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ECON INCORPORATED

VOLUME II
SEASAT ECONOMIC ASSESSMENT
THE SEASAT SYSTEM DESCRIPTION AND PERFORMANCE

ECON INCORPORATED

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PRINCETON, NEW JERSEY 08540
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FINAL

VOLUME II

SEASAT ECONOMIC ASSESSMENT

THE SEASAT SYSTEM
DESCRIPTION AND PERFORMANCE

Prepared for

National Aeronautics and Space Administration
Washington, D.C. 20546

Contract No. NASW-2558

August 31, 1975

NOTE OF TRANSMITTAL

The SEASAT Economic Assessment was performed for the Special Programs Division, Office of Applications, National Aeronautics and Space Administration under contract NASW-2558. The work described in this report began in February 1974 and was completed in August 1975.

The economic studies were performed by a team consisting of Battelle Memorial Institute, the Canada Centre for Remote Sensing, ECON, Inc., the Jet Propulsion Laboratory, and Ocean Data Systems, Inc. ECON, Inc. was responsible for the planning and management of the economic studies and for the development of the models used in the generalization of the results.

This volume presents the results of preliminary trade-off studies of operational SEASAT systems. The trade-off studies were used as the basis for the estimation of costs and net benefits of the operational SEASAT system. Also presented are the preliminary results of simulation studies that were designed to lead to a measure of the impact of SEASAT data through the use of numerical forecast models.

The studies of the utility of SEASAT data were performed by a team consisting of the Goddard Institute of Space Studies and the Jet Propulsion Laboratory. Principal Investigator for the data utility studies was Dr. I. Halberstam of JPL.

The preliminary trade-off studies of possible operational SEASAT systems configurations and costs were performed by the Jet Propulsion Laboratory with the support of ECON, Inc. The system description was prepared by Mr. Robert Nagler of JPL and Mr. S.W. McCandless of NASA.

The SEASAT Users Working Group (now Ocean Dynamics Subcommittee) chaired by Dr. John Apel of the National Oceanographic and Atmospheric Administration, served as a valuable source of information and as a forum for the reviews of these studies. Mr. S.W. McCandless, the SEASAT Program Manager, coordinated the activities of the many organizations that participated in these studies into the effective team that obtained the results described in this report.

B.P. Miller

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1. OVERVIEW OF THE ASSESSMENT

This report, consisting of ten volumes, represents the results of the SEASAT Economic Assessment, as completed through August 31, 1975. The individual volumes in this report are:

Volume	I	- Summary and Conclusions
Volume	II	- The SEASAT System Description and Performance
Volume	III	- Offshore Oil and Natural Gas Industry - Case Study and Generalization
Volume	IV	- Ocean Mining - Case Study and Generalization
Volume	V	- Coastal Zones - Case Study and Generalization
Volume	VI	- Arctic Operations - Case Study and Generalization
Volume	VII	- Marine Transportation - Case Study and Generalization
Volume	VIII	- Ocean Fishing - Case Study and Generalization
Volume	IX	- Ports and Harbors - Case Study and Generalization
Volume	X	- A Program for the Evaluation of Operational SEASAT System Costs.

Each volume is self-contained and fully documents the results in the study area corresponding to the title. Table 1.1 describes the content of each volume to aid readers in the selection of material that is of specific interest.

The SEASAT Economic Assessment began during Fiscal Year 1975. The objectives of the preliminary economic assessment, conducted during Fiscal Year 1975, were to identify the uses and users of the data that could be produced by an operational SEASAT system and to provide preliminary estimates of the benefits produced by the applications of these

Table 1.1: Content and Organization of the Final Report

Volume No.	Title	Content
I	Summary and Conclusions	A summary of benefits and costs, and a statement of the major findings of the assessment.
II	The SEASAT System Description and Performance	A discussion of user requirements, and the system concepts to satisfy these requirements are presented along with a preliminary analysis of the costs of those systems. A description of the plan for the SEASAT data utility studies and a discussion of the preliminary results of the simulation experiments conducted with the objective of quantifying the effects of SEASAT data on numerical forecasting.
III	Offshore Oil and Natural Gas Industry-Case Study and Generalization	The results of case studies which investigate the effects of forecast accuracy on offshore operations in the North Sea, the Celtic Sea, and the Gulf of Mexico are reported. A methodology for generalizing the results to other geographic regions of offshore oil and natural gas exploration and development is described along with an estimate of the world-wide benefits.
IV	Ocean Mining - Case Study and Generalization	The results of a study of the weather sensitive features of the near shore and deep water ocean mining industries are described. Problems with the evaluation of economic benefits for the deep water ocean mining industry are attributed to the relative immaturity and highly proprietary nature of the industry.

Table 1.1: Content and Organization of the Final Report (continued)

Volume No.	Title	Content
V	Coastal Zones - Case Study and Generalization	The study and generalization deal with the economic losses sustained in the U.S. coastal zones for the purpose of quantitatively establishing economic benefits as a consequence of improving the predictive quality of destructive phenomena in U.S. coastal zones. Improved prediction of hurricane landfall and improved experimental knowledge of hurricane seeding are discussed.
VI	Arctic Operations - Case Study and Generalization	The hypothetical development and transportation of Arctic oil and other resources by ice breaking super tanker to the continental East Coast are discussed. SEASAT data will contribute to a more effective transportation operation through the Arctic ice by reducing transportation costs as a consequence of reduced transit time per voyage.
VII	Marine Transportation-Case Study and Generalization	A discussion of the case studies of the potential use of SEASAT ocean condition data in the improved routing of dry cargo ships and tankers. Resulting forecasts could be useful in routing ships around storms, thereby reducing adverse weather damage, time loss, related operations costs, and occasional catastrophic losses.
VIII	Ocean Fishing - Case Study and Generalization	The potential application of SEASAT data with regard to ocean fisheries is discussed in this case study. Tracking fish populations, indirect assistance in forecasting expected populations and assistance to fishing fleets in avoiding costs incurred due to adverse weather through improved ocean conditions forecasts were investigated.
IX	Ports and Harbors - Case Study and Generalization	The case study and generalization quantify benefits made possible through improved weather forecasting resulting from the integration of SEASAT data into local weather forecasts. The major source of avoidable economic losses from inadequate weather forecasting data was shown to be dependent on local precipitation forecasting.
X	A Program for the Evaluation of Operational SEASAT System Costs	A discussion of the SATIL 2 Program which was developed to assist in the evaluation of the costs of operational SEASAT system alternatives. SATIL 2 enables the assessment of the effects of operational requirements, reliability, and time-phased costs of alternative approaches.

data.* The preliminary economic assessment identified large potential benefits from the use of SEASAT-produced data in the areas of Arctic operations, marine transportation, and offshore oil and natural gas exploration and development.

During Fiscal Year 1976, the effort was directed toward the confirmation of the benefit estimates in the three previously identified major areas of use of SEASAT data, as well as the estimation of benefits in additional application areas. The confirmation of the benefit estimates in the three major areas of application was accomplished by increasing both the extent of user involvement and the depth of each of the studies. Upon completion of this process of estimation, we have concluded that substantial, firm benefits from the use of operational SEASAT data can be obtained in areas that are extensions of current operations such as marine transportation and offshore oil and natural gas exploration and development. Very large potential benefits from the use of SEASAT data are possible in an area of operations that is now in the planning or conceptual stage, namely the transportation of oil, natural gas and other resources by surface ship in the Arctic regions. In this case, the benefits are dependent upon the rate of development of the resources that are believed to be in the Arctic regions, and also dependent upon the choice of surface transportation over pipelines as the means of moving these resources to the lower

*SEASAT Economic Assessment, ECON, Inc., October 1974.

latitudes. Our studies have also identified that large potential benefits may be possible from the use of SEASAT data in support of ocean fishing operations. However, in this case, the size of the sustainable yield of the ocean remains an unanswered question; thus, a conservative viewpoint concerning the size of the benefit should be adopted until the process of biological replenishment is more completely understood.

With the completion of this second year of the SEASAT Economic Assessment, we conclude that the cumulative gross benefits that may be obtained through the use of data from an operational SEASAT system, to provide improved ocean condition and weather forecasts is in the range of $859 million to $2,709 million ($1975 at a 10 percent discount rate) from civilian activities. These are gross benefits that are attributable exclusively to the use of SEASAT data products and do not include potential benefits from other possible sources of weather and ocean forecasting that may occur in the same period of time. The economic benefits to U.S. military activities from an operational SEASAT system are not included in these estimates. A separate study of U.S. Navy applications has been conducted under the sponsorship of the Navy Environmental Remote Sensing Coordinating and Advisory Committee. The purpose of this Navy study was to determine the stringency of satellite oceanographic measurements necessary to achieve improvements in military mission effectiveness in areas where benefits are known to exist.* It is currently planned that the Navy will use SEASAT-A data to quantify benefits in military applications areas. A one-time military benefit of approximately $30 million will be obtained by SEASAT-A, by providing a measurement capability in support of the Department of Defense Mapping, Charting and Geodesy Program.

Preliminary estimates have been made of the costs of an operational SEASAT program that would be capable of producing the data needed to obtain these benefits. The hypothetical operational program used to model the costs of an operational SEASAT system includes SEASAT-A, followed by a number of developmental and operational demonstration flights, with full operational capability commencing in 1985. The cost of the operational SEASAT system through 2000 is estimated to be about $753 million ($1975, 0 percent discount rate) which is the equivalent of $272 million ($1975) at a 10 percent discount rate. It should be noted that this cost does not include the costs of the program's unique ground data handling equipment needed to process, disseminate or utilize the information produced from SEASAT data. Figures 1.1 and 1.2 illustrate the net cumulative SEASAT exclusive benefit stream (benefits less costs) as a

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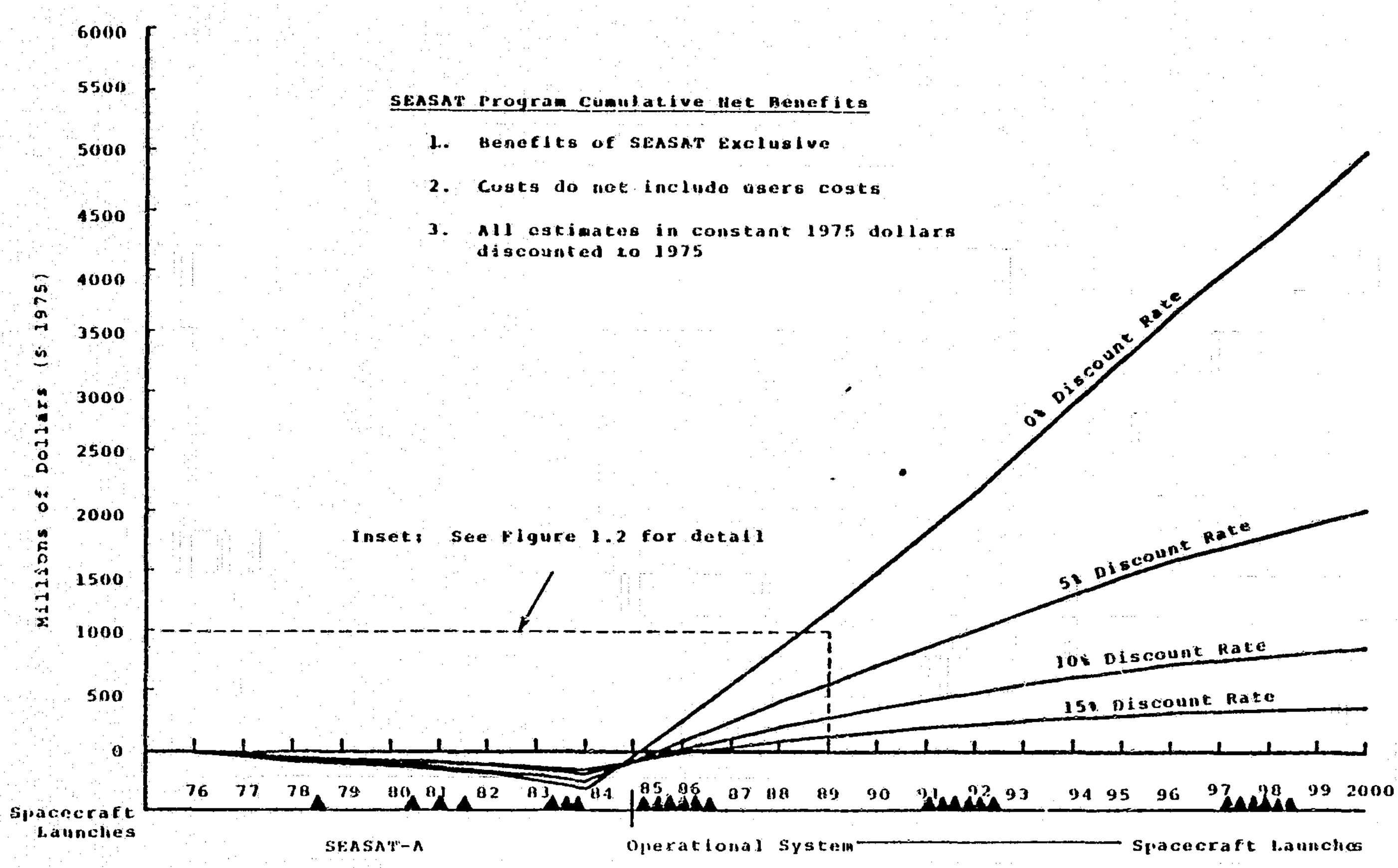
*"Specifications of Stringency of Satellite Oceanographic Measurements for Improvement of Navy Mission Effectiveness." (Draft Report.) Navy Remote Sensing Coordinating and Advisory Committee, May 1975.



Costs*	19	49	78	100	123	151	184	239	307	352	366	373	375	393	437	503	546	566	568	587	629	695	738	753
Benefits*										311	622	933	1244	1555	1937	2319	2701	3083	3465	3847	4229	4611	537[illegible]	5757

*Cumulative Costs and Benefits at 0% Discount Rate (millions, $ 1975)

Figure 1.1 SEASAT Program Net Benefits, 1975-2000

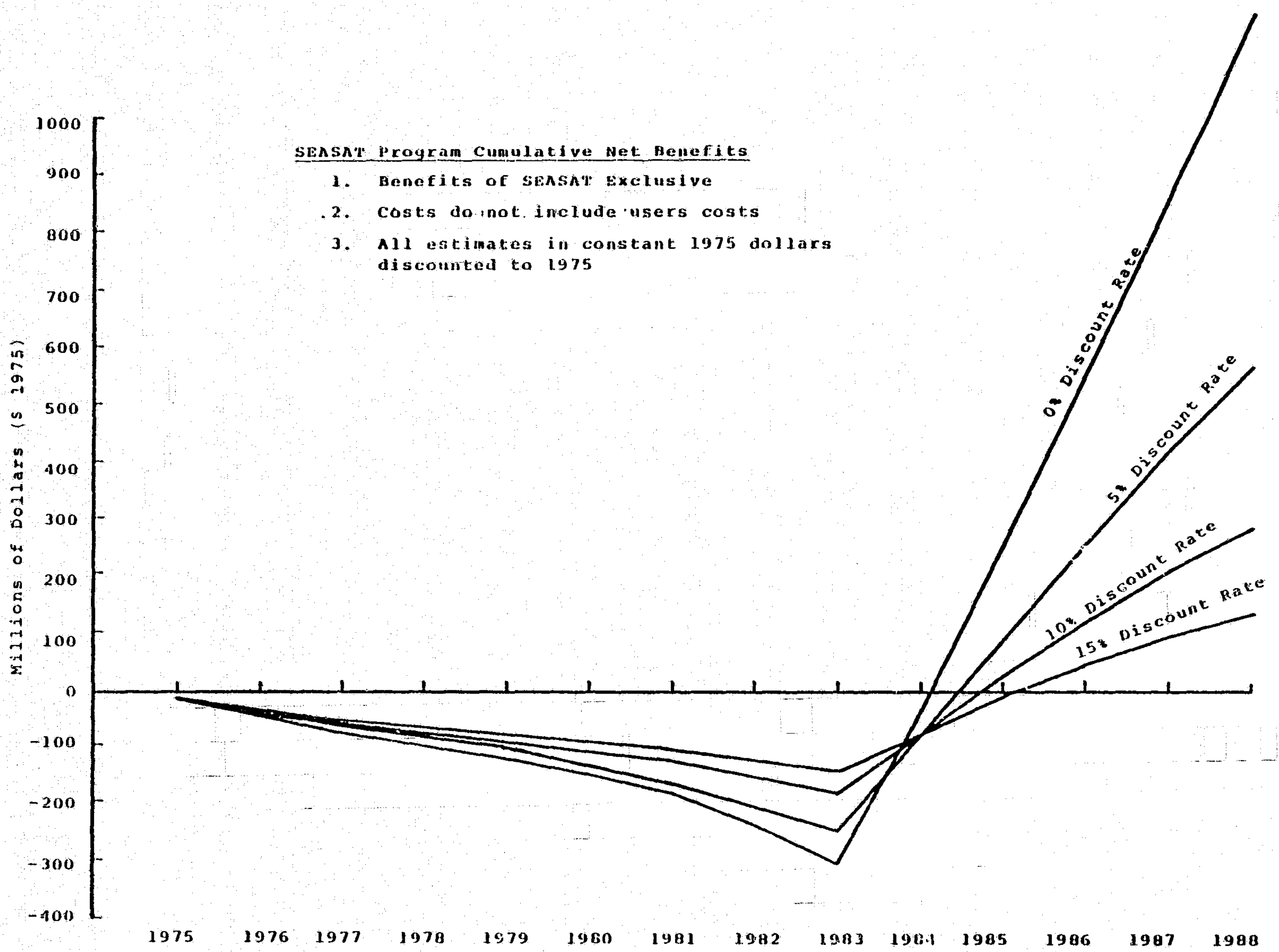


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Figure 1.2 SEASAT Program Net Benefits, Inset function of the discount rate.

This volume presents the results of preliminary trade-off studies of operational SEASAT systems. These trade-off studies were used as the basis for the estimation of costs and net benefits of the operational SEASAT system. Also presented are the preliminary results of simulation studies that were designed to lead to a measure of impact of SEASAT data through the use of numerical forecast models.

2. THE SEASAT PROGRAM

2.1 An Overview of the Program's Evolution

The SEASAT Program provides a base for the use of space platforms for global and local explorations into the dynamics and resources of the ocean; into the effect of the ocean on weather and climate; and into the role the ocean plays in ice and coastal processes. It has been conclusively demonstrated that wave heights, sea-surface wind velocities, temperature, and topography can be measured from space. Tests from airplanes have also demonstrated potential improvements in the accuracies and resolutions measurable, plus additional potentials for measuring wind direction, wave length and direction, vertical temperature soundings through limited cloud cover, and the identification of other special fine-resolution ocean features, such as currents, oil and chemical pollution, upwellings, shoals, ice leads, icebergs, ships, etc. This information can be used in such economic and social applications as improving the efficiencies of weather or sea-state-related operations in the marine industries; providing better warning of severe wind, rain or wave conditions; providing a means of improving or regulating the resource yield in many marine industries; providing improved navigation through ice and currents; and creating a better understanding of the ocean and its dynamics as a guide to better management of the use of this limited resource.

A listing of the investigative possibilities of SEASAT is provided in Table 2.1. To provide a better perspective, these investigative areas are compared with the SEASAT remote sensor types and with the major areas of economic benefit. The first five sensors listed in Table 2.1 are part of the present SEASAT payload. Doppler radar is presently used to track storms from the ground, but may be converted to satellite use later on. The LIDAR uses a laser to provide altimetry, bathymetry, and fluorescence measurements from low-flying airplanes, but is difficult to power on satellites. The areas of economic benefit are listed in terms of the economic function to which the experimental investigation will contribute. Items with shaded circles (●) are key to the effort, while items with open squares (□) represent important but secondary contributions.

