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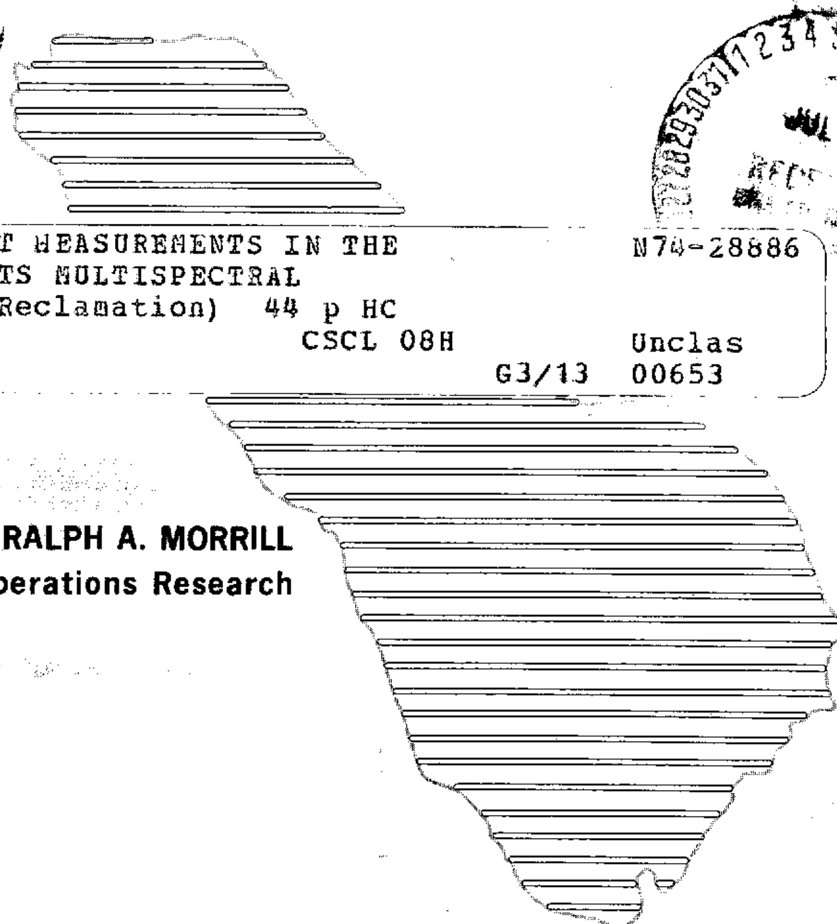
Current Measurements in the Salton Sea Using ERTS Multispectral Imagery

APRIL 1973



(E74-10653) CURRENT MEASUREMENTS IN THE SALTON SEA USING ERTS MULTISPECTRAL IMAGERY (Bureau of Reclamation) 44 p HC $5.25 CSCL 08H

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

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION ○ Engineering and Research Center
Denver Federal Center ○ Denver, Colorado 80225

ABSTRACT

The feasibility of measuring the currents in the Salton Sea of California, using Earth Resource Technology Satellite (ERTS) Imagery, is examined and proved in this study. These measurements may then be used to validate a hydrologic model used as an engineering tool for dike and channel design in the solution of water quality problems in the Salton Sea.

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CONTENTS

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CONTENTS - Continued

LIST OF FIGURES

CONTENTS - Continued

LIST OF FIGURES

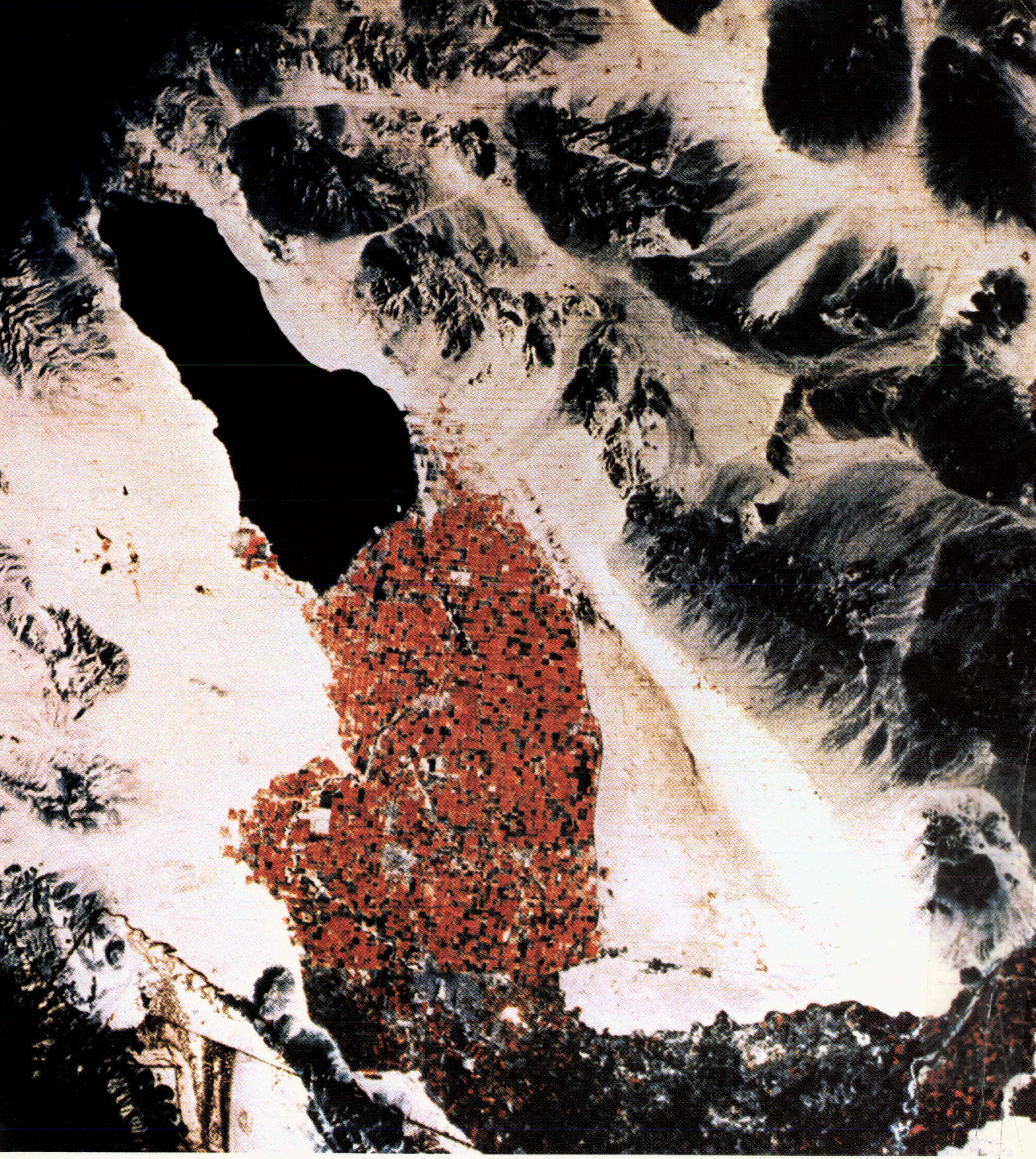


FIGURE i - APOLLO 9 PHOTO - COLOR INFRARED SHOWING SEDIMENTRY INFLOWS INTO THE SEA FROM ITS THREE SOURCES (THE SALTON SEA AND IMPERIAL VALLEY)

