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# Coastal Water Clarity from Space Photographs

**GEMINI photos illustrated that they can be used for mapping coastal water types.**

## Introduction

This study was undertaken for two purposes: (1) to estimate the percentages of the world's coastline having sufficiently clear water for mapping of nearshore submarine topography using airborne optical devices (such as cartographic cameras and pulsed laser range finders), and (2) to determine the feasibility of using space photography to observe water clarity. Available in-situ water transparency data was collected and found to be very sparse for coastal regions of most of the world. Accordingly, many extrapolations were made using more abundant types of oceanographic data on features such as estuarine-delta outflow, distribution of nutrients, zones of coastal upwelling and coral reef distribution.

Abstract. *Mapping ocean water clarity from space ship photography was shown to be feasible by studies of 70 mm color transparencies from GEMINI flights. A prototype global map of coastal ocean water turbidity was constructed on the basis of the relationship between water transparency and its color and the visibility of shoals. For comparison, in-situ transparency data taken by oceanographic ships was mapped. The resulting global maps of coastal water clarity indicate that about 35 percent of the world's coastal sea floor can be mapped out to 20 meters depth by aerial photogrammetry.*

The qualitative determination of water clarity from GEMINI photography was done on the basis of (i) apparent water color and (ii) the visibility of shoals through the water.

## Methods

### In-situ Data (Nonspace)

Figures 1a and 1b are the result of compilation and extrapolation from Naval Oceanographic Office Secchi disk transparency data and published transparency data (References 1, 2, 3, 4, 6, 7, 18, 20, 27, 34, 35, 40, 41, 42). These charts show distribution of estimated average coastal water clarity as it occurs during more than 50 percent of the time. Secchi readings in some areas can show more than 100 percent change in a few hours as well as slower seasonal changes of the same magnitude (34). Local anomalies smaller than 100 miles across are not shown, and only the regional picture is attempted.

Four basic assumptions governed the extrapolations of transparency data:

(i) Water becomes more turbid as the shoreline is approached from the open ocean. In-situ data was seldom taken as close to shore as would be desired for this study. Extrapolation into the coastal zone inshore of the 20 meter isobath or to within ten miles of shore should consider that, in most places, transparency is proportional to distance from shore (34, figure 1).

(ii) Offshore of major estuarine zones of the world oceans, water clarity is proportional to salinity. The 33.5 percent isohaline (22, figure 1) was found to delineate reasonably well those coastal waters with less than 20 m Secchi visibility, as exemplified by the Yellow, Yangtze, Mekong, Ganges, and Mississippi River delta areas, and was therefore used as a criterion for marking turbid water from the Irrawaddi, Congo, Amazon, and Rio Uruguary (also see 7, 39). Water at deltas of these rivers is charted here as having less than 5 m visibility.

(iii) Attenuation of light in water increases with increasing organic matter (16, 17, 18, 19,

