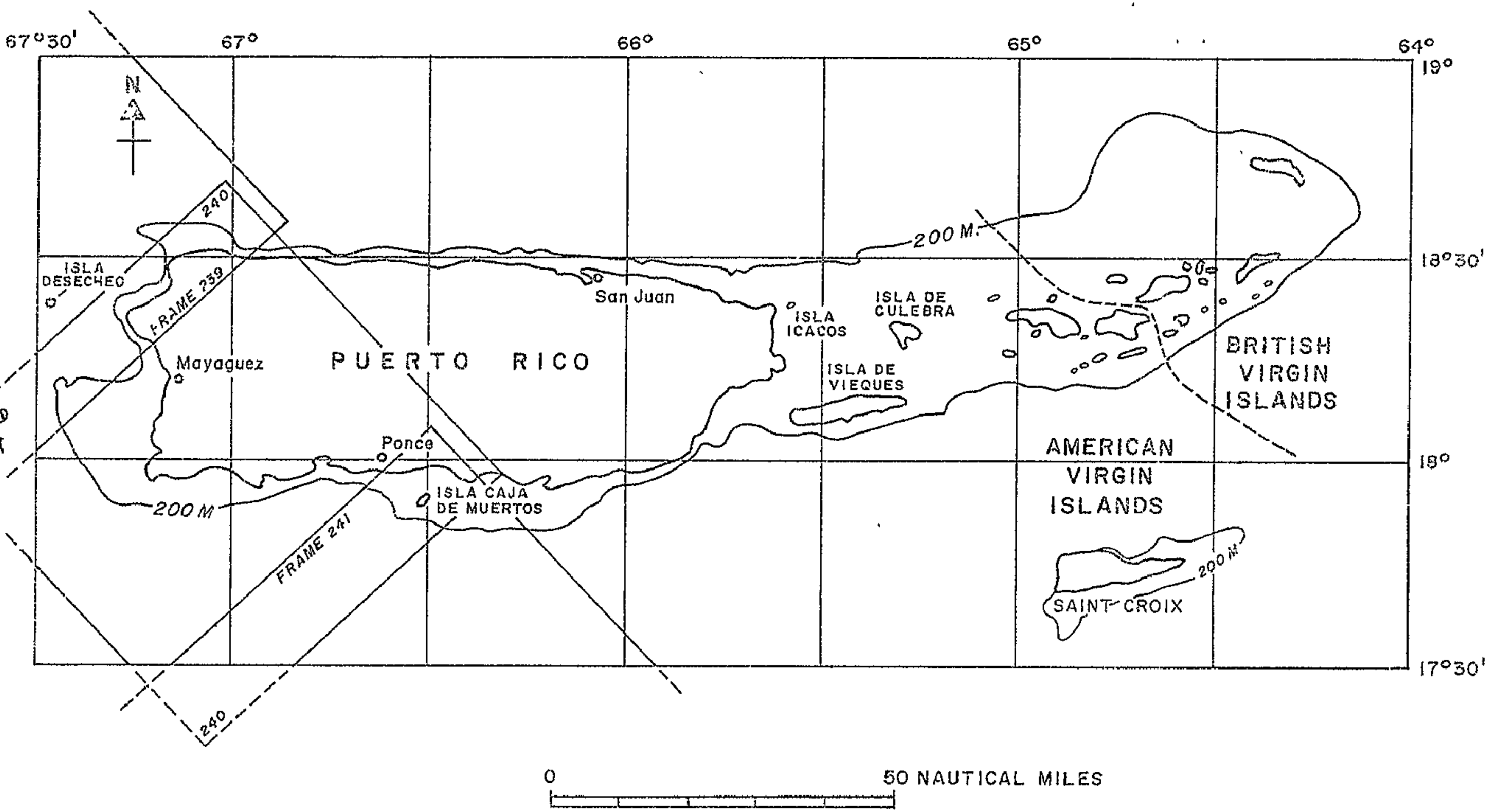


FIGURE 6. COVERAGE DIAGRAM, S190B, SL-2, PASS 6.

could not be studied without such high-quality orbital photography.

The increased resolution and improved scale of the S190B photography compared to the S190A is most useful when studying targets with sharply delineated details, and the long, narrow slicks mentioned in the S190A discussion are a case in point. The S190B film leads directly to the conclusion that in the offshore area they are too numerous and too widespread and lacking in any phenomena at their upwind origin points to be from a man-caused source. Here as elsewhere one gets the impression that they are caused by natural exudates of coral reef organisms.

The offshore narrow slicks of probable natural origin are long and linear because their shape is affected only by the wind. The narrow slicks inshore near the city of Mayaguez, which are probably not of natural origin, are on the other hand short and curved in a complex pattern. That area is almost always protected from the prevailing easterly winds, and the curvature of the slicks seems clearly to be revealing a complex current-eddy pattern.

The shelf edge near the southwestern corner and along the south coast of Puerto Rico is clearly shown on the S190B photography to a maximum depth of about 72 feet (22 meters). This is slightly greater than the S190A color film penetration depth of 60 to 65 feet (18 to 20 meters). The difference may be due in part to the superior resolution of the S190B film.

Some quantification of details of bathymetric features particularly in the Cabo Rojo area at the southwestern corner of Puerto Rico in depths generally of 30 to 40 feet (9 to 12 meters) could be done by density-slicing the image with a small amount of field work for calibration, but in truth the results would be rather crude compared to the results of the admittedly very time-consuming but not too expensive standard ship-bourne methods of bathymetric surveying. Such techniques using orbital photography of less well bathymetrically surveyed or unsurveyed areas of the world would undoubtedly be valuable, however.

The suspected Langmuir cells in the open ocean around Puerto Rico are very prominent on the Pass 6 S190B photography, but they are not to be seen on either the Pass 54 or the Pass 85 photography. It is not known what factor has changed to cause this difference.

Pass 54, 30 November 1973.-- The first thing that must be said of this S190B photography is that it is absolutely magnificent.

The discussion of the Pass 6 S190B imagery in the immediately preceding section was based on examination of 2x film positive enlargements, whereas this Pass 54 S190B discussion is based on examination of an unenlarge 5-inch film positive. The Pass 6 2x enlargements were a bit beyond optimum resolution at a magnification of 7x, the minimum possible with the microscope used to examine them, and thus maximum usable magnification was below 14x. The Pass 54 5-inch transparencies, however, start to lose resolution only at 18x to 20x magnification. It is not specifically known whether this striking improvement from Skylab-2 to Skylab-4 S190B imagery was due to the enlarging process used on the Skylab-2 photos, or to improved film processing techniques developed at NASA's Houston photo laboratories during Skylab. But the hint is to avoid enlargements and employ higher magnification at the original image size.

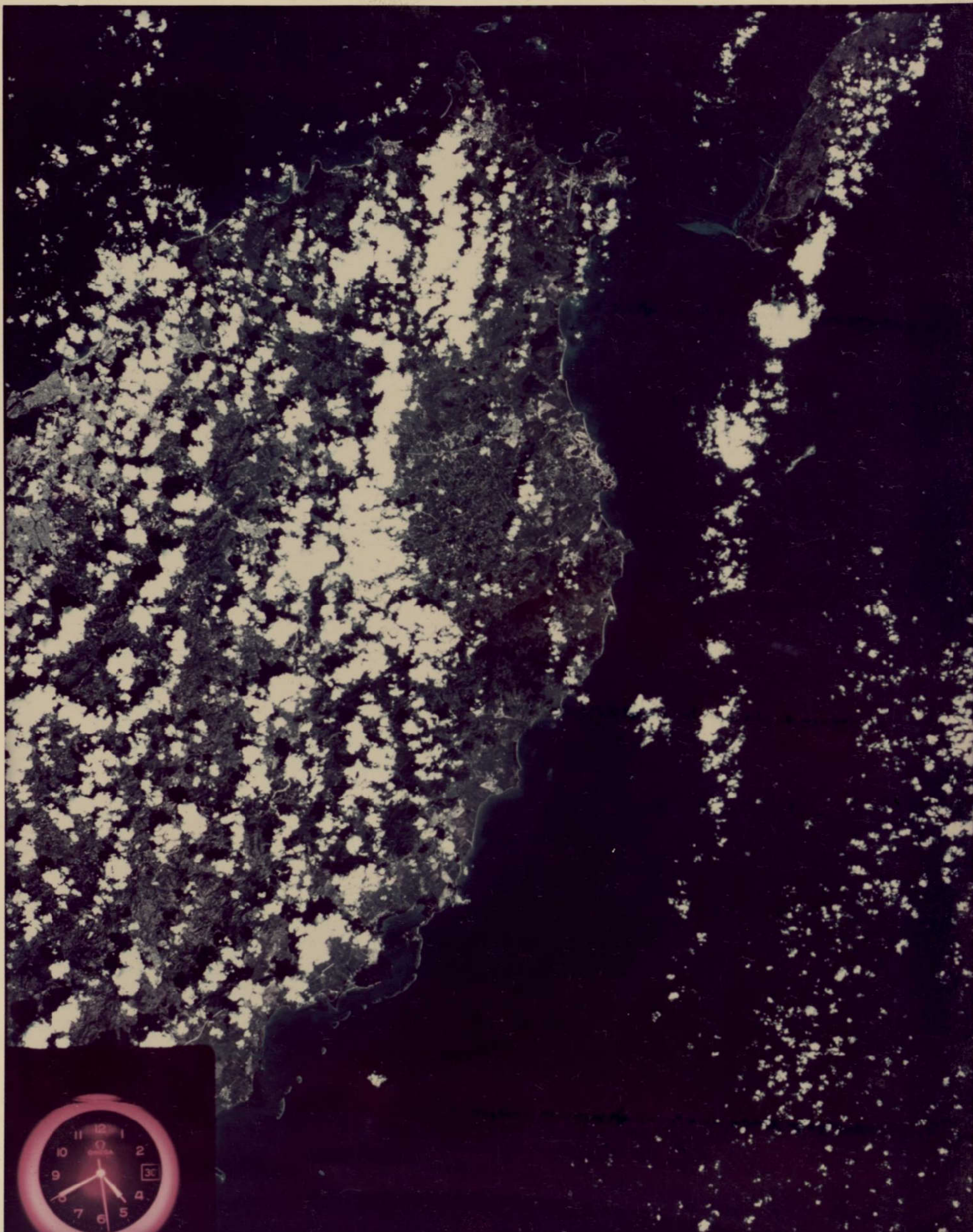
A frame of the S190B Earth Terrain Camera Pass 54 imagery that covers the eastern two-thirds of Puerto Rico and the northwestern tip of the Isla de Vieques is reproduced in figure 7 (following page). The S190B coverage for Pass 54 is shown in figure 8 (following figure 7).

The Pass 54 images are far superior to the Pass 6 images in water and underwater detail. Even inshore on the north coast a wealth of bathymetric detail is evident. In one small area there, between Punta Salinas and Punta Boca Juana, bathymetric detail is revealed that escaped attention on a very precise small-boat bathymetric survey with a north-south and east-west line spacing of about 1,000 feet (305 meters). Of course the small-boat survey is highly accurate quantitatively, but the fact is that it failed to detect numerous bathymetric features with least dimensions on the order of 100 to 200 feet (30 to 61 meters) that do appear in the S190B imagery.

Off the harbor entrance at San Juan the S190B image shows a remarkably well-developed offshore-trending plume of light colored high-turbidity water. The plume extends with a sharp western edge (indicating slight wind-drive from the east) for a distance of 16 nautical miles (30 kilometers) offshore, and is oriented about 35° west of north. Such offshore-trending plumes of much smaller dimensions are commonly seen even from the decks of ships in the San Juan area, and are commonly reported in the literature, but it required

Figure 7 (following page).-- S190B Earth Terrain Camera image from figure 058, Pass 54.

North is to the upper left in this image of the eastern two-thirds of Puerto Rico, the Isla Icacos (top center), and the western part of the Isla de Vieques (upper right). The turbidity of Puerto Rico's coastal waters was remarkably low. The great shoal trending 30 degrees west of north at the northwestern tip of the Isla de Vieques is well shown, as is a series of submarine sand waves east of it. Many intricate details of bathymetry and of patterns of bottom-dwelling biologic communities appear on the original transparency between the Isla de Vieques and Puerto Rico; they are only faintly visible in this reproduction.