A detailed description of a Full Capability Operational SEASAT, which supports all the investigative areas listed to the full limit of our present technology or available investment potential, is not available at this time. For the purpose of the economic assessment, it has been assumed that a full capability system could be provided by 1985. The agency or agencies which will operate this system have not been determined at this time. The sections that follow, however describe some of the capability potentials for SEASAT in the next decade or so, in terms of the measurements feasible to

Table 2.1 Sample Investigative Possibilities for SEASAT

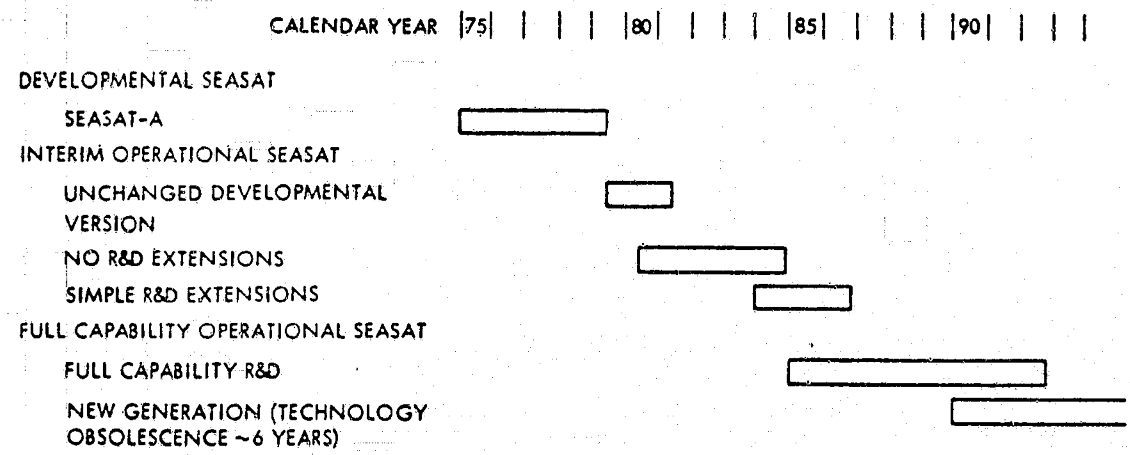
● PRIMARY
□ SECONDARY

SEASAT INVESTIGATION POSSIBILITIES	SENSOR TYPES: VISIBLE AND INFRARED RADIOMETER	MICROWAVE RADIOMETER	SHORT PULSE ALTIMETER	LONG PULSE SCATTEROMETER	COHERENT IMAGING RADAR	DOPPLER RADAR	LIDAR	MAJOR AREAS OF ECONOMIC BENEFIT: SHIP/TANKER-ROUTING/PROTECTION	MARINE FISHERIES-OPERATIONS/YIELD MANAGEMENT	OFFSHORE RIGS/STRUCTURES/PORTS-OPERATIONS/PROTECTION	BEACH/SHOAL-PROTECTION/MANAGEMENT	ICE NAVIGATION-ROUTING/MANAGEMENT	COASTAL INDUSTRY/RECREATION-OPERATIONS SCHEDULING/PROTECTION	AGRICULTURE-YIELD MANAGEMENT	POLLUTION-MONITOR/REGULATE	OCEAN MINING/AQUACULTURE-OPERATIONS
PHYSICAL OCEANOGRAPHY	□	□	□	●	●		□									
CAPILLARY/GRAVITY WAVE GENERATION		□	□	●	●		□			□	□		□			□
WAVE PROPAGATION NEAR STORMS		□	●	□	●		□			□	□		□			□
WAVE PROPAGATION AT CONTINENTAL SHELF			□		●		□			□	□		□			□
INTERNAL WAVE PROPAGATION			□		●		□									
WAVE FORECAST VERIFICATIONS		□	□	●	●		□	●	●	●	●		□			●
LOCATION/DYNAMICS OF OCEAN CURRENTS	□	□	□		●		□	●	●			□				□
TRANSPORT OF POLLUTANTS/NUTRIENTS	●	□			●		□		●						●	
UPWELLING FORECASTS	□	□		●	●				●			□				
TSUNAMI PROPAGATION (FORTUITOUS)			□				□			□	□		□			
CLIMATE	●	●	□	●	□	□	□									
AIR/SEA INTERACTIONS		●	□	●	□		□	●	●	●	●		●	□		□
WIND/CLOUD RELATIONS	●	●						□	□	□	□		□	□		□
WIND/RAIN/TEMPERATURE INTERACTIONS	□	●		●		●		□	□	□	□		□	□		□
SURFACE TEMPERATURE AND STORM GROWTH	□	●	□	●	□		□	□	□	□	□		□	□		□
JET STREAM DEFLECTION	●	●						□	□	□	□		□			
SEVERE STORM GENERATION/PROPAGATION	●	●	□	●	●	□	□	●	●	●	●		●	□		□
HURRICANE LANDFALL FORECASTS	●	●		●	●	□				●	●		●			
POLEWARD TRANSFER OF HEAT	●	●		●								□				
GLOBAL CLIMATOLOGY FORECASTS	●	□		●	□			●						●		□
LOCAL/REGIONAL WEATHER FORECASTS	●	□		●	□	●		●	●	●	●	●	●	●		●
COASTAL	●	□	□	□	●		●									
WAVE PROPAGATION NEAR SHORES			□		●			□		●	●		●			□
TRANSPORT OF POLLUTANTS/CHEMICALS/NUTRIENTS	●	□			●		□		●						●	
COASTAL UPWELLING	□			●	●				●		□	□				
SHORELINE/ESTUARY CURRENT DYNAMICS	●				●			□	●		●	□	●		□	□
TIDAL BEHAVIORS			●				●				□		□			
WATER PILEUP FROM STORMS			●				●			□	●		●			□
FRESH WATER INFLUX	●	□			●				□						□	
SHOAL AND SHORELINE DYNAMICS	□				●		●	□			●		●			
KELP EXTENT					●				□				□			
ICE PROCESSES	□	□	□		●		□									
ICE DISTRIBUTION/EXTENT/AGE	□	●			●							●				□
ICE FORMATION/RIDGING/BREAKUP					●							●				
ICE LEADS LOCATION	□		□		●		□					●				
ICE TRANSPORT					●			●				●				□
RESOURCE USE MANAGEMENT	□	□		□	●											
SHIP/TANKER LOCATION					●			●							●	
POLLUTION SPILLS MONITOR	□	□			●										●	
FISH YIELD FORECASTS	●	●		●					●							
FISHING BOAT LOCATION					●				●							
FISH SCHOOL LOCATION					●				●							
GEODESY			●													
EQUIPOTENTIAL SURFACE			●													
SLOPE OF MEAN SEA LEVEL			●													
FINE GEOID FEATURES			●													

implement from satellites, and the data system which could be made available to provide such measurement data to the user community. Thus, the material described is presented as a guide to planning and a framework for the economic assessment, rather than as a commitment to a particular system concept.

In order to provide a basis for the analysis of the economic potential of the SEASAT Program, it is necessary to hypothesize both schedule and capability for the operational systems that will follow the developmental SEASAT-A. Planning of this nature for the proposed operational system is necessary as the level of benefits is dependent upon the technical capabilities of the operational system, and the timing of the benefits is dependent upon the dates of inception of the operational system. Thus, the benefits ascribed to SEASAT are those associated with an operational system that will provide the continuity of service required to obtain full utilization of the data products by potential government and private users. The general SEASAT schedule shown in Table 2.2 delineates a set of developmental and operational systems that fulfill presently understood user requirements. Only the first element of the program, SEASAT-A, is approved at the present time. The remaining elements of the program, namely the Interim Operational and Full Capability Operational SEASATs, have been hypothesized to provide a basis for evaluation of the economic benefits and are not approved programs. The specific configurations of these

Table 2.2 Postulated SEASAT Inflight Schedule



systems will evolve from an improved understanding of user requirements gained with SEASAT-A, its follow-ons, and the supporting aircraft and Sea-truth program.

The first developmental SEASAT (SEASAT-A) is to be launched in mid-1978, and is anticipated to be a single satellite with a one-to-three year life. In the 1980-1983 period, an interim operational SEASAT system is possible, with three satellites providing twice-a-day global coverage of accurate sea-surface winds, waves, and temperatures, plus several sitings a week of specific ocean features at 25-m resolution. As indicated, several interim capability possibilities with differing investment implications are also available. Some combination of these alternative, interim three-satellite systems is probably needed to provide the user community with the continuity of information necessary to realize their potential economic and social benefits. The full-capability (six-satellite) Operational SEASAT system could become viable in 1985. A new SEASAT generation could then come into being about every six years which represents both a reasonable life expectancy for this time period and a typical technology-obsolescence period where part and component availability will force creation of new design even without the pressures of remote-sensing improvements.

Specific measurement capabilities for each of the SEASAT developmental and operational stages are somewhat speculative at this time, but some assessment of these potentials is probably appropriate. Table 2.3 and Figure 2.1 provide an indication of the kind of capabilities that might be expected and the practicalities of achieving global coverage from satellites. A detailed explanation of how these capabilities were derived and the portion of the user needs they satisfy is given later.

The developmental SEASAT (SEASAT-A) provides the main five-sensor complement - altimeter, scatterometer, imaging radar, microwave radiometer and visible/infrared radiometer - but accuracies and resolutions are limited to those readily obtainable due to either the present state-of-the-art in sensor technology or to the ability of existing spacecraft systems to accommodate sensor support requirements. The

Table 2.3 Measurement Capability Evolution During SEASAT Program

	COVERAGE GOAL	WIND			WAVES			SEA SURFACE TEMPERATURE				VERTICAL SOUNDING				SURFACE PRESSURE		SEA SURFACE TOPOGRAPHY GRID		OCEAN/ICE/ COASTAL FEATURES		SATELLITES IN SPACE	FIRST LAUNCH DATE
					HT	LTH		ALL WTR		MST WTR			VER	HOR	H_2O								
		±m/s	±deg	±km	±m	±m	±deg	± deg	± km	± deg	± km	±deg	±km	±km	±% of g/cm^2	±mb	±km	±cm	<km	±m	km/pass		
DEVELOPMENTAL SEASAT	36-hr GLOBAL	2	20	50				1.5	100	2.0	5									5000	1500		
5 SENSORS	DEMON-STRATION				1	50	15					NO				NO				25	100	1	1978
STDN COMPATIBLE																							
EXPENDABLE LAUNCH	WITHIN 6 mo																	20	18				
INTERIM OPERATIONAL SEASAT	2/day GLOBAL	2	20	50	1	50	15	1.5	100	1.0 2.0	10 5	2.0	5	25	20								
6 SENSORS	2/5 day GLOBAL															NO				25	200	3	1980-1983
TDRS COMPATIBLE																							
EXPENDABLE LAUNCH	EVERY 2 mo																	20	18				
FULL CAPABILITY OPERATIONAL SEASAT — MEASUREMENT OPTIMIZED	4/day GLOBAL	1	15	25				1.5	50	1.0	5	2.0	2	10	20	2	5						
	2/day GLOBAL				0.5	50	10													25	460	6	
5 OR 6 SENSORS	EVERY MONTH																	10	18				1985
TDRS COMPATIBLE — IMAGING RADAR LIMITED	4-6/day GLOBAL	1	15	25				1.5	50	1.0	5	2.0	2	10	20	2	5						
SHUTTLE LAUNCH	2/day GLOBAL				0.5	50	10													25	350	8	
EXTENSIVE ONBOARD PROCESSING	EVERY MONTH																	10	15				
SHORT PULSE ALTIMETER (ALT)					×											?		×					
LONG PULSE SCATTEROMETER (SCAT)		×	×													?							
COHERENT IMAGING RADAR (SAR)						×	×									?				×			
SCANNING MICROWAVE MULTI-CHANNEL RADIOMETER (SMMR)		×						×	×							?							
VISIBLE AND INFRARED RADIOMETER										×	×	×	×	×	×	?				×			
RAIN OR PRESSURE SENSOR																?							

visible and infrared radiometer used has limited performance and no vertical sounding capability. The swathing patterns shown in Figure 2.1 also apply to SEASAT-A except for the imaging radar swath which is only on one side and is only 100 km in width. SEASAT-A provides 36-hour global coverage for all but the imaging radar.

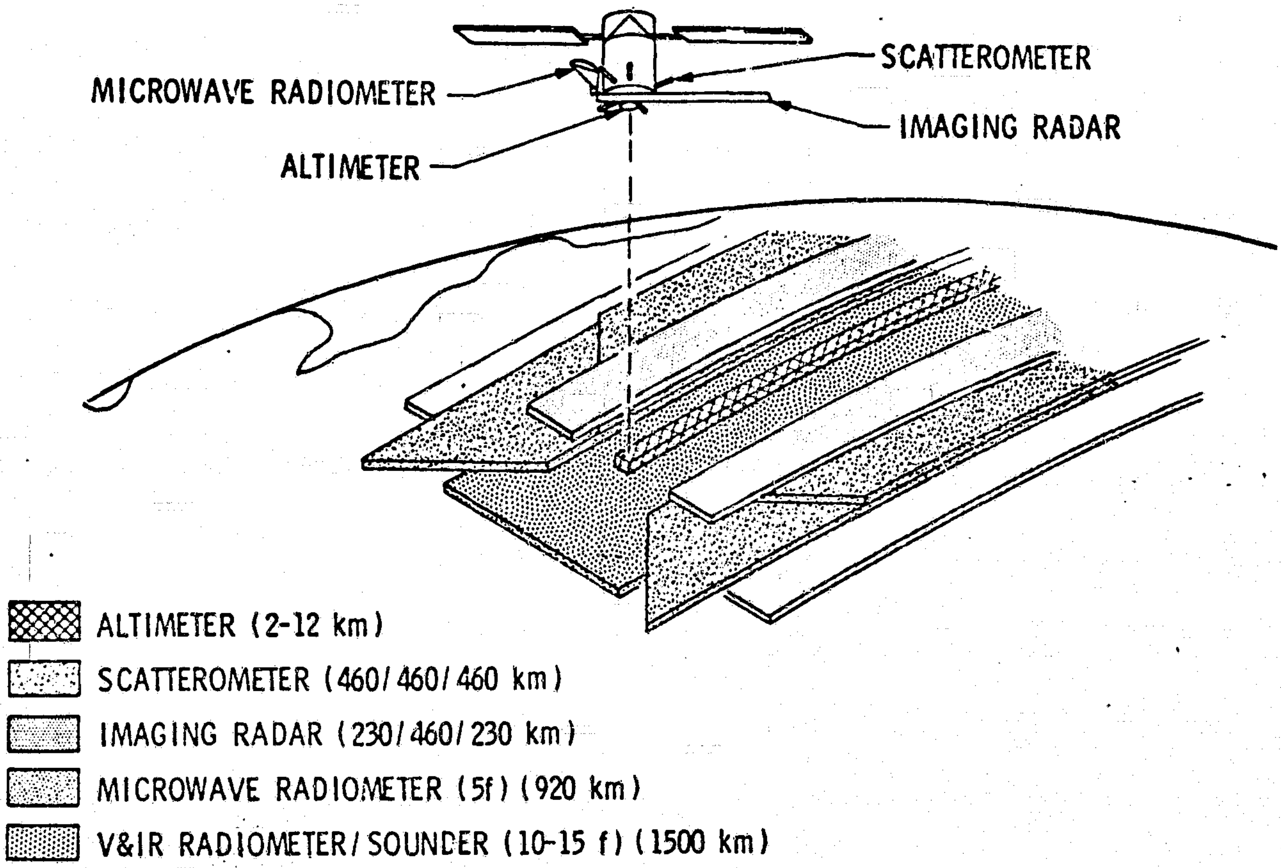


Figure 2.1 Sensor Swaths for Full Capability Operational SEASAT

In the interim operational SEASAT, a three-satellite system is anticipated, with approximately the same complement of instruments as that of SEASAT-A. A 25 percent increase in power and some additional flexibility in data storage and data rate is assumed to be available from the spacecraft without major re-design. Two off-the-shelf visible and infrared radiometers from the TIROS N Program were substituted for the simpler SEASAT-A devices. The Advanced Very High Resolution Radiometer (AVHRR) is used for high-accuracy, clear-weather, sea-surface temperature. The Basic Sounding Unit (BSU) is used for vertical temperature sounding to permit improved interpretation of climatological measurements. Two 100 km swath SEASAT-A imaging radars (one looking right, the other left) are assumed, with simultaneous operation and sufficient additional power available so that compatible LANDSAT ground receivers not on continental North America might also be used for real time data return. The ground swaths thus resemble those in Figure 2.1, except for the reduced imaging radar swath. The three-satellite system thus provides twice-a-day, global coverage for all measurements, except the high-resolution images which could cycle through in about five days for complete global coverage. The interim operational SEA-SAT is intended to be compatible with the Tracking and Data Relay Satellite (TDRS).

The Full-Capability Operational SEASAT is Shuttle compatible and provides extensive onboard processing. The six-satellite, measurement-optimized system provides swaths as shown in Figure 2.1 with the imaging radar swath half the fore/aft scatterometer swaths, and half the center gap between the split swath. This allows six satellites to be staggered so that wind, waves and temperatures are measured four times a day, and complete high-resolution radar images are provided twice a day. The scatterometer wind and microwave radiometer wind and temperature footprint resolutions are improved. Altimeter accuracy is reduced to

± 10 cm, the state-of-the-art for airplane sensors. The AVHRR and BSU are replaced by a combined V&IR instrument that is more effective in measuring clouds. A new sea-surface, pressure-sensing capability is assumed, although no reasonable proposals for this instrument exist at this time. Surface pressure has been identified as a key parameter for weather and sea state forecasting, and is the only important parameter without a present capability for measurement from satellites.

An attempt to reduce imaging radar resolution to 10 meters appears to be extremely difficult, except perhaps in a SPACELAB context. In fact, even at 25 m, it is questionable that a 230 km swath can be achieved with a reasonable expenditure of satellite power. Thus, the imaging-radar-limited case was generated to provide twice-a-day global images with a reduced imaging radar swath. This case, however, requires eight instead of six satellites if twice-a-day global, all-weather images are required, but it halves the power required by the imaging radar.

In 1985, then, SEASAT could be able to sense winds, waves, temperatures, and perhaps, pressure on the ocean surface, both accurately and with reasonably small footprints. It could provide this information globally, four times a day. SEASAT could also provide 25 m images of the ocean surface twice a day, with indications of currents, upwellings, shoals, pollutants and many other phenomena which cause modulations in the wind-driven surface patterns. Reduced accuracy versions of the wind, wave, and temperature information could be transmitted in real time to users anywhere in the world. In addition, full-accuracy information radar images could be transferred in real time through a TDRS-like capability for real time processing and/or dissemination from a central data management center at the TDRS White Sands station. Users could tap into this data bank in the geophysical format generated naturally by the operational agency or can be provided with compatible algorithms for converting the data at the user facility into the information format needed.

2.2 Uses and User Data Needs

The SEASAT Program is a first attempt to exploit the broad applicability of active and passive microwave sensors, in conjunction with more conventional passive infrared sensors, to enhance our understanding of the ocean, the atmosphere, and coastal and ice interactions with both. Most of the Earth's surface is water or ice covered, and the thermal impact of these two environments in absorbing solar energy acts as a driver for much of our weather. Consequently, the atmospheric and ocean dynamics created interact strongly with the coastlines and the sea ice pack. The level of microwave energy backscattered and the shape of the return pulse from the ocean surface are modulated by winds, waves, temperature, salinity, nutrient and pollutant content, current and upwelling motions, falling rain, surface pressure, and the species distribution and density in the gaseous atmospheric column. The energy emitted from the surface is similarly modulated, although the micro-processes may vary somewhat due to the wavelengths of the energy having different transmissivities within the atmospheric column or into the ocean. These differences at different microwave and infrared wavelengths allow us to separate and quantify the various effects, using remote-sensing techniques from satellite distances.

Knowledge of the various thermal exhanges and circulations within and between the ocean, atmoshpere, ice pack and the land provides the insights necessary to understand our global climatic trends and regional weather variations. This understanding is expected to evolve into highly accurate two-day forecasts of weather in the eighties and perhaps as long as a week or more in the nineties. Forecasts of these magnitudes have a considerable potential for economic impact on ship routing; fishing, mining, and aquaculture operations; port operations; offshore structure operations; recreational boating and shore use; etc. An understanding of ocean temperature and current dynamics also contains a potential for yield forecasting in fisheries and aquaculture. Understanding wave dynamics, tidal and storm surges, etc., could further impact ship and offshore structure design (reduce ship losses or design expenses), coastline management, and undersea colony designs. The ice data and fine active microwave surface resolutions will also allow ice management, improved ice navigation (through pack breakup dynamics monitoring and water channel or land identification), and even (to some extent) iceberg route-monitoring.

The measurements desired by the wide range of users consulted in the last few years of SEASAT activity are summarized in Table 2.4. For ocean topography, measurements in the less than 10 cm accuracy/precision range appear well within altimetry capability, but such measurements can be made only directly below the satellite track. Fine-grid or short-term time measurements thus require a large complement of satellites in orbit. Current velocity measurements are expected to be interpretable from the magnitude of the rise in surface level due to the current moving perpendicular to the Earth's rotation, or due to differences in backscatter on each side of a current boundary. Both of these mechanisms have only limited measurement validation at present. Further details on the mechanisms used for these and the other measurements discussed below are provided in Ref. 2.

There is considerable data to show that the magnitude of surface winds can be measured in the range from 3 to 25 m/s, using scatterometry, and from 10 to 50 m/s, using microwave radiometry. Scatterometer mechanization also has the potential

Table 2.4 Geophysical Oceanographic-Measurement Needs

MEASUREMENT			RANGE	PRECISION/ACCURACY	RESOLUTION	SPACIAL GRID	TEMPORAL GRID
TOPOGRAPHY	GEOID		5 cm - 200 m	< ± 10 cm	< 10 km		WEEKLY TO MONTHLY
	CURRENTS SURGES, etc.		10 cm - 10 m 5 - 500 cm/sec	< ± 10 cm ± 5 cm/sec	10 - 1000 m	< 10 km	TWICE A DAY TO WEEKLY
SURFACE WINDS	AMPLITUDE	OPEN OCEAN	3 - 50 m/s	± 1 to 2 m/s OR ± 10%	10 - 50 km	50 - 100 km	2 - 8/day
		CLOSED SEA			5 - 25 km	25 km	
		COASTAL			1 - 5 km	5 km	HOURLY
	DIRECTION		0 - 360°	± 10 - 20°			
GRAVITY WAVES	HEIGHT		0.5 - 20 m	± 0.5 m OR ± 10 - 25%	< 20 km	< 50 km	2 - 8/day
	LENGTH		6 - 1000 m	± 10 - 25%	3 - 50 m		2 - 4/day
	DIRECTION			± 10 - 30°			
SURFACE TEMPERATURE	OPEN OCEAN		-2 - 35°C	0.1 - 2° RELATIVE 0.5 - 2° ABSOLUTE	25 - 100 km	100 km	DAILY TO WEEKLY WITH SPECTRUM OF TIMES OF DAY AND TIMES OF YR
	CLOSED SEA				5 - 25 km	25 km	
	COASTAL				0.1 - 5 km	5 km	
SEA ICE	EXTENT AND AGE			1 - 5 km	1 - 5 km	1 - 5 km	WEEKLY
	LEADS		> 50 m	25 m	25 m	25 m	2 - 4 day
	ICEBERGS		> 10 m	1 - 50 m	1 - 50 m		
OCEAN FEATURES	OPEN OCEAN			50 - 500 m			TWICE DAILY TO DAILY
	COASTAL			10 - 100 m			
SALINITY			0 - 30 ppt	± 0.1 - 1 ppt	1 - 10 km	100 km	WEEKLY
SURFACE PRESSURE			930 - 1030 mb	± 2 - 4 mb	1 - 10 km	1 - 10 km	HOURLY

for establishing the prevailing wind direction within 10 to 20°. The 1 to 2 m/s accuracy at low velocities, to less than 10 percent variation at high speeds, appears well within existing capabilities for resolutions in the 25 to 50 km range. Finer grids require sustained power levels in orbit, which are difficult to implement today but which might be accommodated after 1985. Twice-a-day coverage requires a minimum of two satellites due to orbital characteristics and feasible scan or swath widths.