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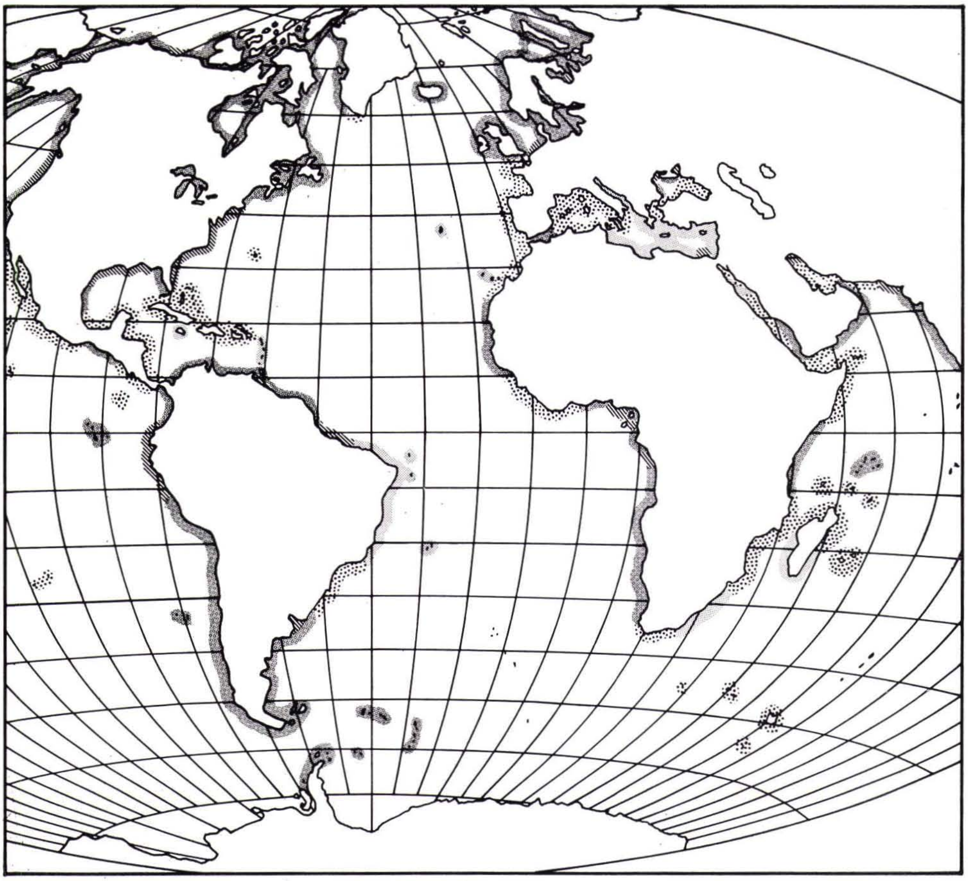



FIG. 1a. Coastal water clarity by extrapolation from *in-situ* data.

25, 31, 32, 33, 44). The correlation between the chart of transparency in Joseph's figure 17 (18) and the chart of water color in Ryther's figure 18 (33) is excellent.

(iv) Living coral reefs occur only in fairly clear water. Areas containing coral reefs (43) were assumed to contain water no more turbid than 5 m Secchi.

Due to lack of nearshore data, Figure 1a and 1b of this report are not expected to reflect the zone closer than two miles of shore. No attempt has been made to show harbors, lagoons and other small scale features.

GEMINI PHOTOGRAPHS

Figures 2a and 2b show water clarity as derived from analysis of 92 selected 70mm color transparency duplicates of photographs taken by astronauts of GEMINI flight numbers IV, V, VI, VII, IX, X, XII. The basis of the method of analysis is the relationship between water color and transparency (5, 8, 14, 17, 18, 19, 21, 24, 26, 28, 29, 30, 36, 37, 38, 39). Figure 3 shows light attenuation as a function of water color. This graph was compiled from irradiance transmittance curves such as shown in Jerlov (17) and from unpublished Naval Oceanographic Office Data of Secchi visibility versus color on Forel scale; the width of the band indicates scatter of the data. Applying this curve to GEMINI photographs, strongly discolored water was considered to be more turbid than 5 meters (approximately 70 percent light transmittance), deep blue water is clearer than 20 meters (92 percent), and all other intermediate water is between 5 and 20 meters transparecny.

The deep brilliant cobalt blue color of clear tropical waters is caused by molecular scattering. As the content of dissolved organic yellow substance and suspended matter in more