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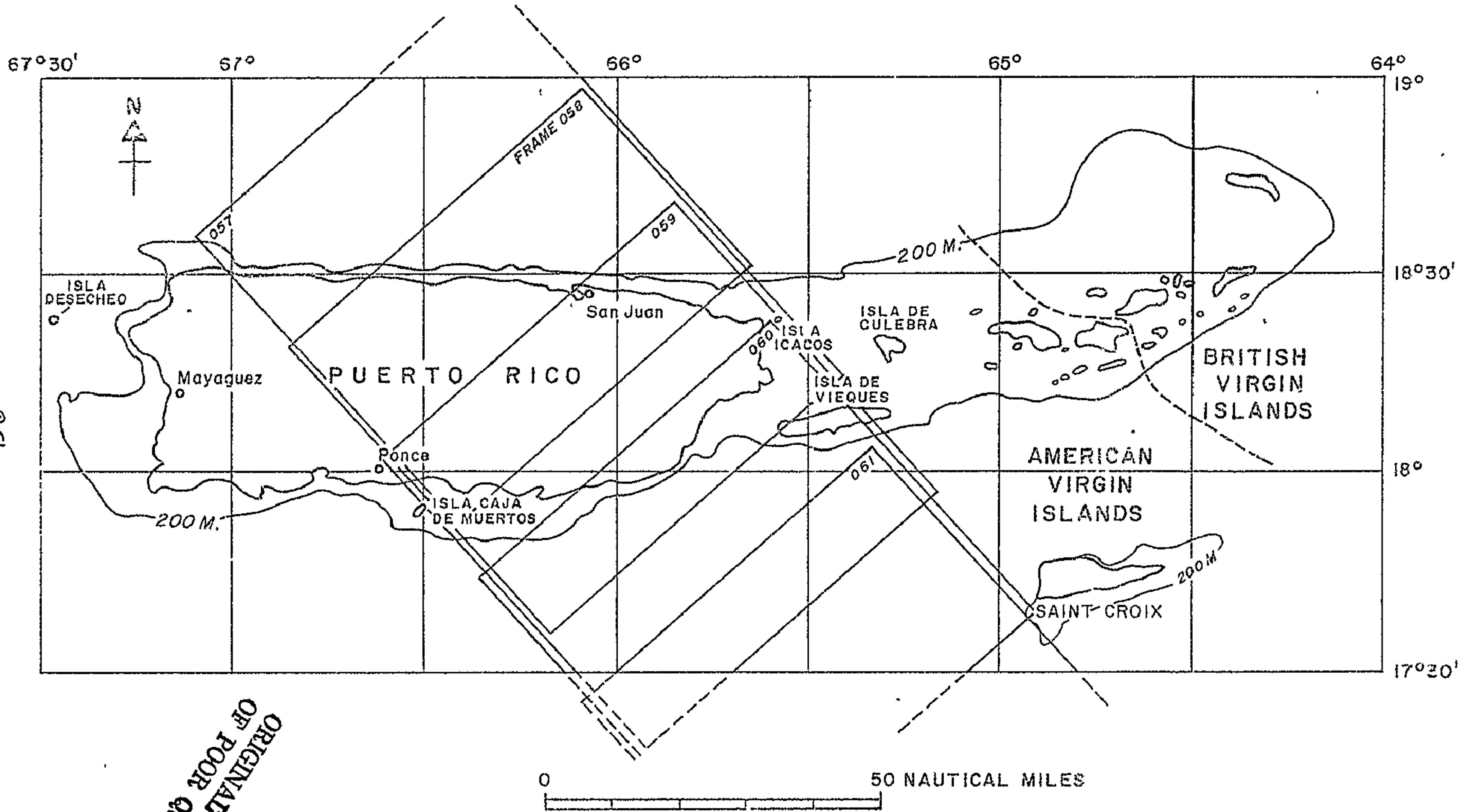


FIGURE 8. COVERAGE DIAGRAM, S190B, SL-4, PASS 54.

28c

the synoptic view that only orbital-height imagery can provide to detect such a large one. It was not detected even by a scouting plane that was sent over the area at 2500 feet (762 meters) on the morning of Pass 54 specifically to search for such phenomena so they could be quantified by a research vessel.

Unfortunately the scout plane located and directed the ship to work on a smaller turbidity feature off Punta Maldonado, slightly east of San Juan, that by simple bad luck was one of the few totally cloud-obscured areas on the north coast at the exact time of the Skylab pass. In this example, as so often, the urgent need and scientific value of rapidly time-repetitive coverage of Skylab S190B quality is evident.

The rarity and value of high-resolution orbital imagery is also emphasized by the overall situation on the north coast of Puerto Rico on the day of Pass 54. So little rain had fallen in previous days that the entire north coast west of a point slightly west of San Juan shows no sediment discharge from rivers, except for a very small plume from the Rio Grande de Arecibo. (It does, however, show a westward-swept plume of spent molasses from a group of rum distilleries on the western side of the city of Arecibo. The area of spent molasses is about 0.4 nautical miles (740 meters) long and 0.1 nautical miles (185 meters) wide.) The absolute lack of the usual coastal belt of turbid water on this long stretch of coast allows identification of many shoal areas that are very probably sand because of their light color, and that represent potential resources of what in Puerto Rico is a scarce and valuable commodity. Neither detailed nearshore bathymetric mapping nor bottom-sampling has been done through most of this distance, and the Skylab images contain much new information, though such a narrow coastal belt can also be covered by high-altitude aircraft photography.

The other side of the coin is that had there been rainfall prior to Pass 54, the rivers and streams of the north coast would have been discharging turbid water, the trends of which could have been used to map nearshore water circulation patterns. This is also a subject of considerable practical and economic value, for measuring the current regime in the vicinity of proposed coastal sewer discharges is a necessary task but a complex and expensive one when done by conventional methods.

On the south coast of Puerto Rico the S190B photography shows both a narrow belt of turbid coastal water and considerable bathymetric detail. Most of the suspended sediment causing the coastal turbidity is coming from normal coastal erosion rather than from discrete river sources, however, and it is accordingly difficult to determine the direction of coastal currents. The situation does allow the identification of coastal sectors that are undergoing erosion by the sea, however.

In the broad shallow area between the Isla de Vieques and Puerto Rico, a highly detailed panorama of bottom features appears on the S190B imagery. It corresponds in every major detail with an accurate bathymetric chart (contour interval, 2 meters) of the area, and in addition it shows patterns not present on the bathymetric chart that can only be interpreted as ecological patterns of bottom-dwelling plant and animal communities. The detail in the photography is so good in this area that a special study employing density-slicing and line microdensitometry on the images and field checking of bottom-dwelling communities simply must be done.

The S190B swath width and the ground track of Pass 54 were such that St. Croix was just missed.

Pass 85, 19 January 1974.-- A frame of the S190B Earth Terrain Camera Pass 85 imagery that covers the eastern two-thirds of Puerto Rico is reproduced in figure 9 (following page), and the S190B coverage for Pass 85 is shown in figure 10 (following figure 9).

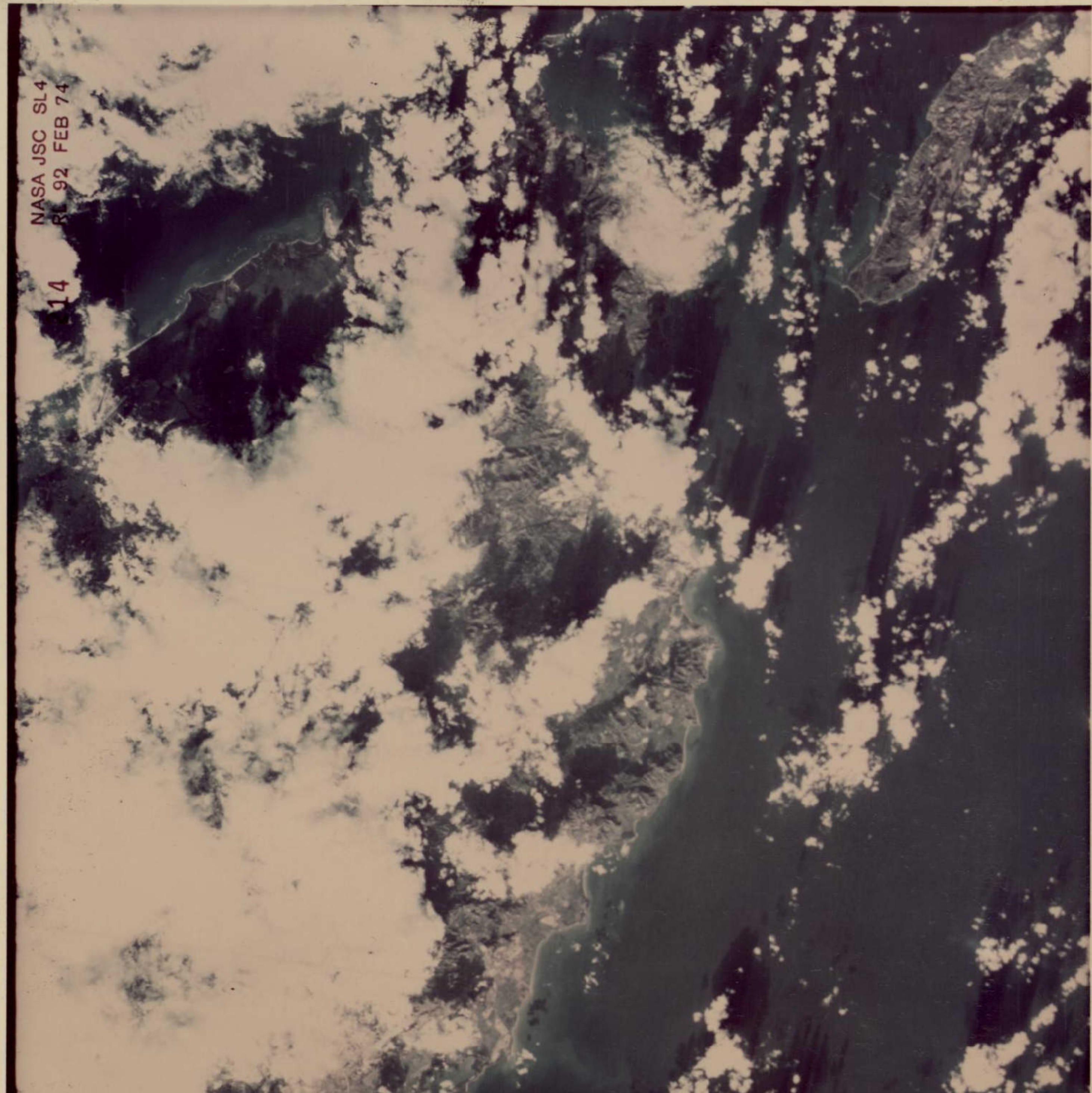
The resolution of the S190B photography is so superior to that of the S190A photography that along the north coast of Puerto Rico considerable bathymetric detail undetected on the S190A photography can be seen both inside and outside the coastal belt of turbid water, despite the low sun angle.

In two north coastal areas not obscured by clouds or cloud shadows, the shape of the coastal zone of turbid water shows that at least the surface currents are west-bound. This is the expected direction, but the situation demonstrates the potential of the method for detecting nearshore reversals of current direction such as are sometimes observed near San Juan and probably occur undetected in other areas.

On the east and south coasts nearly all bathymetric detail is masked by turbid water except for very shoal areas and near islands far enough offshore to be in at least somewhat clear water. As on the north coast, the boundaries of turbid water masses, especially off promontories of the land, show the direction of coastal near-surface currents to have been uniformly westward when the image was made. An

Figure 9 (following page).-- S190B Earth Terrain Camera image from frame 213, Pass 85.

North is to the upper left in this image of the eastern two-thirds of Puerto Rico, the Isla Icacos (top center), and the western part of the Isla de Vieques (upper right). The deleterious effect of scattered cloud fragments combined with a low (18°) sun angle is apparent. Puerto Rican coastal waters were far more turbid than on Pass 54, a comparable image from which is shown in figure 7 (following page 28). A seaward-oriented plume of turbid water near the bottom center indicates a surface water current flowing offshore. This is discussed on text pages 22-23 and 31-32.



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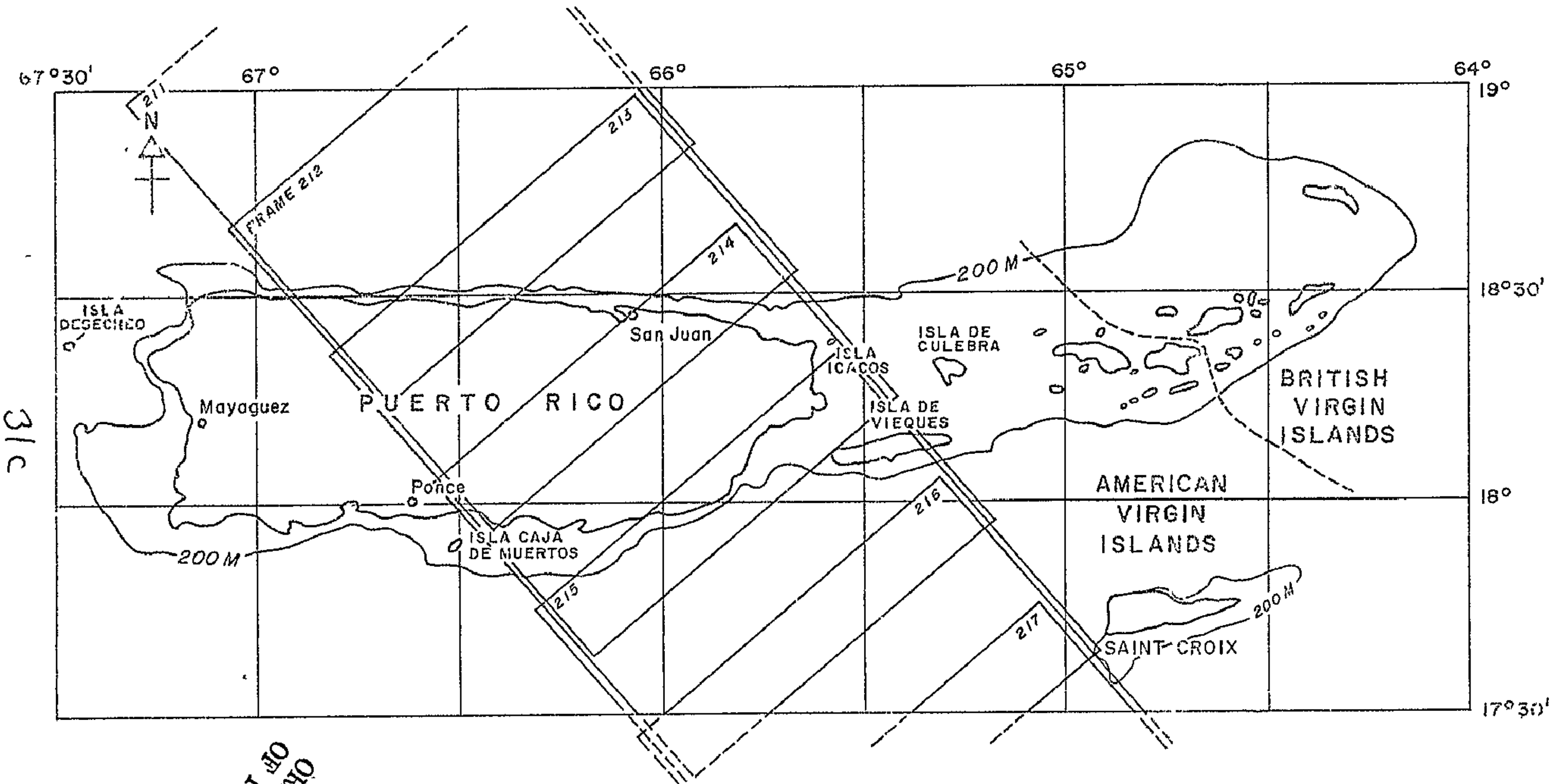


FIGURE 10. COVERAGE DIAGRAM, S190B, SL-4, PASS 85.

