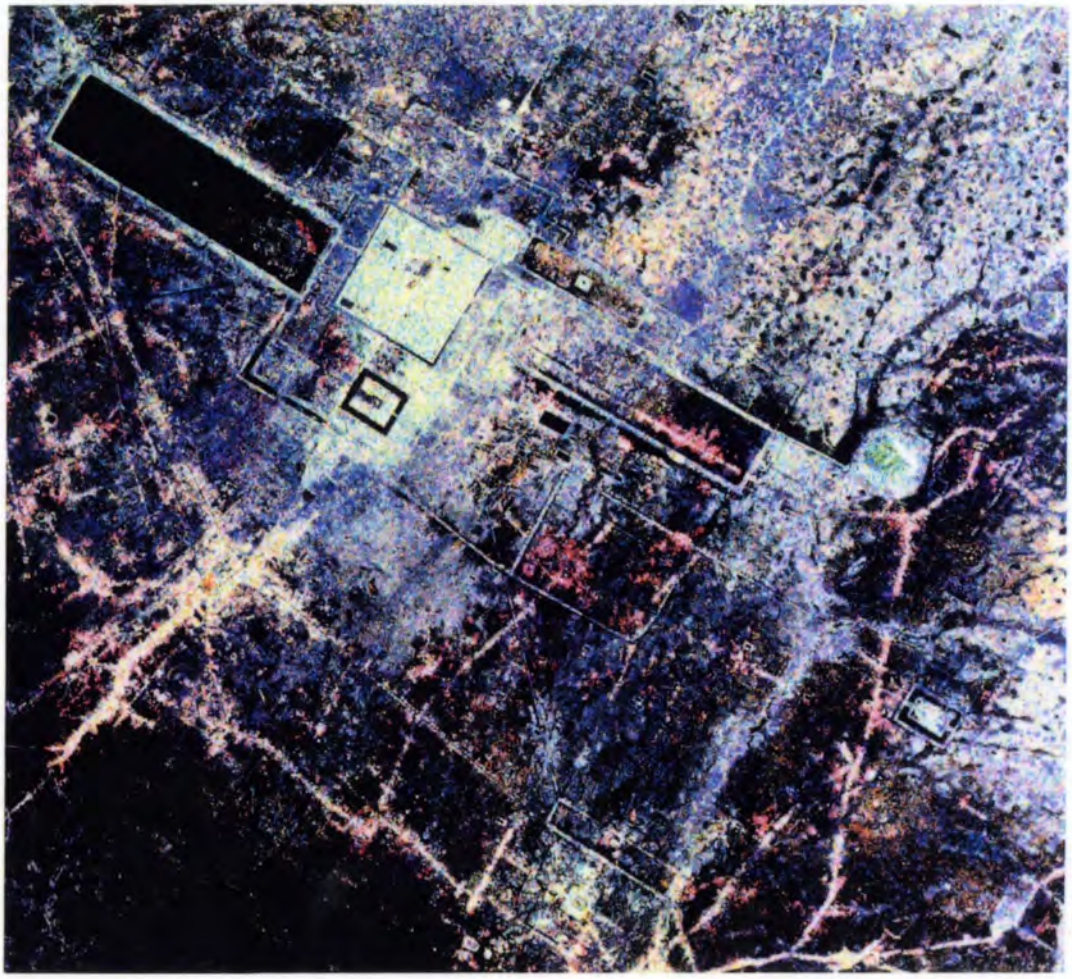
RADAR IMAGING SURVEY OF THE ANGKOR ECO-SITE

Report of the First Scientific Roundtable



WORLD MONUMENTS FUND
ROYAL ANGKOR FOUNDATION

RADAR IMAGING SURVEY OF THE ANGKOR ECO-SITE

REPORT OF THE FIRST SCIENTIFIC ROUNDTABLE

Princeton, New Jersey

February 1-2, 1995

WORLD MONUMENTS FUND
ROYAL ANGKOR FOUNDATION

New York
March 1995

ISBN

Cover and frontispiece: SIR-C/X-SAR radar image of the Angkor Eco-site taken by the Space Shuttle *Endeavour* on October 4, 1995.

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CONFERENCE RATIONAL

The World Monuments Fund, together with the Royal Angkor Foundation, conducted the first scientific roundtable on its Radar Imaging Survey of the Angkor Eco-Site at Princeton University in Princeton, New Jersey on February 1-2, 1995. The purpose was to assess the data collected by the National Aeronautics and Space Administration (NASA) space shuttle *Endeavour* during its April and October 1994 missions and determine the criteria for analyzing the information provided. Using NASA's SIR-C/X-SAR Earth Imaging Radar system, the *Endeavour* collected images of specific archaeological and ecological sites in Cambodia to assist in the documentation and analysis of the Historic City of Angkor in response to a proposal submitted jointly by WMF and RAF, as formalized on July 15, 1994. (See Appendix C)

The roundtable offered a rare opportunity for specialists in archaeological and ecological fieldwork to join forces with scientists in outer space-based radar imaging research to learn how state-of-the-art technology might aid in the pursuit of the knowledge of our past. NASA's Jet Propulsion Laboratory (JPL) was eager to assist the WMF and RAF in the analysis of the *Endeavour*'s radar imaging of Angkor, and the J.M. Kaplan Fund was an enthusiastic backer of this synergistic effort.

The roundtable was organized to be the first general meeting of the international project team to determine the criteria and establish a detailed program for analyzing the information provided by NASA. Participants would be asked to discuss the potential of the research possibilities afforded by the availability of this new technology and develop a list of objectives for the overall research project. Following this, a plan of action was to be organized, with the intent to engage other researchers and address possible future collaborations with NASA on the subjects of cultural heritage conservation, historic eco-systems, and archaeology. The conference was arranged to serve as a significant advancement in an ongoing dialogue between NASA and archaeologists and other researchers with regard to new possibilities in both archaeological research and site conservation.

The roundtable results, as published in this report, will be presented at a meeting of the International Coordinating Committee on the Safeguarding and Development of the Historic Site of Angkor (ICC) scheduled for late March 1995 in Phnom Penh, Cambodia.

ACKNOWLEDGMENTS

The World Monuments Fund (WMF) and the Royal Angkor Foundation (RAF) would like to acknowledge the J.M. Kaplan Fund, whose generous financial support from its *Exploration and New Technologies Program* made this conference possible. Special gratitude is extended to Peter Davidson and Henry Ng of the J.M. Kaplan Fund for their keen interest in this effort and their important backing.