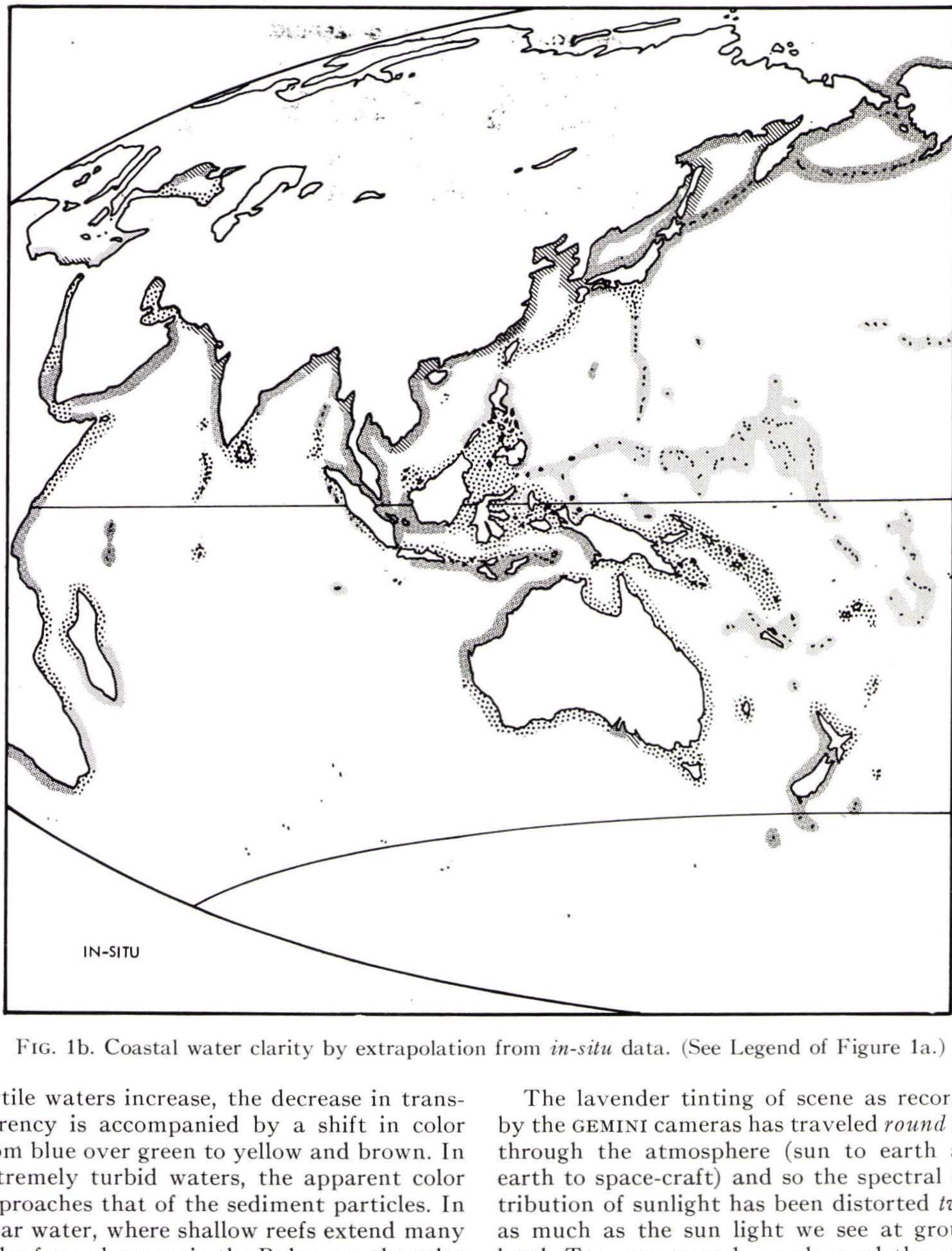


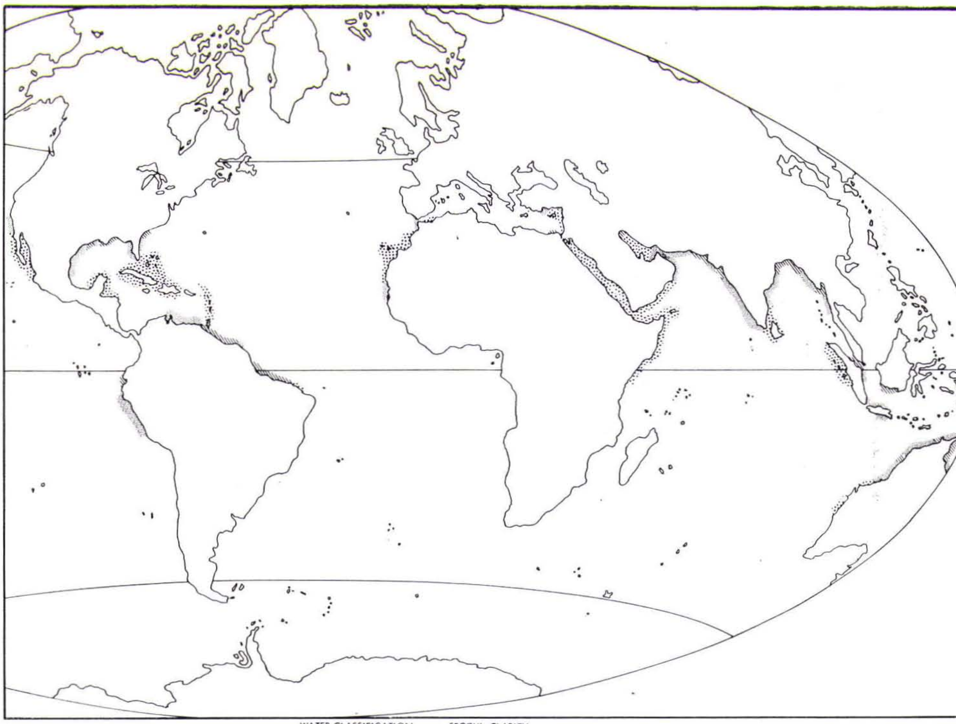

FIG. 1b. Coastal water clarity by extrapolation from *in-situ* data. (See Legend of Figure 1a.)

fertile waters increase, the decrease in transparency is accompanied by a shift in color from blue over green to yellow and brown. In extremely turbid waters, the apparent color approaches that of the sediment particles. In clear water, where shallow reefs extend many miles from shore, as in the Bahamas, the color of the sea floor can be seen through the water, and the water depth can therefore be estimated on this tonal basis (10, 24). Along most coast lines, the shallow sea bottom was not seen due to the small scale of the GEMINI photographs.

The photographs are high in red and excessive in blue, and deficient in yellow and green. Color calibration strips at the ends of film rolls showed that film processing did not cause this color distortion.

The lavender tinting of scene as recorded by the GEMINI cameras has traveled *round trip* through the atmosphere (sun to earth and earth to space-craft) and so the spectral distribution of sunlight has been distorted *twice* as much as the sun light we see at ground level. Two processes have changed the color distribution: (1) absorption, and (2) scattering. (See 11, 15).

The absorption of light by dust particles and water is a subtractive process and attenuates most strongly in the shorter wavelengths (blue and green), passing red most easily. Figure 4 shows the spectral distribution of (*A*) downwelling sunlight above the atmosphere, and (*B*) sunlight at the earth's surface after the second absorption of blues and greens. Curves (*D*) and (*E*) show trans-



| WATER CLASSIFICATION | SECCHI CLARITY |
| --- | --- |
| MUDDY | LESS THAN 5 METERS |
| TYPICAL COASTAL | 5 - 20 METERS |
| VERY CLEAR | MORE THAN 20 METERS |