31c

exception is the offshore-trending turbid-water plume off the unnamed point southeast of the town of Jobos that was discussed in the preceding S190A section. The boundary relations of that plume, better seen on the S190B than the S190A photographs, indicate an anomalous offshore (and crosswind) current.

The deleterious effect on the rendition of bathymetric detail of elongated cloud shadows caused by a low sun angle is well shown on the image of the long north-pointed shoal at the western end of the Isla de Vieques. Megaripple detail is well rendered except where bands of cloud shadow cross the shoal, and in those areas the shoal itself is barely visible.

Multispectral Scanner (S192)

S192 Multispectral Scanner coverage for Pass 6, Pass 54, and Pass 85 is shown in figure 11 (following page).

Pass 6, 9 June 1973.-- Four of the 13 channels of the Pass 6 multispectral scanner imagery are shown in figures 12 and 13 (following figure 11).

The 0.46 to 0.51 micrometer blue-light image shows bathymetric features beautifully, and has nearly as much water-penetrative capability as the best color photography. The image contrast in the bathymetric features is far superior to that in color photography, but by the nature of the multispectral scanner, the resolution of detail is lower. The image of the great blue anomaly in the Bahia de Mayaguez is somewhat degraded in this spectral band; it shows most strongly in the 0.52-0.56 micrometer band. This is further evidence, if any

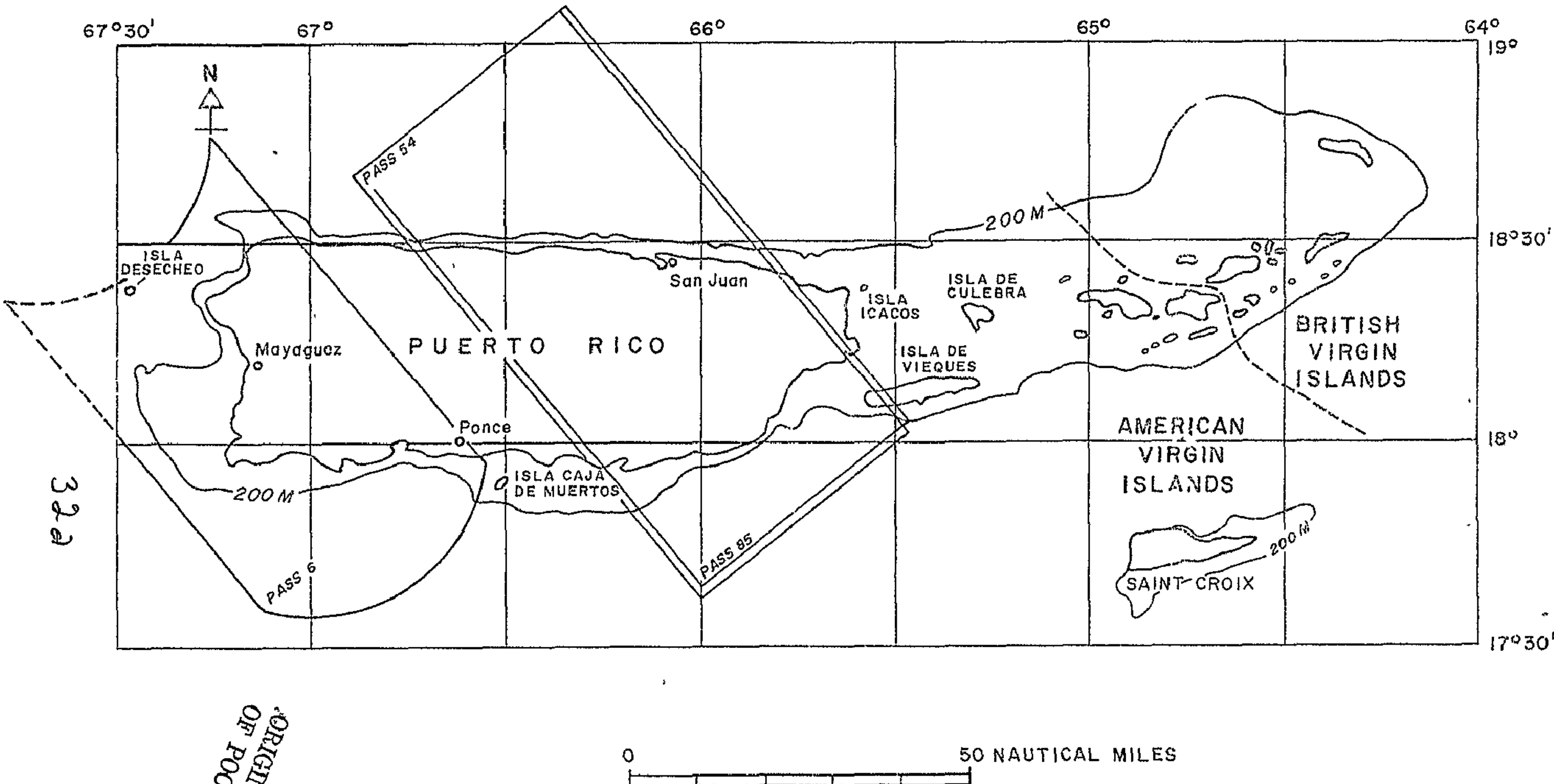


FIGURE II COVERAGE DIAGRAM, S192, PASSES 6, 54, AND 85.

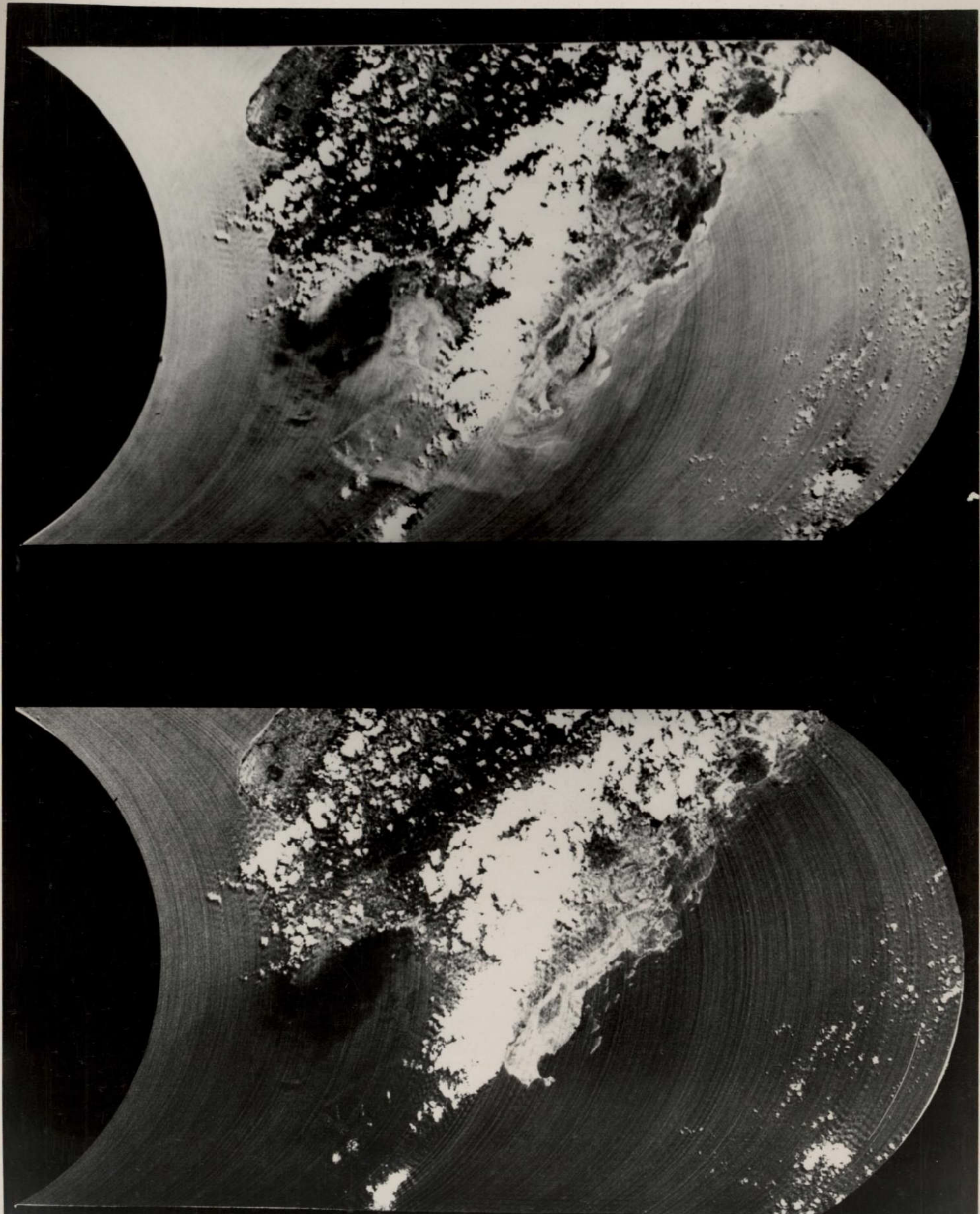
Figure 12 (following page).-- S192 Multispectral Scanner imagery from Pass 6, 0.46 to 0.51 (blue) and 0.62 to 0.67 (light red) micrometer channels.

The upper image is the 0.46-0.51 micrometer blue-light channel. This image should be compared with the Earth Terrain Camera photograph of the same scene shown in figure 5 (following page 25). The scanner image shows nearly as much water penetration as does the color photograph, though of course resolution in the scanner image is lower.

The lower image is the 0.62-0.67 micrometer light-red channel. It shows almost no water penetration and therefore almost no bathymetric detail, but it does show turbid water patterns and thus is useful in differentiating bathymetric and turbid-water patterns.

Other channels of S192 scanner imagery from the same pass are shown in the next figure.

North is to the upper left in each image.



32C

Figure 13 (following page).-- S192 Multispectral Scanner imagery from Pass 6, 0.68 to 0.76 (deep red) and 10.20 to 12.5 (thermal infrared) micrometer channels.

The upper image is the 0.68-0.76 micrometer (deep red light) channel. It shows only the effluent area called the great blue anomaly. The anomaly is broken and dispersed on its south side. That the anomaly is imaged so strongly at this wavelength is evidence that it is some kind of man-caused effluent.

The lower image is the 10.20-12.5 micrometer thermal infrared channel. It shows no detail in these nearly isothermal waters. On land it shows by lighter image intensity that the desert-like coastal area of southwestern Puerto Rico is hotter than the vegetation-covered remainder of the island. The outlines of the city of Mayaguez can be seen at the center of the west coast.

North is to the upper left in both images.

32E

were needed, that the spectral reflectance characteristics of the blue anomaly are unique among all the water-area features shown on all Skylab imagery. Minor herringbone patterns distort the image in scattered places, but reduce its utility but slightly.

The 0.52-0.56 micrometer image, as would be expected for that wavelength band, also has excellent water penetration, though slightly less than the S190B color photography and the preceding 0.46 to 0.51 micrometer S192 image. Rendition of bathymetry of the quality of these S192 images would be useful in a bathymetrically unmapped or poorly mapped clear-water area if photography of S190A or S190B quality were not available.

Overall the 0.52-0.56 micrometer image is excellent but of course it is severely lacking in resolution compared to either S190A or S190B photography. Airport runway patterns are well resolved. The great blue anomaly in the Bahia de Mayaguez is well portrayed, as are sediment plumes, though some herringbone pattern degrades the image of the large plume from the Rio Grande de Añasco on the north side of the blue anomaly. The S192 instantaneous field of view of 260 feet (79 meters) is probably roughly the same as or somewhat greater than the width of the long narrow slicks south of the blue anomaly, and their pattern was almost but not quite resolved. The wake downwind of the Isla Desecheo appears, but it does not on the next band.

The 0.56 to 0.61 micrometer image has less water penetration but for an unknown reason has slightly higher resolution than the preceding band. Islands and their surrounding shoals made of high-reflectance coral sand are particularly well displayed, and the contrast within the image, as with the preceding band, is usefully high.

The 0.62 to 0.67 micrometer image shows almost no water penetration and thus is useful in conjunction with the preceding bands, especially that of 0.52 to 0.56 micrometers, in discriminating bathymetric from turbidity features. The linear light-colored zone oriented 100° that was discussed on page 13 is present, proving further that it is not of bathymetric origin.

The 0.68 to 0.76 micrometer image of course has almost no water penetration, and the images of turbid water are less well differentiated from clear-water areas than in the shorter-wavelength images previously discussed. The great blue anomaly is still strongly portrayed, lending further evidence to the diagnosis that it is neither a bathymetric nor a turbidity phenomenon.

The 0.78 to 0.88 micrometer image, which is in the nearest infrared, shows no other features in water-covered areas than the great blue anomaly. The ability of such longer wavelength as this and the 0.68 to 0.76 micrometer deep red band absolutely to differentiate oil and perhaps other chemical substances from all other phenomena in water-covered areas performs a useful service in the very confused area south of the great blue anomaly. That area has a complex interplay of bathymetric, turbid water, and slick features, but they can be sequentially separated one from another by careful comparison first of the 0.52 to 0.56 image, which shows bathymetry, turbidity, and slicks, then second of the 0.62 to 0.67 micrometer image, which shows turbidity and slicks but not bathymetry, and finally of the infrared 0.78 to 0.88 micrometer image, which shows slicks but neither bathymetry nor turbidity.