Deep appreciation is offered to NASA's Jet Propulsion Laboratory, Pasadena, California for their agreement to conduct the first spaceborne radar imaging of Angkor. The responsiveness, hard work, and good will of Dr. Diane Evans and Ellen O'Leary went "beyond the call of duty" and was invaluable. Thank you, too, to Mary Hardin of NASA'S JPL for her help in coordinating the public relations aspect of this project. The photograph, illustrations, and depictions of the space shuttle *Endeavour* and the Space Radar Laboratory found in this report are the property of NASA's Jet Propulsion Laboratory, which kindly provided permission to reprint them.

Gratitude is expressed to the Royal Government of Cambodia for approving this unique undertaking. The personal interest and approval of The Honorable Vann Molyvann was a critical factor in bringing this project to fruition.

WMF and RAF also thank the Woodrow Wilson School of Public International Affairs and the Firestone Library of Princeton University, which generously donated the use of their facilities for the roundtable discussions, workshops, and computer presentation. A special note of gratitude is extended to Sybil Stokes of the Woodrow Wilson School and Alfred Bush of the Rare Book Department at the Firestone Library.

Subsequent to the symposium, WMF/RAF made the acquaintance of several individuals whose encouragement and support we would like to acknowledge. In particular, we would like to thank Dr. Farouk El-Baz of Boston University's Center for Remote Sensing; Dr. Anthony Freeman and Dr. Tom Sever of NASA's JPL.

These proceedings were prepared by Keith Eirinberg, who served as participant and rapporteur, and were produced in-house by the World Monuments Fund. Gratitude is expressed to Project Co-Director Janos Jelen of the Royal Angkor Foundation, who is currently an Executive Fellow at the Woodrow Wilson School, for arranging the on-site logistics. For the World Monuments Fund, the conference was administered and managed by John H. Stubbs, Program Director and Felicia Mayro, Program Assistant.

1. THE VIEW FROM SPACE

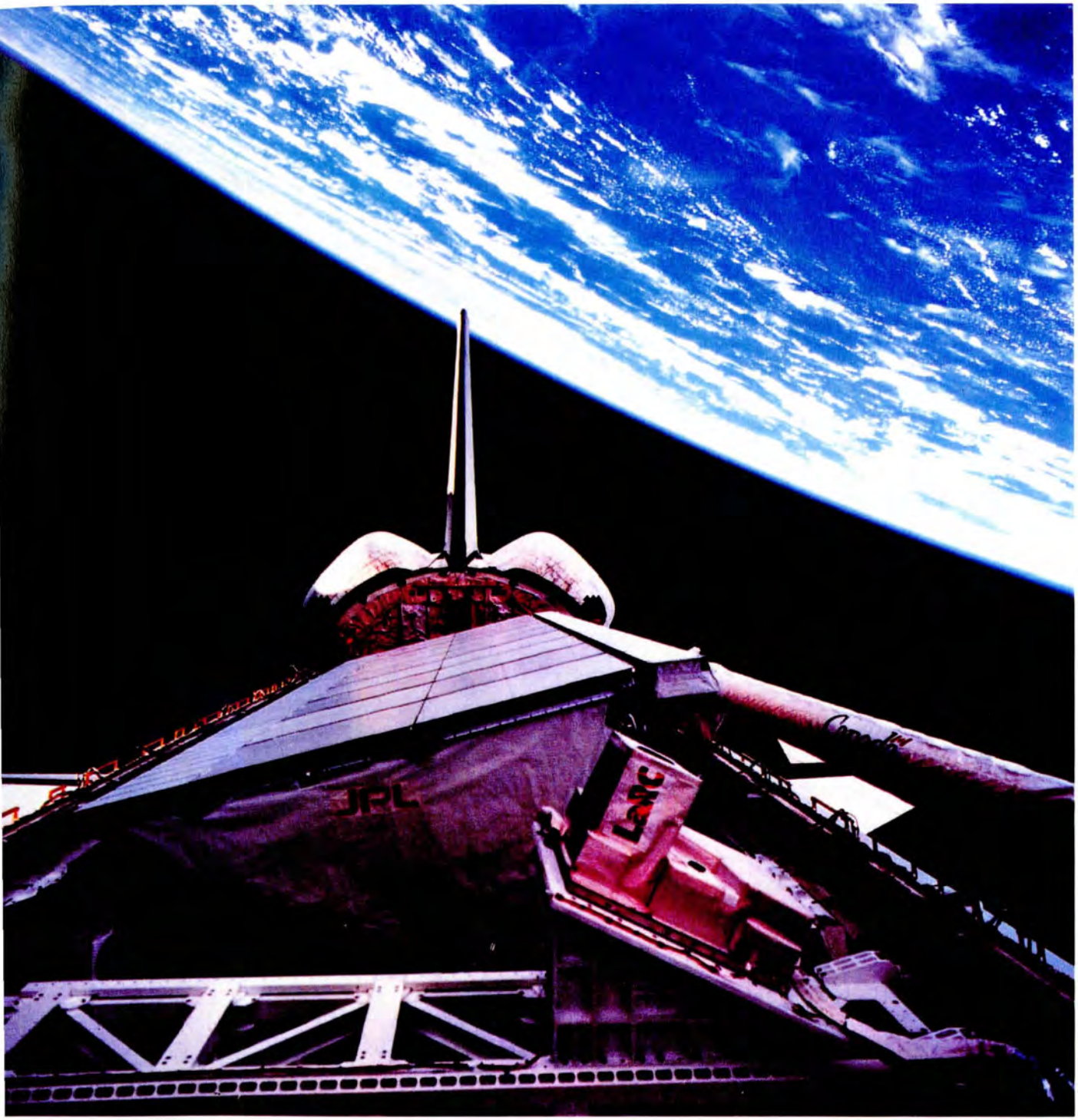
REMOTE SENSING FROM SPACE

SIR-C/X-SAR: A UNIQUE SPACEBORNE RADAR SYSTEM

PROPOSAL TO NASA'S JET PROPULSION LABORATORY

RESULTS OF THE ENDEAVOUR MISSION (SRL-2)

ONBOARD VIEW — SPACE SHUTTLE ENDEAVOUR

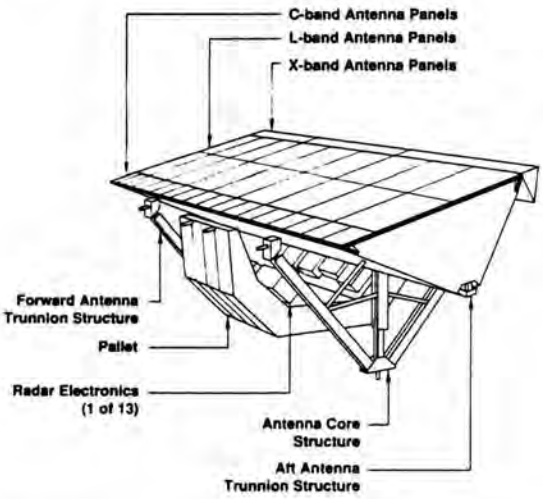


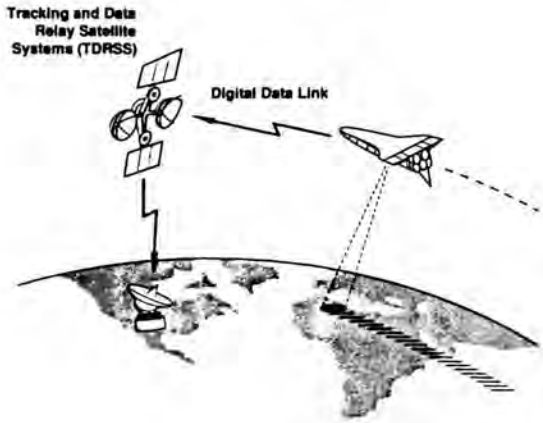
Onboard View — Space Shuttle Endeavour

(P-44164)