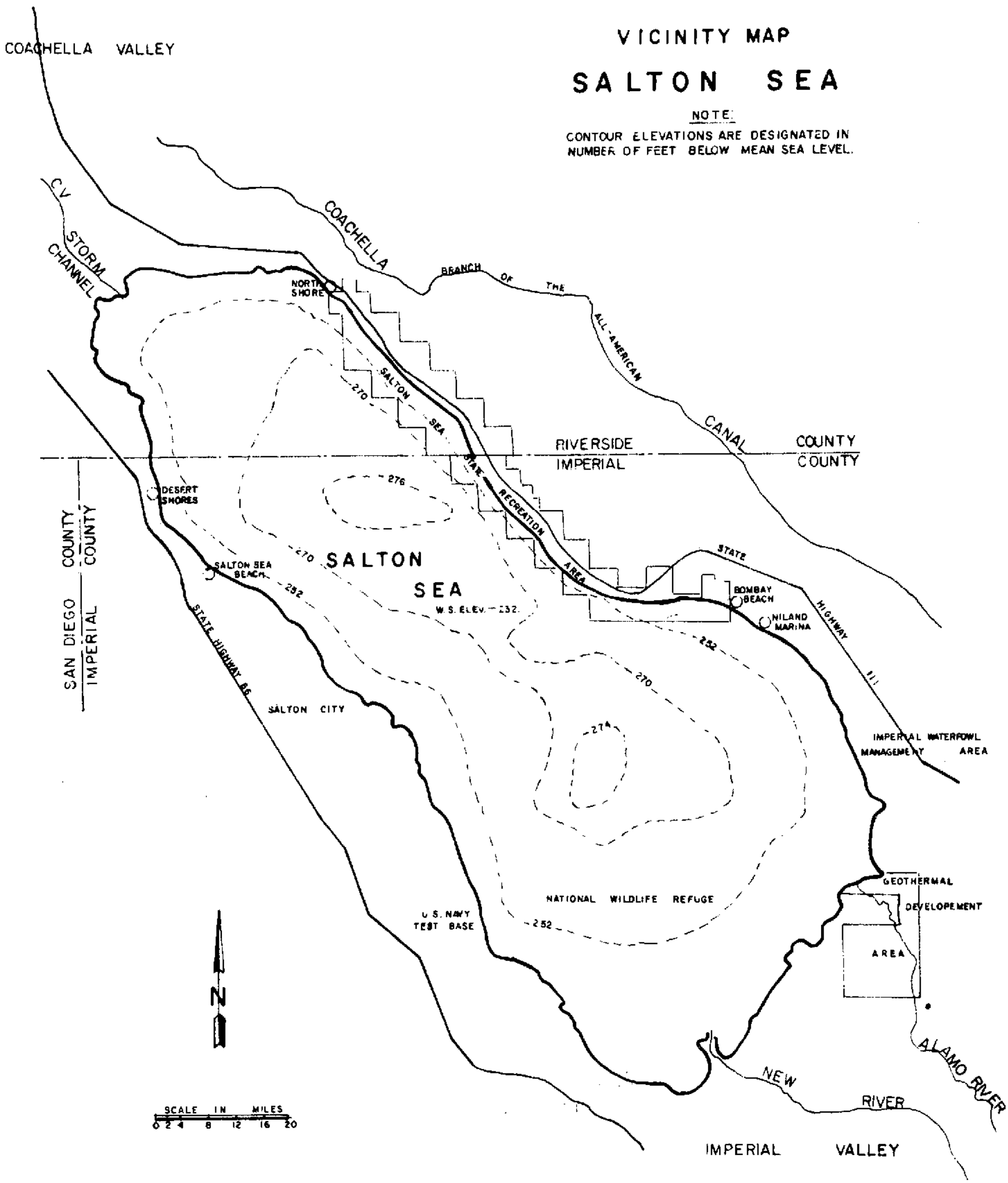


FIGURE ii - VICINITY MAP - SALTON SEA

CURRENT MEASUREMENTS IN THE SALTON SEA
USING ERTS MULTISPECTRAL IMAGERY

1.0 Introduction

The purpose of this research study was to determine if Earth Resource Technology Satellite (ERTS) multispectral imagery could be successfully used to measure the currents in the Salton Sea of California. The results of this research are to be used in an ongoing interagency study of the Sea whose objectives are to obtain control and reduction of the rising salinity, to stabilize the surface elevation, and to reduce the eutrophication of the Sea. The solutions presently under evaluation include the installation of an enclosed 30- to 50-square-mile diked area within the southern end of the Sea that will act as a controlled storage and evaporation area; and practical pumping schemes to remove high salinity water and replace it with brackish well water.

The eutrophication problem could be partially solved in conjunction with the structural alternatives by obtaining better mixing and more uniform distribution of the nutrients contained in the irrigation drainage into the Sea from the New, Whitewater, and Alamo Rivers. This would require careful selection of the diked area size, shape, and location, and could involve channelization of the inflows and the installation of breakwaters to divert or create mixing currents. To evaluate the effectiveness of these structures, a 170-inch hydraulic model is proposed that would be validated if the currents in the Sea were measurable from the ERTS data.

1.1 Summary

The study first looked at the possibility of using photoluminescent dye markers in the Sea to measure the currents. Although possible, this proved to be theoretically impractical and very expensive.

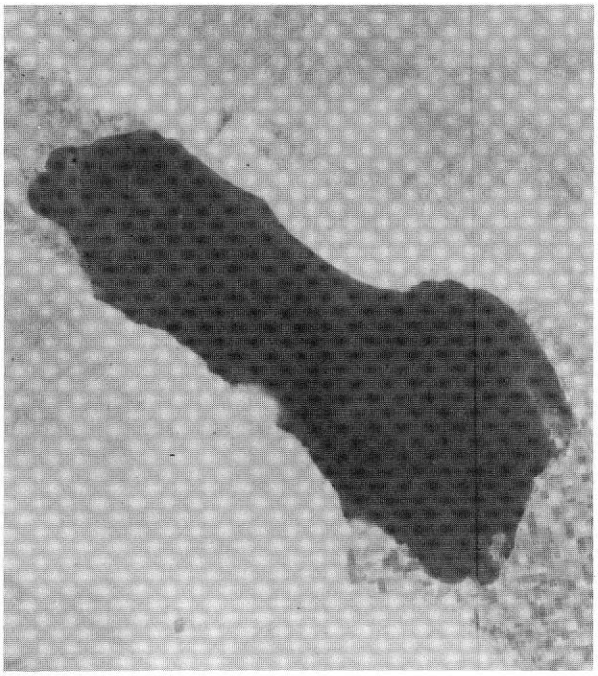
The photoluminescent characteristics of chlorophyll contained in the phytoplankton (algae and other plant life) in the Sea were also analyzed and determined to be the most practical indicator useful in measuring the Sea currents. We have prior knowledge of algae blooms and areas of high eutrophication concentrations within the Sea, and one Gemini 5 photograph apparently shows the algae swirl (Figure 1) centered in the northern sector of the Sea. The spectral response of the film and angle with respect to the sun are proper in this photo to show both near-surface sedimentary deposits and the chlorophyll photoluminescence of algae. The peak emission from chlorophyll is in the spectral band from 6500Å to 6750Å, which also corresponds directly with the ERTS Multispectral Scanner Data Band No. 2. It is also visible in the IR spectrum, Multispectral Scanner Band No. 4. With a data sequence of 18 days between successive ERTS overflights, changes in the density and position of the algae swirl are precisely measurable using ERTS imagery to determine rate and location of currents and the relative severity of the eutrophication problem.

If this information is used to validate the 170-inch hydraulic model, then the effects of diking, channelization of the inflow, and breakwaters can be determined using this model, with high confidence in the results.

1.2 ERTS Data

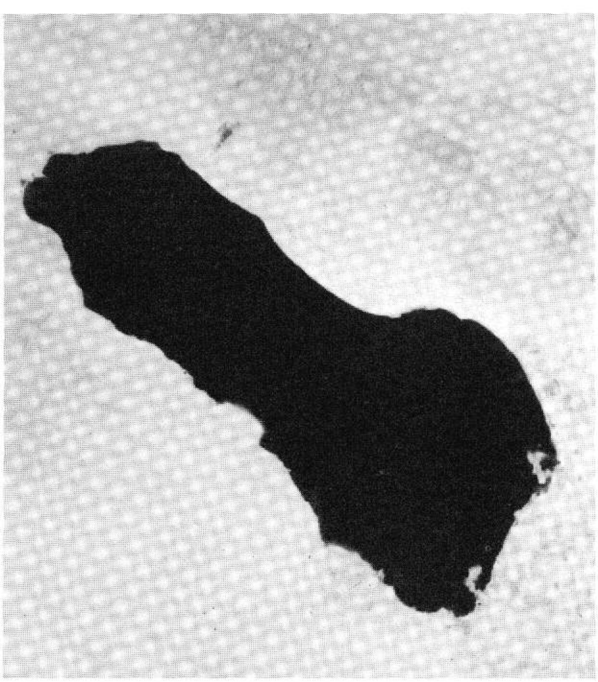
Enlarged prints of the Multispectral Scanner (MSS) imagery from the ERTS-1 mission are shown in Figure 2. These were scanned and recorded simultaneously in an overflight late in August 1972. The predominant difference between these images is sediment inflow, and the photoluminescence of chlorophyll and the IR response in the near-surface algae within the Sea. The angle, light levels, and photo processing are not optimum in this instance to see all the photoluminescent emissions; and the imagery has not been processed to emphasize in-Sea information, as they would be in an actual controlled program. In addition to this the vivid display obtainable by high precision densitometer discrimination processing of RBV and MSS green band imagery (a service of Goddard Labs) was not available for this study but will be for the next phase.