Thus the capability of the S192 multispectral scanner to present images from very discrete narrow spectral bands, a capability that is beyond that of present-day photographic techniques, has a very direct practical application to image discrimination even when viewed only by conventional non-instrumental techniques of photo-interpretation. This emphasizes the high potential of computerized band-ratioing techniques when applied to multispectral scanner numerical data, a field which this investigator cheerfully leaves to others but is very glad to have them working on.

The 10.2 to 12.5 micrometer thermal imagery shows absolutely no detail in water-covered areas. This is only to be expected, for the temperature range in coastal waters in this tropical climate is very small. Maximum temperature range measured on any cruise in Puerto Rican waters during our water study program has been only 2° Celsius.

In the land area of Puerto Rico the thermal imagery shows an interesting effect. In southwestern coastal Puerto Rico rainfall is very low, the vegetation is desert-like, and much of the surface of the ground is exposed. In that area the thermal imagery indicates an appreciably hotter land surface than in the land area in the remainder of the image, which is nearly all covered by flourishing vegetation. The outline of the city of Mayaguez shows in considerable detail on the thermal image, and of course is warmer than the surrounding vegetated areas.

Pass 54, 30 November 1973.-- The image of the violet-light spectral band, 0.41-0.46 micrometers, is smeared, banded, and unusable.

The image from the next spectral band, 0.46 - 0.51 micrometers, is of perfect technical quality on an early screening test strip that was supplied. That image shows considerable bathymetric detail on the south coast but does not show the large plume off San Juan. An image from the same band that was prepared later, however, has instrumentally-caused patterns (associated with high local contrast areas of white cloud and dark land and ocean) and banding, but despite these imperfections it portrays very well the unusually large offshore-oriented turbidity plume in the San Juan area that was previously described in the Pass 54 S190B discussion. This image shows the plume to extend 15 nautical miles (28 kilometers) from the coast, and has enough detail to show that the plume is wind-driven westward. Otherwise, the signatures of bathymetry and turbidity are undifferentiable.

The 0.52 - 0.56 image also shows the plume off San Juan, but less clearly. Bathymetry and turbidity are still generally undifferentiable in coastal zones, and even shoreline rendition on the south coast in cloud-free areas is poor. The image is of little utility.

At 0.56 - 0.61 micrometer wavelength the image of the large plume off San Juan is not observed. In most places the coastline is indistinguishable from bathymetry and turbidity.

At 0.62 - 0.7 micrometer wavelengths in the light red, no features are visible in water-covered areas, but the coastline itself is fairly sharply resolved.

At 0.68 - 0.76 micrometers, the deep red, shoreline detail is crisp on the north coast, but due apparently to some instrumental or processing error, the south coast land-to-water contrast is low and the coastline is not clearly distinguishable.

On the 0.78 - 0.88 micrometer image, an early screening film is technically perfect and shows the entire shoreline in perfect detail. As an indication of detail resolution, an island 600 by 900 feet (138 by 274 meters) is well shown, but smaller islands in general are not.

An image at wavelengths 1.55 - 1.75 micrometers also shows the coastline clearly, but with considerably less resolution, probably because of atmospheric absorption. The 600 by 900 foot (183 by 274 meter) island readily visible at 0.78 - 0.88 micrometers is not visible at 1.55 - 1.75 micrometers.

The thermal infrared band (10.2 to 12.5 micrometers) is strongly banded and shows no detail in water-covered areas, as is to be expected in this nearly isothermal area. On land, metropolitan San Juan shows as significantly higher in temperature than the remainder of the eastern two-thirds of the island covered by the image. The high mountains in the center of the island and the Sierra de Luquillo near the northeastern corner show as distinctly cooler than low-lying coastal areas.

Pass 85, 19 January 1975.-- Pass 85 is the one in which clouds, cloud fragments, and cloud shadows, elongated by a low sun angle, obscure much of the coastline, and the one in which turbid water is prevalent along the coasts.

But the 0.56 - 0.61 micrometer multispectral scanner imagery shows the coastal turbidity only poorly on the north coast, and not at all on the south coast of Puerto Rico. The image is of good technical quality, the curved scan lines being undetectable over most of the image, but the cloud and cloud-shadow problem renders it nearly useless.

The 0.68 - 0.76 micrometer image, being in the deep red, shows no detail in water-covered areas, proving the absence of oil slicks in the area that day. Land topography, incidentally, is shown in splendid detail because of the very low 18° sun angle.

Similarly the 0.98 - 1.08, 1.09 - 1.19, 1.2 - 1.3, 1.55 - 1.75, and 2.1 - 2.35 micrometer images show no detail in water-covered areas, as is to be expected at these infrared frequencies. Through this series of frequencies the contrast between the density of land and sea images decreases progressively, and accordingly, the resolution of shoreline shape details decreases.

The thermal infrared (10.2 - 12.5 micrometers) imagery from Pass 85 shows high contrast between cool clouds and warm land and water, but the contrast between land and water is so slight that the outline of the coast can be detected only with difficulty and in some places not at all.

EVALUATION OF OTHER DATA

High-altitude aircraft (RB57F)

The restricted swath-width of the RB57F photography, even though the flight height was 62,000 feet (18,900 meters), results in a loss of the valuable overall synoptic coverage that the satellite imagery affords. The RB57F photography is of absolutely magnificent technical quality, however, and has a remarkably high information content for marine and coastline studies, as well as for such other areas of study as coastal land-use and vegetation studies. Scientists from a variety of disciplines have already made extensive use of the RB57F photography discussed here.

RC-8 color imagery.-- An example of the RC-8 photography (a portion of a square frame) is shown in figure 14 (following page) in comparison with a portion of a frame taken at the same time from the Zeiss aerial mapping camera that used infrared color film. The focal length of the infrared camera was twice that of the color camera, hence the 2:1 scale difference in the photographs.

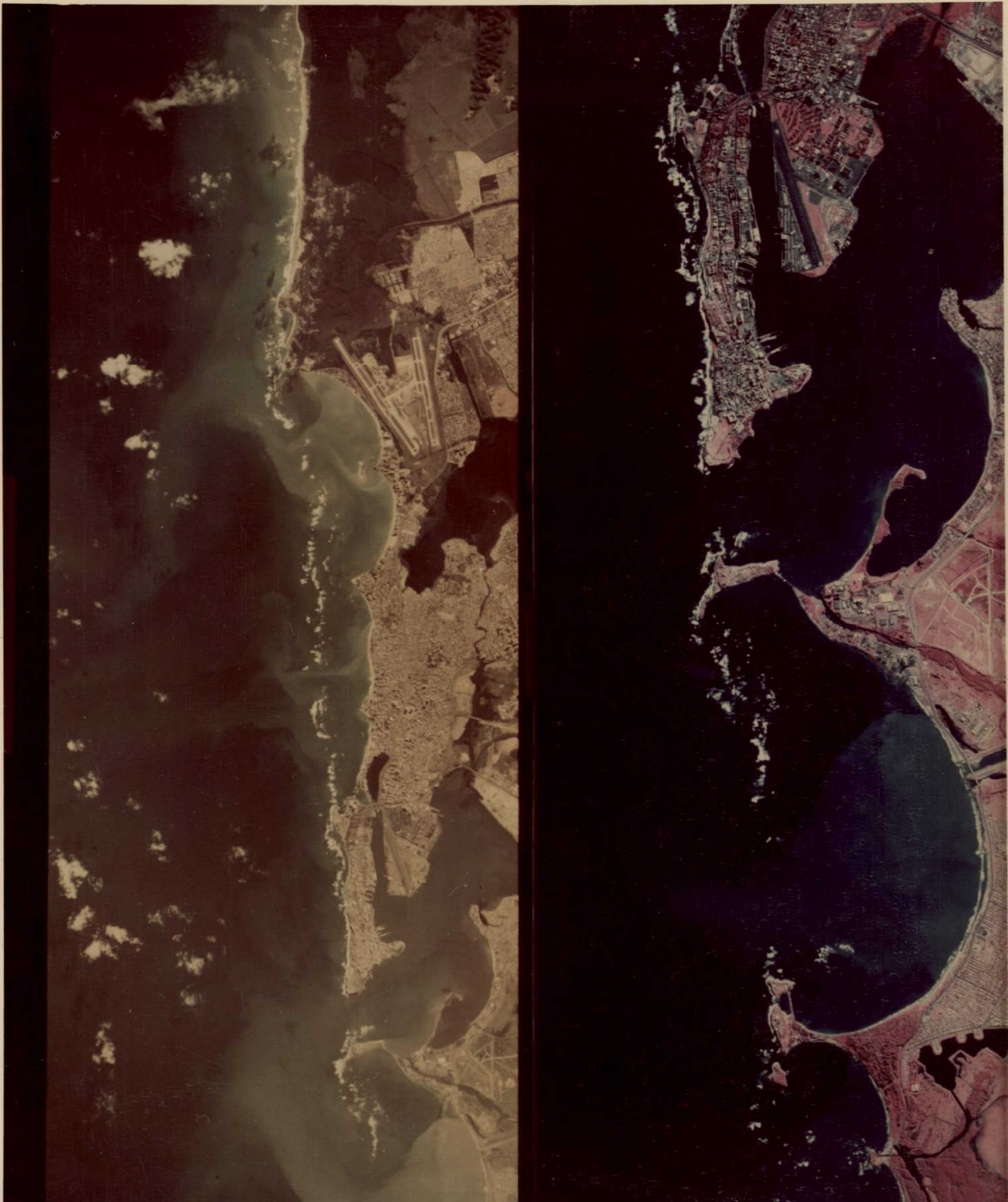
Each RC-8 color frame covers a square that is 15.4 nautical miles (28.5 kilometers) on a side. Such excellent photography of all the coastlines of Puerto Rico and nearly all those of the Virgin Islands provides an absolute cornucopia of information and detail, especially since it was exposed with 60% forward frame overlap so that all of it can be examined stereoscopically.

For instance, figure 14 shows from the shape of the plentiful turbid water plumes that the coastal water currents that day were

Figure 14 (following page).-- RB57F RC-8 color and Zeiss color infrared photographs of the coastal area off metropolitan San Juan.

North is to the left, or offshore, in both photographs. They were taken nearly simultaneously from a flight height of 62,000 feet (18,960 meters). Focal length for the top image was 6 inches and for the bottom image was 12 inches, hence the 2:1 scale difference.

Directions of coastal currents deduced from the upper image are shown in figure 18 (following page 53), which also contains information on amount of suspended sediment, water transparency, and water color that resulted from the work of a research vessel that was in the area at the time.



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flowing eastward off San Juan, an anomalous but not unusual occurrence. When seen in its entirety, that frame shows that the eastbound coastal current extended 1 to 2 nautical miles (1.8 to 3.7 kilometers) offshore, and allows actual mapping of its outer edge. The eastbound coastal current is bordered seaward by a generally continuous zone of slack water ranging in width from 1 to 2 nautical miles (1.8 to 3.7 kilometers), and that zone is in turn bordered seaward by the normal westward-flowing oceanic current that prevails around Puerto Rico.

The illustrated frame and others of the north coast show clearly, moreover, that the eastbound near-shore current is not continuous, but instead is broken up into cells because it turns seaward at coastline or bathymetric prominences. This cell activity causes and explains the occurrence of the northwestward-oriented plumes sometimes detected visually from shore and from research vessels in the San Juan area. The northwestward-oriented plumes are the vector resultant of the offshore-bound eastern end of the nearshore eastward-flowing current cell, and the offshore west-bound oceanic currents.

The water in and adjacent to this northwestward-flowing plume as well as other turbidity features in the San Juan area were measured and sampled from a research vessel at the time of the RB57F flight. The results of that work are described in the succeeding section on ground truth. They quantify the aircraft imagery tightly and well.

The northwestward-oriented plume that was measured and sampled is prominent on figure 14, and is located off Punta Maldonado, opposite the runway pattern of San Juan International Airport. It is 4.5 nautical miles (8.3 kilometers) long.

Does the much larger and longer (15 nautical miles, 30 kilometers) offshore plume off the San Juan harbor mouth detected by satellite imagery and discussed on pages 28-29 have the same origin as that just established for the smaller one off Punta Maldonado? Only orbital photography with its tremendously wide field of view can give the answer, and then only if it happens to be taken on a day when 1) the phenomenon is present, and 2) when extremely numerous and dense coastal turbidity features are present, as they were when the RB57F photography was flown. The second condition did not obtain when Skylab Pass 54 was made, so the question remains unanswered.

Returning to the image shown in figure 14, sources of turbid water, especially along the shoreline of metropolitan San Juan, are readily pinpointed. Their path through the linear but interrupted offshore reef is also evident. What is not evident on figure 14, but is beautifully evident upon stereoscopic examination of that frame and the adjacent ones, is that in places (for example near the middle of the frame image in figure 14) the turbid water actually flows downward beneath clear surface water just outside the reef line. The turbid water, being fresh water from very recent rainfall and thus originally lower in density than salt water, would have floated upon the surface of the salt water had not the heavy load of suspended sediment increased its density above that of seawater and caused it to flow down the inclined sea floor.

The preceding discussion illustrates some pertinent points about the relative utility of orbital and aircraft imagery, and about the luck of timing and the desirability of time-repetitive earth resources sensing. Note that one frame (admittedly one of the more interesting ones) of RB57F photography, with its adjacent frames used stereoscopically, yielded a really significant number of valuable observations. But this does not simply mean that high-altitude aircraft photography shows more than its orbital-height equivalent. It was simply by luck that the RB57F photography was flown immediately following heavy rains which caused the extremely turbid water from the patterns of which the information was extracted. Stereoscopic effect was strong enough with the aircraft imagery to detect the downward-flowing turbidity plume (a rarely observed phenomenon), and satellite photography could not have detected that effect.

On the other hand, had we been lucky enough to have had sateltelite imagery taken when coastal turbidity was so prevalent, other larger features that escaped the relatively narrow field of view of the aircraft imagery would likely have been detected. Note that the very large offshore-trending plume off the mouth of San Juan Harbor that was discovered on the Pass 54 S190B satellite imagery would have escaped detection by coastal high-altitude photography, and was not seen by a plane at 2,500 feet (762 meters) that was in the area expressly to find such features.