SIR-C/X-SAR is shown here in the payload bay of the orbiting space shuttle Endeavour (STS-59), with an area of the Pacific Ocean northeast of Hawaii in the background. The photograph was taken with a hand-held 70-millimeter camera through the space shuttle's aft flight deck windows. SIR-C/X-SAR's antenna, with its large triangular support structure and flat antenna panels, almost fills the payload bay. Embedded in the antenna are hundreds of small transmitters and receivers. The antenna panels gather data simultaneously at three frequencies: C-band, L-band, and X-band. Six NASA astronauts spent a week and a half in Earth orbit in support of the radar mission.

Shown are (below) the SIR-C/X-SAR antenna, and (bottom) SIR-C/X-SAR in operation.





The SIR-C/X-SAR Mission

The Spaceborne Imaging Radar–C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) mission is part of the National Aeronautics and Space Administration (NASA) Mission to Planet Earth, which began in 1991 to enhance our knowledge of the global environment. SIR-C/X-SAR data are improving our understanding of Earth's environment, including the global carbon cycle, the water cycle, climatic and geological processes, ocean circulation, and air–sea interactions. The multifrequency SIR-C/X-SAR data, complemented by information from aircraft and ground studies, will give scientists clearer insights into environmental changes — those caused by nature as well as those induced by human activity.

SIR-C/X-SAR's radar waves penetrate clouds, and, under certain conditions, can also penetrate vegetation, ice, and dry sand. Acquiring data at night as well as during the day, the system allows scientists to make detailed studies of Earth's surface on a global scale, including new measurements such as biomass (surface plant material) and soil moisture.

A precursor to free-flyer satellite missions planned for later in the decade, SIR-C/X-SAR is the first spaceborne radar to simultaneously acquire data at multiple wavelengths and polarizations. The system is an evolution in technology for large-scale radar observations that began with Seasat in 1978 and continued with SIR-A in 1981 and SIR-B in 1984.

SIR-C was developed by the Jet Propulsion Laboratory (JPL), which manages the SIR-C project for NASA. X-SAR was developed by the Dornier and Alenia Spazio companies for the German space agency, Deutsche Agentür für Raumfahrtangelegenheiten (DARA), and the Italian space agency, Agenzia Spaziale Italiana (ASI).

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL 400-528A 6/94

THE VIEW FROM SPACE

On October 4, 1994, the astronauts of the U.S. space shuttle *Endeavour* (SRL-2) orbited their craft on a path that would take them across southern Thailand, over the Dangrek mountains of northern Cambodia, over the ruins of the historic city of Angkor, past Phnom Penh, capital of the Kingdom of Cambodia, and down the Mekong River to the Mekong Delta and the South China Sea. Housed in the payload bay of the space shuttle was a sophisticated spaceborne radar imaging laboratory which, as the shuttle passed silently over Cambodia, was activated to take the first-ever radar pictures of the former capital of the Khmer Empire. In two passes over Angkor, the *Endeavour* collected a wealth of radar data, successfully accomplishing this historic mission.

Part of the National Aeronautics and Space Administration's (NASA) Mission to Planet Earth, the radar imaging mission, known as SIR-C/X-SAR, was the latest technological advance in the rapidly developing field of remote sensing from space. The unique aspect of the two *Endeavour* flights in 1994 was the use of three separate bands of radar for imaging. Only rarely did NASA take this technology beyond its original environmental mission to assist in archaeological discovery. But in April 1994 radar imagery was taken of the southern branch of the historic Silk Road in western China and of the site of the "Lost City of Ubar," a suspected frankincense trade center in Oman. Six months later the Angkor Eco-Site became the latest subject in this exciting marriage of high-tech radar imagery and the study of our past.

REMOTE SENSING FROM SPACE

Remote sensing from space has a short history: in the 1960s, meteorological satellites were first launched to monitor the earth's weather systems. In 1972, the first sophisticated satellite remote sensing devices were launched aboard the U.S. Landsat craft. Since then, the sophistication of the satellite radar imaging systems has grown as have the number of countries that operate these systems.

The function of remote sensing instruments in space is to collect images and quantitative data on Earth and other planets. Imagery of the Earth focuses on its land, seas, atmosphere, and subsurface. The "pictures" the imaging mechanisms take are converted into numerical representations (digitized) and transmitted to a receiving station on the ground where they are stored in a computer. Eventually, the digital information will be transformed by computer program into "pixels," small component elements of an image which together form a comprehensible picture.

Both Landsat and SPOT, a French satellite remote sensing system, have operated over Angkor and its surroundings, providing researchers with useful data to assist in their investigations. Landsat, designed and built by NASA in 1972, has two main sensors: the Multispectral Scanner (MSS), that measures reflected energy over a ground area of about 80 square meters; and the Thematic Mapper (TM), that brings into focus objects as small as 30 meters square. Landsat images are produced in multiple light bands. Using specialized software, scientists can manipulate these bands to locate special features. SPOT is an acronym for Satellite Probatoire d'Observation de la Terre, a French company overseen by the French Space Agency. SPOT, the world's most profitable outfit of its kind, provides satellite images in a single wide light band with a resolution down to 10 meters square. New advanced Landsat and SPOT craft are due for launch in 1997. Meanwhile, other remote sensing satellites already in orbit or scheduled to be launched are projects of the European Community, Japan, India, Russia, and Germany.