Data on gravity waves or swell heights are presently most easily obtained from altimetry. Again, accuracies of 0.5 to 1 m are feasible, but measurements can be made only directly below the satellite. Thus, fine horizontal structure and short-time variations are achievable only by the use of many satellites. Wave length and direction are measurable from active microwave images in the proper resolution scale. Resolution and direction of 50 meter waves or larger are presently achievable from imaging capability within the present state-of-the-art. In the future, smaller waves can be resolved as the power capability on the satellite and the data-handling capacity on the ground are improved. There is some limit on the swaths obtainable with these finer resolutions. For complete global coverage twice a day at 25 m resolution, between 6 and 28 satellites would be required, and total data rates from all satellites in the system exceeding 1000 Mb/s. However, sufficient samples can be taken from a single 100 km swath derived from one satellite to allow monitoring of swell growth and propagation over long distances. There is also some hope that the images can be used to infer wave heights and wind spectra, but no effort along this line is being pursued at present. The horizontal separation between wave height and wave length measurements as presently measured may cause some problems in interpreting the wave energy spectra needed in present forecasting operations.

Ocean surface temperatures in the one degree, absolute accuracy range appear achievable in clear weather, with multi-channel infrared scanners at resolutions in the 10 km range. One-and-a-half to two degrees of accuracy at smaller resolutions appear possible for some coastal interpretation. In addition, careful selection of visible and infrared channels can also provide cloud tags and vertical temperature distributions. For measurements less sensitive to weather conditions, microwave scanners are needed with low frequency channels for minimum atmospheric effects. These low frequencies will require large antennas which limit scanning capabilities. At present, 100 km footprints are thus practical, with 50 km footprints perhaps feasible in the future. Coastal studies of temperature details do not appear feasible with microwave radiometers at satellite distances. Again, selection of additional channels can also provide the wind measurements mentioned earlier, plus atmospheric corrections and vertical temperature soundings.

Sea ice and ocean features originate primarily from the 1 to 5 km capability (clear weather) and wide swath projected for the advanced infrared scanning devices, the 10 to 25 km all-weather capability of the microwave radiometer and the 25 m capability or smaller projected for the imaging radar.

Measurement of salinity at present requires L-band radiometers with diameters greater than four meters for global studies and greater than ten meters for local studies; hence, it is not considered practicable in the near future. Surface-pressure measurements from infrared or microwave sounder-based instruments are only in the conceptual state at present. Devices which infer rain content in process or in clouds are under considerable study at present, but requirements have not yet been adequately quantified to be included here.

2.3 SEASAT-A

SEASAT-A will be considered an interim step to achieving global coverage of all oceanographic, climatic, and coastal and ice process measurements desired by the SEASAT users within the constraints of the measurement feasibilities just discussed. In general, SEASAT-A will produce sea-surface topography; wave height, length, and direction measurements; and fine-detail coastal and ice process data on a limited-swath, non-global, demonstration basis. Sea-surface winds and temperatures will be measured globally on an essentially 36-hour, full-coverage repeat cycle. SEASAT-A is to have a minimum life in orbit of one year with a three-year potential. The first six months of operation will be dedicated to demonstration, calibration, and special experiments. During the remaining time (to end of life), the system has the potential to operate near-operationally, with a short turnaround time (less than three hours) for the availability of processed and located data. The high-resolution (25 m) radar images are presently an exception to this, but efforts to make these data more available in a shorter time are underway. Thus, SEASAT-A objectives are to demonstrate a capability for measuring global ocean dynamics and physical characteristics, to provide useful data for user applications, to demonstrate key features of an operational system, and to help determine the economic and social benefits of user organization products and services. The commitment and close cooperation of interested user organizations is an essential element of SEASAT.

The single SEASAT-A satellite is to be launched in mid Calendar Year 1978 from the Western Test Range into a high-inclination (108°) circular (.006 eccentricity) orbit. The satellite will fly at an altitude of approximately 800 km, circling the Earth every 100 minutes. With these orbit characteristics, sensors with 1000 km cross-track coverage will provide global repeat coverage every 36 hours, using both day and night passes to complete the fill-in (see Figure 2.2). Equatorial passes process about 25 degrees each orbit. At least one tracking and real time telemetry pass per orbit is anticipated. Laser tracking will also be provided when satellite viewing and system availability permit.

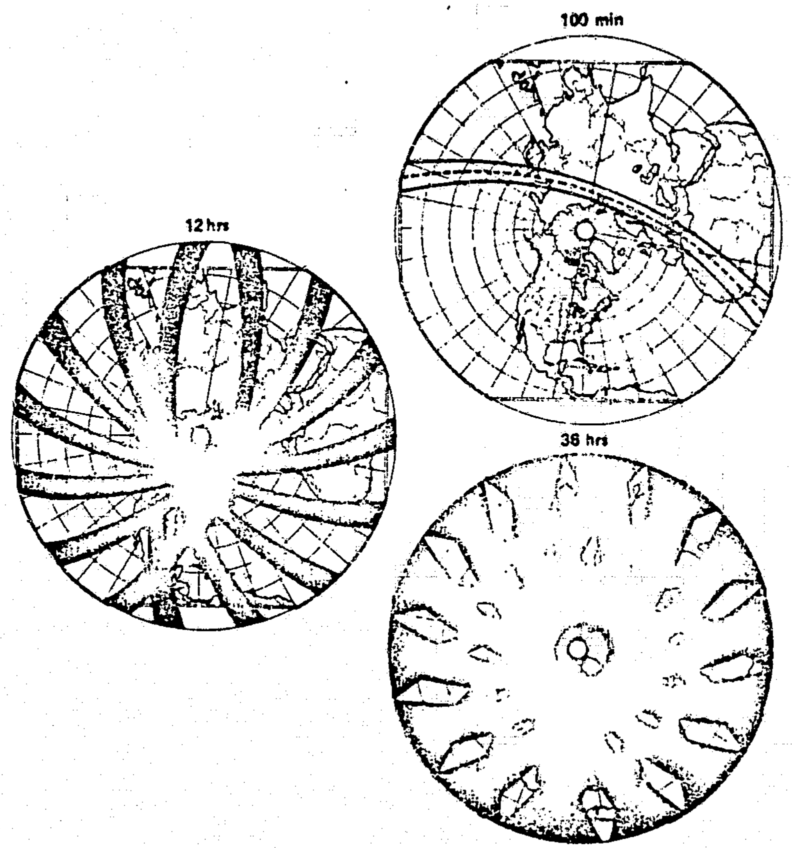


Figure 2.2 SEASAT-A Global Coverage

The major difference between SEASAT-A and previous Earth observation satellites is the use of active and passive microwave sensors to achieve an all-weather capability. The major characteristics of the SEASAT-A sensors are summarized in Table 2.5. Detailed descriptions of the instruments and their conceptual base were generated as part of the SEASAT Instrument Working Group activities. The specific accuracies and coverages anticipated from SEASAT-A are provided in Table 2.6 for comparison with the user desires stated earlier (Table 2.3). The altimeter and scatterometer benefit from the atmospheric corrections provided by the

Table 2.5 SEASAT-A Sensor Characteristics

COMPRESSED PULSE ALTIMETER	MICROWAVE SCATTEROMETER	SYNTHETIC APERTURE IMAGING RADAR	MICROWAVE RADIOMETER	VISIBLE AND INFRARED RADIOMETER
GLOBAL OCEAN TOPOGRAPHY	GLOBAL WIND SPEED AND DIRECTION	WAVELENGTH SPECTRA	GLOBAL ALL-WEATHER TEMPERATURE	GLOBAL CLEAR-WEATHER TEMPERATURE
			GLOBAL WIND AMPLITUDE	GLOBAL FEATURE IDENTIFICATION
GLOBAL WAVE HEIGHT		LOCAL HIGH RESOLUTION IMAGES	GLOBAL ATMOSPHERIC PATH CORRECTIONS	
13.9 GHz	13.9 OR 14.595 GHz	1.35 GHz	6.6, 10.69, 18, 22.235, 37 GHz	0.52 - 0.73 μm 10.5 - 12.5 μm
1 m PARABOLA	5 - 2.7m STICK ARRAYS	14 x 2m ARRAY	0.8-m OFFSET PARABOLA	12.7 cm OPTICS
2.5kW PEAK	125W PEAK RF	800W PEAK	±20-25-deg CROSS SCAN	360-deg SCAN
125 W AVE	165 W AVE	200 - 250 W AVE	50 W	10 W
~ 8 kb/s	2 kb/s	15 - 24 Mb/s	4 kb/s	12 kb/s
SKYLAB/GEOS-C	SKYLAB	APOLLO 17	NIMBUS G	ITOS

Table 2.6 Geophysical Oceanographic-Measurement Capabilities for SEASAT-A

MEASUREMENT			RANGE	PRECISION/ACCURACY	RESOLUTION, km	SPACIAL GRID, km	TEMPORAL GRID
TOPOGRAPHY	GEOID	ALTIMETER	5 cm - 200 m	< ± 20 cm	1.6 - 12	~10	LESS THAN 6 MONTHS
	CURRENTS, SURGES, ETC		10 cm - 10 m				
SURFACE WINDS	AMPLITUDE	MICROWAVE RADIOMETER	7 - 50 m/s	±2 m/s OR ±10%	50	50	36 h TO 95% COVERAGE
		SCATTER-OMETER	3 - 25 m/s	± 2 m/s OR 10%	50	100	36 h TO 95% COVERAGE
	DIRECTION		0 - 360°	± 20°			
GRAVITY WAVES	HEIGHT	ALTIMETER	0.5 - 25 m	±0.5 TO 1.0 m OR ±10%	1.6 - 12	NADIR ONLY	1/14d NEAR CONTINENTAL U.S.
	LENGTH	IMAGING RADAR	50 - 1000 m	±10%	50 m		
	DIRECTION		0 - 360°	±15°			
SURFACE TEMPERATURE	RELATIVE	V&IR RADIOMETER	-2 - 35°C CLEAR WEATHER	1.5°	~5	~5	36 h
	ABSOLUTE			2°			
	RELATIVE	MICROWAVE RADIOMETER	-2 - 35°C ALL WEATHER	1°	100	100	36 h
	ABSOLUTE			1.5°			
SEA ICE	EXTENT	V&IR RADIOMETER		~5 km	~5	~5	36 h
		MICROWAVE RADIOMETER		10-15 km	10-15	10-15	36 h
		IMAGING RADAR		±25 m	25 m		1/14d NEAR CONTINENTAL U.S.
	LEADS		>50 m	±25 m	25 m		
	ICEBERGS		>25 m	±25 m	25 m		
OCEAN FEATURES	SHORES, CLOUDS, ISLANDS	V&IR RADIOMETER		~5 km	~5	~5	36 h
	SHOALS, CURRENTS	IMAGING RADAR		±25 m	25 m	25 m	1/14d NEAR CONTINENTAL U.S.
ATMOSPHERIC CORRECTIONS	WATER VAPOR & LIQUID	MICROWAVE RADIOMETER		±25 m	50	50	36 h

microwave radiometer. The data swaths are conceptually shown in Figure 2.3. Detailed layouts of the spatial grids within the swaths are shown in Figure 2.4. The altimeter provides measurements only at the nadir or ground track location. The synthetic aperture imaging radar looks out at a nadir angle of approximately 20°. The 100 km swath then allows it to overlap its coverage with the scatterometer wind measurements. The scatterometer looks out both sides with narrow fan beams. The fan beams placed 45 degrees forward and 45 degrees back allow

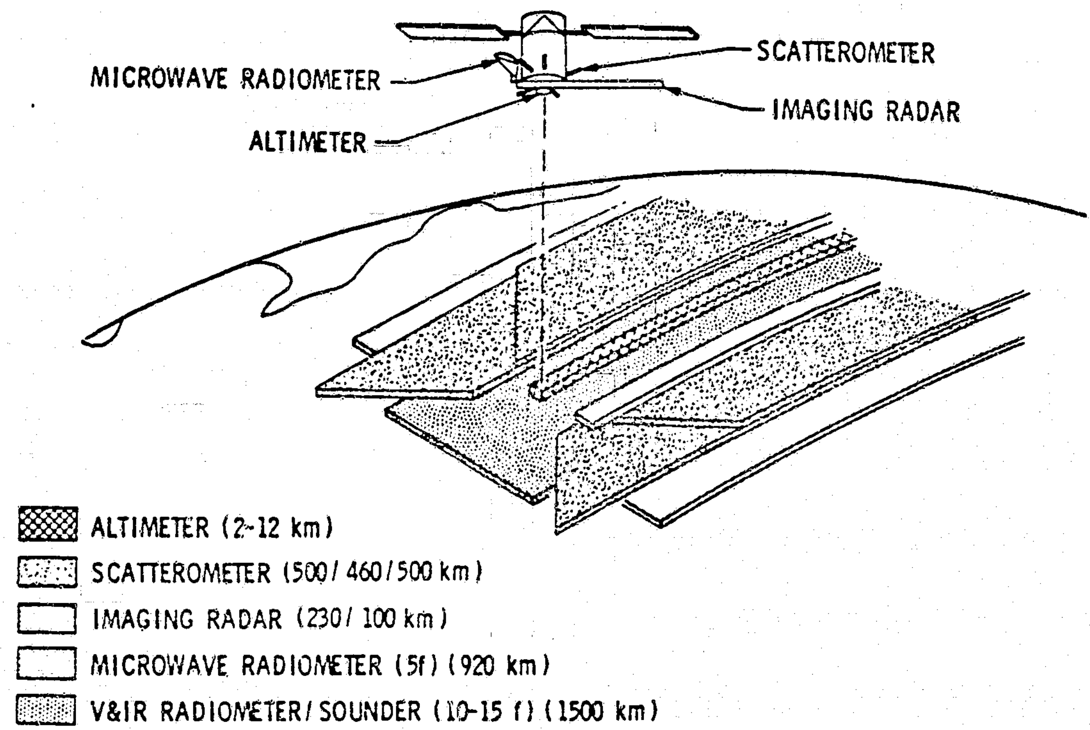


Figure 2.3 SEASAT-A Sensor Swaths

two looks at each piece of ocean separated by 90 degrees to allow a wind direction assessment. The fan beams extend on the ground from a surface incidence angle of 25 degrees to 55 degrees for the full range of winds (3 - 25 m/s), and then to 65 degrees for the higher winds (10 - 25 m/s). Below 25 degrees, the changes in backscatter from different wind speeds are difficult to differentiate. As a result, measurements are not included in those small angles. The microwave radiometer scans ± 25 degrees across track, with a surface-incidence angle of about 55 degrees. The visible and infrared radiometer scans horizon-to-horizon, but only

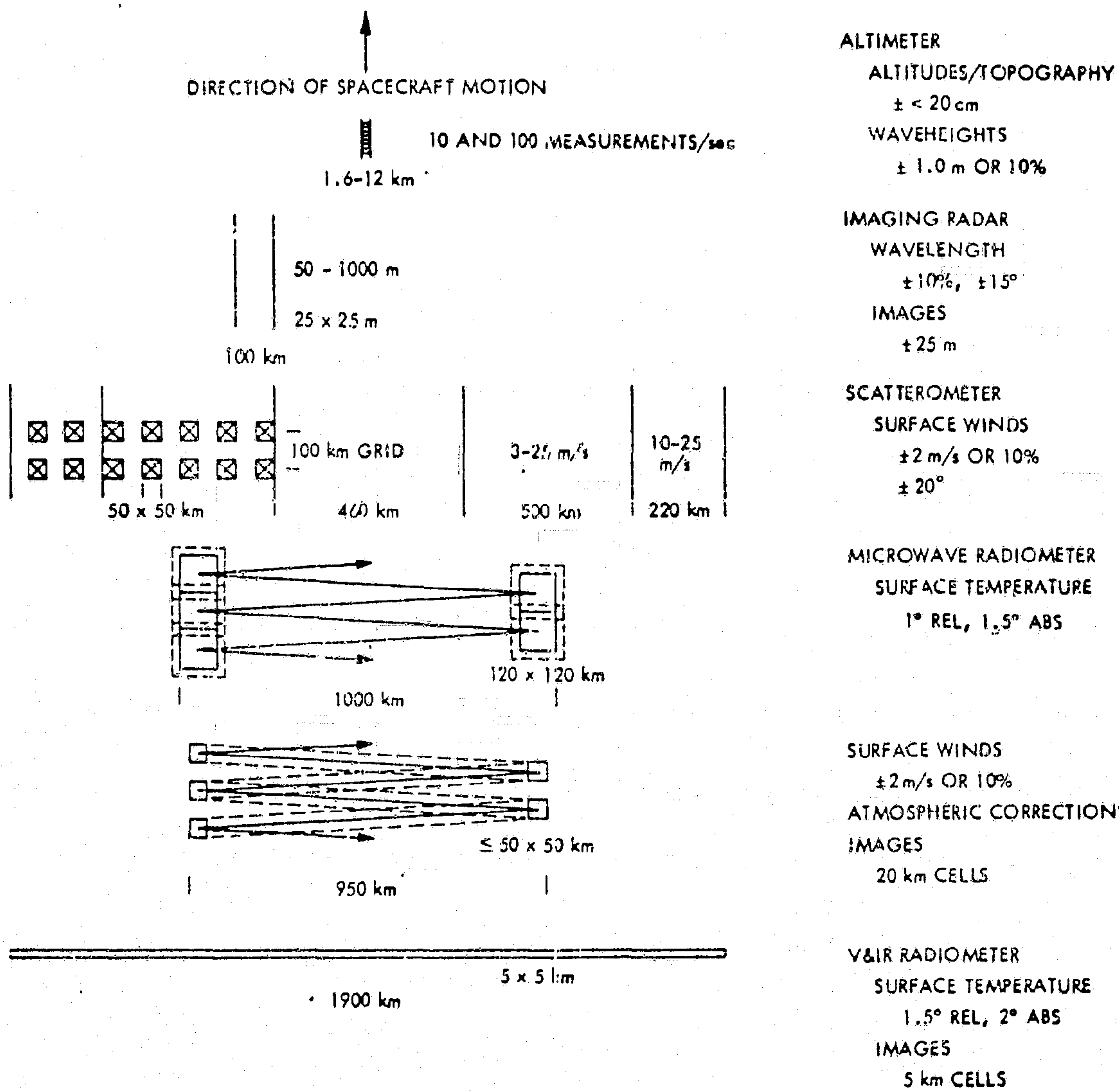


Figure 2.4 SEASAT-A Spatial Grids and Swathing

the middle 70 degrees of scan (or about 1000 km) on the ground produce accurate temperatures. The angular distortions at the higher angles plus increasingly long atmospheric path lengths make accurate interpretation much more difficult.

All of the instruments (except the imaging radar) are expected to be operated continuously during most of the mission to provide global coverage through on-board storage and then dump over one of the five NASA ground stations expected to be active in that period (see Figure 2.5). The imaging radar is to operate in real time only when it is over appropriate high-data-rate STDN ground stations. Present plans use existing stations in Alaska (ULA), California (GOS), and Maryland (at GSFC), and a new station at St. John, Newfoundland, to cover all the coastal waters of the U.S. and the major North American ice fields of interest. An attempt is being made to provide enough excess power capability on-board so that the imaging radar duty cycle can be increased if other high-data-rate international stations show interest in the radar data.