Thus evaluation of the relative utility of satellite and aircraft photography is a bit intricate if both kinds of photography are not done on the same day. In the present study the scheduling and logistics of the high-altitude aircraft for a mission so far from the continental United States prevented simultaneous high-altitude and satellite photography.

This must not, incidentally, be considered as a derogatory comment on the capability of the NASA Earth Observations Aircraft Program. Quite to the contrary, the aircraft support group and flight crew, under the direction of Thomas L. Barrow, Aircraft Project Manager, displayed a high degree of expert competence, motivation and tenacity in the face of bad cloud conditions, poor communications, and instrumental difficulties and thus successfully achieved the project goals.

Obviously first-class high-altitude aerial photography such as was made for this project has its range of scientific and practical potentialities, just as do orbital photography and imagery. These potentialities overlap, though far from completely, in the field of coastal studies. The overall point that this report establishes, however, is that earth-resources sensing by satellite provides much valuable information that cannot be obtained by any other technique.

The preceding part of this text section discussed but one of the many frames of RB57F RC-8 color photography that cover all the Puerto Rican coastline and nearly all that of the Virgin Islands. The many other frames contain an absolute plethora of beautifully-portrayed details of coastal and shallow-water phenomena. Some are portrayed in figure 15 (following page), a reproduction of part of an RC-8 color frame covering the waters between the Isla de Vieques

Figure 15 (following page).-- RB57F RC-8 color photograph of the waters between the Isla de Vieques and southeastern Puerto Rico.

North is to the left, toward the binding. Flight height was 62,000 feet (18,960 meters). Puerto Rican coastal waters were extremely turbid; the turbidity patterns show that coastal surface currents were to the southwest. Outside the belt of turbid water, bathymetric detail and patterns of bottom-dwelling biologic communities are well shown, though not as well as on the original transparency. Megaripples on the great shoal at the northwestern corner of the Isla de Vieques are clearly shown, as are sand waves to the east of that shoal.

Skylab photography of the same area is shown in figure 7 (following page 28), and the next figure shows parts of the same area in color infrared.

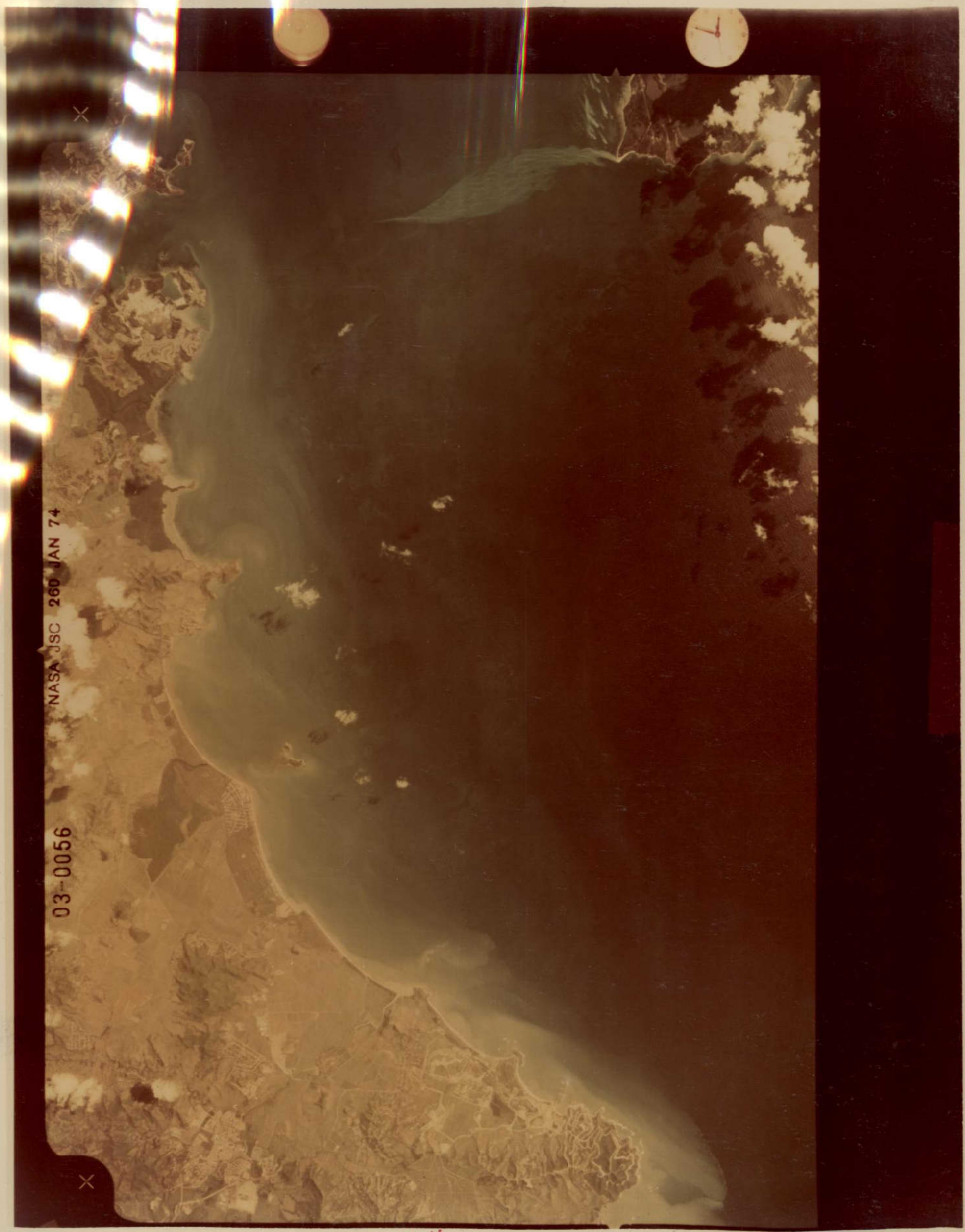

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Figure 16 (following page).-- RB57F color infrared photography of two areas shown in figure 15.

In both parts of the figure north is to the left, toward the binding.

The lower photo shows details of turbid coastal water patterns and two rivers discharging very turbid water. The harbor near the bottom of the photo is at Puerto Yabucoa and was built only a few years ago.

The upper photo is of the sand shoal and sand waves near the northwestern corner of the Isla de Vieques. Comparison with the preceding figure shows the relative inferiority of color infrared film for underwater features.

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and southeastern Puerto Rico. Figure 16 (following figure 15) is a reproduction for comparative purposes of Zeiss color infrared imagery of parts of the area shown on figure 15. It is not within the purpose of this report to describe and evaluate all the RC-8 color and Zeiss color infrared images, but instead to compare the utility of such high-altitude photography with that of Skylab imagery.

Of course the high-altitude aircraft color film shows far more details of bathymetry and turbidity than does the satellite imagery, simply as a function of scale. In addition the aircraft photography is of particular value in mapping the distribution of benthic plant and animal communities because of its scale and because such ecological patterns are inherently much finer and subtler in details of color and outline than are most bathymetric or turbidity features. It has been noted on pages 30 and 31, however, that such ecological patterns are mappable from the best Skylab photography under favorable circumstances.

Considering the need of mapping the tremendous extent of clear-water coastal areas off less developed and therefore much more poorly mapped or unmapped areas and nations than Puerto Rico, the ability of Skylab imagery to portray not only bathymetry and turbidity phenomena but also to some degree the ecological patterns of bottom-dwelling plant and animal communities shows its true potential. Staging and flying the RB57F even to Puerto Rico was a formidable technical feat. Covering many of the little-known coastlines of the world by high-altitude aircraft photography would be staggeringly difficult and expensive. Skylab or a similarly-equipped orbital vehicle, however, could do such mapping easily simply by making minor changes in orbital track. It is in considering this type of world-wide mapping needs that we approach the true potential of such orbital earth-resources observatories as Skylab. One has great hopes for the forthcoming earth-orbiter shuttle system in this matter.

Zeiss color infrared photography.-- This photography is at twice the scale of the RC-8 color photography, and hence has both a narrower swath-width and higher resolution of details. As with the RC-8 color film, the infrared film can be magnified to 20x before the image degrades.

As was previously established for orbital height photography (pages 12-14), the Zeiss color infrared imagery shows neither bathymetric nor turbidity features as well as does the RC-8 color imagery, despite its larger scale. Even the prominent white shallow shoal at the western end of the Isla de Vieques, the finest bathymetric target in all Puerto Rican waters, shows relatively little contrast on the color infrared film. Maximum underwater penetration is on the order of 72 feet (22 meters), but the details are not well rendered because they are lacking in contrast.

Detection of oil slicks is facilitated if the target area is at the edge of the sun-glint pattern, though sun-glint of course also has the adverse effect of wiping out bathymetric detail. The high-altitude aircraft photography, particularly the infrared color because it is at the largest scale, allows the detection of oil slicks at the edge of the sun-glint area in the inner harbor of the Bahia de Ponce on the south coast of Puerto Rico, in the immediate vicinity of tuna-packing and other industrial plants. The sun-glint pattern also sometimes fortuitously allows the complex patterns of wave-front refraction around islands and coastal promontories to be studied. But again, these are really virtues of an adversity, which is the loss of bathymetric and other details in the sun-glint areas. Skylab photography is carefully designed to avoid sun-glint areas, and thus loses no detail to sun-glint, but oil-slicks and wave refraction patterns cannot be detected by use of the sun-glint phenomenon.

One advantage of the large scale of the Zeiss color infrared topography is the detection of floating windrows of seaweed offshore from Puerto Rico. They can be firmly identified because of their pink chlorophyll response, the same as that shown by land vegetation.

Multispectral Hasselblad camera system.-- The portrayal of bathymetry is so good in the two lower-frequency spectral bands of this photography that one feels regret that the waters around Puerto Rico were so turbid on the days (16 and 17 January 1974) when it was flown. High-turbidity water features cover a large area following heavy rains, as was the case on those days. The acceptance angle of the Hasselblads with 80-mm lenses gave at this flight-height an image about 7.5 nautical miles (13.9 kilometers) square, and this is narrow compared to the extent of the turbid-water features, but for most places is not too narrow to portray coastal bathymetric features.

The Hasselblad film, all of which is black-and-white, is grainy at 7x magnification, and the effect is particularly strong after one has been examining the large-format high-resolution color and color infrared film also used in the RB57F. Nevertheless fairly fine bathymetric detail is very well portrayed at the lower wavelengths in clear-water areas.

A set of multispectral Hasselblad images is shown in figure 17 (following page). The area shown is a part of the same San Juan area shown in figure 14 (which follows page 40).

The 0.48-0.58 micrometer Hasselblad film has bathymetric detail to water penetration depths of about 84 feet (26 meters) in areas of clearest water where detailed bathymetric mapping was available for comparison. These areas are the shelf southeast of the Isla Caja de Muertos, the shelf west of the western end of the Isla de Vieques, and the broad shoal area east of St. Croix. The shelf-edge in the Cabo Rojo area, off the southwestern corner of Puerto Rico, is normally in perfectly clear water, but the extremely high turbidity of Puerto Rican coastal waters along the coast to the east seems to have resulted in some occlusion in the Cabo Rojo area, which is down-current from the south coast. Maximum penetration there was about 72 feet (22 meters).

Operational resolution of the 0.48-0.58 micrometer film on land targets was on the order of 30 to 40 feet (9 to 12 meters) or less.

The 0.52-0.58 micrometer Hasselblad film shows details of turbid waters significantly better than does the 0.48-0.58 micrometer

Figure 17 (following page).-- RB57F Multispectral Hasselblȧd camera photographs of the San Juan harbor mouth area.

North is toward the top of the page in each image. Color and color infrared photographs of most of the same area are shown in figure 14 (following page 40).

The upper left image was made by light of wavelengths 0.48 to 0.58 micrometers, the upper right image by wavelengths of 0.52 to 0.58 micrometers, the center left image by wavelengths of 0.54 to 0.60 micrometers, the center right image by wavelengths above 0.60 micrometers, and the lower image by infrared wavelengths of 0.70 to 0.89 micrometers. The infrared image shows only breaking waves in water-covered areas, though the faint trace of a smoke plume from a thermal power plant can be seen at the right side of the bay on the left; the wind was from the east.





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film, probably because of atmospheric absorption at the bluer end of the spectral interval, and possibly also because the two films were apparently developed to different gammas: the 0.52-0.58 micrometer film is less dense and contrasty than the 0.48-0.58 micrometer film. Details of land targets are significantly more poorly resolved on the 0.52-0.58 micrometer film than on the 0.48-0.58 micrometer film. The same type film (EK 2402 Plus-X Aerographic) was used in both cameras. One suspects a slight laboratory processing error in the case of the 0.52-0.58 micrometer film.

The 0.52-0.58 micrometer film shows very slightly less depth of water penetration than does the 0.48-0.58 micrometer film, as might be expected from its spectral coverage. Thus we have the same effect observed on the Skylab multispectral imagery: the blue end of the visible spectrum is superior for water penetration and detail, and the green-yellow-orange band is superior for rendition of turbid water. This hardly comes as a surprise, since bathymetric detail _is_ blue and turbid water _is_ greenish-yellow.

The 0.54-0.60 micrometer Hasselblad film is slightly but distinctly inferior to the 0.52-0.58 micrometer film in maximum depth of portrayal of bathymetric features, just as the spectral-band numbers would indicate. Similarly, the rendition of turbid-water features is rather better. Resolution of land targets on the 0.54-0.60 micrometer film is slightly inferior to the 0.48-0.58 micrometer film but far superior to that of the 0.52-0.58 micrometer film.

The Hasselblad camera containing the 0.54-0.60 micrometer film-filter combination failed near the end of the first flight line, but note that this was the only known camera malfunction in a mission that used a total of 8 cameras of 3 types for 2 long flying days in which a total of 765 data miles (1417 kilometers) was covered.