FIGURE 1 - APPARENT ALGAE SWIRL (BLUE GREEN SPECTRAL BAND) IN THE SALTON SEA - GEMINI 5 PHOTOGRAPH

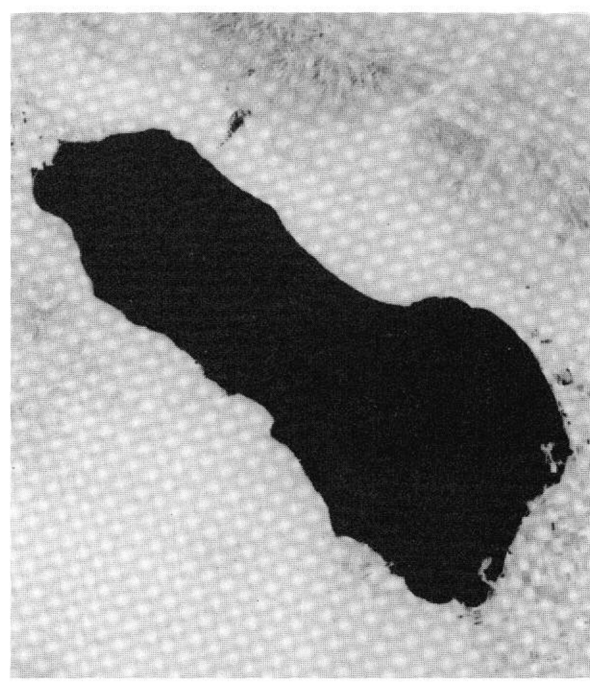


MSS BAND 4 - 5000 to 6000 ANGSTROMS

MSS BAND 5 - 6000 to 7000 ANGSTROMS



MSS BAND 6 - 7000 to 8000 ANGSTROMS



MSS BAND 7 - 8000 to 11,000 ANGSTROMS

FIGURE 2 - ENLARGED MSS IMAGERY AUGUST 1972 OVERFLIGHT

1.3 Conclusions

The conclusion of this study is that ERTS Reverse Beam Vidicon and Multispectral Scanner imagery can be used to accurately measure the currents in the Salton Sea thereby validating the hydraulic model and thus the effects of alternative structures and forms installed within the Sea. The only reservation to this conclusion is that the ERTS imagery must be obtained during the season when high algae concentrations are present in the Sea and wind effects are negligible. These are coincident between June and October.

On the reasonable assumption that ERTS-2 (due to be launched in November 1973) will not experience sensor failures, then approximately $12,000 should be budgeted in 1973 for data analysis and plotting of the currents in the Salton Sea during the next study phase.

The alternative of aerial photoimage data collection and analysis would not be possible for less than $100,000. This would require several sweeps (five or more) over the Sea with multispectral instrumentation, spaced out approximately 1 to 2 weeks apart and calibrated for ground truth with stadia points and in-Sea dye markers or floats. The estimated instrumented flight time, including calibration, would be 5 hours per sweep for a minimum of five sweeps. The analysis and reduction of these data would also be considerably more difficult, requiring professional photogrammetry equipment and experts.

2.0 Photoluminescent Dye Tracing

Current measurement in rivers, streams, and lakes using dye markers is not a new process, but has advanced rapidly in recent years as new dyes and instrumentation have been developed. The emphasis of this advancement has been in relationship with pollution control and the mixing and absorption of effluents in natural water bodies.

Using dyes of various properties, measurements have been made of time-of-travel, dispersion, discharge, current dynamics, circulation and stratification of water in large bodies as well as ground-water dispersion, the tracing of evapotranspiration losses, and the tagging of herbicides and insecticide sprays.

Most fluorometric procedures involve the controlled introduction of dyes into water and the subsequent collection and measurement of concentration levels in samples using a fluorometer. It is an extremely simple procedure, reliable in the repeatability of results and sensitive down to concentrations of less than 1 part per billion (ppb) of dye.

Fluorometric dyes are also used in photogrammetric remote sensing that spectrally separate the dye luminescent spectra from the incident radiation which may be either sunlight or a high intensity artificial light centered in the absorption band of the dye. In this case, using frauuhoffer line-discrimination, sensitivities have been obtained of well under 5 ppb.

2.1 Properties of Dyes

Several dyes have been developed which exhibit strong fluorescence in direct sunlight and retain this characteristic for long periods of time when mixed in various types of water, i.e. polluted, salty, alkaline, or acid. Four dyes used most extensively as tracers are Rhodamine B, Rhodamine WT, Pontacyl Pink, and Fluorescein. They each have different fluorescent spectra and properties adaptable to a wide range of applications:

1. Water soluble;
2. Highly detectable in low concentrations;
3. Harmless in low concentrations;
4. Inexpensive; and
5. Stable in normal water environments.

Additional properties that must be considered in selecting a specific dye for a particular application is its:

1. Spectral response in relationship with the background radiance;
2. Quenching of the luminescence due to silt, chemicals, and other water properties;

3. Rate of dispersion in open waters and decay rate in full sunlight; and
4. Sensors being used; resolution, granularity, sensitivity, motion, aperture and remote range to the tracer; including atmospheric absorption and radiance noise.

These factors are illustrated in Figure 3 and are particularly important when using scanning sensors typical of satellite imagery instruments (Vidicons and spot scanners).

Of the dyes commonly used, Rhodamine WT appears to be the most practical for use in the Salton Sea. It is a water soluble dye with peak emission radiance at 5780Å and half-power spectral bandwidth from 5650Å to 6000Å. Tank tests verified excellent detection levels in salt water of less than 5 ppb using a frauuhoffer line-discriminator. Other characteristics of the dye are given below:

<u>Rhodamine WT</u>

$$\text{Temp. coef.} = \frac{0.02}{(T^{c} - 20^{\circ c})}$$

T^{c} = Temp. in Deg. Cent.

for $T > 20^{\circ c}$

Decay Rate:

- Fixed concentrations = 40%/2 mo. in daylight
- In open waters = 80%/4 days in full daylight