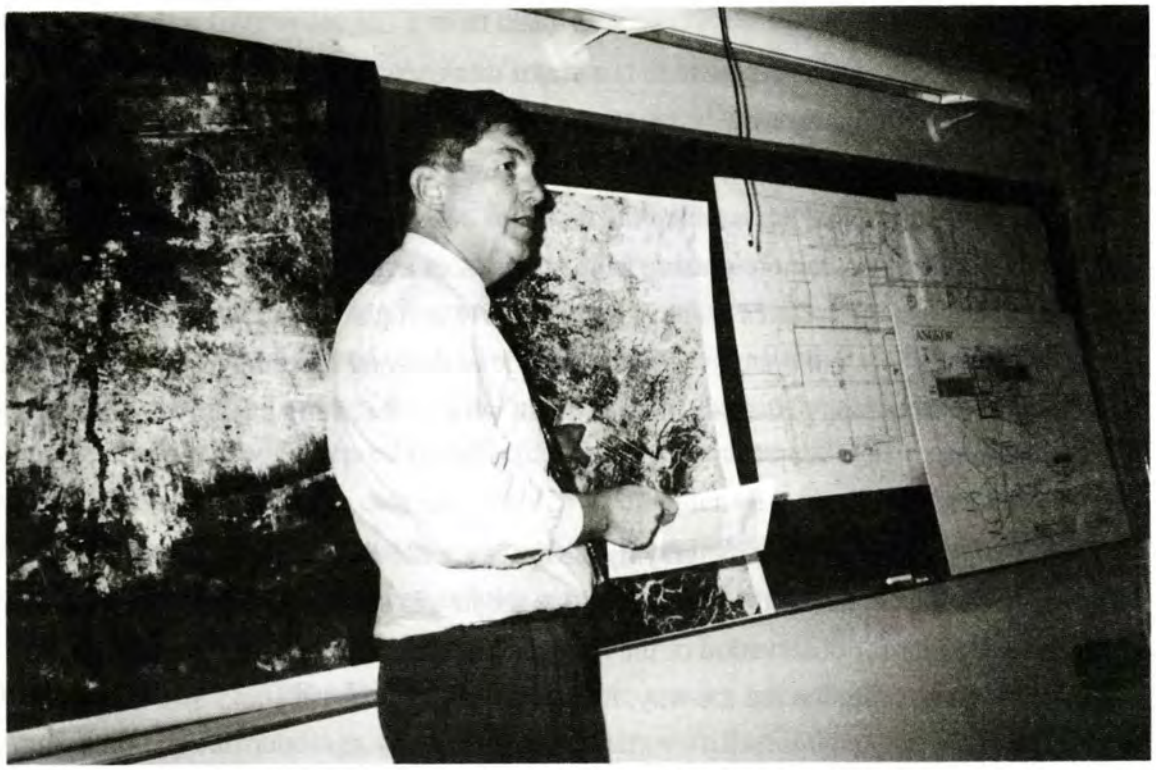
There are several benefits provided by this type of remote sensing from space. From such a high altitude, much more can be seen than from traditional aerial photography or from fieldwork on the ground. This has definite advantages for viewing an area within a regional context and for cost-effectiveness. The satellite or manned spacecraft can

repeat its orbit, providing further opportunities to observe and monitor any changes. Remote sensing from space can also be time-efficient -- the images can be obtained quickly compared to the earth-bound alternatives.

But this is not always the case which is a major weakness of remote sensing from space. Satellite imaging, such as that done by Landsat, is dependent on visible light to record its target. Cloud cover, vegetation, dry sand, and dust can obscure the object of the imagery. In tropical areas where the monsoon season can leave an area under constant cloud cover, remote sensing from space faces a major obstacle. Imagery from these remote sensing systems is similarly ineffective at night. The quality of the image can vary as well. Some systems will not provide as detailed a picture as desired, although the technology is rapidly improving in what is becoming a highly competitive environment.

The use of spaceborne radar imagery by the space shuttle *Endeavour* is the latest and most sophisticated, use of this type of remote sensing in space. NASA began its use of large-scale radar for observation of the Earth and nearby planets in the late 1970s. In 1978, the Seasat mission led the way, followed by SIR-A in 1981 and SIR-C in 1984.

Remote sensing from space using this radar technology has obvious advantages, beyond those common to all spaceborne imaging systems as discussed earlier. Microwave radiation can penetrate clouds and rain, vegetation, ice, and porous sand. It is not dependent on visible light and can be operated at night. The microwave is transmitted by an antenna on the space platform, bounces off the planet's surface, and returns to its source where it is measured. This raw data (core data set) is then transmitted to Earth. The 1994 SIR-C/X-SAR missions of the *Endeavour* were a major advance in the utilization of radar imaging. Unlike the radar systems carried by spacecraft in the past where one band was operated, these two missions carried three separate radar bands producing different frequencies which penetrate different layers of Earth's features. This system also allows for multi-polarization, a manipulation of the imagery produced by the three bands that can reveal otherwise unseen features. Radar imagery on the *Endeavour* missions offered another unique advantage: the *Endeavour* was flown with its back to the Earth, so that the radar lab mounted in the payload bay could obtain distinct "look angles" as the imagery proceeded. "Look angle" refers to the direction and degree of the radar This offered different perspectives of the same target, a feature that cannot be achieved from non-radar satellite monitoring systems.