The Hasselblad film that recorded the red wavelengths upward from 0.60 micrometers shows numerous turbid-water features, particularly off San Juan and along the southeast coast of Puerto Rico where those features were most strongly developed. Red light also portrayed turbidity features in the Skylab S192 multispectral scanner imagery of Pass 6 (page 34), when turbidity conditions were perhaps about average. We conclude that red light does record water turbidity, but not at all well compared with the shorter wavelengths in the green-yellow. The fact that it does record turbidity is of practical utility as a turbidity-bathymetry discrimination tool, for it records bathymetry only of the lightest-colored and shallowest features.

Usable ground detail resolution for land targets of the red-light Hasselblad image is far superior to that of the longer-wavelength Hasselblad images just discussed. Sidewalks about 6 feet (2 meters) wide in parks in San Juan are very clearly portrayed, and individual vehicles on highways are discernible.

The infrared (0.7-0.89 micrometer) Hasselblad film shows no water penetration whatsoever on even the shallowest and brightest targets. It does, however, show a weak image of some of the most intensely developed turbid-water plumes, though surprisingly not including those off the San Juan area. An unexplained phenomenon is the presence of a complex pattern in the brackish-water Laguna San Jose near the southeastern side of metropolitan San Juan. The cause is most likely floating vegetation or plankton.

The resolution of land targets on the infrared Hasselblad film is inferior to all other such films excepting only that containing the 0.52-0.58 micrometer image.

Low-altitude aircraft.-- The use of light aircraft at altitudes between about 1500 and 12,000 feet (450 and 3660 meters) to observe and photograph coastal and coastal-water features does of course produce great quantities of useful information. The fine details of such locally variable phenomena as coastal erosion and sedimentation and the distribution of underwater benthic communities can be seen and understood much better at low altitudes than by the use of orbital photography.

Note, however, that such fine details can be observed even better by personal visits to the study area and by instrumental oceanographic techniques, but that the time factor per unit area mapped goes up steeply the closer the observer is to the study area, just as does the degree of detail that can be mapped. Many months, indeed years, would be required to visit in person and map the coastal features of Puerto Rico and the Virgin Islands, a light aircraft would require but two days to cover them, the RB57F photographed them in 104 minutes, and Skylab crossed them in 18 seconds.

The light aircraft does fill a useful role as a general observation platform in earth-resources studies, but there are some particular things that it does exceedingly well, and a great many it cannot do at all.

The primary singular advantage of light aircraft in earth resources work is their immediate availability at most locations for observation of transient phenomena or for quick looks at local conditions at any time. An example is their use in turbid-water studies as spotters to direct surface research vessels to areas where the ship's work will be most production, as was done in this study.

Another singular advantage of light aircraft is in detection and detailed studies of oil slicks by the edge-of-the-sun-glint technique (discussed on pages 46 and 47), for the viewing angle of any target area with respect to the sun glint may be changed as desired, as of course can altitude for close-up detection of the source of slicks. But for detection and general portrayal of oil slicks, orbital-height multispectral imagery is of similar acuity, and furthermore has that marvelous synoptic ability that all other methods lack.

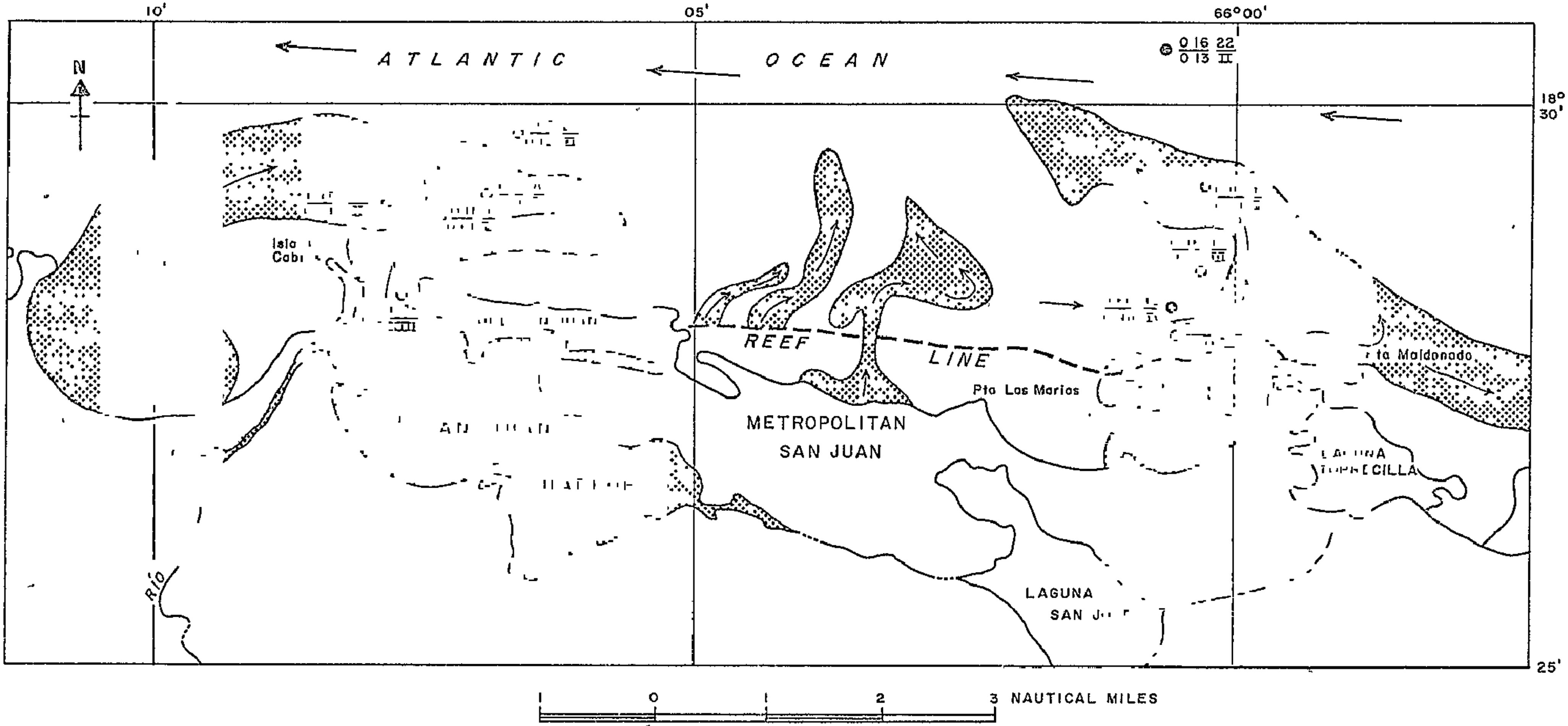
It is this almost magic synoptic ability of orbital imagery that is completely lacking when light aircraft are used. They simply cannot go high enough to see more than a small area at a time.

Ground truth.-- The 65-foot (20-meter) research vessel Jean A., owned and operated by the Department of Natural Resources of the Commonwealth of Puerto Rico, made a total of seven cruises to measure the properties and take samples of coastal waters near Puerto Rico in support of this investigation. Cruises and the portions of longer cruises devoted to water measurement and sampling ranged in length from one to four days. This considerable amount of expensive ship-time was a valuable contribution by the Puerto Rico Department of Natural Resources to the success of this investigation, and it resulted in a considerable saving of scarce NASA funds. Grateful acknowledgement is made to the Department of Natural Resources not only for the extensive use of their research vessel, but also for their splendidly cooperative attitude.

The vessel was not available at the time of the Skylab EREP Pass 6 on 9 June 1973. It took a very successful series of water stations off San Juan during EREP Pass 54 on 30 November 1973, but by bad luck the area in which the work was done was obscured by an isolated cloud patch at the moment that Skylab imaged the area. During the first day of the RB57F flights, 16 January 1974, the research vessel again made a highly successful cruise off Punta Maldonado and the mouth of San Juan harbor, and the results key beautifully to the detail on the high-altitude aerial photography, as discussed and illustrated later in this section. Because of poor commercial communications facilities at the Puerto Rico end, it was not known in San Juan until 21 January 1974 that EREP Pass 85 of 18 January 1974 had taken place, but on 22 January the ship put to sea in an attempt to quantify the imagery to some extent. Cloudiness along

Figure 18 (following page).-- Outlines of major turbid waterbodies, direction of surface currents, amount of suspended sediment, transparency, and color of coastal waters off San Juan on 16 January 1974.

Outlines of turbid water bodies and direction of currents are taken from the high-altitude aircraft photograph reproduced in the upper half of figure 14 (following page 40). For discussion, see text pages 40 to 42.



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EXPLANATION

WATER STATIONS

AREAS OF MOST TURBID WATER

ARROWS SHOW DIRECTION OF SURFACE CURRENTS DEDUCED FROM TURBIDITY PATTERNS

DECODING EXPLANATION FOR NUMERICAL DATA:

SUSPENDED SEDIMENT IN SURFACE WATER, MG/L	TRANSPARENCY BY SECCHI DISC, METERS
SUSPENDED SEDIMENT AT DEPTH OF 10 METERS, MG/L	WATER COLOR ON FOREL-ULE SCALE (I MOST BLUE, XX = MOST YELLOW)

the north coast of Puerto Rico and low sun angle during Pass 85 made the data useless for quantifying the Skylab imagery, but of course the data serve further to describe the properties of Puerto Rican coastal waters. Four other water cruises not time-related to Skylab passes or RB57F flights were made on 21-22 October 1973, 3-12 December 1973, 17-19 July 1974, and 4-5 August 1974 in order further to describe the properties of the ocean water near Puerto Rico.

Much of the information that resulted from these water cruises is not pertinent to this report, nor is a detailed description of the properties of Puerto Rican waters. A brief general description of their pertinent characteristics follows.

The clear tropical waters far from land in the Canal de la Mona (Mona Passage) west of Puerto Rico normally have from 0.02 to 0.04 milligrams per liter (hereinafter expressed as mg/l) of suspended sediment, Forel color number of I or II (the first two steps on a 20-step blue to yellow scale), Secchi-disc transparency readings in the high twenties of meters (meaning that a standard white disc 20 centimeters in diameter goes out of sight from a ship's deck at that depth), and salinities between 35 and 35.9 parts per thousand. Such characteristics may be considered typical of the clear-water areas used for comparative water-penetration estimates in the earlier sections of this report, viz. the Cabo Rojo area, the shelf south of the Isla Caja de Muertos, the shelf west of the western end of the Isla de Vieques, and the broad shoal area east of St. Croix, as well as of the broad oceanic areas away from the influence of the Puerto Rico land mass.

Coastal waters in the zone between three and five miles off the north coast of Puerto Rico in general have from 0.04 to 0.33 mg/l of suspended sediment, Forel color numbers from III to V, and Secchi-disc transparency readings from 10 to 25 meters. The wide range in these properties portrays well the wide range of turbidity conditions in Puerto Rican coastal waters. Incidentally, it is not likely that the figures on suspended sediment concentrations for the general Puerto Rico area include any significant component caused by planktonic or other organic material.

Of the seven water cruises made, only that of 16 January 1974, the first day of the RB57F flights, really serves to quantify imagery made by either Skylab or the RB57F. The turbidity situation off the San Juan area that day has been described in some detail on pages 40 to 42, and may be seen in figures 14 (following page 40) and 17 (following page 48). Pertinent results of the ship's work that day are shown on figure 18 (following page 53), superimposed on the pattern of major bodies of water and with arrows added to indicate the direction of surface currents revealed in the high-altitude photographs. The RB57F aircraft made its images of the area at 1025 local civil time, and the ship's observations and sampling were done between 0930 and 1400 local civil time.

The numerical data of figure 18 show that the water leaving San Juan harbor was extremely turbid, very low in visibility, and rated XIII on the Forel scale, or in other words was a yellow-brown color. The measurements of suspended sediment, visibility, and color at the station in clear water outside San Juan harbor contrasted strongly with those of the three stations nearer shore within the turbid plumes.

Off Punta Maldonado the numerical data of figure 18 show the same general pattern seen off San Juan harbor: nearshore very highly turbid water moved offshore as a plume and by mixing became less turbid. Note in the numerical data of figure 18 that the northwestward-trending turbid-water plume off Punta Maldonado is bordered both on its landward and seaward sides by much less turbid water. The remarkably high Forel color number of XV for the most turbid water at the station furthest inshore off Punta Maldonado, incidentally, is caused by the high organic content of water that has come from an extensive mangrove swamp.

It is strongly to be emphasized that information on coastal water characteristics and currents such as that shown in figure 18 could be determined also from orbital-height photography of S190B quality under favorably cloud and turbidity conditions, except for the numerical data provided by the research vessel. But such numerical data could well be used to calibrate the density of orbital photographic images, and thus to extend quantification of the photographic images in at least an approximate way well beyond the limited area that can be sampled in a short time by a research vessel.

EVALUATION OF RESULTS

The overall aim of this report is to determine the extent to which orbital sensing can be used for analysis of shallow-water and coastal conditions and phenomena in a clear-water tropical area. This section of the report defines as clearly and succinctly as possible what the various types of orbital sensing can and cannot do in investigating that subject area. It also contains information on the optimum use of the imagery from each Skylab sensor (S190A, S190B, and S192), and suggestions for further investigation of the Skylab data using instrumental techniques of image enhancement and data extraction.

Bathymetric mapping

The S190B Earth Terrain Camera with its high-resolution color film is the best of the Skylab sensors for detection of bathymetric detail. Its swath-width is less than that of the S190A, but its resolution is much greater, and its water-penetrative capability is slightly higher (maximum 72 feet, 22 meters, for S190B; maximum 60-65 feet, 18-20 meters, for S190A).

The S190A results show that color infrared film is inferior to high-resolution color film in portrayal of bathymetric as well as turbidity features.

For direct photo interpretation, S190B film should be observed as a film positive at its original 5-inch size through a microscope rather than by use of an enlargement; the enlarging causes a significant loss of resolution. Paper prints of course have even poorer resolution.