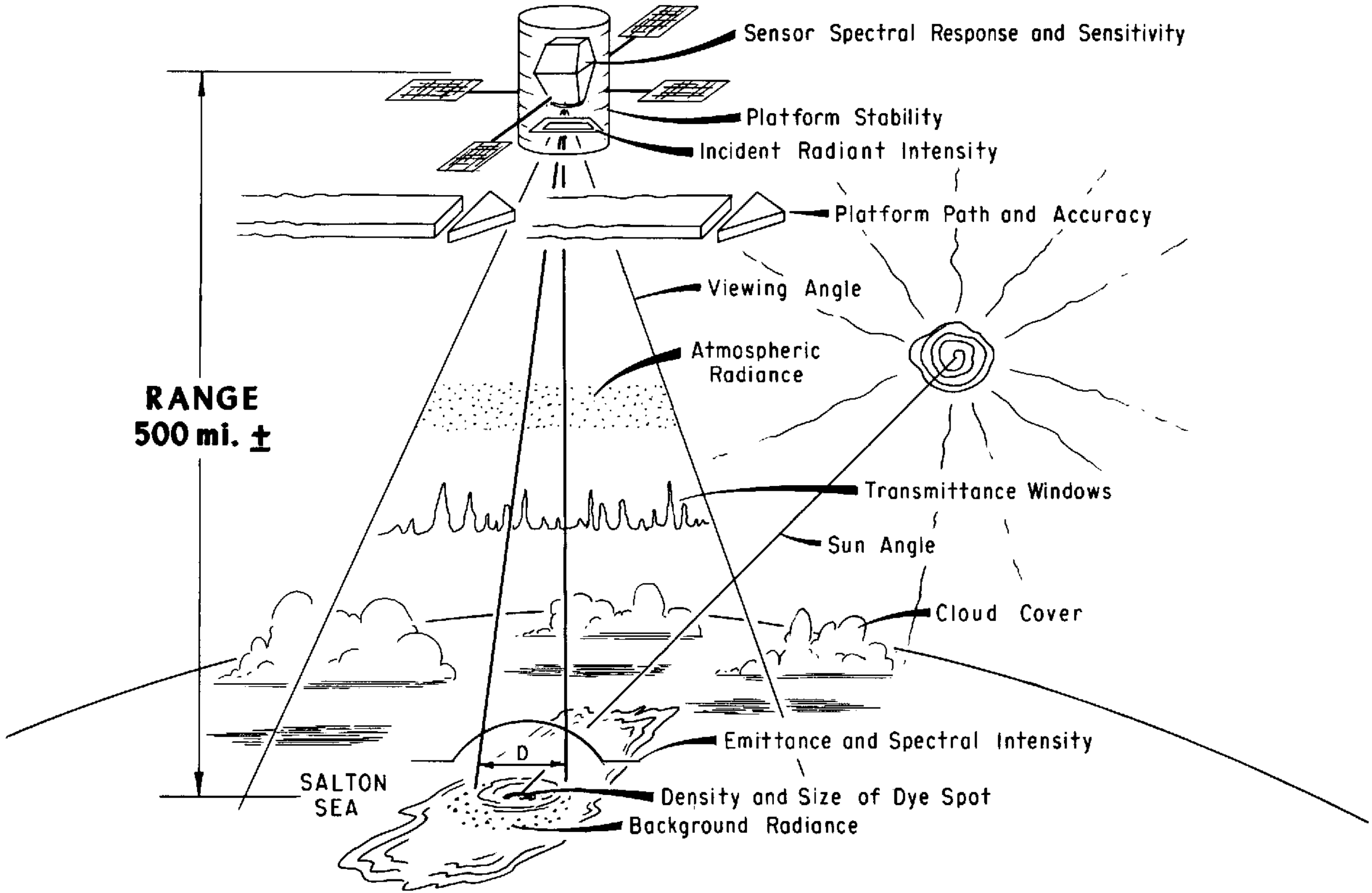


FIGURE 3
REMOTE SENSING CONSIDERATIONS

Ph sensitivity: (estimated from Rhodamine-B char.)

5 - 10	0%
below 5	7%

Note: Specific gravity of sea water = 1.03

Ph of sea water 7.5 - 8.3

Surface water temperature on Salton Sea is 3° - 8° less than air temperature (85° - 115° F in August) and inflows from New and Alamo Rivers range from 77° to 83° F, at a Ph of 7.1 to 7.9. Winds in the period June to October average 3-5 mph and some thermal stratification occurs in the Sea.

In tank tests it was shown that the relationship between dye concentration and luminescence intensity is nearly linear. A slight increase occurs as the water temperature increases. The optimum time for daylight photoimagery detection is between 10 a.m. and 2 p.m. for maximum intensity. Helicopter tests in San Francisco Bay measured concentrations of 0.5 to 1.4 ppb.

Absorption of incident and emitted light by the media (water) is more significant than the incidence of excitation and emission of the dye. Formulae have been derived relating the relative attenuation of the emission to the sun angle, water temperature, and vertical distribution of the dye.

2.2 Other Luminescent Sources

Absorption and emission of light by chlorophyll are directly related to photosynthesis - a fundamental function of all plant life including algae and other phytoplankton in sea water (Figure 4). Maximum emission is at 6500 to 6750Å. Quantum yields are 0.17 - 0.27 in solution or about 24 percent of the equivalent emissivity of Rhodium WT dye in the same solution.

Bioluminescence of marine plants is at relatively low levels in the 4200 to 5400Å range. Levels range from $1X10^{-6}$ to $1X10^{-1}$ microwatt per square centimeter of surface, received at a range of 1 centimeter. Luminescence from Dinoflagellatae (one-celled plants) increases after twilight and is inhibited by daylight.

3.0 ERTS Satellite and Sensors

The purpose of Earth Resources Technology Satellite (ERTS) program is research into applications of remote sensing technologies to techniques of earth resources management. To assess the feasibility of these techniques, NASA will launch two experimental satellites into a 494-nautical-mile earth orbit: ERTS-1 was launched in July 1972 and ERTS-2 will be launched in November 1973. Each satellite will acquire multispectral images of the earth's surface and transmit these data to ground stations where it will be forwarded to the Goddard Space Flight Center in Greenbelt, Maryland, for conversion to black-and-white or color photographs and computer

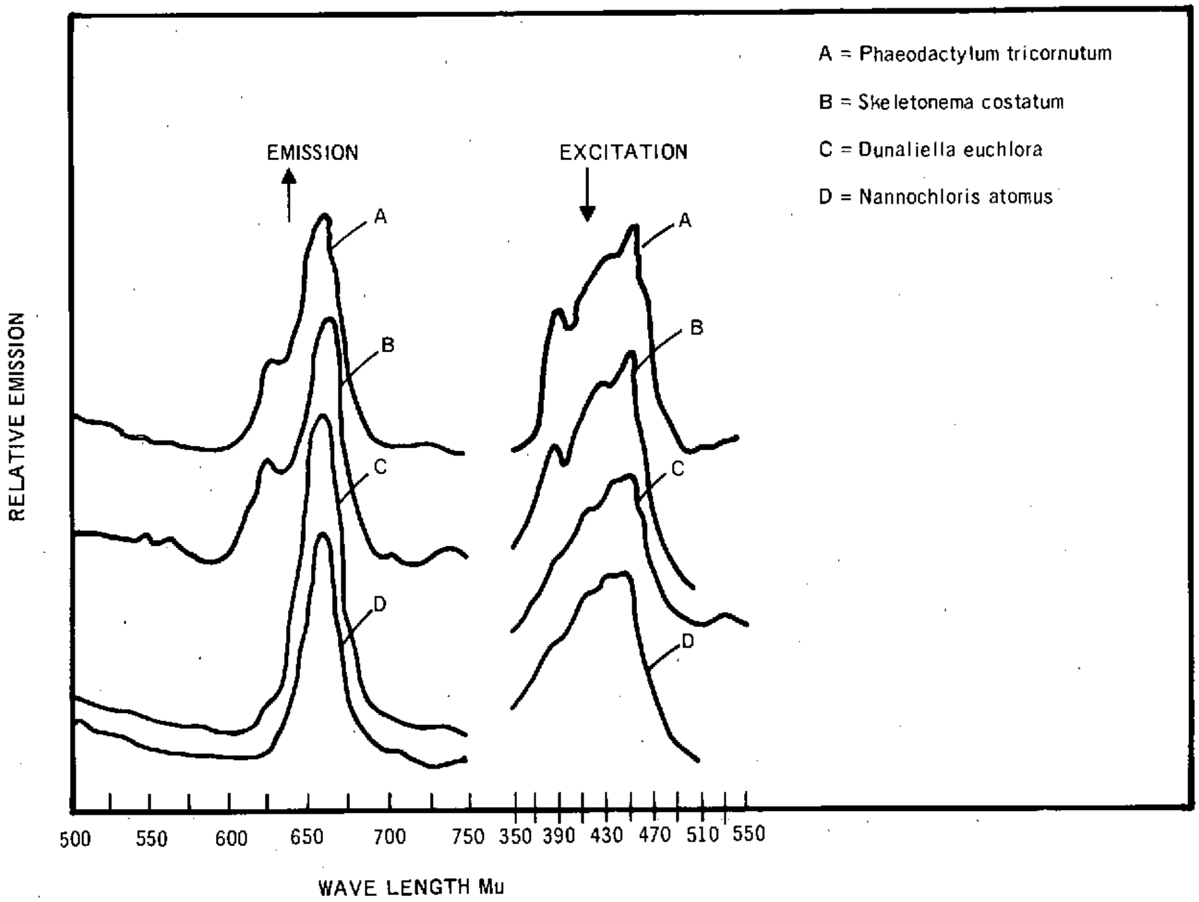


FIGURE 4 - EXCITATION AND EMISSION SPECTRA FOR SEVERAL CULTURES OF MARINE PHYTOPLANKTON

tapes. Additional ERTS systems will collect and relay weather and environmental data from remote ground-based sensor platforms back to Goddard Space Flight Center for compilation and correlation with the photoimage data.