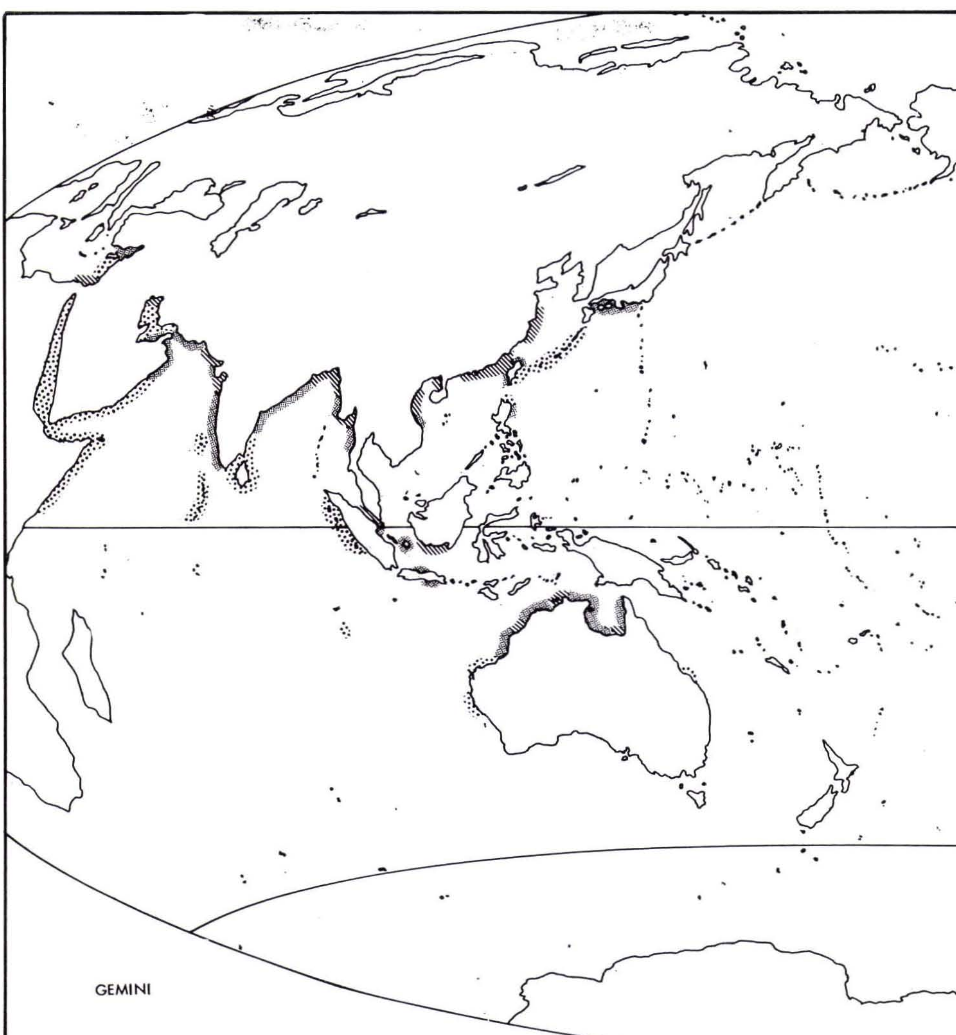


FIG. 2a. Global distribution of coastal water clarity as extracted from GEMINI space photographs. (Season variations were not considered.)

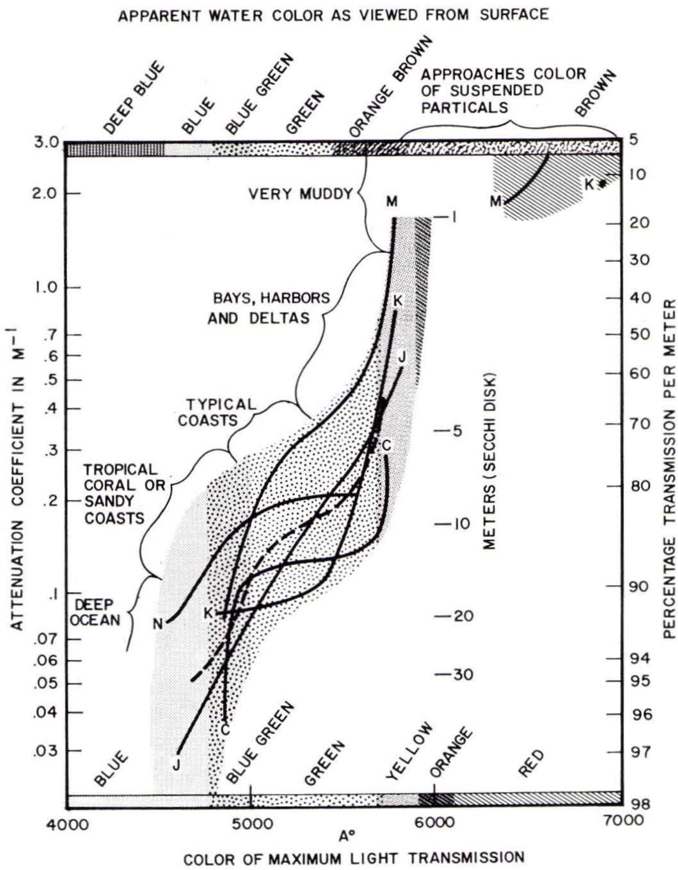



FIG. 3. Light attenuation as a function of water color. *Sources: N*, unpublished U. S. Naval Oceanographic Office data (Secchi disk and Forel scale). *J*, Jerlov (16, 17). *M*, Moore (24). *K*, Kinney (21). *C*, Clark (5). *Dashed line*, Curve used for this study. Width of shaded band indicates approximate extent of data scatter and natural water variability.

mission percentage for one and two ways, respectively.