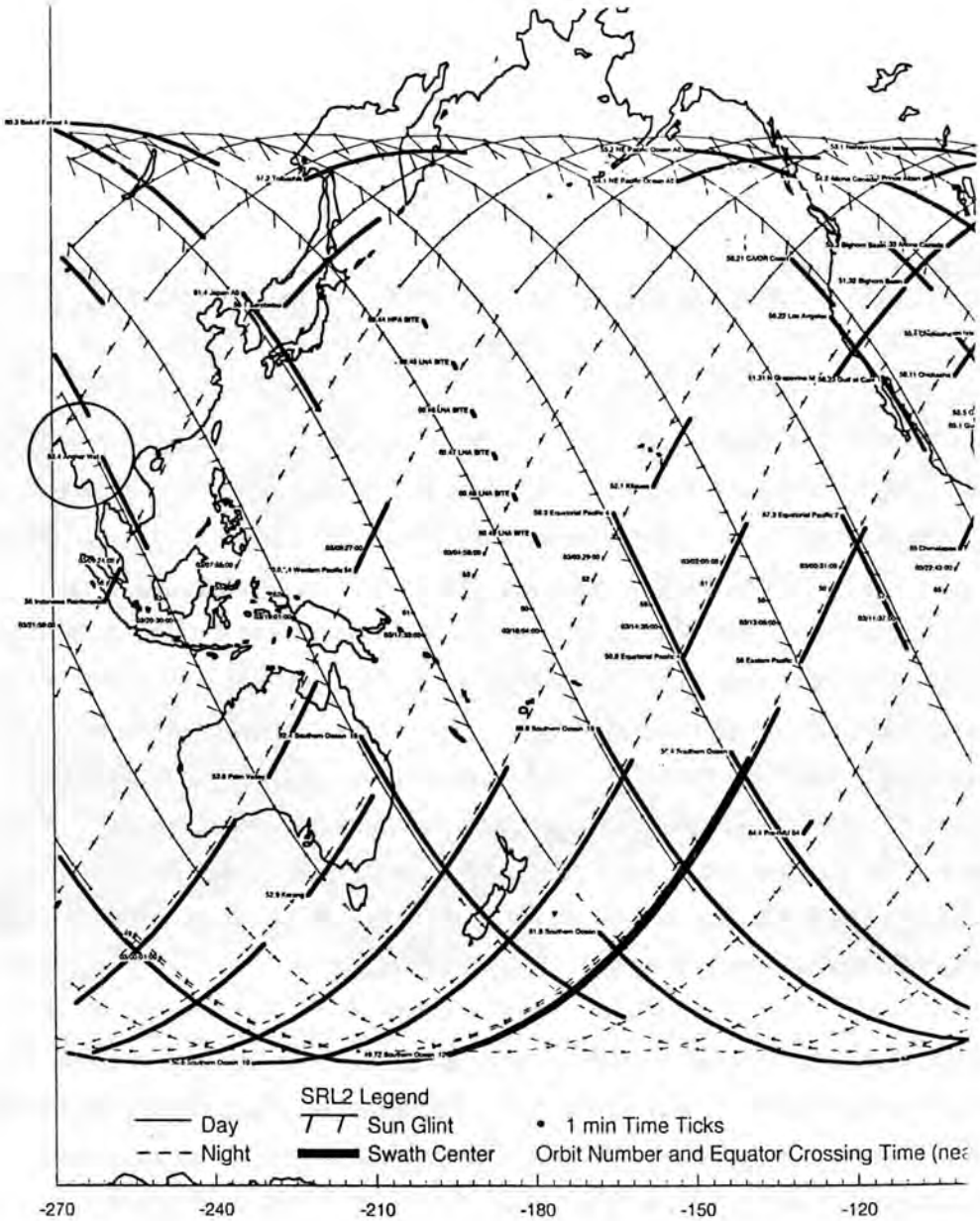
Ecologist/Landscape Architect Terry Schnadelbach points to the radar image of Angkor generated by the space shuttle Endeavour's Spaceborne Radar Laboratory. To his left is a Landsat image of the same area.

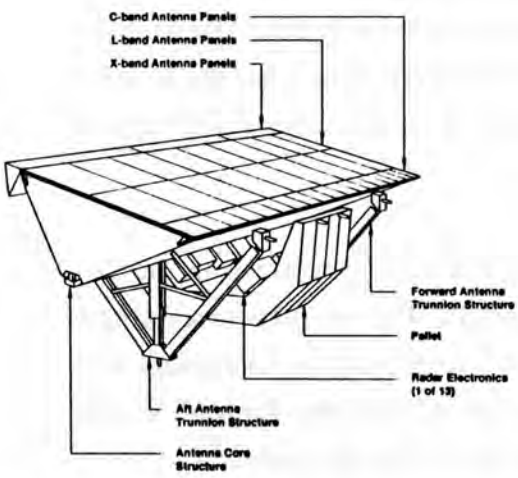
SIR-C/X-SAR — A UNIQUE SPACEBORNE RADAR SYSTEM

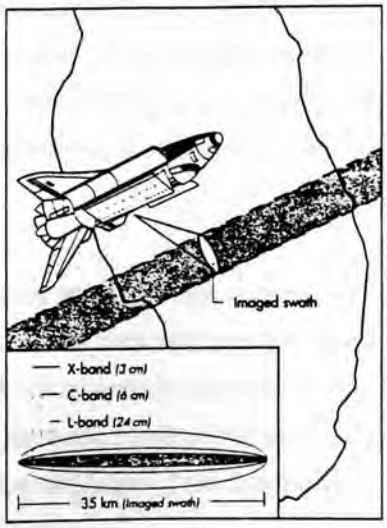
Behind the "SIR-C/X-SAR" acronym lies an ambitious project, one that is already helping mankind better understand the global environment. "SIR-C" indicates that the Space Imaging Radar is being used for the third time (SIR-A and SIR-B having been flown in the early 1980s). X-SAR means X-band Synthetic Aperture Radar, and signifies the addition of the X-band to the array of frequencies in the lab. X-SAR was developed by Dornier and Alenia Spasio for DARA (German) and ASI (Italian) space agencies. This mission, developed by NASA'S Jet Propulsion Laboratory in Pasadena, California, was part of NASA's ongoing effort to learn more about the environment. The use of a multiple wavelength and multiple polarization radar laboratory was not meant to eliminate the need for other monitoring systems, rather it would complement satellite, aircraft, and ground studies to help scientists understand the cause of environmental changes.

The space shuttle *Endeavour* carried the radar lab aloft in two missions in 1994. The first flight in April (SRL-1) was followed by a flight that was launched on September 30 (SRL-2), after a slight delay. While several hundred targets for imaging were chosen covering over 12 percent of the planet's surface, the focus of 52 teams of project scientists was on 19 "supersites" that offered the best view of different environments. These supersites included areas ranging from Death Valley in California to the mountain gorilla habitat in Rwanda to the Amazon Basin in Brazil. The missions were also prepared to cover the sudden occurrence of natural events -- and did so, for instance, when the Kliuchevskoi volcano in Siberian Russia erupted during the flight of SRL-2.

This unique radar system uses three wavelengths: the X-band of 3 centimeters; the C-band of 6 centimeters; and the L-band of 23.5 centimeters. The two longer wavelength bands were developed in the United States by NASA'S Jet Propulsion Laboratory and the Communications Systems Division of Bell Aerospace Corporation for NASA. The C-band and the L-band are polarized radiation, where an electric field vibrates







(Left) The SIR-C/X-SAR antenna.

(Right) The SIR-C/X-SAR imaging swath can vary from 15 km to 90 km, depending on the orientation of the antenna beams. The 35-km swath shown here comprises all three of SIR-C/X-SAR's operating frequencies: X-band, C-band and L-band.

horizontally or vertically from the frequency, so that the returning radiation can be received in either mode. This allows scientists to have a different view of the object irradiated, a view that might distinguish between objects. The X-band radar receives and transmits vertically polarized signals.

The radar is used as a means of receiving data about the reflector, the surface that has echoed the microwave back to an antenna. By comparing the outgoing and incoming ray, a scientist can learn the nature of the surface, including its size, texture, distance, and orientation.

Because an object will usually reflect a wavelength that matches its size, SIR-C/X-SAR was constructed with three radar bands, in frequencies of 1 GHz to 10GHz, all in the microwave portion of the electromagnetic spectrum. The L-band, at 23 centimeters, will reach to the ground. The C-band will penetrate farther to the surface than the X-band in areas of vegetation. The combination of the three bands, their polarizations, and the different look angles as the shuttle passed over the monitored site, provides a plethora of data that gives investigators many options in their search for answers. SIR-C/X-SAR has capabilities other radars lack. Under certain conditions, the three radar bands can penetrate vegetation, snow, ice, and dry sand.