The SEASAT-A spacecraft concept emphasizes the use of existing satellite systems and subsystems and requires no new technology. Launch is provided by the Thor Delta or an equivalent Atlas F with a suitable second stage, depending on the selected satellite configuration. The total average power required in space is about 400 watts, with 325 watts allotted to the sensors. Attitude is controlled to $\pm$ .5° of an Earth-centered location, with post-knowledge of the actual attitude known to about $\pm$ .1 to .2°. There is presently no on-board data processing, but data storage for the low rate (non-imaging radar) data is provided to allow a maximum of two to four orbits of accumulation before playback ($\sim 2 \times 10^8$ b capacity). Data rates from the low rate instruments plus housekeeping are in the 25 to

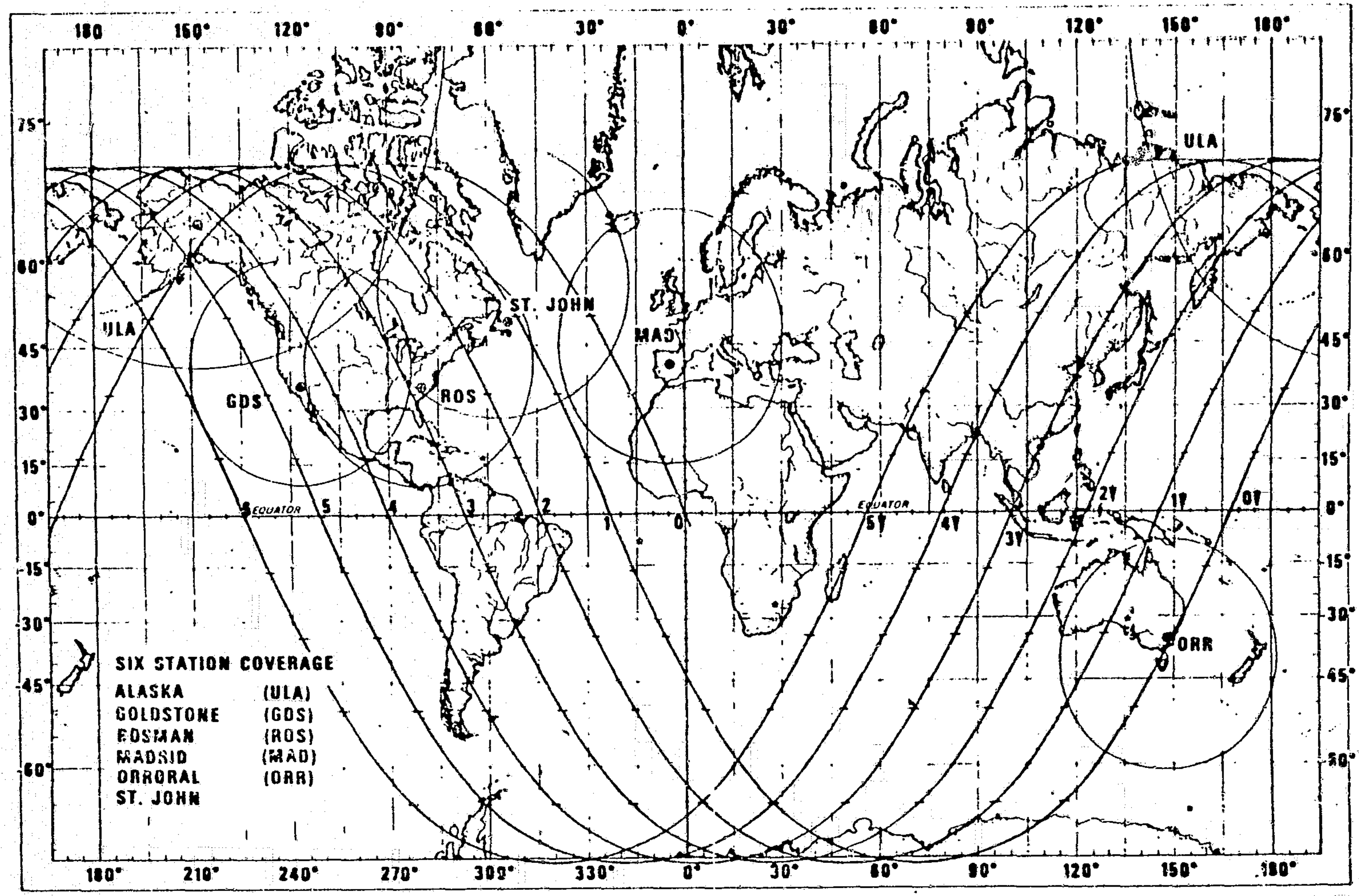


Figure 2.5 SEASAT-A Trajectory and Ground Station Coverage

30 kb/s range and the imaging radar is telemetered through a separate link in the 15 to 24 Mb/s range.

NASA data products in the early stages of the mission will consist primarily of data tapes of the various measured parameters in engineering units. The data will be error-checked and decoded from the telemetry process, and located on the Earth relative to the nominal tracking and attitude capabilities. The nominal tracking and attitude capabilities make use of weekly updated trajectory predicts and the attitude sensor accuracies to produce ground locations within 1 to 3 km of actual. The data tapes for detailed tracking records will also be available for users requiring more exact location. During the early stages, NASA will also be doing considerable work developing and verifying the processing algorithms which convert the engineering units into geophysical units. After the processing algorithms are developed and verified, they will be turned over to users for detailed real time processing. The U.S. Navy Fleet Numerical Weather Center has agreed to process all but the imaging radar data in real time (several hours turnaround at most) for its own use and to make the output available for NASA dissemination to other users. Some processing of imaging radar data into digital and optical images plus Fourier transforms of the wave length spectra will be undertaken by NASA on a demonstration basis. Undertaking reasonably fast turnaround of processed imaging radar data on a regular basis is presently being negotiated with several user agencies, including the Canadian government, relative to the Newfoundland station coverage. The nominal grid structure for the data for each measurement is shown in Figure 2.4. The actual grid structure will be slightly different for the scatterometer and microwave radiometer, since geometries do not provide quite so regular a patterning. The scatterometer parallel rows will be shifted slightly forward or backward along track due to the 45-degree nature of the fan beams, the time integration of the signal along track and the variable motion of the ground along the 108-degree inclination due to the Earth's rotation. Similarly, the microwave radiometer does not produce exact footprint multiples in the 5 microwave channels on the same antenna, so the final data matrix produced cannot be more precisely described at this time. Potential user products from SEASAT-A include data tapes, maps, and warning advisories. Some of the possible map products for digital tape or photographic dissemination are listed in Table 2.7. The accuracies and grid characteristics of these products are shown in Table 2.6 and Figure 2.4.

2.4 Interim Operational SEASAT

The capability assumed for the Full Capability Operational SEASAT requires some investment in research and development in order to be available for a 1985 launch. On the other hand, it is probable that once SEASAT-A has demonstrated the value of sea-state and ocean-feature data, an interim three-satellite opera-

Table 2.7 Potential User Agency Products

	SEASAT OPTIONS		
	A	INTERIM	FULL CAPABILITY
SURFACE WIND FIELD MAPS	36h	2/d	4/d
SURFACE WIND FORECASTS - ONE-DAY AND TWO-DAY FORECASTS	36h	2/d	4/d
WAVE FIELD MAPS	2w	1/2-5d	2/d
WAVE FORECASTS - ONE-DAY AND TWO-DAY FORECASTS OF WIND-DRIVEN WAVES; LONGER FORECASTS FOR ESTABLISHED SWELLS	–	1/d	2/d
SURFACE TEMPERATURE FIELD MAPS	36h	2/d	4/d
SURFACE TEMPERATURE FORECASTS - ONE-DAY AND TWO-DAY FORECASTS OF CURRENT AND UPWELLING BOUNDARIES	36h	2/d	4/d
WEATHER MAPS (WIND, WAVE, AND TEMPERATURE, PLUS CLOUD MOVEMENT, RAIN, ETC.)	–	2/d	4/d
WEATHER FORECASTS - ONE-DAY AND TWO-DAY FORECASTS	–	2/d	4/d
ICE MAPS - EXTENT, LEAD LOCATIONS	2w	1/2-5d	2/d
COASTAL MAPS - EROSION PROCESSES, SHOAL MOTION, WAVE REFRACTION PROCESSES	2w	1/2-5d	2/d
OCEAN DYNAMICS MAPS - CURRENTS, UPWELLINGS, TIDES, SURGES, ETC.	–	1/2-5d	2/d
GEODETIC MAPS	YRLY	6/y	MONTHLY

tional SEASAT capability will be economically justifiable and strongly requested by SEASAT users. A number of options are possible for this interim capability. The simplest one would be to proliferate and launch duplicate SEASAT-A spacecraft. The next simplest would be to extend the SEASAT-A capability to include improvements which require no research and development expenditures, such as extending the imaging radar to global coverage, adding a second imaging radar to simultaneously view the other side of the spacecraft, and substituting improved visible and infrared sensors available from TIROS-N. Such improvements would provide accurate clear-weather, sea-surface temperature and vertical-temperature sounding for improved climatology, ocean dynamics, and coastal processes studies. These improvements primarily entail increasing the power and telemetry rate capability on the spacecraft. A final bounding option would be to add those improvements which could be implemented with reasonable investment in this earlier time frame, such as larger antennas for the scatterometer and passive microwave radiometers to produce smaller footprints, expanding the SAR swath width, or replacing the two TIROS-N visible and infrared radiometers with a single improved instrument, making both kinds of measurements with similar accuracies.

Described here is the second case in which SEASAT-A is upgraded by improving the spacecraft support capability and by substituting other satellite-tested sensors which do not require outside expenditure for research and development. The measurements, sensors, and support capabilities needed for this interim operational capability are outlined in Table 2.8. Improvements over SEASAT-A include the second synthetic aperture radar and the substitution of the 5-channel AVHRR* and 14-channel BSU** from TIROS-N. The measurement accuracies and spatial and temporal measurement grids accommodated in this operational system are shown in Table 2.9, with the swathing changes illustrated in Figures 2.6 and 2.7. The only major swathing change is the addition of the second imaging radar. The 200 km swath thus allows complete global coverage to be achieved in five days by shifting the nadir point 100 km each day. Since the present SEASAT-A geodesy requirement is not anticipated for this mission, the 100 km daily shift is well within capability. The other swathing change is the reduced size of the resolution cell in the AVHRR sensor and the increased size of the resolution cell of the BSU. A 10 x 10 grid of these 1 km AVHRR measurements is required to produce the fine-temperature sensitivity mentioned. The 1 km cell, however, does provide improved visible and infrared images. The vertical temperature and humidity distributions provide an important additional measurement specifically requested by the

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*AVHRR - Advanced Very High Resolution Radiometer
**BSU - Basic Sounding Unit

Table 2.8 Interim SEASAT Sensor Characteristics

COMPRESSED PULSE ALTIMETER	MICROWAVE SCATTEROMETER	SYNTHETIC APERTURE IMAGING RADAR	MICROWAVE RADIOMETER	VISIBLE AND INFRARED RADIOMETER	
GLOBAL OCEAN TOPOGRAPHY	GLOBAL WIND SPEED AND DIRECTION	WAVELENGTH SPECTRA	GLOBAL ALL-WEATHER SEA SURFACE TEMPERATURE	GLOBAL CLEAR-WEATHER SEA SURFACE TEMPERATURE	
			GLOBAL WIND AMPLITUDE	GLOBAL FEATURE IDENTIFICATION	
GLOBAL WAVE HEIGHT		LOCAL HIGH RESOLUTION IMAGES	GLOBAL ATMOSPHERIC PATH CORRECTIONS	GLOBAL VERTICAL TEMPERATURE SOUNDING	
13.9 GHz	13.9 OR 14.595 GHz	1.35 GHz	6.6, 10.69, 18, 22.235, 37 GHz	0.55 - 0.9 μm 0.725 - 1.0 μm 3.55 - 3.93 μm 10.5 - 11.5 μm 11.9 - 12.9 μm	.340, .432, .532 .6685, .678, .690 .700, .715, .735 .750, .899, 1.030 2.350, 2.700 μm
1 m PARABOLA	5 - 2.7 m STICK ARRAYS	2 - 14 x 2 m ARRAYS	0.8 m OFFSET PARABOLA	20.32 cm OPTICS	8 and 6 cm OPTICS
2.5 kW PEAK	125 W PEAK RF	800 W PEAK	±20 - 25 deg CROSS SCAN	360-deg SCAN	±49.5° in. 1.8° ST
125 W AVE	165 W AVE	400 - 500 W AVE	50 W	25 W	34 W
~8 kb/s	2 kb/s	30 - 110 Mb/s	4 kb/s	6, 22, 540 kb/s	2.88 kb/s
SKYLAB/GEOS-C	SKYLAB	APOLLO 17	NIMBUS G	TIROS N:	TIROS N:

Table 2.9 Capabilities for Interim Operational SEASAT

MEASUREMENT			RANGE	PRECISION/ACCURACY	RESOLUTION, km	SPACIAL GRID, km	TEMPORAL GRID
TOPOGRAPHY	GEOID	ALTIMETER	5 cm - 200 m	<± 10 cm	1.6 - 12	~10	LESS THAN 2 MONTHS
	CURRENTS, SURGES, ETC		10 cm - 10 m				
SURFACE WINDS	AMPLITUDE	MICROWAVE RADIOMETER	7 - 50 m/s	± 2 m/s OR ±10%	50	50	2/d
		SCATTER-OMETER	3 - 25 m/s	± ~2 m/s OR 10%	50	100	2/d
	DIRECTION		0 - 360°	± 20°			
GRAVITY WAVES	HEIGHT	ALTIMETER	0.5 - 25 m	± 0.5 TO 1.0 m OR ± 10%	1.6 - 12	NADIR ONLY	
	LENGTH	IMAGING RADAR	50 - 1000 m	± 10%	50 m		1/2-5d
	DIRECTION		0 - 360°	± 15°			
SURFACE TEMPERATURE	RELATIVE	V&IR RADIOMETER	-2 - 35°C CLEAR WEATHER	1.0°	10	10	2/d
	ABSOLUTE			1.5°			
	RELATIVE	MICROWAVE RADIOMETER	-2 -35°C ALL WEATHER	1.0°	100	100	2/d
	ABSOLUTE			1.5°			
VERTICAL TEMPERATURE DISTRIBUTION	RELATIVE	V&IR RADIOMETER	-2 - 65°c	2°	2 - 5 VERT 22 HOR	22	2/d
SEA ICE	EXTENT	V&IR RADIOMETER		1 km	1	1	2/d
		MICROWAVE RADIOMETER		10-15 km	10 - 15	10 - 15	2/d
		IMAGING RADAR		25 m	25 m		
	LEADS		> 50 m	25 m	25 m		
	ICEBERGS		> 25 m	25 m	25 m		
OCEAN FEATURES	SHORES, CLOUDS, ISLANDS	V&IR RADIOMETER		~1 km	~1	~1	2/d
	SHOALS, CURRENTS	IMAGING RADAR		±25 m	25 m	25 m	1/2-5d
ATMOSPHERIC CORRECTIONS	WATER VAPOR & LIQUID COLUMN	MICROWAVE RADIOMETER	0 - 6 g/cm²	20% OF g/cm²	50	50	2/d
	VERTICAL HUMIDITY DISTRIBUTION	V&IR RADIOMETER	0 - 6 g/cm²	20% OF g/cm²	22	22	2/d

weather and climate-modeling organizations. It was considered important to obtain this data coincident with the wind, wave and surface-temperature data rather than rely on the TIROS-N system, which will not be time-synchronized with SEASAT.

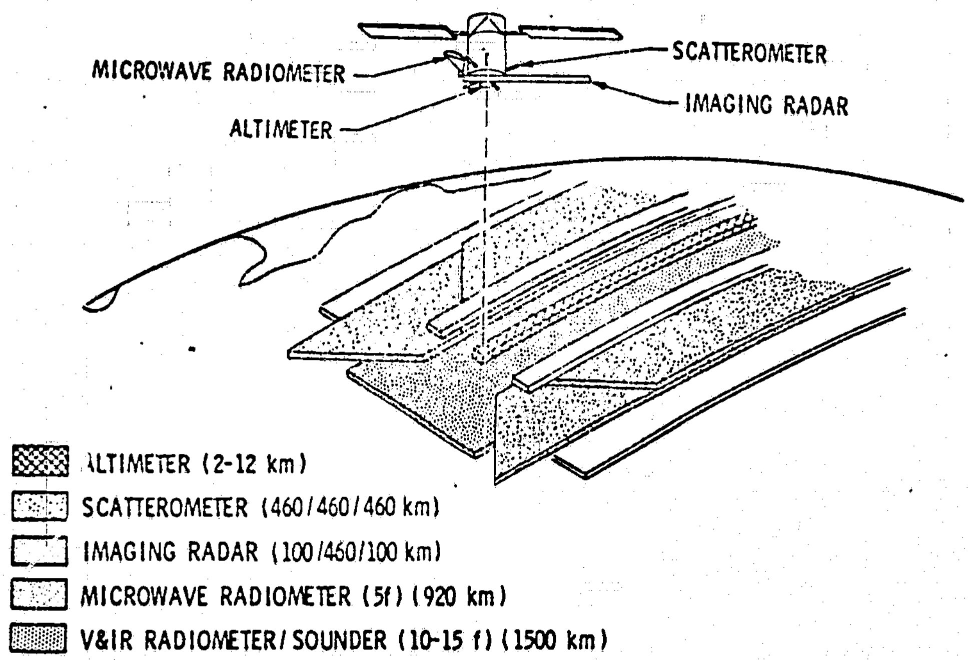

Figure 2.6 Interim Operational SEASAT Sensor Swath

This three-satellite operational system provides twice-a-day coverage (approximately 12 hours apart) of wind, wave, surface and vertical temperature, and vertical humidity. There is a good balance of redundant or complementary measurements at several accuracies and resolutions. Sea-surface temperatures are available in both the conventional high-resolution, clear-weather systems and in a bigger footprint, but all-weather microwave system. The high-resolution (25 m) images are provided globally every five days, and the temporal availability of these images is good for monitoring the slow changes of ice packs, shorelines, and shoals, and also provides more than adequate

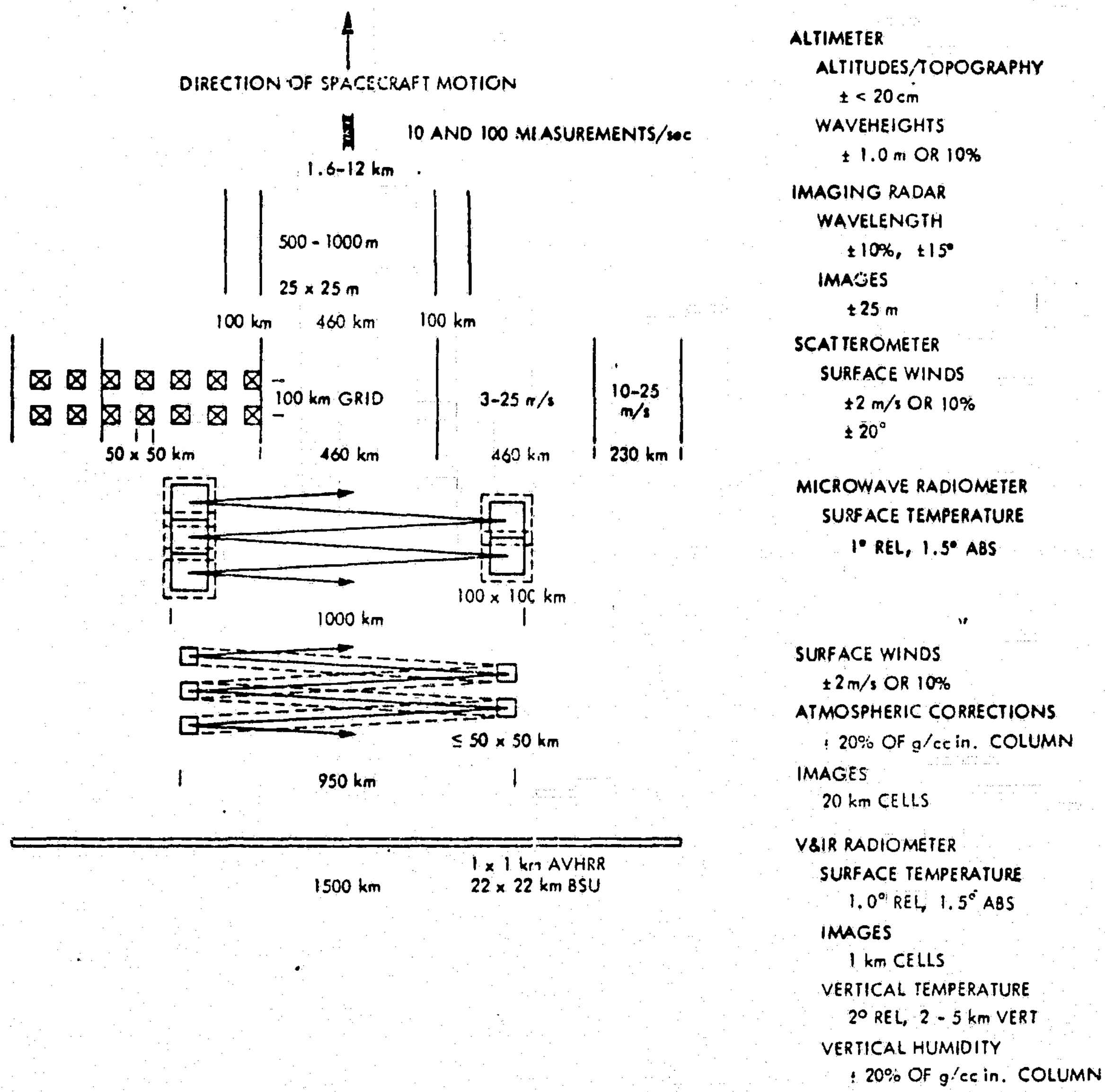

Figure 2.7 Interim Operational SEASAT Spatial Grids and Swathing

verification of wave-forecasting models. The five-day coverage does not satisfy the requirements for ice lead navigation, iceberg and fishing boat surveillance, or ocean current meandering surveillance.

2.5 Full Capability Operational SEASAT

The Full Capabililty Operational SEASAT offers the best compromise between the capability necessary to satisfy user needs and 'reasonable' investment of research and development funds. The particular capability described herein emphasizes attainable capability within the physics of the measurement process and the ability of projected spacecraft capabilities to provide the necessary support services. A summary of the sensor characteristics for this full capability operational SEASAT is given in Table 2.10.