The scattering of light by the molecules of air is effective in the short wavelengths (blue and ultraviolet) and is an additive process, as far as color tint of space photographs is concerned. The resulting blue luminance is visible from the ground as skylight and from space craft as a hazy layer that adds a blue hue to ground and sea surface.

## RESULTS AND RECOMMENDATIONS

### GLOBAL DISTRIBUTION OF COASTAL WATER CLARITY

The global distribution of coastal water clarity is summarized Table 1.

FIG. 2b. Global distribution of coastal water clarity as extracted from GEMINI space photographs. (Season variations were not considered.) (See Legend of Figure 2a.)

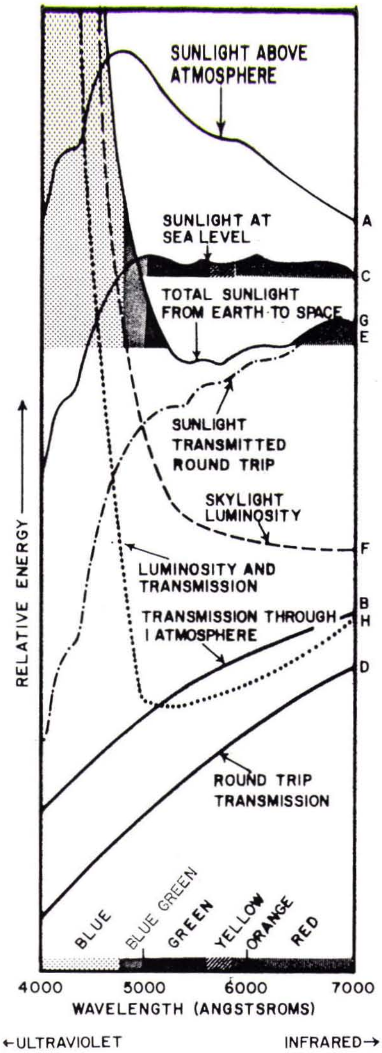



FIG. 4. Spectral curves illustrating the increase of atmospheric color distortion observed from space.

The results of this study indicate that, where speed is important and the water clarity is better than 5 m Secchi, coastal surveys of bathymetry out to 20 meters depth should use aerial photographs simultaneously with airborne laser fathometers. Aerial photography will enable synoptic depth contouring and shoreline mapping, and the pulsed laser will directly give a depth profile and extension to water depths and/or turbidity beyond photographic capabilities.

### GEMINI PHOTOGRAPHS

The correlation between Figures 1a and 1b, constructed only from in-situ data, and Figures 2a and 2b, made only by the analysis of GEMINI photographs, demonstrates the feasibility of coastal water classification from space photography.

It is recommended that, for oceanographic purposes, spacecraft photography should be made with metric cameras in multi-spectral array or with color film with strong minus-blue (dark yellow) filters or film without the blue emulsion layer. This will cause clouds to appear yellow—no disadvantage to the oceanographer or geologist—but will help

TABLE 1. GLOBAL DISTRIBUTION OF COASTAL WATER CLARITY

| *Percent Transmission Per Meter* | *Percentage of World Coastlines* | *Where Found* | *Implications* |
|---|---|---|---|
| 0 to 70% (0 to 5 m Secchi) | 15% | Near all deltas of major rivers draining humid areas (e.g. Louisiana, China) | *Not* amenable to optical methods of bathymetric survey to 20 meters. Sonar needed. |
| 70 to 92% (5 to 20 m) | 50% | Coastal water in temperate and arctic regions. Found also in tropics where upwelling occurs (West Africa, West Coast of S. America, N. W. Australia). | Amenable to optical airborne bathymetric survey by laser fathometer to at least 20 meters depth. |
| more than 92% (over 20 m) | 35% | Tropical and Mediterranean water in areas free from upwelling (Caribbean, Mediterranean, S. E. Brasil, Madagascar, East Australia). | Amenable to airborne laser bathymetry to over 40 m depth. Amenable to aerial photographic depth contouring to over 20 m depth. |
| more than 95% (over 30 m) | 10% | Lesser Antilles, Eastern Mediterranean, Hawaii, S. W. Pacific Islands. | Amenable to airborne laser survey to over 60 m depth. Amenable to air photo contouring to over 30 m depth. |

prevent the unwanted blue fogging that degraded the GEMINI imagery.