Fairly accurate contoured bathymetric charts could be made of clear-water areas by density-slicing the S190B photographic images, and for control, some microdensitometer profiles could be made to compare with actual bathymetric profiles done by a research vessel. It is much to be regretted that this study could not include such work, but as an indication of its practical utility, the cooperative U. S. Geological Survey--Commonwealth of Puerto Rico Marine Geologic Mapping Project plans to perform just such work when time allows. An area of significant new information expected as a result is the detection of sedimentologically significant areas where the bathymetry has changed since original surveys by surface ship were made.

The applicability of bathymetric contour charts prepared from Skylab imagery to poorly surveyed or unsurveyed shallow clear-water coastal areas of the world is obvious. Experience in Puerto Rico in this study shows, however, that repetitive coverage or at least repetitive opportunities for coverage would be required, for conditions both of extremely low cloud cover and extremely low turbidity in coastal waters would be necessary.

Differentiation of the signatures on S190B photography of bathymetry and of turbidity features is not difficult under good conditions in coral-reef and in most areas of hard rock bottom, but it is difficult in areas of smooth sand or mud bottom. Here the utility of the S190A multispectral camera comes into play, for as discussed on pages 17-18 and 24, the 0.6-0.7 micrometer S190A photographs show only turbidity features, while the 0.5-0.6 micrometer and the color photographs show both turbidity

C.2

and bathymetry. S192 imagery is also useful in differentiating images of bathymetry and turbidity. The 0.62-0.72 micrometer band used in comparison with other spectral bands is particularly useful in this regard (page 34). Low sun angle also aids in differentiating between the signatures of turbid water and of bathymetry on S190B color film (page 22), but the bargain is a poor one because low sun angle limits water penetration.

One problem in viewing bathymetric detail on the Skylab photography, especially that of the S190B Earth Terrain Camera, is that patterns of bottom-dwelling marine biologic communities are easily confused with patterns of bathymetry. Highly detailed bathymetric mapping will differentiate the two, of course, but few areas even of Puerto Rican waters are as yet covered by bathymetric contouring of sufficient detail. The RB57F RC-8 color photography is useful in this differentiation because, viewed stereoscopically, the actual underwater relief of bathymetry can be seen and thus the ecological patterns differentiated. Orbital photography does not provide enough stereoscopic effect for this differentiation. But note that the orbital photography does give details of patterns that are known to result from either bathymetric or ecologic boundaries, and those patterns could readily by put into map form. A modicum of field-checking would then serve to identify the origin of each pattern.

Detection on the S190B photographs of Langmuir circulation cells in the near-surface water can be used to determine the direction of surface winds and local variations in their direction. They were detected on SL-2 Pass 6, but not on SL-4 Passes 54 or 85. Identification of the factors causing this difference would be required before using them.

Coral-reef distribution.-- The material of and hence the debris from coral reefs is in general very white, and accordingly it images very well on orbital photography. The superior resolution of the S190B color camera of course makes it the preferred source of information on the location, distribution, and shape of coral reefs. The narrow-band 0.56-0.61 micrometer S192 band in particular displayed unusually high contrast for coral-reef and coral-sand targets (page 34), however, and that band might well be used as a discrimination tool.

One of the primary deterrents to coral reefs studies has been the lack of precise detailed information on their distribution and map-plan morphology over broad areas. Use of Skylab-quality imagery, if it could be made available over broad areas, as perhaps it can be in the future by the use of the shuttle-orbiter system, would upon suitable interpretation supply exactly the information needed.

Sedimentation.-- Skylab photography, especially the color images from the S190B Earth Terrain Camera, proves to be very useful both in gaining an overall concept of the source, movement, and deposition of sediments along coast and in shallow waters, and in providing specific information on those subjects in localized areas.

Patterns of coastal turbidity (further discussed in a succeeding section) show clearly the source and the direction of transportation of the finer-grained sedimentary particles that have slow settling rates and which therefore remain suspended in the surface water for an appreciable period. Turbidity patterns of imagery from different Skylab passes and from the RB57F flights can be compared in order to differentiate sediment coming from rivers and that coming from coastal erosion. Under the right circumstances (as on Pass 54, page 30), the exact portions of the coast undergoing erosion can be identified. In such studies of variable and transient phenomena the need for more time-repetitive orbital photography of at least S190B quality is strongly apparent.

Sedimentary particles of sand size and larger have high settling rates and thus are only very rarely lifted appreciably above the sea floor during transportation. They are not present high in the water, do not occur in the surface layers of turbid water so prominent in orbital-height photography, and cannot in general be detected during the process of transportation. They most assuredly can be detected where they accumulate, however, if the site of accumulation is within the prevailing water-penetration limit, which has a maximum of about 84 feet (26 meters) for clear water.

Sand bodies formed from the accumulation of individual grains are prominent on the Skylab photography in many places around the coast of Puerto Rico. The major ones were already known, as for instance the great north-trending shoal off the west end of the Isla de Vieques and the deposits in the Cabo Rojo area at the southwestern corner of Puerto Rico. But a number of additional though generally smaller sand deposits have been located by examination of the Skylab photography, particularly along the little-known north coastal waters of Puerto Rico (pages 29-30).

One sedimentary property that cannot be determined even from low altitude, to say nothing of orbital altitude, is the particle-size of sedimentary deposits. Hence some of the areas of accumulation stated in the preceding paragraph to contain sand may well instead be sand and gravel, or simply gravel. But both sand and gravel are in short supply and are valuable commodities in Puerto Rico.

Relation of bathymetry to geologic structure.-- It was thought that geological lineaments, particularly fault lines or trends of bedrock outcrops, might be expressed in the general trend of the sea-floor topography or in the growth area patterns of different bottom-dwelling plant and animal communities, particularly in the broad shallow area between the Isla de Vieques and southeastern Puerto Rico. Trends or patterns that could be so interpreted were not observed, however, though minor ones may be present and so far have escaped detection.

But if such geologically-caused features had been present, they would probably have been detected on the Skylab photography. This means that the concept is still valid for other areas where such phenomena might be present in shallow water.

Water circulation

Patterns of inshore coastal water circulation are highly time-variant and are laborious and difficult indeed to measure by conventional ground-borne and shipboard methods, and yet a knowledge of them has a great deal of both practical and scientific significance. Practically, a knowledge of the entire envelope of coastal-current conditions, highly time-variant as they are, is essential for the proper location of sewer outfalls, and for predicting the probable disposal directions of suspended sediment particles from construction projects such as the dredging of new harbors, the dispersal directions of industrial wastes, and the future effects of offshore sand dredging. Sedimentation of silt and clay particles has already killed or crippled the growth of many of Puerto Rico's coral reefs, various new harbors have been dredged, expensive surveys are now being made to locate numerous sewer outfalls, and the consequences of offshore sand-removal is a currently pertinent question. Scientifically the study of coastal-current conditions is important to an understanding of natural processes of shoreline erosion, sediment transport, and sediment deposition; the distribution of the factors that affect marine biological communities; and in the study of the dynamics of water bodies in general.

In mapping the details of movement of coastal surface waters the capabilities of orbital-height photography can make a unique contribution. The information shown on figure 18 (following page 53) is an excellent case in point, and it is from only one frame of high-altitude aircraft photography. Had orbital photography been made on a day of such fortuitously good turbid-water and cloud-cover circumstances, much more would have been revealed, especially about water-circulation phenomena in areas further offshore. Skylab detected the giant turbidity plume off San Juan harbor on Pass 54 (pages 28-29), and the offshore- and crosswind-directed plume off Puerto Rico's southeastern coast was detected on Pass 85 (pages 22-23, 31-32). Neither of those passes was at a time of optimum turbid-water development, nor indeed was the the RB57F flight that resulted in the information shown in figure 18 (following page 53).

The urgent need for more time-repetitive orbital coverage is strongly apparent here. The satellite Earthsat -1 extended the time range of orbital-altitude imagery of Puerto considerably, but even it did not make images of Puerto Rico very frequently, and the resolution of its images is very poor compared to Skylab photography. A check of all Earthsat-1 Puerto Rican coverage reveals one multispectral scanner image set dated 18 October 1972 that shows a sediment plume over 10 nautical miles (18.5 kilometers) long headed almost directly seaward from the mouth of the Rio Grande de Arecibo, a remarkable phenomenon in that area of westward-flowing currents. That image was made on a perfectly arbitrary date with respect to the condition of the natural phenomena in Puerto Rican coastal waters, as of course were all the Skylab images, except for consideration of the cloud-cover conditions.

Sediment plumes.-- Plumes of sediment-laden water come not only from point sources such as river and narrow harbor mouths, but also from areas of coastal erosion, areas disturbed by such operations as dredging, and (it is thought) from the re-suspension of bottom-sediments by long-wave-length swells from distant storms. Sediment plumes are the phenomenon that enabled the discussion of coastal currents in the immediately preceding paragraphs, but it must be re-emphasized here how well they portray the trend of coastal currents and therefore of coastal erosion and sediment deposition.

Sediment plumes change continually in intensity of development because of a variety of factors, chief of which are rainfall, the local wind-driven sea, the arrival of long-period swells, and the coastal works of man. The pattern of plumes (as differentiated from their intensity) is, as we have seen, a result of coastal current circulation patterns and to a much lesser extent local surface winds. All of these factors can be elucidated by the study of sediment plumes, but, to repeat for emphasis, they are a rapidly time-variant phenomenon, and the full utilization of their information content must await the availability of rapidly time-repetitive orbital photography.

<u>Effluent discharges and oil slicks</u> These phenomena, while usually smaller in size than turbidity phenomena, are also readily detectable by orbital-height photography and imagery. As has been shown (pages 18-19, 24, 34-35, 38), their images can readily be differentiated from those of bathymetry and turbidity because they are more reflective at the longer wavelengths. Also they are more responsive to surface winds than surface currents, an additional aid in their identification.

The importance to man of oil-slick detection does not need elaboration here. What does deserve elaboration is their detectability from orbital altitudes, and therefore, the power of such high-resolution satellite photography as Skylab's in their potential detection on a world-wide repetitive basis.

The great blue anomaly in the Bahia de Mayaguez, discussed at considerable length in this report (pages 11-12, 25-26, 31-32) and illustrated in figures 2 (following page 10), 5 (following page 25), and 12 and 13 (following page 32), which is clearly caused by discharge of some effluent, is so large and diffuse when viewed from low altitude that it had never been detected previous to Skylab Pass 6, and was not seen from an elevation of 12,000 feet (3660 meters) during Pass 6. It has incidentally, been seen from a high-altitude commercial airline plane, some months after Pass 6.

Small size appears to be no impediment to the detection of oil slicks from orbital altitude, for slicks less than 100 meters wide and less than a mile long were well above the detection of S190A photography (page 15), though in at least that case and probably as a general rule, the sun azimuth from the photo center must be near to or greater than 90 degrees. Much narrower slicks thought to be of natural origin have also been detected on the S190A images (page 12), though as with most other targets they are better portrayed on the S190B images (page 26). The shape of oil slicks usually indicates the direction of surface winds, but under windless conditions their shapes can reveal patterns of surface currents (page 26).

<u>Distribution of bottom-sediment types</u> Though the beaches of Puerto Rico are made up of a variety of types of sand (Guillou and Glass, 1957), and the shallow sea floor is also widely varied in sediment type and particle-size, neither the Skylab nor the RB57F photography is of much use in discriminating the types.

Organically-derived sand and gravel containing many particles of coral and commonly known by the name is the predominating type of beach and near-shore bottom sediment in most Puerto Rican and Virgin Islands coastal area. It is light-colored and therefore photographs and images well on all Skylab and RB57F coverage of suitable wavelengths. Most other sediment types are darker in color and hence would photograph with less contrast and at shallower water-penetration depths. Some of the underwater patterns thought to be boundaries of different types of bottom-dwelling plant and animal communities may indeed be boundaries of sediment types, but the presence and boundaries of sediment types other than highly-reflective coralline sand and gravel are not generally identifiable.

Distribution of marine biologic communities - A variety of photographic features known to be boundaries of different types of bottom-dwelling plant and animal communities appears on the Skylab S190B photography in clear-water areas. They are particularly well portrayed in the area between the Isla de Vieques and southeastern Puerto Rico (pages 30-31), but unfortunately they did not reproduce at all well in figure 7 (following page 28). They may be seen fairly well in the same area in the RB57F RC-8 color photograph reproduced as figure 15 (following page 44).

The difficulties with these ecological patterns, aside from the fact that particularly clear water conditions are a necessary condition for their portrayal, lie 1) in differentiating them from bathymetric features, and 2) in determining exactly what plant or animal communities the patterns represent.

Differentiating ecological boundaries from bathymetric features on first-class orbital photography such as that of the S190B can be done to some extent by an experienced person on the basis simply of the outline and details of the patterns. High-altitude aerial photography (or low-altitude, for that matter) flown with 60% forward overlap for stereoscopic viewing is of great assistance in the differentiation, also. At least a few well-located bathymetric profiles made by a ship would be necessary in most areas for full differentiation, however.

Once the pattern of plant-animal communities is differentiated from bathymetric patterns, the question becomes exactly what plant-animal communities are being portrayed. There is simply no way to determine this except to get a boat and dive on or at least swim over the target areas. Exactly such work was done by Kumph and Randall (1961) off St. John in the U. S. Virgin Islands using conventional aerial photography and a diving sled towed by a small boat. They found, as would surely be the case with similar work on the Skylab S190B or the RB57F photography, that after becoming familiar with the area they acquired the ability to interpret the aerial photograph patterns rather well with a limited number of additional check dives.

Use of Skylab imagery as benchmark data Shoreline and coastal phenomena are highly time-variant over an exceedingly wide range of rates of change with time. Coastal water currents and turbidity conditions change daily, shoreline shape changes a known maximum rate in Puerto Rico of 5 feet per year (Kaye, 1959, p. 116) but far less in most areas, and modern mapping in many places shows from negligible to considerable change in bathymetric features since the early years of the present century. In addition, the works of man create sudden perturbations superimposed on the changing natural factors.