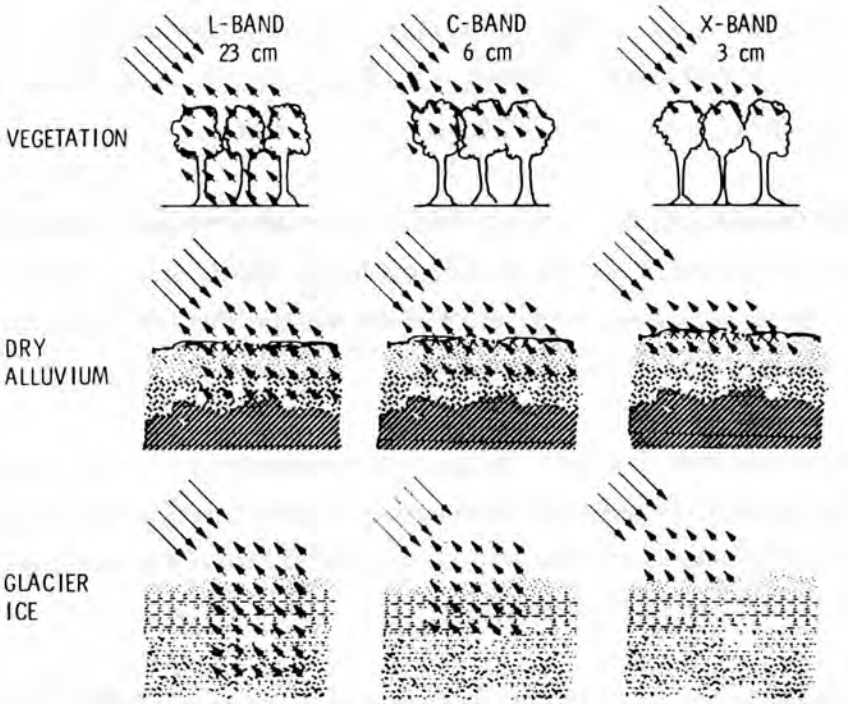
The SIR-C/X-SAR system provides valuable information on the global carbon cycle by measuring amount and type of vegetation evolution, and the state, distribution, and health of forests and natural wetlands. Besides biomass data, the radar can detect patterns of natural and human disturbance.

Regarding the hydrological cycle, the amount of moisture in surface materials can be learned from SIR-C/X-SAR data. Soil moisture, snow cover/glacier types, seasonal changes, rainfall interstices, evaporation rates, and floodwater presence and distribution in wetlands may then be interpolated.

The L-band radar has the ability to penetrate sand in arid regions allowing climatic and geological processes to thereby be observed. The L-band can be an important tool in the study of drainage systems, soil erosion, transportation, deposition/degradation, volcanism, and tectonism. The course of ancient rivers or even caravan trails may be detected.

The radar can also help to reveal the existence and nature of past human habitation. The reflection of microwaves off surfaces of different textures, may lead to clues, as it did when combined with Landsat technology in the discovery of the "Lost City of Ubar." In that case, infrared and radar sensing technology was used to locate ancient camel caravan tracks beneath the surface, leading to the site of Ubar. The combination of radar's long L-band penetration of the porous sand with the infrared wave's facility for locating heat sources proved a successful combination when manipulated by a resourceful team of scientists and archaeologists.

MULTIWAVELENGTH RADAR RESPONSE TO TERRAIN COVER AND SUBSURFACE HORIZONS



PROPOSAL TO NASA'S JET PROPULSION LABORATORY

The launch of the Spaceborne Radar Laboratory aboard the space shuttle *Endeavour* in April 1994 received international attention. Its experimental use of advanced radar imaging technology for global environmental research was widely heralded. Lesser known was the use of the radar as a research tool for archaeologists. Spaceborne radar had only recently contributed to the discovery of "The Lost City of Ubar." The April shuttle mission focused its radar on Ubar and on an area outside Hotan in western China, where archaeologists hoped to find the remains of caravan outposts along the southern branch of the historic Silk Road trade route in China.

When news of the use of spaceborne radar imagery for archaeology reached the World Monuments Fund and the Royal Angkor Foundation, the possible application of such technology at Angkor seemed evident. Initial inquiries to NASA'S JPL SIR-C Project Scientist Dr. Diane Evans revealed that there was no site in Southeast Asia on the next *Endeavour* mission and that the selection of the Angkor Eco-Site for radar imagery was possible.

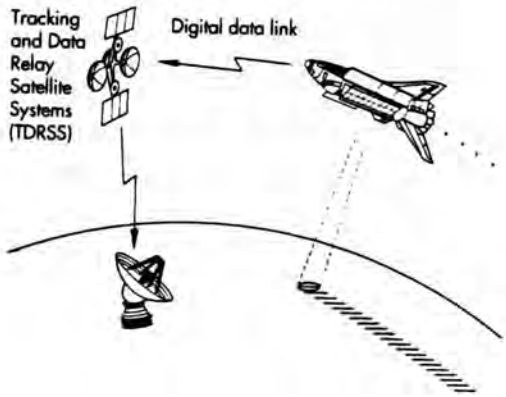
A scientific collaboration was formed between WMF and RAF for this survey. The proposal to NASA'S JPL (see Appendix C) listed four specific study areas: the region referred to as the Eco-Site of Angkor and the three temple sites within: Preah Khan, the Bayon, and Preah Ko. Both organizations saw the SIR-C/X-SAR data as having the potential to aid the archaeological and geographical programs underway at Angkor and to facilitate, for the first time, a coherent and comprehensive analysis of both surface and sub-surface features, particularly environmental, archaeological, and hydrological anomalies. In addition, the radar data might offer a new methodology for the study of the site. The project quickly took shape. The proposal, submitted to NASA'S JPL on July 15, 1994, was approved. The Royal Cambodian Government announced its support (see Appendix D). And on October 4, 1994, the *Endeavour* passed twice over Cambodia with its radar laboratory at work.

RESULTS OF THE ENDEAVOUR MISSION (SRL-2)

The Space Radar Laboratory launched onboard the space shuttle *Endeavour* on September 30, 1994 succeeded in achieving all of its imaging goals. It surveyed the planned sites and managed to cover real-time dramatic events, such as the erupting Kliuchevskoi volcano in Kamchatka, Russia and the aftermath of an earthquake that struck near Hokkaido, Japan.

The amount of data acquired in both missions is staggering: the SIR-C/X-SAR instruments accumulated about 32 terabits (32,000,000,000,000 bits) of data, or as NASA states, the equivalent of 20,000 encyclopedia volumes. Over 20,000 photographs were taken of the more than 400 target sites. These photographs and the astronauts' recorded comments will help explain anomalies in the radar record. The raw SIR-C data has begun to be processed at NASA'S Jet Propulsion Laboratory in California, while the X-SAR data is being processed in Germany and Italy.