Wide-angle lenses are preferred because this enhances the prime advantage of spacecraft photography—large synoptic coverage. The wide-angle GEMINI photography was the most useful for the present study.

## SUMMARY AND CONCLUSIONS

Space Photography can be used for mapping coastal water types.

On a yearly average, 85 percent of the world's coastal water is sufficiently clear for the use of an airborne laser fathometer for mapping sea floor topography from shore out to at least 20 meters depth; 35 percent is clear enough for mapping by aerial color photogrammetry to at least 20 meters depth and for laser sounding to more than 40 meters; 10 percent is clear enough for aerial photography to more than 30 meters.

## REFERENCES


1. Beeton, A. M. (1962). Light penetration in the Great Lakes, Pub. No. 9, Inst. Science and Technology, University of Michigan. pp. 68–76.
2. Bumpus, D. F. and A. H. Clarke (1947). Hydrography of the western Atlantic; transparency of the Coastal and oceanic waters. TR #10. WHOI.
3. Burt, W. Y. (1958). Selective transmission of light in tropical Pacific waters. *Deep-Sea Research*, V 5 pp 51.
4. Clarke, G. L. (1938). Light penetration in the Caribbean Sea and in the Gulf of Mexico. *J. Marine Research*, V 1, n2, pp 85–94.
5. Clarke, G. L. and James, H. R. (1939). Laboratory analysis of the selective absorption of light by sea water. *J. Opt. Soc. Amer.* v 29, n 10, pp 43–55.
6. Clarke, G. L. and M. G. Kelly (1966). Variations in transparency and bioluminescence on longitudinal transects in the western Indian Ocean. In International Indian Ocean Expedition Collected Reprints, UNESCO.
7. Dietrich, Gunter (1960). *General Oceanography*. Interscience, Wiley. p. 526.
8. Duntley, S. Q. (1965). Oceanography from manned satellites by means of visible light. *Woods Hole Inst.*, Oceanography from space. Ref 65-10. p. 39.
9. Duntley, S. Q. (1963). Light in the Sea. *J. Opt. Soc. Amer.*, V 53, pp. 214–233.
10. Gettys, R. F., Evaluation of color photos exposed from the GEMINI (GT-4) flight over the Gulf of California, Unpublished manuscript, U. S. Naval Oceanographic Office, Washington, D. C. 1965.
11. Hardy, A. C. (1936). *Handbook of Colorimetry*, M.I.T., Cambridge. pp. 17–18.
12. Harvey, H. W. (1963). *The Chemistry and fertility of sea water*. Cambridge. pp. 115.
13. Hedgepeth, J. W. (1957). Marine biogeography. *Geol. Soc. Amer. Memoir* 67. p. 1. Plate I. p. 398.
14. Hulburt, E. O. (1945). Optics of distilled and natural water. *J. Optical Soc. Amer.* 35: 698–705.
15. Itek Corp. (1965). *Photographic considerations for aerospace*. Itek Corp. 118 p.
16. Jerlov, N. G. (1964 A). Optical Classification of Ocean Water. *Physical Aspects of Light in the Sea*. University of Hawaii Press.
17. Jerlov, N. G. (1964 B). Factors influencing the color of the sea. *Studies in Oceanography*, M. Sears, ed.,
18. Joseph, J. (1953). Meeresoptik. *Landolt-Bornstein*, III Band, Astronomic and Geophysic. p. 452.
19. Kalle, K. (1960). What do we know about "gelbstoff"? in Symposium of radiant energy in the sea. Aug. 1960 Helsinki, Proc. Imprime par L'institut Geographique National Monograph n. 10, Jerlov, N. G., ed. (1961).
20. Ketchum, B. H. and Shonting, D. H. (1958). Optical studies of particulate matter in the sea. WHOI Ref. No. 58-15. (unpublished manuscript).
21. Kinney, J. S., Luria, S. M., and Wertzman, D. O. (1967). Visibility of colors underwater. *J. Opt. Soc. Amer.* v 57, N6, pp. 806–809.
22. McHugh (1967). Estuarine Mekton. *AAAS pub. n. 83*, Estuaries. G. H. Lauff, ed. pp. 582–583.
23. Meisburger, E. P. (1962). Distances from shore to 10-fathom depths off continental coasts. *Research Rep.* 1725-RR, U. S. Army Eng. Res. & Dev. Labs. Ft. Belvoir, Va.
24. Moore, J. G. (1947). The determination of the depths and extinction coefficients of shallow water by air photography using color filters. *Roy. Soc. Phil. Trans.* 240A: 163–217.
25. Osborne, M. F. M. (1965). The effect of convergent and divergent flow patterns on infrared and optical radiation in the sea. *Sonderdruck asis dem Deutschen Hydrographischen Zeitschrift*, 18, 1.
26. Oster, R. H. and Clarke, G. L. (1935). Penetration of the red, green, and violet components of daylight into Atlantic waters. *J. Opt. Soc. Amer.* V25 pp. 84–91.
27. Pettersson, Hans, ed. (1951). Report of the Swedish deep-sea expedition in 1947–1948. *Goteborg, Elanders Boktryctken Aktieboloy, Vol. III, Physics and Chemistry*, November 1951.
28. Phleger, F. B. (1965). Study of river effluents from space vehicles. WHOI *Oceanography from Space*, Ref. 65-10. pp. 425–426.
29. Powell, W. M. and Clarke, G. L. (1936). The reflection and absorption of daylight at the surface of the ocean. *J. Opt. Soc. Amer.* V26, pp. 111–120.
30. Redfield, A. C. (1965). Estuaries. WHOI *Oceanography from Space*. Ref. 65-10. p. 427.
31. Riley, G. A. (1938). The significance of the Mississippi River drainage for biological conditions in the northern Gulf of Mexico. *J. Marine Res.* v1, n1, pp. 62, 64.
32. Rockford, D. J. (1966). The surface waters of the S. E. Indian Ocean and the Arafura Sea in the spring and summer. *Internat. Indian Ocean Exped.* Collected Reprints I, UNESCO.
33. Ryther, (1963). Productivity, definition, and measurement. *Seas*, v 2. N. M Hill, ed. p. 157.
34. Satyanarayana, Rao, T. S. (1957). Studies of the penetration of light in the Bay of Bengal. *Proc. Nat. Inst. Sc. India*, v 23, para. B. nos. 5 & 6.