Table 2.10 Full Capability Operational SEASAT Sensor Characteristics

COMPRESSED PULSE ALTIMETER	MICROWAVE SCATTEROMETER	SYNTHETIC APERTURE IMAGING RADAR	MICROWAVE RADIOMETER	V&IR RADIOMETER
GLOBAL OCEAN TOPOGRAPHY	GLOBAL WIND SPEED AND DIRECTION	GLOBAL WAVE LENGTH SPECTRA	GLOBAL ALL WEATHER TEMPERATURE	GLOBAL CLEAR WEATHER TEMPERATURE
			GLOBAL WIND AMPLITUDE	GLOBAL FEATURE IDENTIFICATION
GLOBAL WAVE HEIGHT		GLOBAL HIGH RESOLUTION IMAGES	GLOBAL ATMOSPHERIC PATH CORRECTION	GLOBAL VERTICAL TEMPERATURE SOUNDING
			GLOBAL ICE IMAGES	GLOBAL ATMOSPHERIC PATH CORRECTION
13.9 GHz	14.5 GHz	1.35 GHz	6.6, 10.69, 18, 22.235, 37, 95 GHz	~17 CHANNELS IN 6 BAND REGIONS: 0.7, 3.7, 4.3, 6.3, 11.1, 15 μm
1 m PARABOLA	4-5 m STICK ARRAYS	2-1.1 m x 38 m ARRAYS	2.5 m OFFSET PARABOLA	20-25 cm OPTICS
			±35 deg CROSS SCAN	HORIZON TO HORIZON SCAN
2.5 kW PEAK	250 W PEAK RF	3K W PEAK		
125 W AVERAGE	300 W AVERAGE	2K W AVERAGE	80 W	50 W
~8 kb/s	~2 kb/s	~240.4 Mb/s	~10 kb/s	~25, 600 kb/s

The altimeter is essentially unchanged, except topography and wave-height measurements are emphasized over geodetic altitude. This could simplify the system somewhat. The microwave scatterometer assumes a larger array and higher power in order to achieve finer footprints. The microwave radiometer assumes larger antennas with wider scans and a sixth channel at 95 GHz for finer resolution of ice images. The visible and infrared radiometer assumes some combination of the new generation of sea-surface temperature and atmospheric sounders presently under development at several NASA centers. The 17 channels suggested include three channels in the visible for optical-reference, blue-green nutrient monitoring, and yellow-shoal monitoring; one channel in the surface radiance window region near 3.7μ; eight channels for vertical-temperature sounding near 4.3μ; one channel for water-vapor sounding near 6.3μ; one channel near 11.1μ as an additional surface radiance window, and three channels in the 15μ region for cloud sounding. Other combinations are also possible from instruments expected to be existing in the early to mid-1980s. The synthetic aperture imaging radar has the largest change in capability. Two 1.1 x 38 m arrays are needed to provide 230 km swaths on both sides of the spacecraft at the assumed power levels and noise figures. The 240 Mb/s data rate fits a telemetry capability presently under development for advanced LANDSAT missions. Onboard correlation would bring the data rate down to 24 Mb/s and checkerboarding to 4 Mb/s uncorrelated.

Checkerboarding is a term for sampling 10 km by 10 km ocean sections every 200 km along track. The power demand is well below the 3 km solar array capability anticipated for a number of shuttle missions. Space-qualified 1.5-kw units exist now.

With such capability, 48-hour weather forecasts should be commonplace and forecasts up to a week might be possible with some advancement in our understanding of modeling the physics of weather and climate change. The specific accuracies/precision, resolution, spatial grids and temporal grids for the Full Capability Operational SEASAT are shown in Table 2.11, assuming six satellites in orbit. The six satellites would be shifted in time from each other approximately four hours and in space by approximately 500 km so that there would be a complete coverage at least four times each day, with each local region sampled at least once every four hours. This satellite system attempts to satisfy users with combined requirements of weather, climate, ocean dynamics, coastal processes, and ice processes.

The layout of footprints for each of the sensors is shown in Figure 2.8. Again, the real data will be slightly distorted from the regularities shown, since angular scanning and fan beam implementations do not create these idealized patterns. Topography and wave-height measurements are made 10 or 100 times a second, but only along the nadir track below the satellite. Wave-length features can be taken from the full-detail 460 km swath radar images when special-interest phenomena are within the

Table 2.11 Geophysical Oceanographic-Measurement Capabilities for a Full Capability Operational SEASAT (6 Satellites in Orbit)

MEASUREMENT			RANGE	PRECISION/ACCURACY	RESOLUTION, km	SPACIAL GRID, km	TEMPORAL GRID
TOPOGRAPHY	GEOID	ALTIMETER	5 cm - 200 m	< ±10 cm	1.6 - 12	~10	LESS THAN 2 MONTHS
	CURRENTS, SURGES, ETC		10 cm - 10 m				
SURFACE WINDS	AMPLITUDE	MICROWAVE RADIOMETER	7 - 50 m/s	± 1 m/s OR ±10%	25	25	4/d
		SCATTER-OMETER		± 1 m/s OR ±10%	25	25	4/d
	DIRECTION		0 - 360°	± 15°			
GRAVITY WAVES	HEIGHT	ALTIMETER	0.5 - 25 m	±0.5 m OR ±10%	1.6 TO 12	~900	1/d
	LENGTH	IMAGING RADAR	50 - 1000 m	±10%	50 m	50 m	2/d
	DIRECTION		0 - 360°	± 10°			
SURFACE TEMPERATURE	RELATIVE	V&IR RADIOMETER	-2 - 35°C CLEAR WEATHER	1°	5	5	4/d
	ABSOLUTE			1.5°			
	RELATIVE	MICROWAVE RADIOMETER	-2 -35°C ALL WEATHER	1.5°	50	50	4/d
	ABSOLUTE			2°			
SEA ICE, CLOUD LOCATIONS, AND OCEAN FEATURES	EXTENT	MICROWAVE RADIOMETER		10 km	10	10	4/d
		V&IR RADIOMETER		1 km	1	1	4/d
		IMAGING RADAR		25 m	25 m		2/d
	LEADS		> 50 m	25 m	25 m		2/d
	ICEBERGS		> 25 m	25 m	25 m		2/d
ATMOSPHERIC CORRECTIONS	WATER VAPOR AND LIQUID	MICROWAVE RADIOMETER		20%	25	25	4/d
ATMOSPHERIC TEMPERATURES	VERTICAL PROFILE	IR SOUNDER		2°, 5 km	10	10	4/d
ATMOSPHERIC HUMIDITY	VERTICAL PROFILE	IR SOUNDER	0-6 g/cc	20% OF COLUMN	10	10	4/d
SURFACE PRESSURE	g OF PERCIPITANT			2-4 mb	5	5	4/d

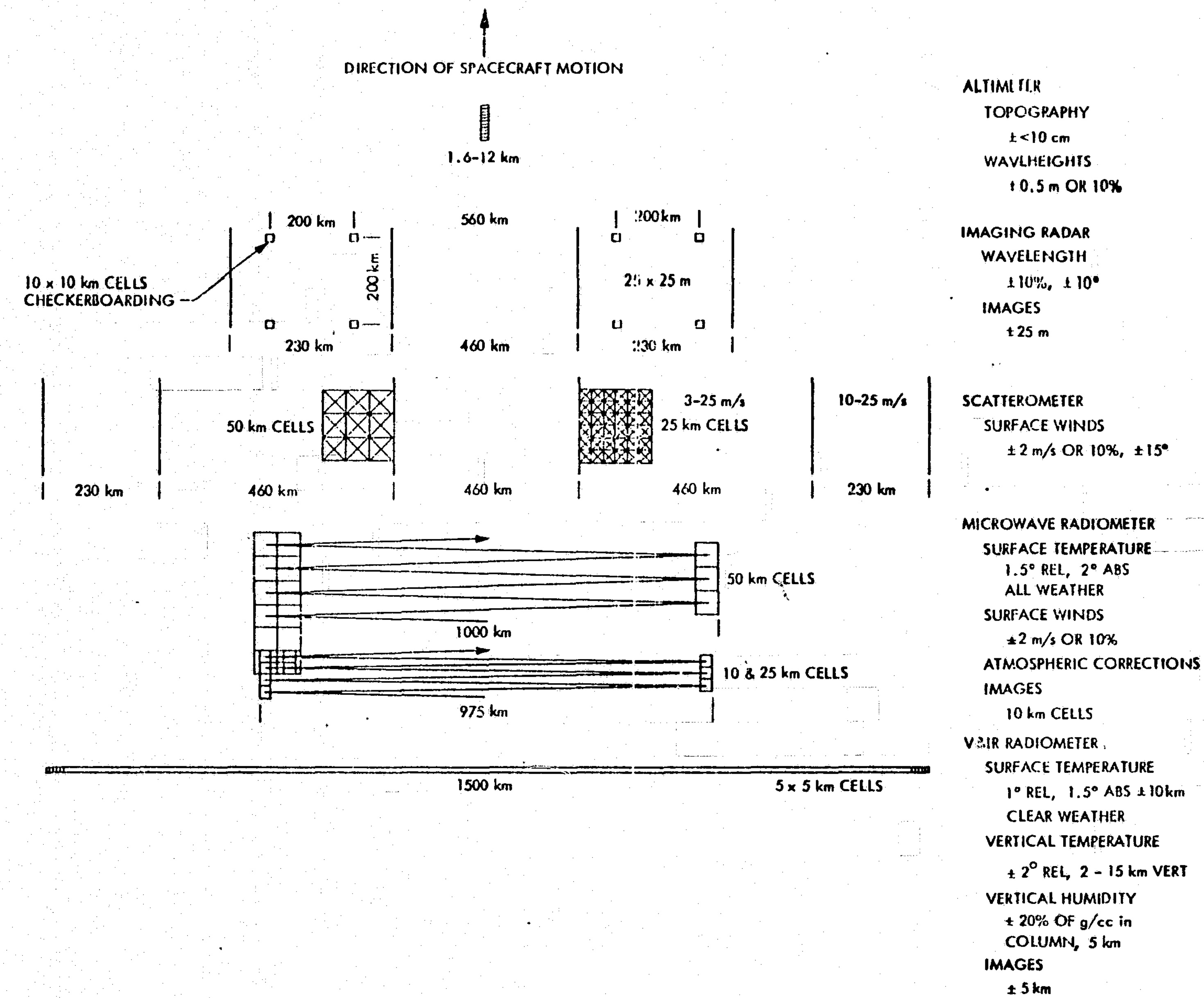

Figure 2.8 Full Capability Operational SEASAT Spatial Grids and Swathing

picture, but a second alternative is also shown. Ten kilometer squares can be processed in a checkerboard pattern on approximately 200 km (1.8°) centers to provide reference points for the global weather and climate models without overloading the data recording system. The scatterometer also has two alternatives. The first provides a nominal 50 km footprint for global weather model inputs; a second option provides 25 km footprints for special-feature evaluations near storms or coastlines.

The microwave radiometer will probably be divided into two scanning systems as shown, since the 50 km cells of the temperature channel could benefit from a slower scan to provide high accuracy, while retaining the forward contiguous nature (~ 6-7 seconds per cycle). The higher frequencies have smaller footprints and must be scanned faster to achieve a contiguous forward pattern (1 to 2 seconds per cycle). The visible and infrared radiometer is assumed to be a combined sea-surface temperature and vertical sounder instrument. A goal of 1° relative accuracy for sea-surface temperature is assumed with cell sizes about 1 km to achieve 5 km averages. The V&IR temperature sounder provides eight vertical measurements which yield vertical profiles accurate in altitude about ± 2 km near the surface (to 300 mb), ± 5 km between 300 and 100 mb and ± 15 km above 100 mb.*

*Water vapor vertical resolution is about a factor of 2 greater than this.

All of this capability is feasible in the mid 1980s and is directly projected from existing development efforts and trends. A shuttle launch is needed to launch the volume estimated for antennas, solar arrays, and processing electronics, but existing buses with similar capabilities already exist for other purposes and the Shuttle-compatible, low-cost standard buses presently under development by NASA provide an additional option.

2.5.1 Potential Data Modes for the Operational System

Three potential data modes are anticipated for this system. The data modes considered are:

- Oceanographic Data Services
- Direct Satellite Readout
- Conversational Retrieval and Analysis

These data are discussed in the following sections.

2.5.1.1 Oceanographic Data Services

The data products in this data mode are similar to those of Table 2.7 (with the addition of maps of the vertical-temperature and water-vapor distribution and vertical cloud locations). The nowcast data characteristics are as shown in Table 2.11.

The major thruput system absorbs the wideband 240 Mb/s imaging radar data rate when operating directly through the TDRS for ground processing. Similarly, the 1 Mb/s rate from the other instruments with or without the 4 Mb/s rates from the checkerboarding mechanization of the imaging radar can be funneled directly down through the TDRS for ground processing.

All of these data will be error-checked and decoded from the telemetry process, converted into engineering units, and spatially and temporally located by the operational agency. Conversion to located geophysical units could be accomplished by the various user agencies in support of their constituents, using simple computer hardware with standard software packages furnished by the SEASAT Program.

Possible institutional sources of data processing to support this mode of operation include the Navy's Fleet Numerical Weather Central at Monterey, California, NOAA's Weather Processing Center at Suitland, Maryland, and participating foreign meteorological services. It should be noted that in the processing to provide forecasts at these centers the SEASAT data will be blended with data from other satellite systems, aircraft, ships, buoys and balloons.

A tracking and data relay satellite system is assumed for the major SEASAT satellite-to-ground data link. Data could thus be cleaned up and located at the centralized user site in real time. This engineering unit data can then be processed for some users at that site or transshipped by communication satellite to regional or centralized user-agency-forecasting or dissemination centers where it can be further processed and disseminated through satellite or ground or radio links to specific users. The goal for this entire process would be for a less than two-hour turnaround, including the imaging radar data.

2.5.1.2 Direct Satellite Readout

The second data mode considered is a direct readout system, which could supply real time weather maps to ships at sea, local weather stations, or local business operations with sensitivity to the weather. In this mode, onboard processing is used to convert a limited portion of the data into located geophysical units. Many of the parameters would be less accurate and have a grosser surface grid than possible with the full data load, but considerable utility is still anticipated. Data of this format would be generated in real time and transmitted in real time. Ground stations would pick up the satellite when it is 5 to 10 degrees above the horizon and follow it as long as it is in view. During this period, wind, wave, temperature and cloud cover information quantified and located to within 2 or 3 km on a 10 km map would be transmitted. A ship at sea could thus have a real time map covering 1000 km or more in each direction, an area equivalent to several days sailing time, and storm centers or other phenomena could be tracked and avoided. The locating would be done onboard the satellite by storing the predicted trajectory in the satellite computer (updated weekly only), with locations calculated from predicted nadir positions plus real time measurements of attitude and scan position. The data content for this direct readout mode is summarized in Table 2.12. This data might also be transmitted with the main data stream for rapid dissemination from the centralized facility before the main processing begins.

Table 2.12 Direct Readout Data Content

	ACCURACY/ PRECISION	RESOLUTION CELLS, km	GRID/SWATH, km	INSTRUMENT
TEMPERATURE	1.5° RELATIVE	50	50/1000	μω RADIOMETER
ALL WEATHER	2° ABSOLUTE	50		
WIND				
-AMPLITUDE	2 m/s OR 10%	50	50/1900	μω RADIOMETER AND SCATTEROMETER
-DIRECTION	± 20°			
WAVE				
-HEIGHT DISTRIBUTION	±1.0m OR 10%	10	NADIR ONLY	ALTIMETER
-LENGTH DISTRIBUTION	± 10%	10	-280/1000	IMAGING RADAR
-DIRECTION	± 10°			
OCEAN FEATURE AND CLOUD	10-15km	10-15	10-15/19000	V&IR RADIOMETER
LOCATIONS	10-15km	10-15	10-15/1000	μω RADIOMETER

2.5.1.3 Conversational Retrieval and Analysis

This mode of operation would be available on demand within a planned service capability (probably via one or more of the user service facilities discussed in Section 2.5.1.1) for use by scientific and other investigative users. The basic SEASAT and other source data would be maintained at these processing centers in its detailed form (i.e., as instrument data products) and held in file for a period of perhaps 30 to 60 days. the exact period for retaining these data would be determined by trade-offs between library size, cost and data demands. These data could be retrievable on demand from the responsible user agency or agencies, with conversational direct lines available to high-volume users. A limited set of data in the form of specially coded globally-synoptic maps of about 4 GMT could be stored in an archival sense for long-duration studies.

2.6 A Preliminary Estimate of the Operational SEASAT System Costs

In order to fully evaluate the economics of the operational SEASAT program it is necessary to estimate both the benefits and the costs of achieving the benefits. Specifically, the measure of interest is the Net Present Value of the Benefits (NPV_B) which is defined as:

$$NPV_B = PV_B - PV_C$$

where:

PV_B = Present Value of the Benefits

PV_C = Present Value of the Costs

The main thrust of the SEASAT Economic Assessment has been the analysis and estimation of the potential economic benefits that could be produced by the implementation of an operational SEASAT system. These potential economic benefits, when appropriately discounted and aggregated, yield the Present Value of Benefits (PV_B). During 1975, an effort was started to develop the methodology and collect the data base needed to estimate the costs of the operational SEASAT system (PV_C) which could provide these benefits. By August of 1975, the development of a methodology for the estimation of the operational SEASAT system costs as a function of system requirements, including the evaluation of risk and uncertainty effect on costs was completed.* However, as of August 1975, the assembly of the data base needed to use the model had not been completed. The data base, which is being assembled by JPL, is scheduled for completion in 1976, and it is anticipated that the model and the data base will be applied at a later date to the estimation of operational SEASAT system costs.

In order to provide an estimate of the costs of an operational SEASAT system (PV_C) at this time for use in the estimation of the Net Present Value of Benefits (NPV_B), a deterministic model of the programmatic options which could lead to an operational SEASAT system was prepared. The intent of the deterministic model was to illustrate the bounding alternatives to an

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* SEASAT Economic Assessment, Volume X, A Program for the Evaluation of Operational SEASAT System Costs, August 1975.

evolutionary SEASAT development, with assumed capabilities for each instrument or capability change option, plus integrated performance requirements for each spacecraft. In this manner, the model shown in Figure 2.9 is useful as a basis for estimating the cost of an operational SEASAT system. The schedules, as shown in Figure 2.9, show contract start dates in circles, hardware delivery dates in squares, and launches in triangles. Each new system is assumed to have an engineering model which is refurbishable to a flight spare, if necessary. It should be noted that this deterministic cost model is not intended to be a program plan for an operational SEASAT system. As of this date, only SEASAT-A is an approved program. The requirement for systems beyond SEASAT, including the operational SEASAT system, will evolve from user needs and experience with the use of SEASAT data.

The cost estimates based upon this model were developed using JPL earth orbital cost modelling capabilities, and are considered to be preliminary estimates of the costs of an operational SEASAT system. As such, these preliminary estimates are probably accurate to about ±50%.

Several crucial assumptions were used in the preparation of these costs estimates, and some of these assumptions require further study to confirm their validity. The underlying assumptions are:

1. Shuttle Utilization

   The operational SEASAT will be placed in orbit by the Space Shuttle operating from the Western Test

	PROGRAM GENERATIONS	PWR w	DATA RATES b/s	A/C deg
A	SENSORS – ALT 20 cm	125	8k	<0.75
	– SCAT 50 km CELLS, FAN	110	0.5k	<1
	– SMMR 5f, 120 km max	65	4k	<1
	– SR 2f	10	12k	≤0.5
	– SAR 25m, 100 km, RF ONLY (10%), ANALOG	25	55M	≤0.5
	SPACECRAFT ~1100 kg	400	25k, 15 MHz	≤0.5
	GROUND SYSTEM			
A'	SENSORS – ABOVE UNCHANGED	335	25k, 15 MHz	<0.5
	SPACECRAFT – EARLIEST USER RESPONSIVE DATE ~1100 kg	400	25k, 15 MHz	≤0.5
	– LATEST USER RESPONSIVE DATE	400	25k, 15 MHz	≤0.5
A''	SENSOR MODS – AVHRR 5f, 1 deg SST – REPLACES SR	30	6, 22, 540 k	≤0.5
	BSU 14f, SOUNDER	35	3k	<1
	– SAR 25m, 100 km; 50m, 200 km; RF ONLY (20%) ANALOG	50	12M, 55M	<0.5
	– SMMR 5f, 90 km max	65	5k	≤1
	SPACECRAFT MODS – TDRSS COMPATIBILITY + SENSOR MODS ~1350 kg	500	25k, 560k, 15 MHz	0.5
	GROUND SYSTEM			
B	SENSORS – INCL. A'' MODS – PREVIOUSLY FLOWN	415	25k, 560k, 15 MHz	≤0.5
	– FIRST FLIGHT OF MODS	415	25k, 560k, 15 MHz	≤0.5
	SPACECRAFT – INCL TDRSS COMPATIBILITY ~1350 kg	500	25k, 560k, 15 MHz	0.5
B'	SENSOR MODS – SCAT. 25 km CELLS, FAN	200	2k	≤0.2
	– SMMR 5f, 50 km max	80	10k	<0.5
	– ADVANCED IR SOUNDER – REPLACE AVHRR + BSU	35	25k, 600k	≤0.5
	– SAR – 2 A' SARS, GLOBAL, DIGITAL	500	25M, 110M	≤0.5
	– 25m, 460km GLOBAL	2k	300M	≤0.1
	– L X, 25/25, 460 100, GLOBAL	6k	600M	≤0.01
	– ONBOARD CORRELATION	1k	X 1/12	-
	– DIRECT WAVE SPECTRA READOUT	50	1k	-
	ALT – DONE BY SAR, 10 cm	50	–	≤0.01
	– RAIN OR PRESSURE SENSOR ADDITION, 5k	200	10k	<0.5
	SPACECRAFT – ACCOMMODATING ALL ABOVE EXCEPT 2f SAR	4k	50k, 600k, 300M	≤0.1
	GROUND SYSTEM			
C	SENSORS – INCL. B' MODS – PREVIOUSLY FLOWN	4k	50k, 600k, 300M	≤0.1
	SPACECRAFT	4k	50k, 600k, 300M	≤0.1
C'	SENSORS – INCL. B' MODS – FIRST FLIGHT	4k	50k, 600k, 300M	≤0.1
	SPACECRAFT – FIRST FLIGHT WITH MODS	4k	50k, 600k, 300M	≤0.1
	– ON BOARD PROCESSOR FOR ALL DATA	4.5k	50k, 600k, 300M	≤0.1
	GROUND SYSTEM			
	PRESHUTTLE NEW SENSOR DEMONSTRATION/FREQUENCY EVALUATION	≤120	≤3M	~0.5
	OCEANOGRAPHIC LABORATORY – INCL DESIGN DATA AND DEMO. ON NEW SENSORS	~8k	~G	≤0.01