The photographs made during the three Skylab EREP passes over Puerto Rico may be viewed as three closely-spaced frames of a long motion-picture which seen in its years-long entirety would show the coastline being eroded landward at some places and built seaward in others, the growth of mangrove islands off the south coast, numerous changes in the shape of the shallow sea-floor and coral reefs and in the outlines of biologic sea-floor communities, and the effects of the works of man.

In this context the value of the Skylab photography and imagery as benchmark data recording in detail a tremendous variety of characteristics of the natural environment of coastal Puerto Rico as they were in June and November 1973 and January 1974 becomes apparent. Comparison of the Skylab photographs and imagery with data of similar quality taken in future years will be a powerful investigative tool in a wide variety of fields of study.

SUMMARY OF UTILITY OF SKYLAB DATA

This study has demonstrated the following:

1. Skylab earth-resources photography and multispectral imagery made during three passes over Puerto Rico contains a wealth of data of both practical and scientific use in a number of fields of study. The broad-area synoptic property of the Skylab information allows detection and study of phenomena impossible by any other existing technique.

2. A wealth of bathymetric detail is contained in the Skylab S190B color photography. Details of bathymetry are visible to a maximum depth of 84 feet (26 meters) in areas of clearest water, but turbidity of coastal waters near Puerto Rico is commonly so high as to reduce water penetration drastically or eliminate it entirely. Fairly accurate contoured bathymetric charts could be made by density-slicing the clear-water S190B images and using microdensitometer profiles compared with actual echo-sounder profiles for control. A combination of low cloud cover, high enough sun angle, and low water turbidity is necessary for good portrayal of bathymetry.

3. Patterns of bathymetric detail and of turbid-water features are differentiable by use of multispectral data of either photographic or multispectral scanner origin. Images from wavelengths in the range 0.6-0.7 micrometers show only turbidity features, while images in the range 0.5-0.6 micrometers show both bathymetric and turbidity features.

4. The identification, distribution and map-plan morphology of coral reefs can be determined from orbital photography of S190B quality, and coverage of large areas by such photography would be of great value in coral-reef studies.

5. The source, movement, and deposition of sea-floor and beach sediments and the location of areas of coastal erosion can be studied very well by orbital-height photography of S190B quality.

6. Potentially economic offshore deposits of sand, sand and gravel, or gravel (which are not differentiable except upon field examination) are readily detected on orbital-height photography of S190B quality, provided that water-transparency conditions are favorable.

7. Traces of geological faults and geologically significant lines of rock outcrops on the shallow sea floor were not detected in clear-water areas, simply because they were not there. They would be detectable in areas where present.

8. The discrimination of different types of bottom-sediments in shallow-water areas is inefficient or impossible by the use of orbital height photography. Actual field work is necessary for their differentiation.

9. Much detailed information on patterns of coastal water currents is readily available from orbital-height photography of S190B quality, but conditions of high turbidity in the coastal waters are necessary.

Coastal currents are so variable and so rapidly time-variant that abundant time-repetitive coverage would be necessary to their detailed study. Anomalous large-scale offshore-oriented plumes of turbid water can only be detected by orbital-height photography, and their study would result in new information on the behavior of water currents in coastal areas.

10. Effluent discharges and oil slicks, even those of small dimensions, are readily detectable by orbital-height photography and are differentiable from other phenomena by comparison with the longer wavelength bands of multispectral cameras or scanners. Large diffuse and presumably potentially ecologically damaging effluent discharges can be detected and studied well only by orbital-height photography. A limiting requirement for oil-slick detection seems to be that the slick must not be in the sun-azimuth direction from the photo center.

11. Portrayal of the patterns and boundaries of bottom-dwelling plant and animal communities is excellent for clear waters on orbital-height photography of S190B quality, though those patterns are somewhat difficult and sometimes impossible to separate from bathymetric patterns. This is a tool of great potential value, even though actual identification of the biologic communities responsible for the patterns requires personal observation on the scene.

12. The applicability of Skylab-quality earth-sensing data is limited to relatively clear-water areas for studying and mapping bathymetry and patterns of bottom-dwelling biological communities and detecting potential offshore sand deposits. It is not limited to clear-water areas for studies of nearshore currents, coastal erosion and sediment transportation, or detection of oil slicks. Extremely highly turbid water conditions are desirable for studies of coastal water currents.

13. The Skylab photography and multispectral scanner imagery are a highly detailed record of coastal conditions in Puerto Rico at a certain time, and hence are of great potential value for they can be compared with future coverage of the same type to determine the trend of a variety of slowly time-variant phenomena.

14. Color infrared film is inferior to high-resolution color film in water penetration and therefore in the portrayal of bathymetry and patterns of bottom-dwelling biologic communities. It is also inferior to color film in rendition of turbidity features, and would seem to be preferable to color film only for studies involving vegetation at or above the water surface.

15. Stereoscopic effect as seen in a standard office-type stereoscope is not strong enough on orbital-height photography to show apparent relief of bathymetric features, and therefore stereo-overlap orbital-height photography is not inherently efficient considering the restricted

film-carrying capacity of most spacecraft. It would be more efficient to use the film saved to increase either the area or frequency of coverage. High-altitude photography does allow underwater stereo-relief effect, and this is useful in differentiating patterns of bathymetry and seafloor biologic communities.

16. Although high-altitude aerial photography is a tremendous source of detailed information on the restricted area it covers, and gives stereoscopic relief effect underwater as orbital-height photography does not, dollar for dollar the use of light aircraft up to altitudes of 12,000 feet (3660 meters) is considerably more efficient. This is particularly so because of their general ubiquity and quick availability.

17. Full interpretation of the wide range of details of shallow-water areas shown on orbital-height photography of S190B quality would require considerable field inspection by research vessels and in-the-water personal observation. The use of light aircraft to locate significant phenomena and direct research vessels to them is highly efficient, though because of the wide-area synoptic capability of orbital-height photography and imagery, not all phenomena detected from orbital height can be seen from low-altitude aircraft.

18. More rapidly time-repetitive orbital-height photography is urgently needed for a wide variety of studies. It is hoped that the shuttle-orbiter system can supply this.

19. The applicability and potential value of Skylab-quality data in studies of bathymetry, patterns of coastal currents, coastal erosion, sediment transportation and accumulation, effects of coastal works of man, and oil-slick detection to the less well-developed coastal areas of the world is high. It is a great potential use of orbital-height earth-sensing data in the service of mankind.

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APPENDIX A

LOG OF ALL FIELD OPERATIONS

JUNE 1973 - AUGUST 1974

4 June 1973 - A Skylab EREP Track 19 (descending across Puerto Rico) pass (no. 4) was scheduled. Westward track shift of 60 miles from nominal track. Time over P.R. est. $17^h 16^m$ GMT. Difficulties with spacecraft prevented imaging Puerto Rico. A light-plane low-altitude reconnaissance and photographic flight of the north, west, and south coasts of Puerto Rico was made. The research vessel used by the Puerto Rico project, which is operated by the Puerto Rican government, was not available for taking water samples and measurements.

9 June 1973 - Another Skylab Track 19 pass (no. 6) resulted in successful S190 A and B and S192 imagery. Track still 60 miles west of nominal, which gave good coverage of Mona Passage and roughly the western half of Puerto Rico. Much useful data in the images. Another light-plane low-altitude flight synchronized with the Skylab pass resulted in valuable observations and photographs, but the research vessel was still not available so no quantitative data on water characteristics became available.

21 October 1973 - Research vessel cruise from San Juan westward along north coast of P. R., down west coast, and west to Isla de Mona resulted in suspended sediment, water clarity, color, salinity, and temperature data over that area. These are the standard measurements hereinafter referred to as "water stations".

23 November 1973 - Load and prepare research vessel to make water stations during Skylab EREP pass scheduled for 25 Nov.

24 November 1973 - Light-plane reconnaissance flight to observe turbidity patterns so as to locate research vessel water stations for maximum information. Further prepare ship for cruise. Notified in late PM of cancellation of EREP pass scheduled for 25 Nov.

30 November 1973 - Skylab SL-4 EREP pass 54 on Track 19 resulted in data takes by S190A and B and S192. Track 19 now in nominal position. Light-plane reconnaissance and photographic flight at nominal 11,000-foot altitude covered all coasts of Puerto Rico except Isla de Mona (not within EREP views) and including west half of St. Croix; east half and other Virgin Islands were cloud-covered. Research vessel took very successful series of water stations off San Juan and in vicinity of Boca de Congrejos centered on time of Skylab pass.

3-12 December 1973	- Research vessel took good series of water stations along north coast of Puerto Rico, south on west coast to Mayaguez, west to Isla de Mona, and return.
14 January 1974	- Light-plane low-altitude observation and photographic flight in San Juan coastal area (Dorado - Pta. Picua) to optimize locations of water stations to be taken by research vessel during RB-57 60,000-foot Mission 260 flight scheduled for 15 January.
15 January 1974	- Similar light-plane flight, also RB-57 flight, conducted but solid clouds produced negative results.
16 January 1974	- Successful 1) RB-57 mission; 2) Research vessel water stations made off Boca de Congrejos near San Juan; and 3) light-plane low-altitude observations and photography from Dorado through San Juan area to Pta. Picua.
17 January 1974	- RB-57 returned to photograph portions of track lines obscured by clouds on previous day.
18 January 1974	- Skylab SL4 EREP pass no. 85 on track 19 made but no notification received in Puerto Rico until 21 Jan. due to poor communications.
22 January 1974	- Research vessel took series of water stations from San Juan west along north coast and south on west coast to Mayaguez; following day made water stations from Mayaguez west to Isla de Mona. This was an attempt to get best possible water data to support EREP pass of 18 Jan.
24 January 1974	- Light-plane flight at low to medium altitude from Isla de Mona to Mayaguez area and thence to San Juan along north coast; excellent observations and photos of slicks and turbid plumes in Mayaguez Bay area and on north coast. (Research vessel returned to San Juan 29 Jan.).
17-19 July 1974	- Research vessel cruise for water stations from San Juan east to Culebra and return. (First availability of research vessel since January).

4 August 1974 - Start of water-station cruise from San Juan west along north coast and south on west coast to Mayaguez; next day west across Mona Passage to Isla de Mona. Excellent observations and sampling of mixing water masses off Punta Higuero, the western tip of Puerto Rico.

End of field phase of Skylab investigation.

Note: All water samples from water stations were analysed in the laboratory for suspended-sediment content and for salinity. Those results and those of temperature, color, and transparency (Secchi) were then plotted in the office.

APPENDIX B - ROLL NUMBERS OF SKYLAB PHOTOGRAPHIC IMAGERY AND DECODING LIST FOR IDENTIFICATION OF S192 CHANNELS

Roll numbers of Skylab photographic imagery

Numbers of individual frames are shown on the individual coverage diagrams within the text.

S190A

Camera station	Spectral band 1/	EREP Pass 6, 9 June '73	EREP Pass 54, 30 Nov. '73	EREP Pass 85 18 Jan. '74
1	0.7-0.8	07	49 2/	67
2	0.8-0.9	08	50	68
3	Color IR	09	51 2/	69
4	Color	10	52	70
5	0.6-0.7	11	53 2/	71
6	0.5-0.6	12	54	72

1/ In micrometers.

2/ Not used in this study.

S190B

EREP Pass 6, 9 June 1973	-	Roll 81
EREP Pass 54, 30 November 1973	-	Roll 90
EREP Pass 85, 18 January 1974	-	Roll 92

Decoding list for identification of S192 channels

Data printed on the film rolls containing the black and white images made from the S192 multispectral scanner do not include a direct indication of the spectral band shown in each image. Instead, following the data line "Channels requested" is what may be considered a code number that identifies the spectral band.

The following list may be used to convert from the code number to the spectral band and band number.

Band number	Spectral band 1/	Code number
1	0.41 to 0.46	22
2	0.46 to 0.51	18
3	0.52 to 0.56	1,2
4	0.56 to 0.61	3,4
5	0.62 to 0.67	5
6	0.68 to 0.76	7,8
7	0.78 to 0.88	9,10
8	0.98 to 1.08	19
9	1.09 to 1.19	20
10	1.20 to 1.30	17
11	1.55 to 1.75	11,12
12	2.10 to 2.35	13,14
13	10.20 to 12.5	15,16,21

1/ In micrometers.

APPENDIX C - FISCAL SUMMARY

Summation of Skylab Project expenditures, (USGS project 4-9450-01103; NASA Contract T-4658) during fiscal year 1974.

(Note: Skylab investigations in Puerto Rico began their active field phase on 4 June 1973, which was fiscal year 1973. Within the Geological Survey this Skylab project was not fiscally begun until the start of fiscal year 1974. Acting with clearance from my USGS administrators, I spent my own project funds on necessary NASA-project procurement in late FY 1973, and paid them back equally by using the NASA funds for my own project in FY 1974.)

1. Salary, 1/2 year for Principal Investigator $12,495

2. Other expenses, including temporary salaries

   1. Miscellaneous field and laboratory supplies and equipment (no item over $200.). $5,015.95

   2. Major items of field, laboratory, and office equipment:

1. Millepore filter manifold	$ 209.85
2. Raytheon echo-sounder	$2,395.00
3. Light table with microscope carriage	$1,437.00
4. Analytical balance	$1,375.90
5. Nikonos camera	$ 347.50
6. Oceanographic water sampling bottle	$ 286.00
7. Drafting table	$ 231.01
Total	$6,282.26

   3. Aerial photographic and reconnaissance flights in light planes $1,793.00

   4. Photographic equipment and supplies $ 980.61

   5. Travel, shipping, and communications $1,170.89

   6. Personal services (assistance on ship) $ 352.35

Total, other expenses including temporary salaries $15,595

Skylab Project expenditures - continuation

3. Common Service Costs (a pro-rated charge to each Geological Survey project for use of USGS facilities such as library, laboratories, etc.) . . . . $ 2,520

4. Geological Survey Assessment Costs $14,100

Total project expenditures $44,710

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