35. Spillhaus, A. F., Jr. and W. S. VonArx (1966)—Measurements of the forward scattering of a laser beam in sea water. *Deep-Sea Res.* v 3, pp. 755–759.
36. Stamm, G. L. and Langel, R. A. (1961). Some spectral irradience measurements of upwelling natural light off the east coast of the United States. *J. Opt. Soc. Amer.* V51, n 10, pp. 1000–1004.
37. Stommel, H. (1963). Rapid serial survey of the Gulf Stream with camera and radiation thermometer. *Science* 117: 639–640.
38. Strandberg, Carl (1967). *Aerial discovery manual.* Wiley (in press).
39. Sverdrup, H. U. et al (1942). *The Oceans.* Prentice Hall pp. 34–35.
40. Utterback, C. L. and J. W. Boyle (1933). Light penetration in the waters of San Juan Archepelago. *J. Opt. Soc. Amer.* v23, n10, pp. 333–338.
41. Utterback, C. L. (1933) Light penetration in the waters of southern Alaska. *J. Opt. Soc. Amer.* v23, n10, pp. 339–341.
42. U. S. Naval Oceanographic Office (1965)—*Oceanography and underwater sound for naval applications* SP 89. pp. 28–34.
43. Wells, J. W. (1957). Coral reefs. *Geol. Soc. Amer.* Mem. 67, v1. plt. 9, p. 630.
44. Wyrtke, K. (1966). The upwelling in the region between Java and Australia during the S. E. Monsoon. *International Indian Ocean Expedition*, Collected Reprints I, UNESCO.

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