The ERTS "precision photoimagery" is produced at a scale of 10^6:1. To achieve the mission objectives and satisfy user requirements, ERTS-1 and 2 will provide for the repetitive acquisition of moderately high resolution multispectral data of the earth's surface on a global basis. The imagery instruments used in ERTS are (1) a four-channel Multispectral Scanner, and (2) a three-camera (four in ERTS-2) Return Beam Vidicon. Each Vidicon camera simultaneously samples a different spectral band in the range of 4800Å to 8300Å (visible wavelengths). They are operated only in daylight periods of the orbit. The viewed area is 100X100 nautical miles (185 km) and is advanced at the orbital angular velocity every 25 seconds. The Multispectral Scanner scans six lines simultaneously across the 100-nm-wide orbital track traced on the earth, covering four spectral bands in the range from 5000 to 11,000 Angstroms. (A fifth infrared band in the thermal spectra will be included in the ERTS-2 payload.)

The ERTS orbit is a 494-nautical-mile altitude with a 103-minute periodicity and completes 14 orbits per day. It repeats its viewing coverage every 18 days over the same ground point within plus or minus 10 nm.

3.1 RBV Image Resolution

The Return Beam Vidicon (RBV) cameras have a spectral sensitivity shown in Figure 5. The scan rate is 4,125 lines per frame with a focal length (f.l.) of 126 mm. Image exposure times are 4, 5.6, 8.0, 12, and 16 msec. This gives an average ground point resolution for all three cameras of about 750 feet (high emissivity dyes against an H_2O background and probability of detection of 0.90) from a 494-nautical-mile orbital altitude. The spot size vs Probability of Detection is shown in Figure 6.

The limit of spot size resolution on the Vidicon image surface is dependent on the line scan count per unit area of the target photoconductor.

Video saturation of cells of the photoconductive surface of the RBV Camera No. 1 at the various shutter speeds is:

Shutter Speed	Saturation Radiance
4 (ms)	1.80 (mw/cm^2, per steradian)
5.6	1.29
8	0.90
12	0.60
16	0.45

A dye density of greater than 35 ppb against the background of salt water will give a relative radiance intensity of 2.5 mw/cm^2 - sr or more at the RBV camera. The ratio of dye density per unit/area to peak emissivity at 5780Å (or solar intensity at 5540Å) is shown in Figure 7.

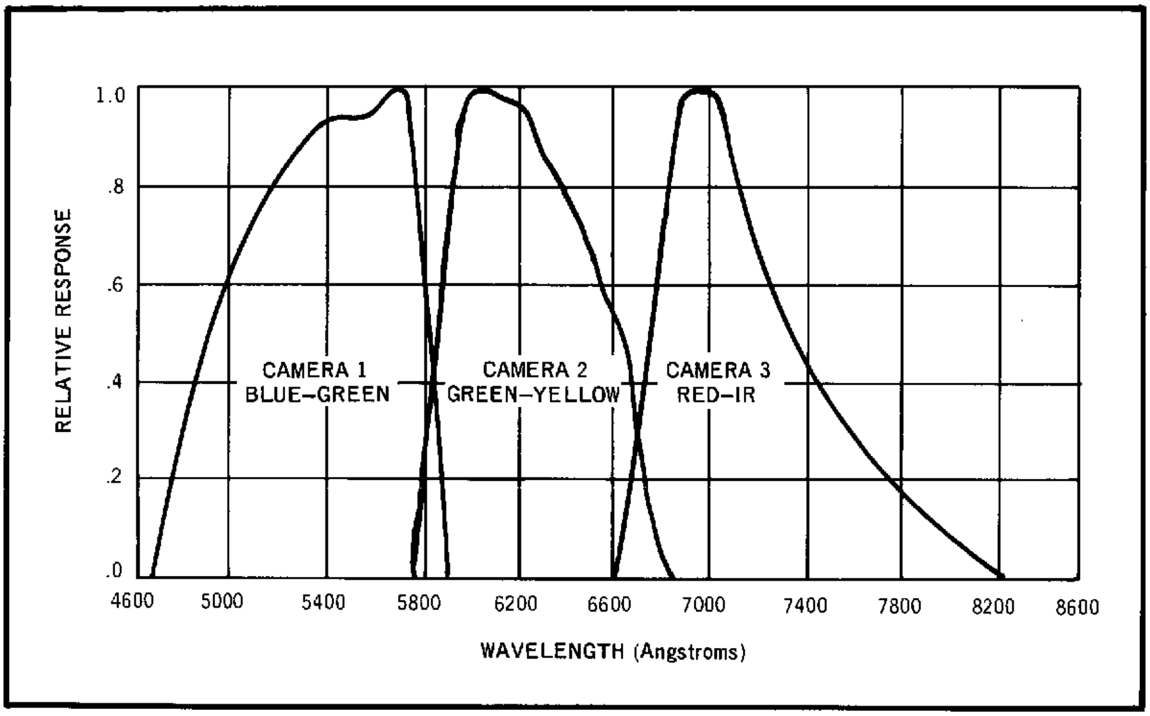
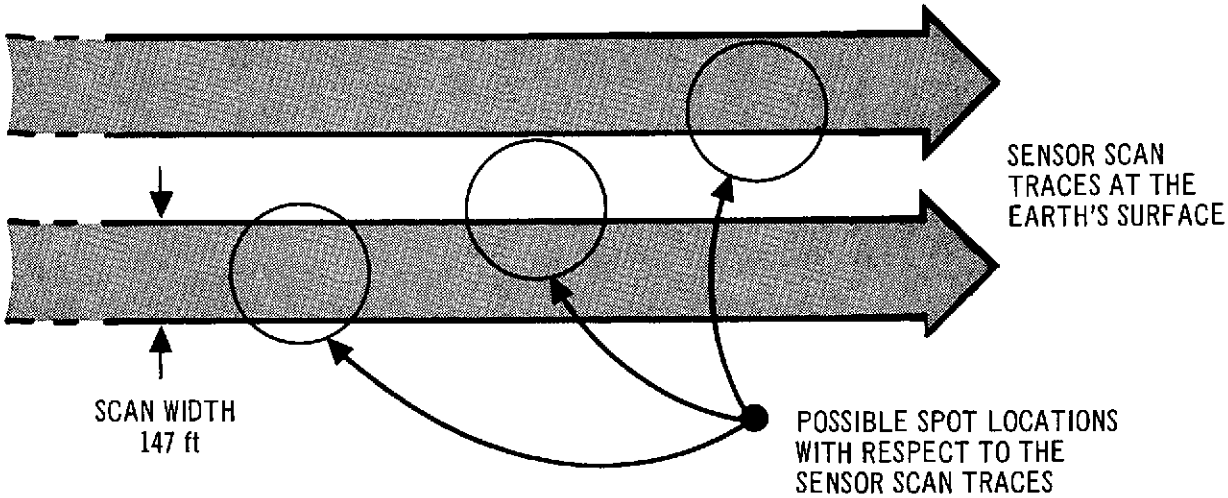