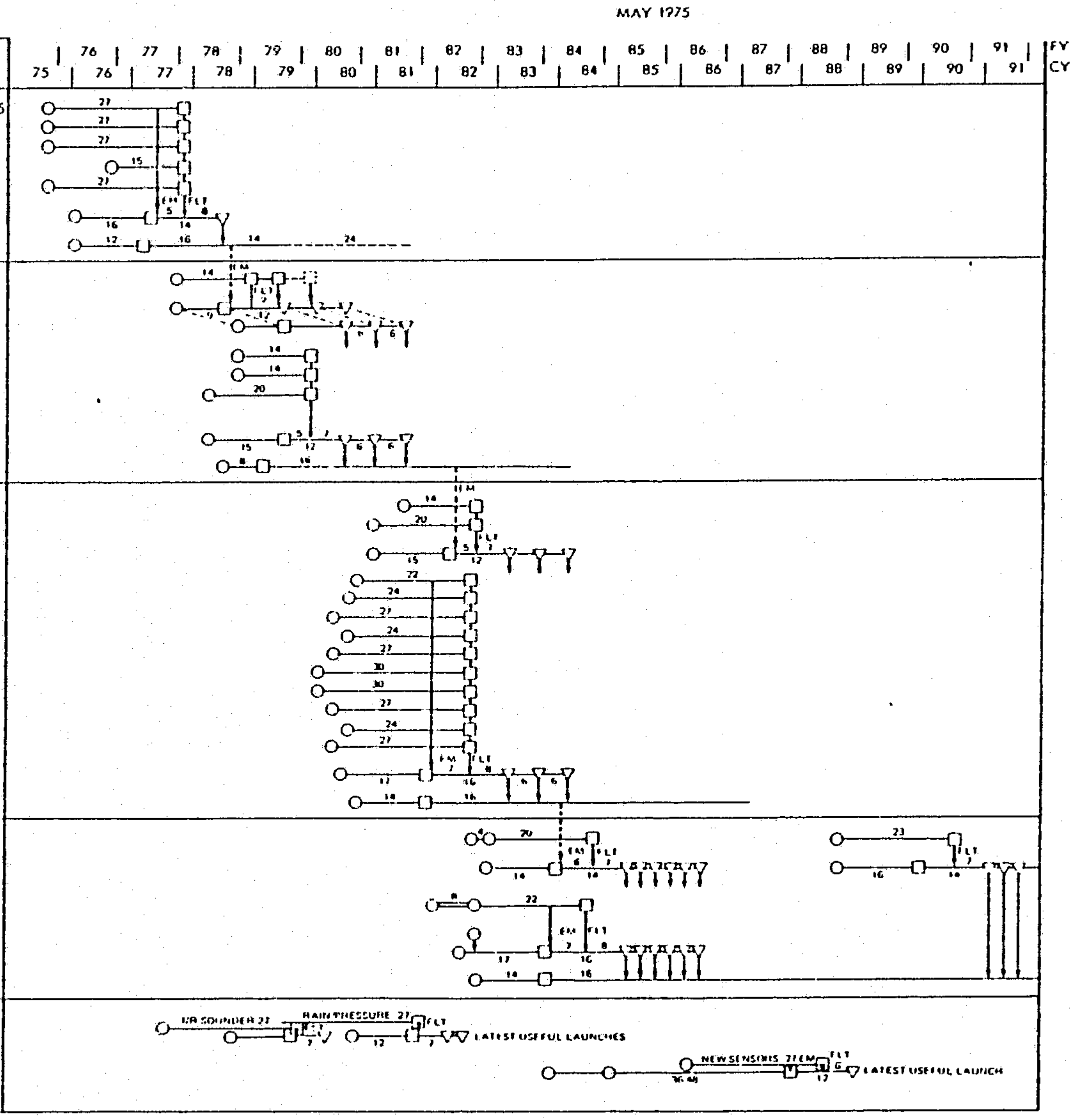

Figure 2.9 HYPOTHETICAL SEASAT SATELLITE PROGRAM
Ocean/Climate/Ice/Coastal Benefits

Range. It was assumed that the shuttle (plus an appropriate upper stage) will be capable of delivering three operational SEASAT spacecraft to orbit in a single flight. A launch cost of $10,000,000 was assumed for each shuttle flight.

2. Spacecraft Life

The early repeat launches of additional spacecraft in the SEASAT-A configuration will achieve a three year life. A six year life was assumed for the operational spacecraft.

3. Learning

A 90% learning curve was used. Included in the costs are the costs of science development, spacecraft development, launch costs, mission operation, integration and program management. Not included in the costs are STADAN/NASCOM costs, data analysis, and the costs of facility acquisition.

The elements of cost for the system alternatives are shown in Tables 2.13 and 2.14 for the systems options. All costs are in $1975. Those cost elements were then used to compute the cost stream and the Net Present Value of Benefits shown in Figure 1.1.

Table 13. COST ELEMENTS FOR SEASAT EVOLUTION DELAYED DEVELOPMENT

SEASAT A

	N/R	R#4	Total
Science	13.	4.	17
Spacecraft	17.	6.	23
Launch Vehicle	--	7.	7
Integration	2.	1.	3
Operations	6.	2.	8
Management	5.	1.	6
Total	43.	21.	64.

SEASAT A' Repeat

	N/R	R#2	R#3	R#4	Total
Science	2.6	3.6	3.3	3.1	12.6
Spacecraft	3.4	5.4	5.0	4.7	18.5
Launch Vehicle	--	7.0	7.0	7.0	21.0
Integration	1.0	0.5	0.4	0.3	2.2
Operations	3.0	1.0	1.0	1.0	6.0
Management	2.0	0.5	0.5	0.5	3.5
Total	12.0	18.0	17.2	16.6	63.8

SEASAT B

	N/R	R#5	R#6	R#7	Total
Science	2.6	3.0	2.9	2.9	11.4
Spacecraft	3.4	4.6	4.4	4.3	16.7
Launch Vehicle	--	7.0	7.0	7.0	21.0
Integration	0.5	0.3	0.3	0.3	1.4
Operations	2.0	1.0	0.5	0.5	4.0
Management	1.5	0.5	0.3	0.2	2.5
Total	10.	16.4	15.4	15.2	57.0

SEASAT B

	N/R	#1	#2	#3	#4	#5	#6	Total
Science	20.	4.0	3.6	3.3	3.1	3.0	2.9	39.9
Spacecraft	50.	10.0	9.0	8.3	7.8	7.5	7.3	99.9
Launch Vehicle	--	10.0	--	--	10.0	--	--	20.0
Integration	5.	2.0	2.0	1.5	1.5	1.0	1.0	14.0
Operations	4.	1.0	1.0	1.0	1.0	1.0	1.0	10.0
Management	7.	0.5	0.5	0.5	0.5	0.5	0.5	10.0
Total	86.	27.5	16.1	14.6	23.9	13.0	12.7	193.8

N/R = Non Recurring Cost

R# = Recurring Cost

Table 14. COST ELEMENTS FOR SEASAT EVOLUTION EARLY DEVELOPMENT

SEASAT A = Delayed Development Cost A

SEASAT A'

	N/R	R#1	R#2	R#3	Total
Science	16.	4.	3.6	3.3	26.9
Spacecraft	25.	7.	6.3	5.7	44.0
Launch Vehicles	--	7.	7.0	7.0	21.0
Integration	3.	1.	0.5	0.5	5.0
Operations	5.	1.	1.0	1.0	8.0
Management	6.	1.	0.5	0.5	8.0
Total	55.	21.	18.9	18.0	112.9

SEASAT B'

	N/R	R#1	R#2	R#3	Total
Science	20.	4.0	3.6	3.3	30.9
Spacecraft	50.	10.0	9.0	8.3	77.3
Launch Vehicles	--	10.0	--	--	10.0
Integration	5.	2.0	2.0	1.5	10.5
Operations	4.	1.0	1.0	1.0	7.0
Management	7.	0.5	0.5	0.5	8.5
Total	86.0	27.5	16.1	14.6	144.2

SEASAT C

	N/R	R#4	R#5	R#6	R#7	R#8	R#9	Total
Science	4.0	3.1	3.0	2.9	2.9	2.8	2.7	21.
Spacecraft	15.0	8.0	7.8	7.5	7.3	7.2	7.0	59.
Launch Vehicle	--	10.0	--	--	10.0	--	--	20.
Integration	3.0	1.5	1.0	1.0	0.5	0.5	0.5	8.
Operations	3.0	1.0	1.0	1.0	1.0	1.0	1.0	9.
Management	5.0	0.6	0.5	0.5	0.5	0.5	0.5	8.
Total	30.0	24.2	13.3	12.9	22.2	12.0	11.7	126.

N/R = Non Recurring Cost
R# = Recurring Cost

3. SIMULATION EXPERIMENTS TO QUANTIFY THE IMPACT OF SEASAT DATA ON SHORT-TERM WEATHER FORECASTING

3.1 Perspective on Weather and Climate Prediction in the Next Decade

When asked from where improvements in weather forecasting are most likely to come in the next decade, most meteorologists are likely to reply that they are probably to be found in the upgrading and further development of numerical models of the atmosphere. Although weather forecasting has not improved dramatically since the introduction of numerical models, there has been a constant drift in the direction of improved objective forecasting, and this trend is most likely to continue in the future. The new developments in these models should increase man's ability to forecast weather more accurately over the short range (6 hours to 5 days), the intermediate range (5 days to 2 weeks), and even the hitherto unreachable long range (2 weeks to a season). Coupled with this effort will be the emergence of new models designed to study climatic fluctuations and man's effect on them.

The improvement in numerical forecasting can best be understood through the study of the errors which cause the forecasts to fail even in the short range. These errors can be classified in three major groups, namely,

- misrepresentation of the physics,
- initialization error, and
- truncation error.

(1) The Physics

Atmospheric circulation involves interaction at many different spatial scales. Even global patterns are eventually influenced by such micro-meteorological phenomena as evaporation from the ground, cumulus convection, or snow-melt. It is, however, virtually impossible to include every feature of the atmosphere explicitly in a numerical model of the atmosphere. It is thus necessary to parameterize some of the phenomena as accurately as possible. A numerical model which has a grid resolution of several hundred kilometers must take into account such sub-scale phenomena as thunderstorms, fronts, sea breezes, and topographical effects, all of which are important to the general energy balance of the atmosphere. There are also phenomena which occur within the limits of the grid mesh which are not properly understood and their representation is in error. Large scale cloudiness and precipitation, tropical disturbances, air-sea interactions, and other large-scale boundary influences are complicated processes which are for the most part overly simplified in numerical models. To overcome this source of error requires scientific research efforts backed by sufficient empirical evidence for parameterization and verification.

(2) Initialization

No forecast can be made without good knowledge of current conditions. Thus, even if a perfect model of the atmosphere existed, it could not provide accurate forecasts without a precise initialization. The data that are available at present on a daily basis are both imbalanced and insufficient for the initial conditions required by almost all numerical models. This is because

(a) there are not enough observations taken over the globe, especially over the oceans, and

(b) the numerical schemes which solve the equations in the models are sensitive to the kind of data they can handle.

The lack of observations is due simply to the lack of meteorological observing stations in unpopulated areas. Even in regions of the world where surface data are available to some extent, like in shipping lanes, upper air data may be missing entirely. Even the data that are measured are influenced by many factors, many of them not contained in the numerical models because of grid size or some simplifying assumptions. Thus, the data must be tempered to the resolution and physics of the model before they can be utilized effectively. Otherwise the model will interpret the data incorrectly and produce spurious atmospheric phenomena, at best, or become unstable, at worst. To overcome these problems, more observations are required along with balancing schemes for each particular model in order to extract the useful portion of the data while insuring computational stability and reasonableness.

(3) Truncation

Coarse resolution in a numerical model is a source of error in both a mathematical and physical sense. Mathematically, errors are caused by the use of finite differences on a coarse grid to approximate the true derivative at a point. Physically, the errors are created by a failure to account for many processes which could affect the dynamics and energy balance in the atmosphere. In current models, a complete hurricane could fit snugly within a grid box. Other mesoscale phenomena, such as fronts, thunderstorms, tornadoes, sea breezes, and the like, will appear only as noise in the initial conditions and will probably be filtered out by the model. The same problem exists in the vertical, despite the generally assumed hydrostatic equilibrium which in effect makes the various levels in the model vertically independent. Yet terms may exist in the equations which require vertical derivatives, and a coarse vertical resolution will create significant truncation error. Also, the vertical profiles of many variables will be poorly represented in the analyses. To reduce these errors greater resolution is required through improved computer technology or through better parameterizations of the sub-scale phenomena which can be achieved through a better understanding of the underlying physical principles.

These three classes of errors affect long-range, and even climate, models of the atmosphere. The climate models, however, are less affected by the initialization error, but are highly sensitive to errors in physics.

The efforts in the next decade will be aimed at diminishing the above errors by a general program of research, data gathering, and technology improvements.

The Global Atmospheric Research Program (GARP) objectives are tied to this goal, as well, and it is hoped that with concentrated, international programs these objectives can be met.

A concept of the general flow of activity in the next decade is shown in Figure 3.1. The first thrust has been in the direction of decreasing initialization errors by improving the world observing network. The increased number of observations requires immediate solution of data management and initial balancing problems to be of any benefit. The increased data records can also be used in research as empirical information to eventually improve physical representations and as sources of verification data for weather and climate models.

Of all observing systems, satellites are probably the most promising because of their large coverage capabilities. By remote sensing, many areas of the oceans and continents will no longer be voids in the meteorological data network. The role of satellites in weather forecasting and climate studies is diagrammed in Figure 3.2 The various

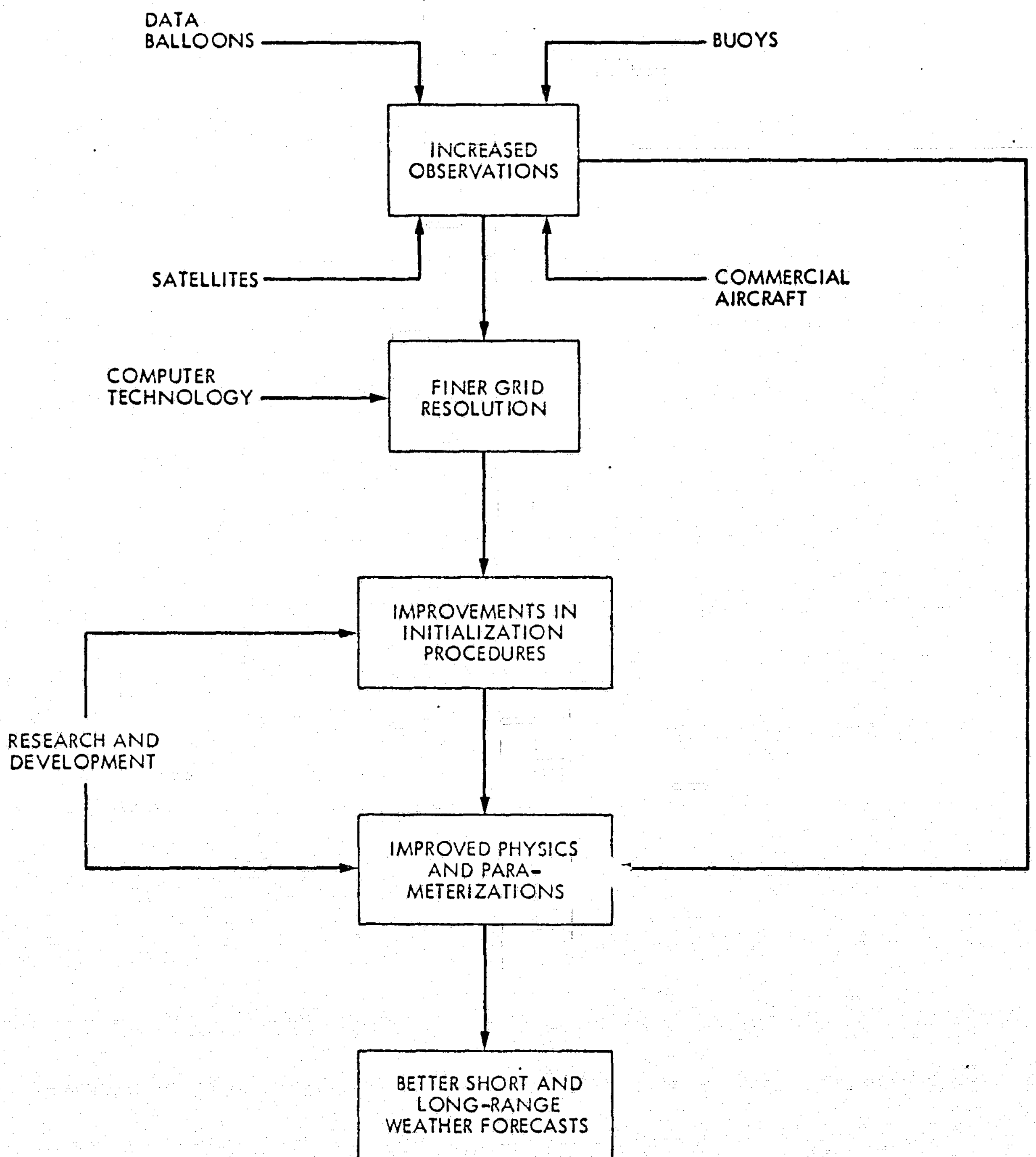

Figure 3.1 Flow Chart of Procedures for the Improvement of Weather Forecasts by 1985

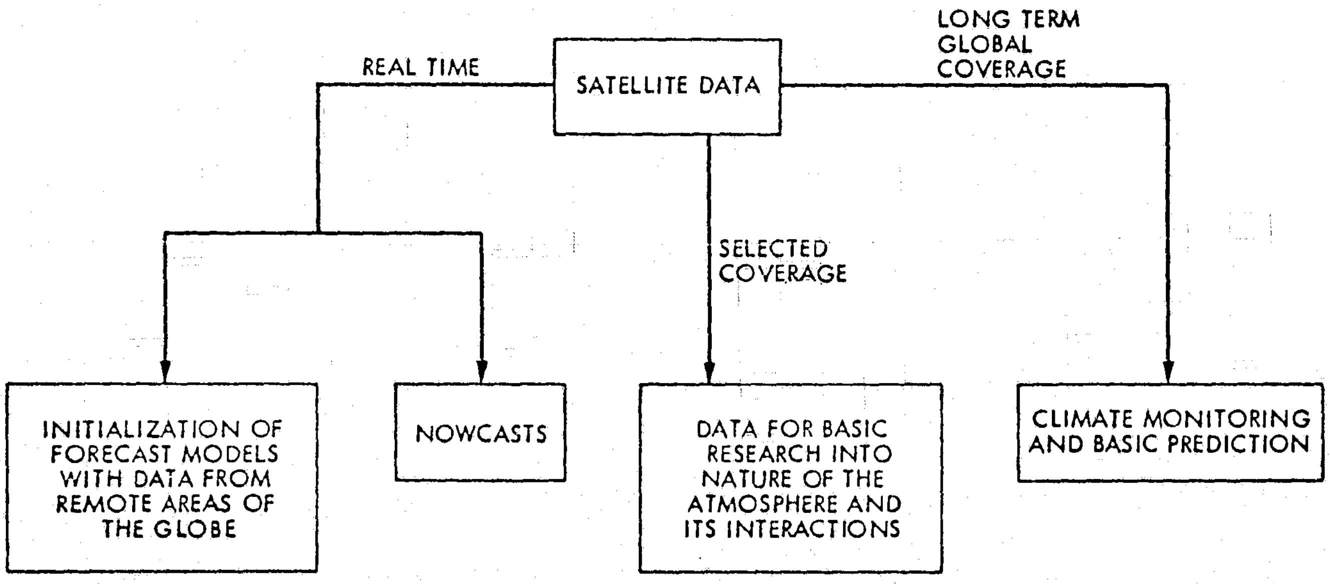

Figure 3.2 Diagrammatic Display of the Different Uses for Satellite Data, and Their Respective Processing-Time Requirements

time scales refer to the turn-around time between measurement and actual utilization of the data. Very short processing is required for real-time forecasting and nowcasting (i.e., simply knowing the present conditions), while longer processing time is permissable for research studies or climate prediction. Accuracy, however, is essential for the latter two purposes. Spatial and temporal resolution requirements will depend on the parameter to be measured from space and on its expected utilization.

SEASAT involves all three utilizations of satellite data. The satellites' capabilities to measure winds at the sea surface along with, possibly, temperature profiles can create useful update information for short-range forecasts. Wave forecasts will also be aided by measurements of sea state and wave spectra. Sea surface temperatures can be logged for long range and climate predictions. All of these data, of course, can also be used in studies involving air-sea interactions and ocean dynamics.

Although it is widely believed that measurements by SEASAT's scatterometer of surface winds is vital for numerical weather forecasting, there is no single accepted objective method for incorporating wind velocities into models of the atmosphere. Subjectively, winds over the oceans have been used to correct the pressure field in areas devoid of good pressure analyses. Yet, it is not clear how this process can be applied operationally to satellite-derived winds over the oceans. Nor is it clear what impact inserting these wind data into numerical models will have on the models' forecasts. The only practical way to determine an optimum method for wind assimilation and to weigh its impact, in the absence of real derived wind data prior to the launch of SEASAT, is through simulation experiments. These simulations can be carried out with the use of a current numerical general circulation model (GCM) of the atmosphere and generated, rather than observed, data. An optimum assimilation technique can be developed by comparing improvements in simulated forecasts using different techniques. Estimates of the usefulness of the data will then also be available.