The "data takes" -- similar to camera exposures -- of the Angkor Eco-Site were accomplished. Along with the radar imagery, the astronauts recorded on film a 30 kilometer-wide swath reflecting the shuttle's passage across southern Thailand, Cambodia, and Vietnam to the South China Sea. Due to the northwest to southeast orbital path of *Endeavour* nearly all of the lower portion of the Mekong Delta was documented, along with Angkor and its immediately related principle water body -- the Tonle Sap. Much of the Angkor Eco-site can be clearly seen, with Angkor Wat a striking presence.



Once aboard the space shuttle, SIR-C/X-SAR will transmit pulses of microwave energy toward Earth and measure the amount of energy reflected back. The raw data collected will then be processed digitally by ground equipment into an image of the target area.

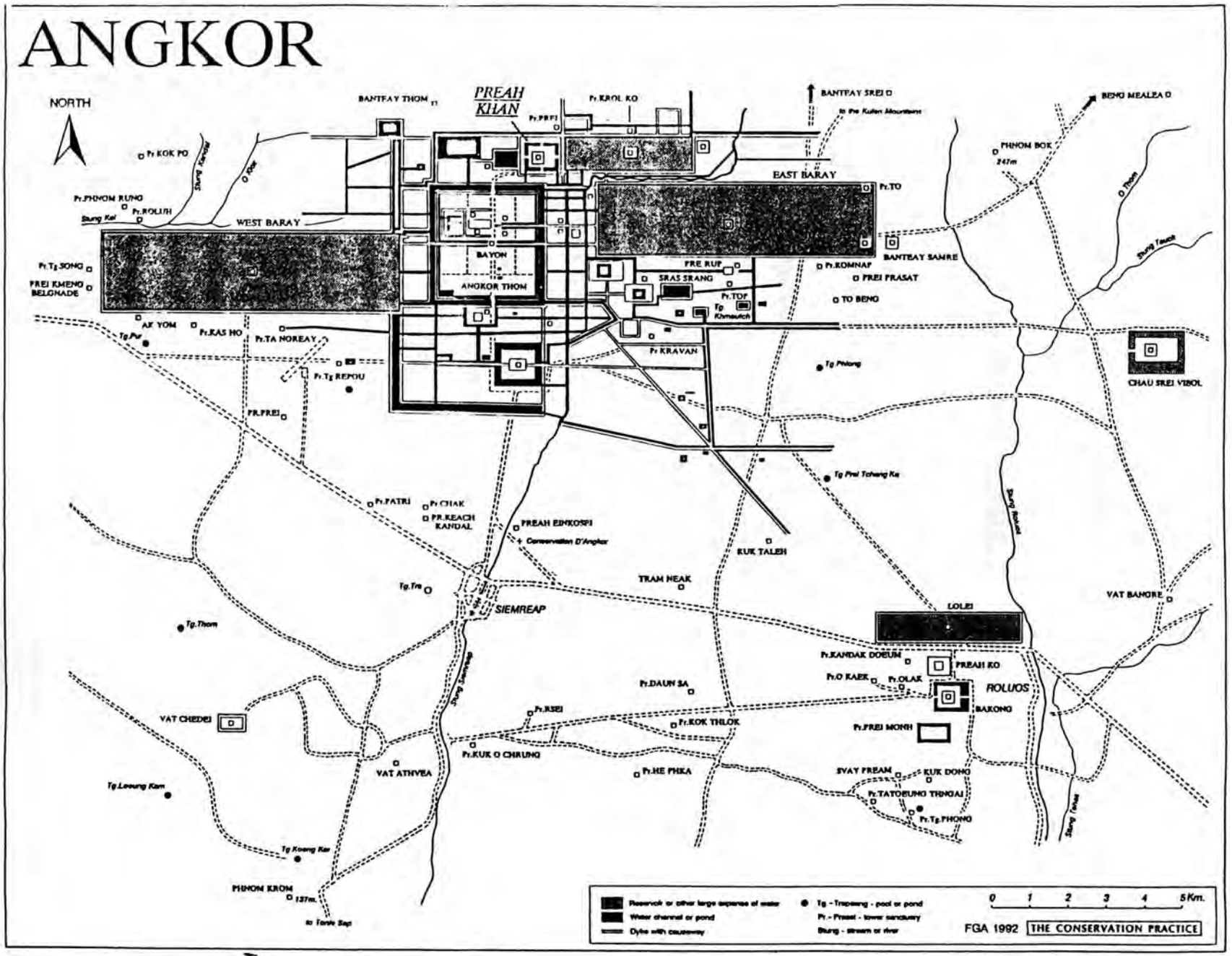
2. THE VIEW FROM EARTH

PRACTITIONER'S REQUESTS OF RADAR IMAGING

RADAR POTENTIAL AT ANGKOR ECO-SITE

RADAR WITHIN AN ANGKOR RESEARCH STRATEGY

ANGKOR


NORTH
PREAH KHAN
BANTEAY THOM
Pr.KROL KO
BANTEAY SREI
to the Kulen Mountains
BENG MEALEA
Pr.KOK PO
Pr.PHNOM RUNG
Pr.ROLUH
Stung Kei
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PHNOM BOK
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BAYON
ANGKOR THOM
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SRAS SRANG
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Tp Khmeuch
Pr.KOMNAP
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Pr.KAS HO
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Pr KRAVAN
Tg Phiong
CHAU SREI VIBOL
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Pr.CHAK
PR.REACH KANDAL
PREAH EINKOSPI
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SIEMREAP
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VAT BANORE
Tg.Thom
Pr.KANDAK DOEUM
PREAH KO
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BAKONG
Pr.DAUN SA
Pr.RSEI
Pr.KOK THLOK
Pr.PREI MONH
VAT CHEDEI
Pr.KUK O CHRUNG
VAT ATHVEA
Pr.HE PHKA
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KUK DONG
Pr.TATOEUNG THNGAI
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PHNOM KROM
137m.
to Tonle Sap
Reservoir or other large expanse of water
Water channel or pond
Dyke with causeway
Tg - Trapeang - pool or pond
Pr. - Prasat - tower sanctuary
Stung - stream or river
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FGA 1992
THE CONSERVATION PRACTICE

2. THE VIEW FROM EARTH

"For those of us working to conserve and present this World Heritage Site the radar scan data provided by NASA should aid the research efforts of well over 150 scientists, scholars and researchers in the fields of geography, hydrology, archaeology, history, land conservation, architectural conservation, site management, tourism and education."

From the World Monuments Fund and the Royal Angkor Foundation Proposal to NASA'S Jet Propulsion Laboratory, July 15, 1994.