FIGURE 5 - RBV SPECTRAL SENSITIVITY



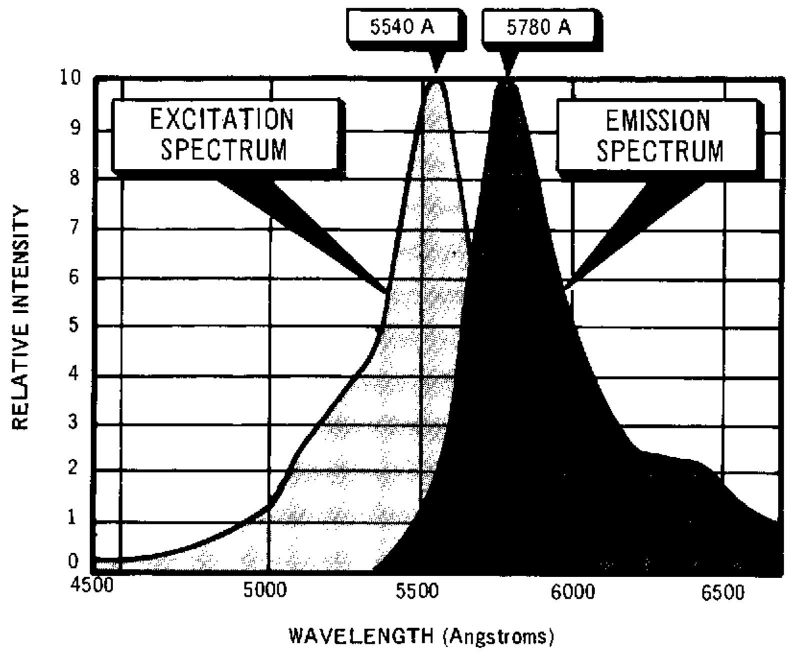
PROBABILITY OF DETECTION

$$P_D = 1-(1-P_i)^n$$

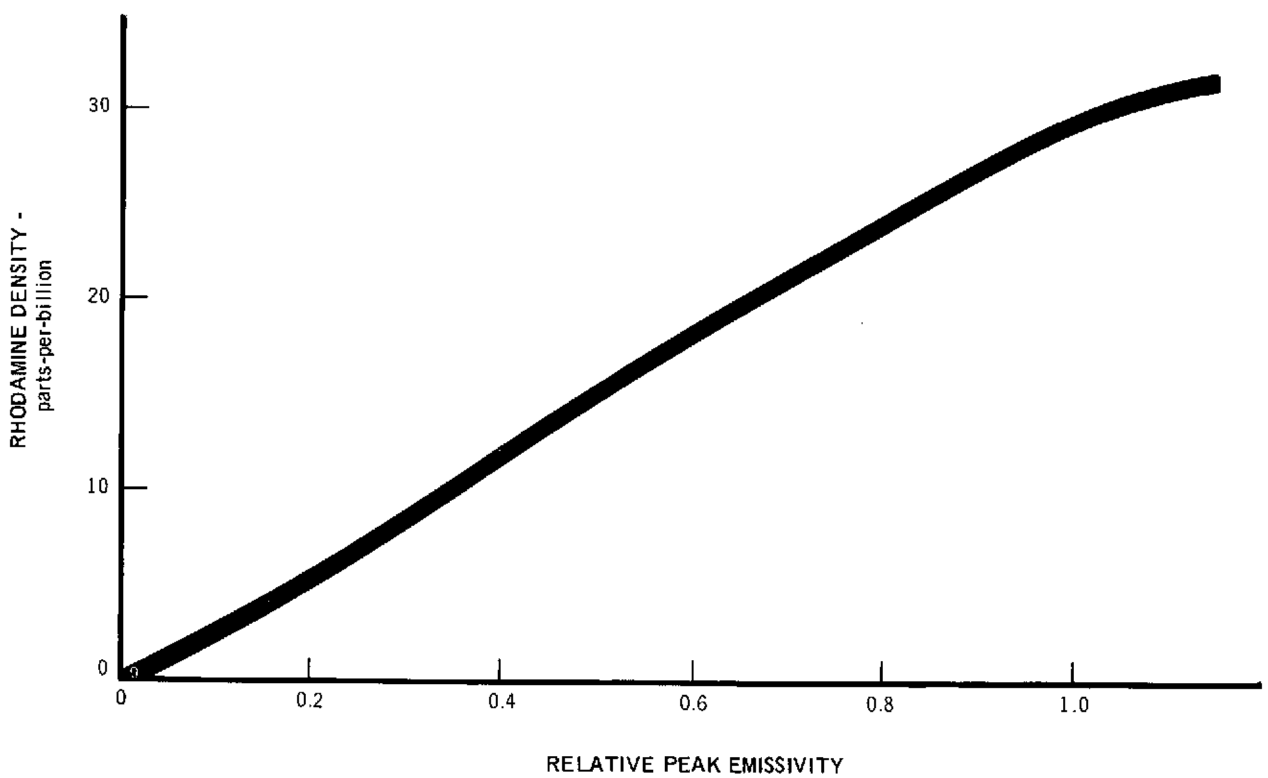
let $P_i = 0.5$ for one line of scan

TARGET SIZE - ft	P_D - PROBABILITY OF DETECTION
147	0.5
295	0.75
453	0.875
590	0.9375
740	0.96875
885	0.9844
1035	0.9922

FIGURE 6 - PROBABILITY OF DETECTION AS A FUNCTION OF GROUND TARGET DIAMETER



EXCITATION AND EMISSION SPECTRA OF RHODAMINE WT DYE



NOTE: Above 35 parts-per-billion, the radiant intensity of Rhodamine WT is about the same as the solar incidence intensity - like fresh snow.

FIGURE 7 - RHODAMINE WT DENSITY VS PEAK EMISSIVITY

For direct photoimagery it would be possible to use an X4 magnification and reduce the spot size to about 200 feet since the dye spot would be presented in very high contrast to the dark background of the Salton Sea. The Rhodium WT dye emission spectrum corresponds exactly to the RBV Camera No. 1 (blue-green) peak spectral response.

3.2 MSS Image Resolution

The ground resolution of the Multispectral Scanner is much higher than the RBV for a high radiance target such as the Rhodium dye.

MSS Parameters

Scan Width =	56 meters ± 15 across ± 3 along
	(continuous coverage - six bands - over 100-nm width)
Bands =	0.5 - 0.6 μm 0.6 - 0.7 μm 0.7 - 0.8 μm 0.8 - 1.1 μm
(Thermal IR ERTS-2 only)	(10.4 - 12.6 μm)
Sensitivity:	
For full output:	2 - 4.6 mw cm^2/steradian

3.3 Probability of Successful Imagery

For the Salton Sea area the probability of obtaining successful imagery (Figure 8) for the measurement of Sea currents is computed as follows:

Probability of Image Capture

Probability of cloud cover = 0.2 (for the Salton Sea Area in August)

p_i = (1-0.2) = 0.8; probability of no cloud cover or "seeing"

P_c = probability of image capture = $F(p_i, k)$
k = number of passes

P_d = detection probability = $F(n, I)$
n = spot size (Figure 6)
I = minimum intensity (Figure 7)

Probability of Successful Imagery P_s

$P_s = P_c \bullet P_d$; the joint conditional probability,

Given p_i, what is the P_s for various spot sizes?