3.2 Formulation of the SEASAT Simulation Plan

In order to obtain a concensus from the general meteorological community on the nature and benefits of simulation experiments to be performed for SEASAT, a special meeting was arranged in March 1975 at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The attendees included a fair cross-section of meteorologists engaged in both research and daily operations who had an interest in the uses of satellite data for initialization and forecasting. Organizations and institutions represented at this meeting included the City University of New York, ECON, the Goddard Institute for Space Sciences, the Jet Propulsion Laboratory, NASA, the National Weather Service, NDAA, The National Center for Atmospheric Research, Ocean Data Systems and the University of California at Los Angeles. After discussions on simulation experiments in general, a list of recommended experiments was drawn up. These experiments were segmented into three chronological divisions corresponding to the immediate, near and distant future.

The earlier experiments were to consist of "identical twin" experiments which means that only one model would be used to furnish both the simulated forecasts and the generated "real" data for verification and simulated satellite observations. Each of these experiments would be conducted using the equivalent of one satellite and then the equivalent of three SEASAT's to determine whether a system of multiple SEASAT's is much more advantageous than only one. The recommended experiments are as follows:

(1) First stage -

(a) Simple insertion of winds at lowest layer of the model - This experiment involves simply replacing forecast values of the winds near the surface by simulated observed data. The insertion can be done both synoptically or asynoptically with errors imposed on the data similar to the errors estimated for SEASAT.

(b) Adjustment of surface pressure - The winds here should be inserted with some comparable adjustment of sea-level pressure near the insertion site. At this point, this need not be a systematic fit of pressure and surface winds, but merely an estimated reduction of pressure error around the points of insertion.

(c) Inclusion of temperature profiles - To test whether temperature measuring instruments would be useful aboard SEASAT, an experiment simulating an insertion of both surface winds and temperature profiles should be conducted.

(d) Sea-level pressure and upper-air adjustment - By using both wind data and the measured temperature profiles, it should be possible to balance the surface pressure with the wind data and redefine the geopotential heights of the upper pressure levels assuming hydrostatic equilibrium.

(e) Satellites only - A simple test to ascertain whether complete coverage of the oceans could be left to satellites. This experiment would be performed by omitting all conventional observations on the oceans in the initial state and determining whether the continuous insertion of satellite data over a few days could result in a realistic field.

(2) Second stage -

(a) Improve methods for adjusting pressures - An objective method should be developed for reanalyzing sea level pressures based on surface wind measurements. This could be done locally if the wind data are provided asynoptically and over the entire domain if the data are synoptic.

(b) Various orbits for 3 satellites - If 3 satellites are to be used, then combinations of orbits should be tested to determine which configuration of orbits will provide optimum coverage.

(c) Include systematic errors - In describing the initial field and the simulated satellite data, realistic systematic errors should be incorporated to determine the effect of these errors on the forecast.

(d) Atmospheric sounder - Precise errors anticipated with atmospheric sounders presently under development should be specified in the simulations involving insertions of temperature profiles.

(e) Define areas of moist adiabat - Experiments should simulate the use of available information on cloud cover and temperatures to define areas where the temperature profile below the clouds are moist adiabatic. This would allow inclusion of temperature profiles in areas which are otherwise not directly measurable by satellite because of the interfering cloud cover.

(f) Dynamic balancing - Improvements of the insertion techniques should be attempted. Asynoptic data to be inserted should first be balanced and filtered similar to initialization procedures.

(3) Third stage -

(a) Non-identical twin experiments - The simulations should be repeated using a different model to produce the verification fields and satellite observations. This would prevent the optimistic bias that results from using a single model.

(b) Local feature comparisons - Impacts made by SEASAT on local or meso-scale forecasting should be evaluated. Some of SEASAT's data could be of more use to coastal areas, for instance, than to inland areas.

(c) Average statistics - An evaluation of SEASAT's performance should be made by studying the long-term statistics such as atmospheric energetics and how they are affected by SEASAT data.

(d) Real data - Attempts should be made to do real data tests, although great difficulties will be encountered in trying to obtain sufficient observations to make the experiment feasible. A detailed search of ships' logs and marine records from other nations would be necessary, while interpolation to areas and times devoid of data will also be required.

It was recommended that these experiments be conducted for various synoptic situations so that generalized conclusions can be made.

Initial investigations of the simulations recommended for the first stage were made at JPL and GISS during FY'75. During August, 1975, the group that developed the above experiment plan met again at the Geophysics Fluid Dynamics Laboratory of NOAA at Princeton, New Jersey, to review the results to that date. The following three sections present a summary of these experiments and the outlook for future experiments as of August 1975.

3.3 Modeling at JPL

A limited two-dimensional model of the atmosphere has been under development at JPL to help in the study of model responses to the insertion of SEASAT data. Results from this simplified model could serve as a guide to the simulation experiments to be carried out at GISS. The fact that the model at JPL is only two-dimensional, i.e., changes occur only in the vertical (z) and East-West (x) direction, allows for greater economy in running the model for long periods of simulated time. The model can then be used for long-term assimilations to test the effectiveness of SEASAT data and a number of schemes designed to adjust and balance the surrounding pressure and temperature fields to the winds. Although conclusions reached with the simple model are not necessarily indicative of the large model's reaction, the results produced by the limited model could at least indicate the direction which the simulations should be headed.

A first version of the model was completed and tested around the end of 1974. It consisted of a staggered grid with 10 pressure levels in the atmosphere and one at the surface. The horizontal grid stretched only in the x-direction, all changes in the North-South (y) direction were fixed for all time. Surface pressure was also held constant at 1,000 mb. There were equations for the prediction of the horizontal wind velocity coordinates (u and v) and one for the prediction of temperature (T). The geopotential heights of the layers above the surface were calculated diagnostically with the hydrostatic equation. At the surface, assumed to be ocean throughout, the temperature remained constant for all time, while the drag on the wind was computed as a function of the magnitude of the wind vector. The model was dry, i.e., no moisture was computed in the atmosphere, but convective adjustments took place to prevent superadiabatic lapse rates.

Experiments with this and all other models consist of three major computer runs. The first serves as the real world and will be referred to as "nature." It is used to produce the verification fields and the simulated satellite data. The second run is a "control" run which consists of all the input information except for SEASAT data. The initial conditions would, however, be changed from nature's initial conditions so that the "forecast" created by the control run would be significantly different from nature. The third run would involve adding SEASAT data to the input information included in the control and noting the change produced in the forecasts. If there is a noticeable shift in the forecast in the direction of nature, then it can be concluded that SEASAT data do contribute beneficially to the forecast. If there is no favorable impact, then the SEASAT data, as assimilated by the model, are not constructive in producing better forecasts. In order to compare the various forecasts fields, both objective and subjective techniques can be implemented. The objective method employs a statistical indicator of the correlation of the forecast field to the nature field. Such indicators include absolute errors, root mean square (rms) errors, correlation coefficients, and variances. Subjectively, one can evaluate the forecasts by comparing surface and upper air maps and noting the differences, if any, in the synoptic-scale pressure systems and their attendant wind and temperature distribution.

In the first experiment with the JPL model, rms errors were evaluated for the control and SEASAT forecasts for all variables every three hours. For the SEASAT run various combinations of wind and temperature data were inserted. Some runs were made with simple insertions of wind velocities near the surface, while other runs were made with combined wind and temperature profile data. SEASAT data were assumed perfect for these experiments, the only possible error arising from interpolation of some of the data to the assumed position of the satellite in space and time. Unfortunately, the experiment failed mainly because the control run failed to show any significant growth of rms error near the surface.

During the first few hours, the errors actually decreased, then stabilized for most of the 48-hour run. The SEASAT data could hardly be expected to show any realistic benefit on a field of self-improving variables. What did occur was that immediately following the time of an insertion, errors at the grid point of the insertions and in neighboring points quickly declined, but soon rose to approximately the same level as the control. The only exception occurred when temperature profiles were inserted. Here, the upper-air temperature errors declined and stayed fairly below the control errors for the entire 48-hour period. These results seemed to be completely independent of whether winds had been inserted near the surface or not. Thus two factors contributed to the failure of the experiments. First, the initialization procedure used only random errors which were easily filtered by the model itself (even as the GISS model did, as shall be described in the next section), and, second, the fixed surface pressure forced the other fields, especially the wind field, back into the configuration of nature.

Further experimentation with this first version was thus abandoned in order to upgrade the model and make it more responsive to wind data near the surface. Attempts were and are being made to predict surface pressure rather than holding it constant. At present, the pressure tendency equation is being used to forecast the pressure. This equation relates the change of pressure near the surface to the column integral of mass divergence. In pressure coordinates this equation has a rather simple form, provided the vertical velocity is fixed at a given boundary. Unfortunately, the model has not yet been stabilized so that after approximately three hours of simulated time, the computations become invalid. These instabilities may be a result of the numerical scheme or of some physical inconsistency. Instead of compensating for large pressure gradients, the winds seem to enhance them by lining up in full column divergences or convergences. Once the instability is brought under control, further experimentation will be attempted with the JPL model.

3.4 Experiments at GISS

Three experiments were performed with the nine-level model at GISS designed to test the impact of SEASAT wind data on a simulated forecast. The first two were simple sensitivity tests to observe the response of the model to an altered wind-field. The third experiment was a long-term assimilation of wind data along with synoptic updates of pressure and asynoptic updates of temperature. The format of these experiments was similar to those at JPL, where a nature run was produced by integration of the model for several days and a control run was made by integration of the model for several days and a control run was made by perturbing the initial conditions with random error. The SEASAT runs were made by substituting simulated SEASAT-observed winds for the computed wind-field at the lowest level over the oceans (commonly referred to as "level 9" of the model, at approximately 950 mb).

In the first two experiments it was tacitly assumed that the SEASAT network could cover the entire ocean in near-synoptic time. As such, the wind data were inserted into the initial conditions at every point in the oceans. This meant reducing the initial random error of the level-9 winds to SEASAT specifications with a magnitude of 2 m sec^{-1} and an ambiguity in direction of $\pm$ 15°. The initial errors over the oceans for the control run were of the order of 8 m sec^{-1} for each velocity component. Again, because the initial errors were random and not systematic, the model was able to filter out many of the initial errors so that the error level dropped for the first few hours. In fact, after about 1 1/2 days, many errors were half their original values. The reduction of initial error in the SEASAT run accomplished very little, because the lower errors remained about the same or even increased until they were at the same level as the control. Table 3.1 indicates this trend for the surface pressure, level-9 zonal winds, vertically averaged zonal winds, and vertically averaged temperatures for various land and ocean areas. Note how all errors rapidly drop after the initial conditions, due to the large-scale adjustment process. The SEASAT wind errors, on the other hand, increase so that after a quarter to half a day they are equivalent to the control winds. The pressures

Table 3.1 RMS Errors from Day 1 to Day 3 for Surface Pressure (PS), 950 mb Winds (U9), Vertically Averaged Winds ($\bar{U}$), and Vertical Mean Temperature ($\bar{T}$), for the Control Run (C) and The SEASAT Run (S), Averaged Over a) Eastern and Western Hemisphere Land Areas and b) the Atlantic and Pacific Oceans.

	Eastern Hemisphere								Western Hemisphere							
(a) Day	PS (mb)		U9 (m sec^{-1})		$\bar{U}$ (m sec^{-1})		$\bar{T}$ (°C)		PS		U9		$\bar{U}$		$\bar{T}$	
	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S
1.00	1.97	1.97	4.00	4.00	3.96	3.96	1.40	1.40	2.06	2.06	3.89	3.89	3.80	3.80	1.37	1.37
1.25	1.86	1.73	2.15	2.09	3.57	3.55	1.37	1.37	1.89	1.88	2.19	2.22	3.53	3.53	1.39	1.38
1.50	1.34	1.30	1.85	1.80	3.45	3.43	1.35	1.35	1.72	1.65	1.93	1.94	3.33	3.33	1.36	1.36
1.75	1.55	1.52	1.76	1.74	3.30	3.30	1.35	1.35	1.31	1.26	2.04	2.04	3.37	3.37	1.40	1.40
2.00	1.35	1.39	1.64	1.59	3.19	3.18	1.38	1.38	1.80	1.77	1.60	1.56	3.20	3.19	1.46	1.46
2.25	1.38	1.23	1.57	1.52	3.15	3.17	1.36	1.36	1.44	1.40	1.72	1.72	3.29	3.26	1.52	1.52
2.50	1.24	1.23	1.59	1.56	3.14	3.13	1.43	1.42	1.66	1.63	1.96	1.93	3.41	3.40	1.56	1.54
2.75	1.27	1.26	1.59	1.56	3.18	3.15	1.44	1.42	1.81	1.73	2.10	1.99	3.57	3.51	1.68	1.66
3.00	1.34	1.30	1.63	1.57	3.25	3.23	1.51	1.48	2.12	2.25	2.19	2.16	3.75	3.73	1.85	1.83

	Atlantic								Pacific							
(b) Day	PS		U9		$\bar{U}$		$\bar{T}$		PS		U9		$\bar{U}$		$\bar{T}$	
	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S
1.00	3.54	3.54	7.76	2.18	7.10	6.48	2.48	2.48	5.88	5.88	11.20	3.49	10.80	10.00	3.80	3.80
1.25	2.73	2.48	3.07	3.00	5.77	5.73	2.03	2.02	3.72	3.57	5.39	5.11	9.10	9.02	2.93	2.91
1.50	2.24	2.17	3.59	3.43	5.39	5.38	1.87	1.87	3.13	3.06	5.09	4.70	8.37	8.28	2.83	2.82
1.75	2.02	1.96	2.97	2.82	4.95	4.96	1.77	1.77	2.85	2.79	4.56	4.40	7.92	7.88	2.77	2.74
2.00	1.98	1.96	2.68	2.82	4.68	4.71	1.77	1.76	3.00	2.97	4.03	3.96	7.41	7.40	2.82	2.76
2.25	2.23	2.20	3.29	3.45	4.70	4.75	1.82	1.80	2.76	2.74	4.43	4.20	7.18	7.14	2.84	2.82
2.50	2.25	2.13	3.26	3.22	4.62	4.66	1.84	1.83	2.90	2.82	3.90	3.63	7.17	7.11	2.90	2.91
2.75	2.43	2.34	2.89	2.89	4.37	4.41	1.92	1.89	3.15	3.11	4.51	4.32	7.09	7.05	2.87	2.87
3.00	2.41	2.34	2.85	2.90	4.39	4.44	1.98	1.95	3.49	3.46	4.99	4.77	7.33	7.24	2.94	2.93

and temperatures do not seem to respond at all to the inserted winds as can be seen by comparing the error levels of the SEASAT and control winds over land and sea. Note that the initial errors over the oceans were made substantially higher than the land errors. It is not clear, however, why the errors over the Pacific are so much greater than the respective errors over the Atlantic, since both oceans were treated alike.

In order to overcome the problem of the filtering effect on random errors, another experiment was conducted where the initial conditions were taken from the control forecast of day 2.5. That is to say, the lower SEASAT errors were inserted over the oceans at a point where most of the initial error had been filtered out and the errors were beginning to rise once more. The rms errors of level-9 winds at day 2.5 were still higher than the 2 m sec^{-1} assumed for SEASAT as can be seen in Table 3.1 (b). Thus, if SEASAT winds do have an impact on forecasts, a lower error should be noted after reduction of the errors at day 2.5. Table 3.2 shows the results for the SEASAT run after only 12 hours which can be compared to the control case errors found in Table 3.1 at day 3. The errors are approximately equal for all variables, including the level-9 winds, indicating that the model is insensitive in the insertion of low-level winds alone.

The third experiment was geared to determine whether a long term assimilation of wind data and temperature profiles together with pressure updates would result in a beneficial impact. This time, pressure was updated every 12 hours

Table 3.2 RMS Errors at Day 3 for Various Regions After Reducing 950 mb Wind Errors at 2.5 to SEASAT Specifications

	PS	U9	$\bar{U}$	$\bar{T}$
E. Hemisphere	1.31	1.59	3.24	1.50
W. Hemisphere	2.29	2.08	3.74	1.84
Atlantic Ocean	2.25	2.83	4.36	1.97
Pacific Ocean	3.33	4.77	7.29	2.93

with a random error of ±3 mb over the oceans and ±1 over land. The temperature profiles were inserted commensurate with the orbital pattern of 2 polar-orbiting satellites. The error was assumed to be 2°C for the entire profile. Parameters which were not updated by simulated observations were left at their forecast values. This procedure was continued for 21 days. During the SEASAT run, wind data were also inserted synoptically every 12 hours at level-9 with the prescribed SEASAT error. The differences between the control and SEASAT runs for various land and ocean areas are given at 12 1/2 days in Table 3.3. The greatest impact of SEASAT data can be located in the Eastern Hemisphere, especially in Europe where the errors are from 30-40 percent lower when SEASAT data were used. The impact over the Western Hemisphere is much more limited.

Table 3.3 RMS Errors for Control and SEASAT Runs After 12.5 Days of Insertions of Temperature Profiles, Updating of Pressure Analysis, and for the SEASAT Run, Updating of Level-9 Winds.

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		REGION	Surf.	Pres.	U9		$\bar{U}$		V9		$\bar{V}$		$\bar{T}$	
			Cont.	Seasat	Cont.	Seasat	Cont.	Seasat	Cont.	Seasat	Cont.	Seasat	Cont.	Seasat
Land	-46--6 290-335	AUSTRALIA	2.73 mb	1.74	2.97	2.96	5.85	5.30	2.65	3.42	5.63	5.54	1.99	1.87
Land	-54--10 95-150	S. AMERICA	1.85	1.71	4.08	3.85	7.36	6.88	3.67	3.45	6.99	7.22	1.96	2.00
Land	30-86 0-165	W. HEMISPHERE	1.66	1.37	3.03	2.80	4.32	4.09	3.03	2.69	4.24	4.11	1.84	1.74
Land	30-86 165-355	E. HEMISPHERE	2.48	1.62	3.63	2.60	5.56	4.46	3.39	2.55	5.27	4.44	2.03	1.79
Water	30-86 80-175	ATLANTIC OCEAN	2.20	1.33	3.56	2.96	4.71	3.85	3.22	2.56	4.51	4.14	1.91	1.73
Water	30-86 275-420	PACIFIC OCEAN	3.31	2.95	5.37	4.80	7.22	6.73	5.34	4.66	7.41	6.70	3.02	2.62
Land	-26-+26 0-355	TROPICAL BELT	2.01	1.70	3.85	3.67	8.25	8.21	3.61	3.54	8.32	8.19	2.01	2.02
Water	-2-+26 0-355	TROPICAL BELT	2.14	2.04	3.87	3.73	7.61	7.65	3.86	3.71	7.59	7.50	2.02	1.96
Land	34-70 170-220	EUROPE	3.56	1.94	4.39	2.56	6.35	3.95	3.47	2.84	5.36	3.77	2.01	1.81
Land	30-54 50-105	U.S.	1.53	1.33	3.00	3.25	4.73	4.71	3.25	3.04	4.67	4.57	1.82	1.71

Errors in the Pacific are again higher than in the Atlantic and the impact seems to be greater in the Pacific for that reason. Why these differences occur among the various land and ocean regions is unclear since the only distinctions made were between land and water without regard to geographical location. Figures 3.3 a-c show the pressure analysis at the surface after 12 1/2 days for nature, the control run, and

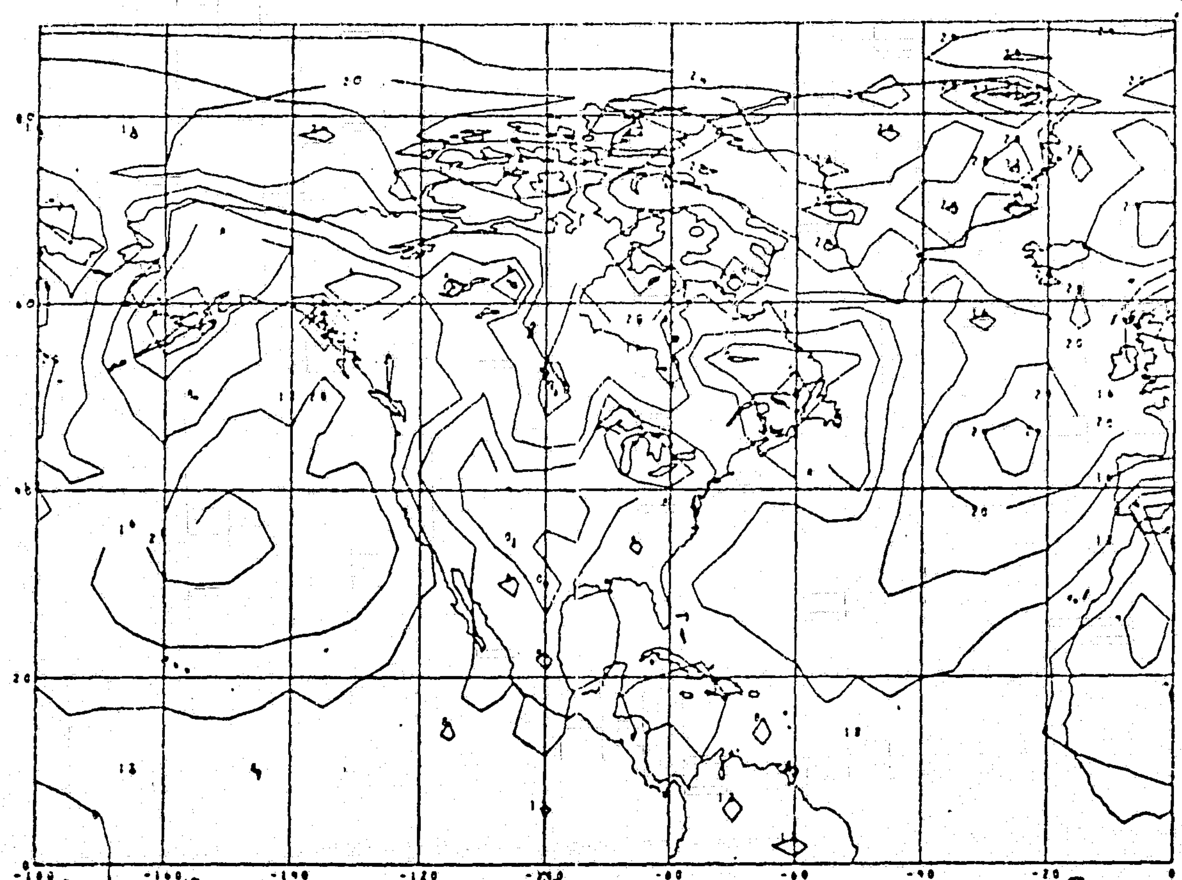

Figure 3.3a Surface Pressure Analysis for the Western Hemisphere after 12.5 days for Nature