Assume a spot size and intensity for

$P_d = 0.99 \approx 1.0$

and $P_c = 1 - (1-p_i)^k = 1 - (0.2)^k$

where k = number of passes or overflights

k	$P_c \approx P_s$
1	0.8
2	0.96
3	0.992
4	0.9984
5	0.99967

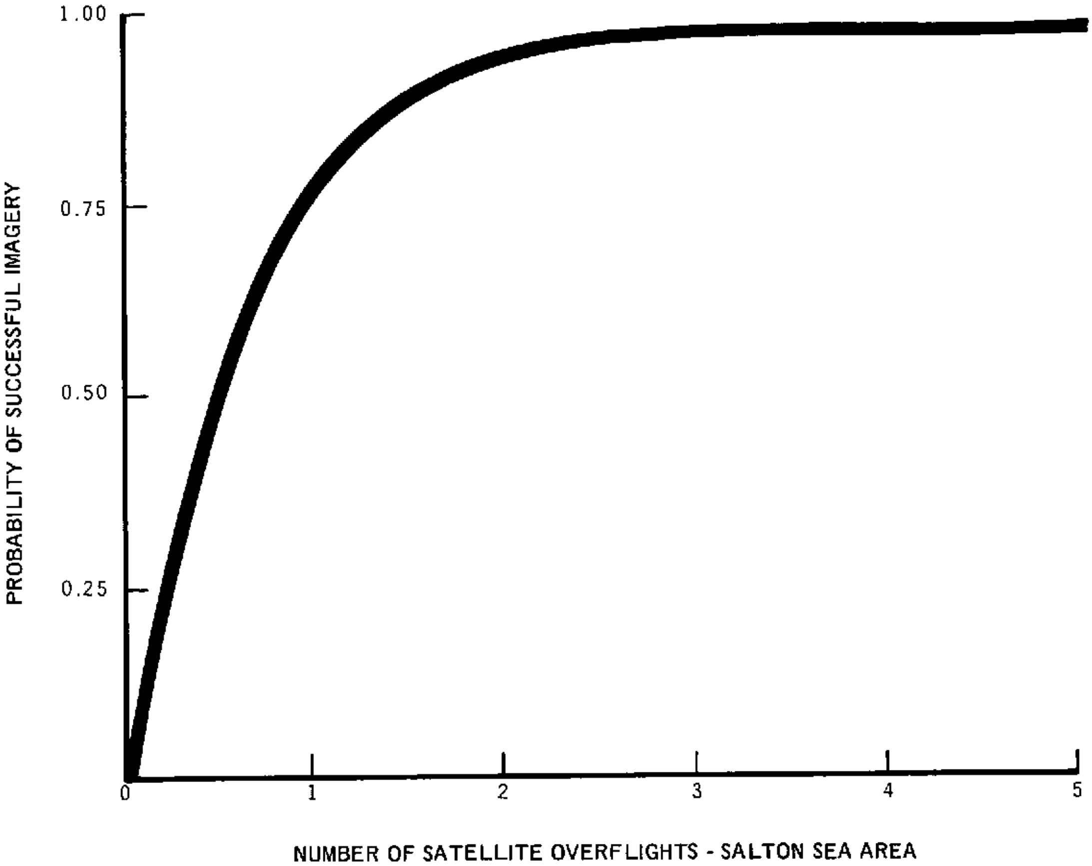


FIGURE 8 - PROBABILITY OF SUCCESS VS NUMBER OF SATELLITE OVERFLIGHTS

Therefore the rational minimum number of successive image sets required is three, for a success probability of 0.99 in measuring the currents in the desired season.

3.4 Atmospheric Noise and Absorption

Atmospheric radiance is dominantly in the blue spectra and thus will introduce negligible noise in the 5000 to 7000Å band. The atmospheric absorption, or transmittance of light through the atmosphere, is shown in Figure 9. In the 5000 to 6000Å and 6000 to 7000Å spectral band transmittance windows occur in the atmosphere that pass all but about 40 percent of the photoluminescent radiance of chlorophyll.

4.0 Feasibility Conclusions

Dye markers located in the Salton Sea would have to be sustained over a minimum of three each 18-day periods at a minimum concentration of 35 ppb or more within a spot size of about 750 feet in diameter in order to be consistently detectable on ERTS RBV imagery. Because of the decay or quenching of the dye, a special design slow-release container would be required of about 20 to 50 gallons in size. These would be a hazard to sport fishing and boating as well as a nuisance to swimmers or boaters should they get dye on them - for it cannot be washed off but is absorbed by skin and plastics and must wear off by ablation.

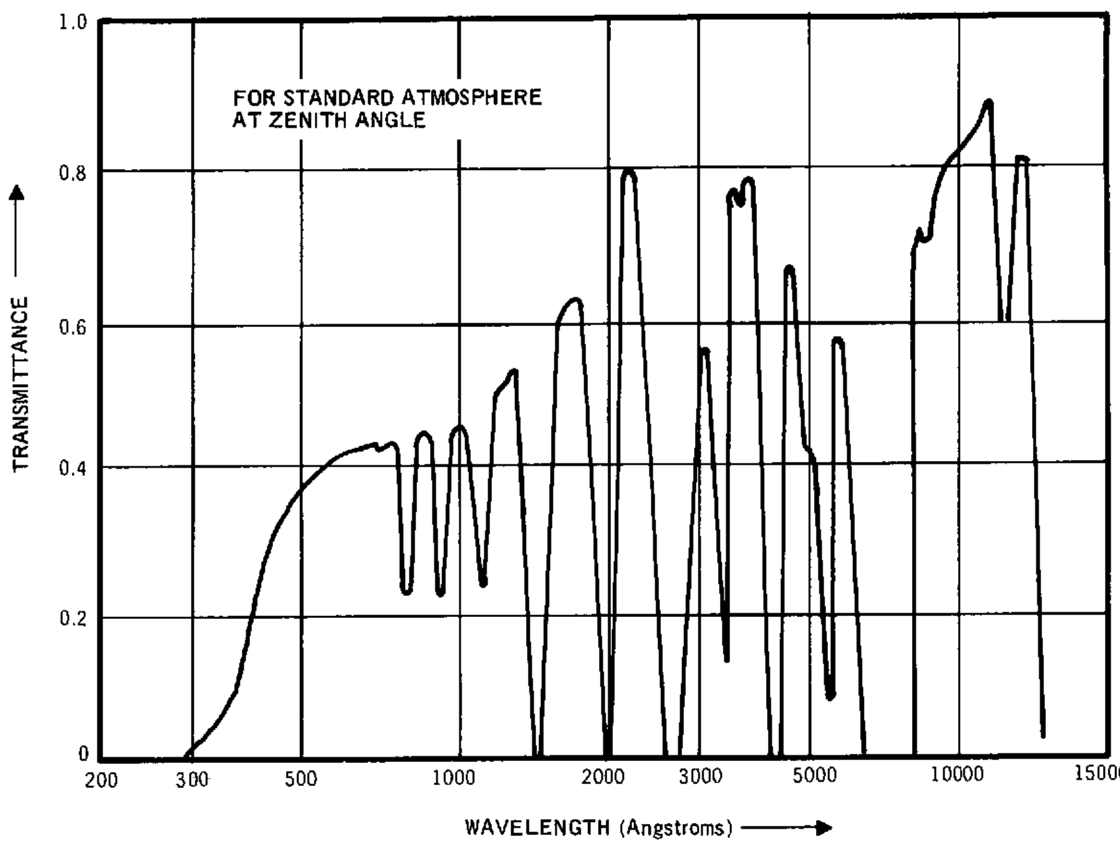


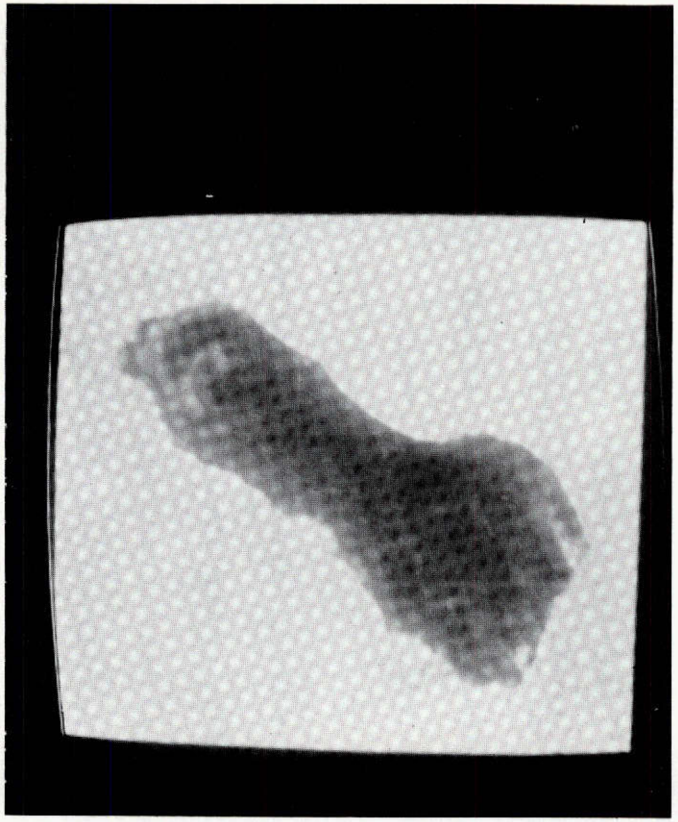
FIGURE 9 - ATMOSPHERIC TRANSMISSIBILITY

The photoluminescence of chlorophyll, contained in the algae and other phytoplankton within the Sea, is a far more effective source than dye markers. We have certain knowledge that the nutrients contained in the irrigation drainage introduced into the Sea from the Imperial Valley and Coachella Valley produce algae blooms that are sustained over virtually the entire cropping season - particularly between July and October. This is also the season of low winds and no appreciable cloud cover over the area.

The algae stay near the surface and move with the currents produced by the inflows from the rivers and the rotation of the earth. A sample of the ERTS MSS imagery (Figure 2) clearly shows the green spectra of the chlorophyll in contrast with the sedimentary deposition and the IR response of the algae. The 6000 to 7000Å image was subjected to back lighting, video contrast enhancement, and multicolor densitometer readings to obtain high contrast definition of the algae locations in the Sea (Figure 10).

Little doubt now remains that by observing the movement of algae swirls and blooms in the 18-day intervals between ERTS orbital overflights, the currents within the Sea can be accurately measured for the season of high levels of eutrophication.

By using this current information to design and validate a physical hydrologic laboratory model of the Sea, the effects of structural



VIDEO ENHANCED MSS IMAGE
6000 to 7000 ANGSTROM MSS BAND

DENSITOMETER ENHANCED IMAGE OF
SAME MSS PHOTO

FIGURE 10 - DENSITOMETER READINGS TO OBTAIN HIGH CONTRAST DEFINITION OF ALGAE LOCATIONS

features introduced into the Sea can be predicted. Adjusting the shape and location of these features it should be possible to design them in such a way as to maximize their influence on the currents to obtain more uniform diffusion or mixing of nutrients and thus distribute them to a greater volume for absorption by the natural biological processes of the Sea.

4.1 Aerial Photoimagery Alternative

It follows from the preceding discussion that the chlorophyll luminescence can also be used as a current marker in aerial photoimagery. There are additional requirements, however, for ground truth data and orthocorrection of such photos that make this a relatively expensive alternative to using ERTS imagery. This is particularly true for an area as large as the Salton Sea, where precision flight trajectories would be virtually impossible to maintain for multiple sweeps over a 35-mile-long flight leg. Therefore, sophisticated photogrammetry equipment would be necessary to orthocorrect the resulting imagery.

Each frame of the aerial photography would require at least two, and optimally five, ground stadia points. These could be provided by 10- to 15-foot square floats securely anchored in the Sea at points carefully surveyed in relationship with shore markers painted on roads and highways.

To obtain current dynamics from algae motion in the Sea would require five or more successive passes, spaced out at 1- to 2-week intervals. Because of the slow current rates, timing errors would be well within the error tolerance of a 170-inch physical laboratory model of the Sea.

The photogrammetric orthocorrections of the photos could be performed by the U.S. Army Map Service, Fort Belvoir, Virginia. They have some automatic photogrammetry equipment that is both fast and accurate called UNIMACE (Figure 11).

4.2 Cost Comparisons

ERTS multispectral imagery can be obtained from Goddard Labs, orthocorrected, and fully interpreted by densitometer, in 40- by 40-inch sizes. The process of overlay mapping of currents would then be a rather routine matter using image transparencies from successive overflights.

The cost of ERTS-2 data (specially processed imagery) would be less than $2,000. The manual mapping of currents could be accomplished for less than $10,000 - a total of $12,000 for the whole process using ERTS-2 imagery.

The alternative of aerial photoimage data collection and analysis would not be possible for less than $80,000, and would probably

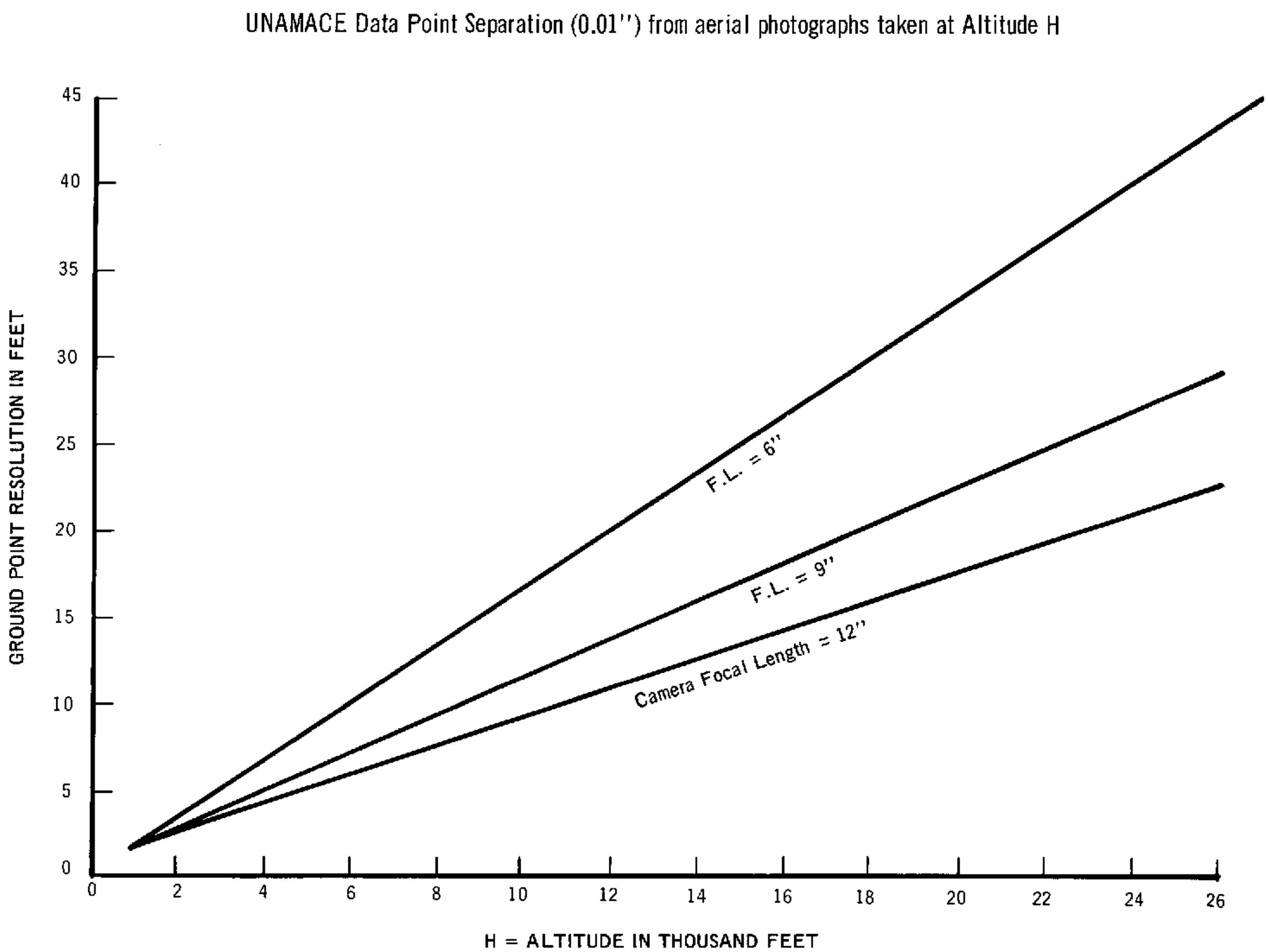


FIGURE 11 - GROUND POINT RESOLUTION OF AERIAL IMAGERY

run more than $100,000 including the UNIMACE processing charges which are estimated at about $2,200 per hour.

Five successive aerial sweeps over the Salton Sea, spaced at 1- to 2-week intervals would require a full-time contractor. His costs are estimated on the basis of 5 hours of aircraft operating time ($2,000-$3,000 per hour) including ground crews, flight crew, calibration and multispectral instrumentation and mapping radar ($60,000-$70,000).

The cost of survey, location, manufacturing of floats, and installation of stadia points in and near the Sea is estimated at about $20,000 or more.

Once the data have been collected, corrected, and interpreted, the cost of current mapping would be essentially the same as that required for the ERTS-2 data ($8,000-$10,000).

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