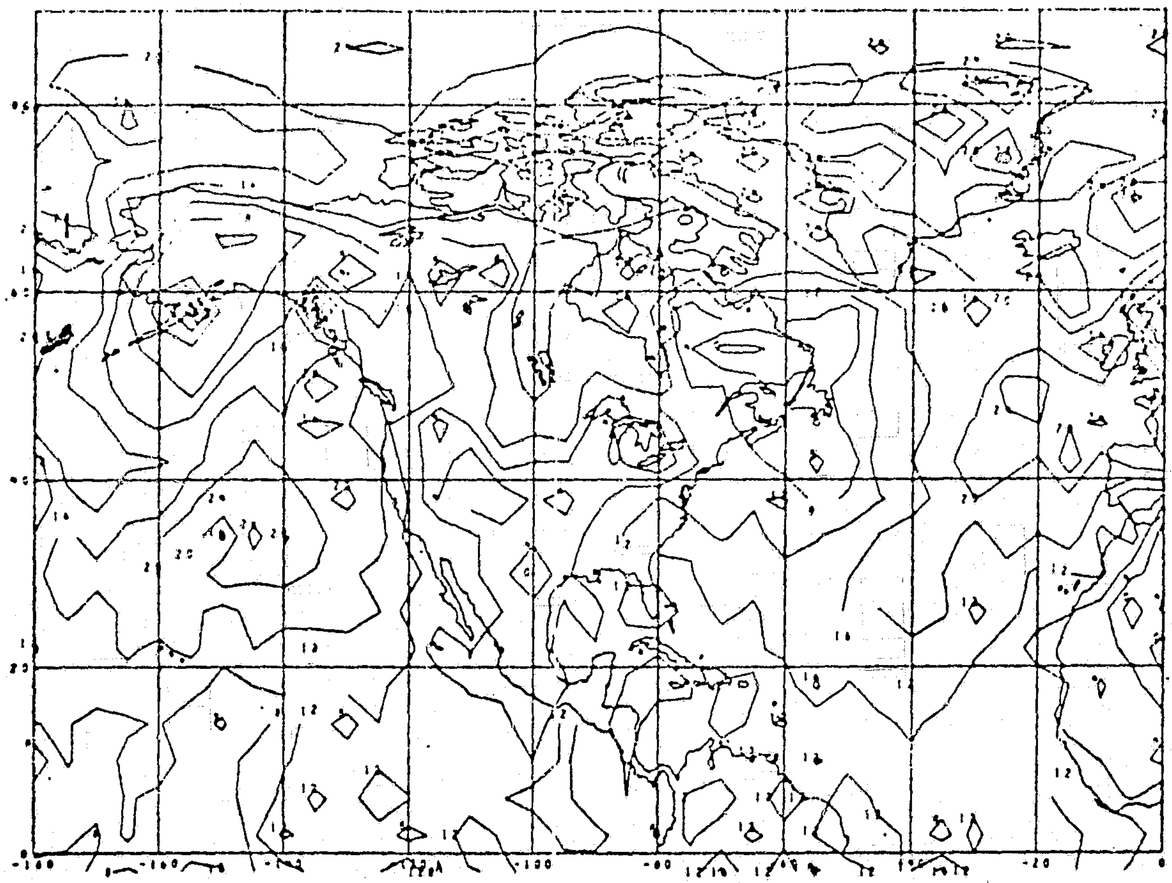

Figure 3.3b Surface Pressure Analysis for the Western Hemisphere after 12.5 days for the Control

the SEASAT run, respectively. In addition, the corresponding 500 mb geopotential height charts are included for completeness (Figures 3.4 a-c). Some differences in the maps are noticeable, but they are of a rather random nature. They all seem to depict the same major pressure systems in the same basic geographic regions, but perhaps with different orientations or contours.

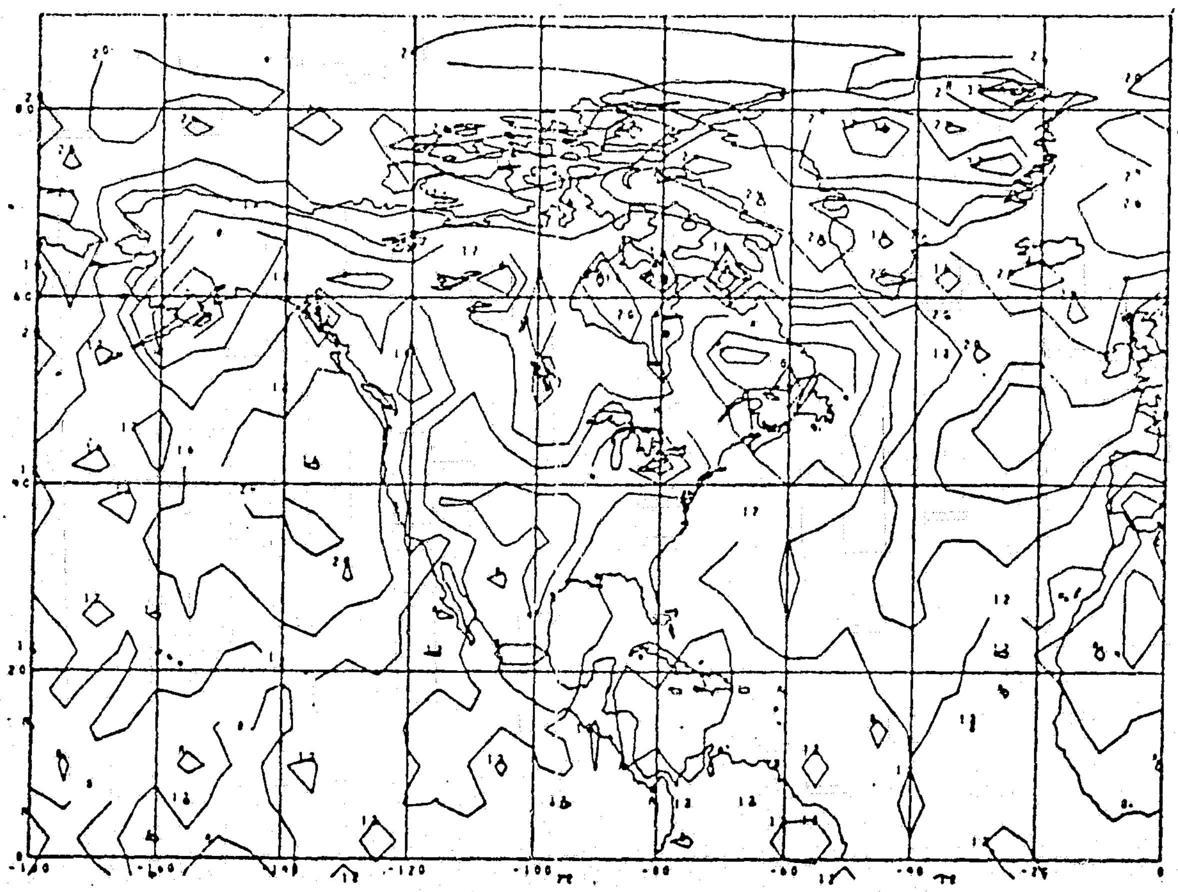

Figure 3.3c Surface Pressure Analysis for the Western Hemisphere after 12.5 days for the SEASAT Runs

Although this experiment does seem to indicate a positive impact caused by the long-term assimilation of surface wind data and temperature profiles, some aspects of the experiment are open to criticism The updating of pressures every 12 hours was done to simulate the real-world situation where synoptic reports are used to create new analyses twice daily. The errors assumed in the analysis

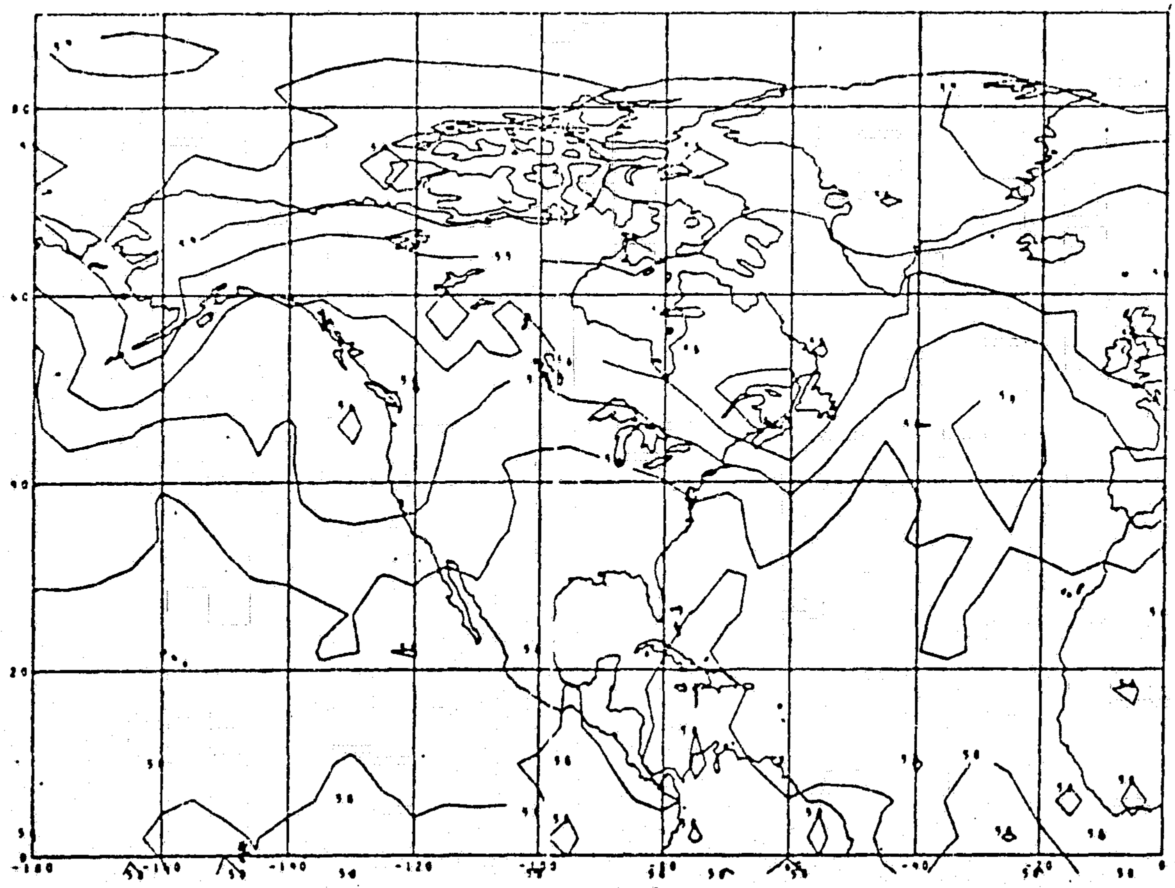

Figure 3.4a 500 mb Pressure Analysis for the Western Hemisphere after 12.5 days for Nature

were of the estimated order of errors in real-world analysis. However, the errors here were also generated as uniform random errors which were again successfully filtered by the model and the errors dropped significantly for the first few hours. After 12 hours, the errors were still below their initial value of 3 mb, although they had begun to grow before the 12th hour had been reached. The update thus substituted

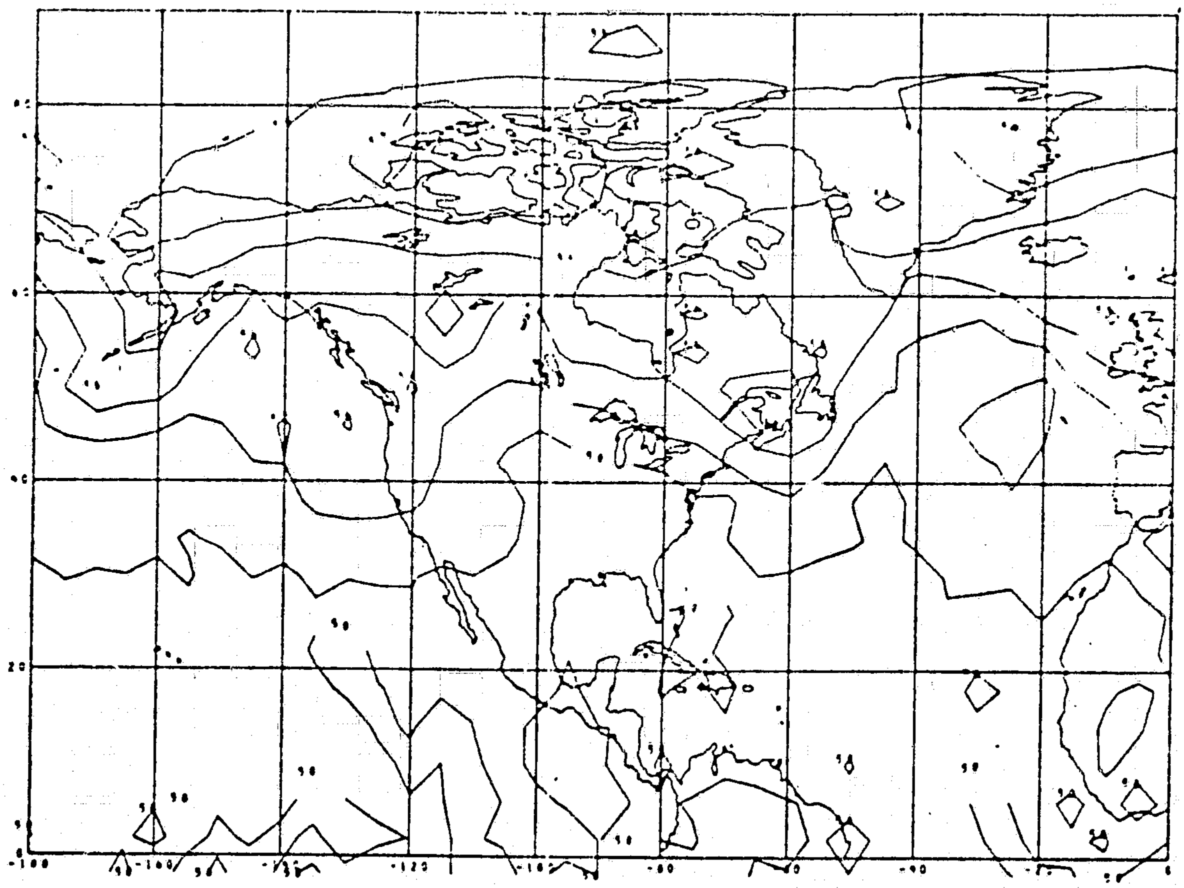

Figure 3.4b 500 mb Pressure Analysis for the Western Hemisphere after 12.5 days for the Control

worse "observed" data for better computed data. Such an occurrence is virtually impossible in the real world where the errors are more systematic and grow immediately. A better experiment would have been to use a smaller error or to update the pressure only once every 24 hours instead of every 12.

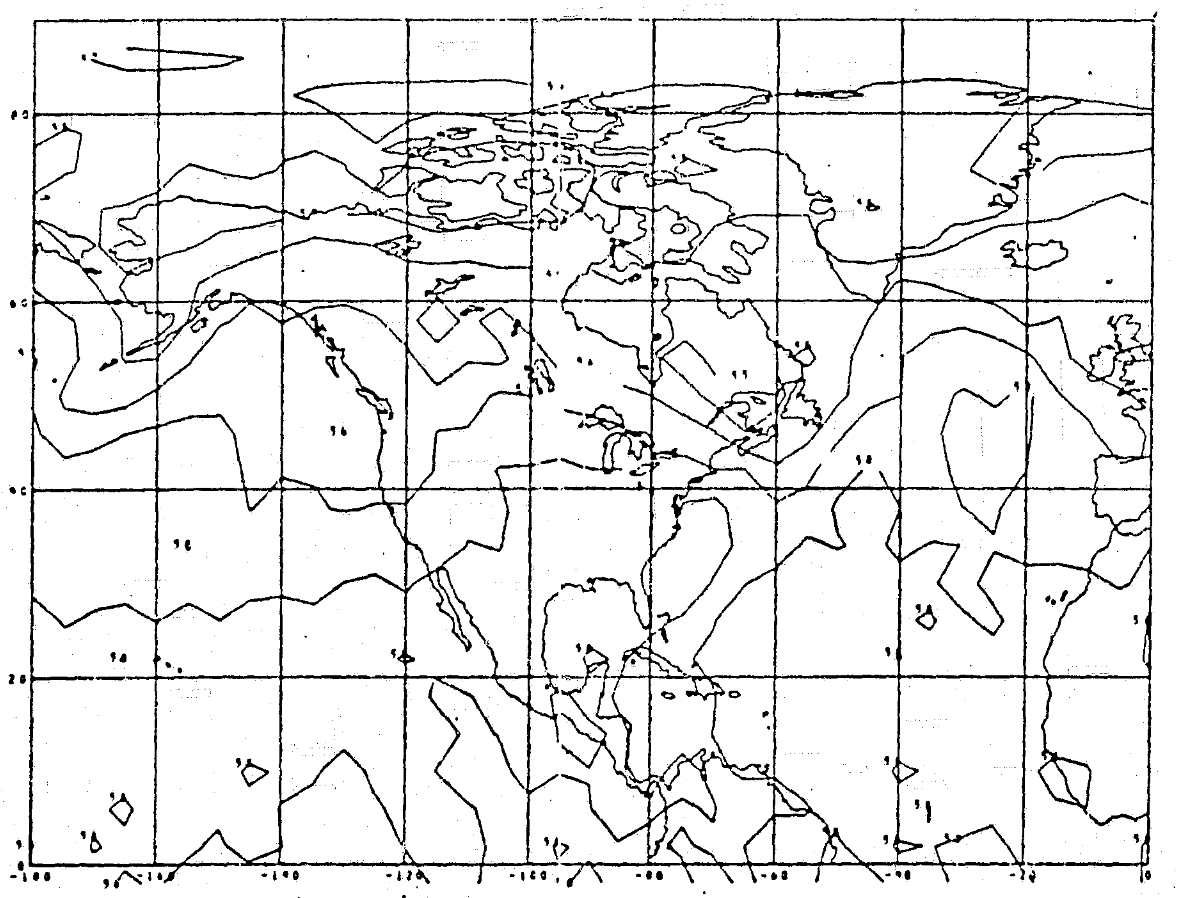

Figure 3.4c 500 mb Pressure Analysis for the Western Hemisphere after 12.5 days for the SEASAT Runs

3.5 Future Experimentation

The experiments performed to date suffer major shortcomings which render them generally inconclusive. It has become obvious, however, that in order to conduct a more meaningful simulation experiment, there is a need to improve the initial error distribution and to devise a more meaningful assimilation scheme for the winds. The random errors used in initializing the field of variables are of little value, if they are rapidly reduced by the numerics of the model. An assimilation scheme is required because the mere insertion of winds apparently will have no effect even on a short-term basis.

One way of systemizing the errors in a realistic fashion would be to imitate the operational methods for analysis updates. This would involve starting with a field of random errors as in the previous experiments. After about 12 hours, the variable fields should be updated but only by assuming a realistic distribution of data. This requires that surface data be applied uniformly over civilized land areas, spottily over well-travelled ocean areas, and very sparsely in untravelled ocean regions. Upper air information should be "available" only in areas where radiosonde stations are located and in the air corridors at 200-300 mb. In all other regions the predicted values should remain while a smoothing operator is used to spread the effect of the observed values to other grid points. This procedure should be repeated every 12 hours for approximately 2 to 3 days and should result in a realistic initial error for the control of SEASAT runs. SEASAT data could be used in conjunction with continued 12-hourly updates to determine whether they have any effect in decreasing the analysis error after a few days and whether a lower analysis error leads to a better forecast.

But inserting wind data alone will not be sufficient, as was demonstrated by the first two experiments, unless the pressure and/or upper wind fields are adjusted to the low-level winds, as suggested by the NCAR group. Subjectively, winds are used operationally to redefine pressure gradients, especially in areas devoid of good pressure readings. This is done by assuming some inflow angle towards low pressure and a relationship between the velocity magnitude and the pressure gradient. The new pressure gradients are then linked by eye to more reliable pressure contours. An objective scheme would probably be similar to this subjective method. It should make use of some boundary layer model designed to provide relationships among the surface winds, the inflow angle, and the pressure gradient. Satellite observation of the local surface winds could then be used to compute the magnitude and direction of the pressure gradient. This must then be anchored to some known pressure values and smoothed into the surrounding fields. If simultaneous temperature profile measurements are also available, it would then be possible to correct the heights of upper pressure surfaces which, upon mutual adjustment of the surrounding height field, will have a direct effect on the upper-level winds.

If positive conclusions can be drawn from simulations using these methods, a great deal will have been done to accomplish the goals set forth by the NCAR group. Indeed, the entire first stage plus the beginning of the second stage involve the perfection of a wind assimilation technique and its relationship to the other variable fields. When a proper technique is developed through simulation experiments, real data can be used in an initial test to determine whether the model can indeed become operational.