PRACTITIONER'S REQUESTS OF RADAR IMAGING AT THE ANGKOR ECO-SITE

After the first day of plenary discussions dealing with the background on the project and orientation for new members of the research team, the roundtable participants divided into three working groups to discuss how the radar data set would best be used in their disciplines and how it could be shared with all interested parties. The following summaries reflect the exchange of views of the Architecture and Archaeology Group, the Site, Landscape, and Botany Group, and the Methodology and Communications Group. The synopsis for each group includes related ideas that were raised during plenary sessions in the two-day symposium.

Architecture and Archaeology

Participants: John Stubbs, Janos Jelen, Elizabeth Moore, Diane Evans, Felicia Mayro

The Architecture and Archaeology Group met to discuss how they hoped radar imagery would unlock the many unresolved mysteries about the history of the Angkor site and the adjacent areas connected to the pre-history of the Khmer civilization. Some of the larger questions to be answered are:

- Why did people settle at this location from prehistoric times on? Is there an "interface" between the two "golden ages" of prehistoric circular roads and Angkorian rectilinear reservoirs?
- How and why did different components of the site develop?
- Why were the temples and barays built in the positions they are?
- Where was the mining of laterite for the Angkorian temples conducted?
- How did the hydrological system work during the prehistoric and Angkorian times? Where was its water source and how was that water managed? Were the reservoirs used for irrigation or sacred purposes or both?

The prehistory of the area is virtually a blank slate and might benefit enormously from the information the radar data might provide. As Dr. Elizabeth Moore noted, it is not yet possible to accurately date the prehistory of Angkor. The traditional date of 802 A.D. is often given as the date Angkor was founded. But a city is generally founded on an earlier settlement site. A prehistoric city had been established near Ak-yum and Roluos, prior to the construction of the first Khmer capital, e.g. the city of Hariharalaya, on or near the same site.

There are at least 68 prehistoric mounds in the area that may date to 5000 B.C. or 500 A.D., but little is known about them. A survey that found stone tools curiously failed to discover bronze or iron or any metal items. Some prehistoric mounds were surrounded by earthworks and moats. As of yet, there has been no radiocarbon dating at Angkor or significant test excavations, but radar data may begin to fill this void of information. It may also allow research where ground surveys are difficult -- land mines and a security problem in the area hamper investigation of most of these sites.

Twelve kilometers south-east of Angkor is a modern city called Rolous. There has been very little work done at the nearby area comprising several major and minor temples, such as Preah Ko, Bakong, Lolei, etc., the first reservoir of Indratataka, all of that referred to at some time as Hariharalaya, or the first major capital city of Angkor. French archaeologists have looked at some of the temples, reconstructed a few of them, and classified the iconography, but nobody has looked at the overall context in which these temples exist. It is important to look at the whole environment of the city to better understand the individual temples.

It is hoped that the radar imagery might clarify how the hydrological system worked and identify how its components fit together. At present, archaeologists are stymied by the jumble of evidence of various periods: the canals, water features, and temples are layered, so it is difficult to reconstruct how the site looked at a particular moment. The radar data might hold the clues for understanding Angkor's morphological development.

Dr. Moore presented a proposal to the group (see Appendix B) that suggests a plan for the use of the radar data in connection with the 9th century A.D. city of Hariharalaya, and its prehistory. The radar might provide clues to the prehistoric period that have been lacking due to the confusion stemming from numerous overlays at the main central Angkor area. Dr. Moore is particularly interested in the pre-historic to historic period interface. With these as subjects, she hopes to use the radar as an investigative tool to interpret the visual images and to understand the area in spatial and chronological terms. The sophistication of Dr. Moore's proposal will be of immediate benefit as the interpretation of the radar core data set begins.

John Stubbs, who has researched the site of Preah Khan and its environs at the north edge of the Angkor Archaeological Park since 1992, noted some intriguing evidence of probable early land settlement patterns to the north of Preah Khan. Though road and agricultural planting patterns are clearly evident, no traces of architectural remains have been noted in this area. It is hoped that further use of SIR-C/X-SAR radar imaging will help in addressing further the question of how agricultural patterns and everyday life was conducted at Angkor. Stubbs is also interested in the new information that radar imaging may provide relevant to the Preah Khan-Neak Pean-Ta Som urbanistic ensemble, all creations of Jayavarman VII (12th century), which are oriented in relation to one of Angkor's largest barays. An understanding of the hydrology of Angkor is absolutely essential to an understanding of the whole complex. The use of the radar data to learn more about the dikes, moats, barays, canals, and other water works, along with the course of present and extinct rivers would shed light on this hugely important facet of Khmer society.

The radar data might also contain clues to the location of buried temples and palaces built from perishable materials situated near the stone monuments, and other evidence of the Khmer civilization. Heavy sedimentary deposits in the alluvial fan near Siem Reap may have covered some of these ruins.

The radar may also be an important addition to the current imagery tools used in the archaeological study of Angkor. Other aerial and space imagery sources with which it can be compared are:

- Aerial photographs taken over Angkor in 1936
- World War II Royal Air Force photos taken in 1945
- French aerial imagery of Indochina from 1954
- U.S. Air Force photos taken in the 1960s
- Finnish aerial cover conducted in 1992
- SPOT images
- Landsat images
- Helicopter videos taken during the time of the United Nations Transitional Authority in Cambodia (UNTAC)

Super-imposing these digital data sets using a Geographic Information System (GIS) would allow comparisons to be made. All of these resources should be used to classify different areas and subjects.

While the use of spaceborne radar may help to explain the past, such study may have particular importance for the present. In determining the logic for the Khmer civilization being established in the pre-historic and Angkor periods, useful information may be discovered to assist the area's current development. For example, it may be helpful in determining proper management of the scarce hydrological resources, including issues such as whether barays may be successfully re-filled, one of the many ideas that UNESCO's Zoning and Environmental Management Plan (ZEMP) says should be carefully studied.

Site, Landscape and Botany

Participants: Terry Schnadelbach and Keith Eirinberg

The Site, Landscape, and Botany Group focused on the ecology of the Angkor Eco-site. The session participants and observer, led by ecologist/landscape architect Terry

Schnadelbach, discussed the surface and sub-surface discoveries that they hoped the radar imagery would reveal. Mr. Schnadelbach's proposal can be found in Appendix B.

There are certain geological surface features, particularly textural changes, that the radar data might help define. Specifically, it may help in defining bedrock, alluvial, and sedimentary geological features. The variations in soil type within alluvium stratum/bands should be checked and, if possible, an explanation should be sought for the width of wet phase soils within drainage ways.

The radar data should also be used to define the subsoil conditions. If the microwaves possibly penetrated the temple complex sands, they might have produced data indicating the variations in depth, ground water, soil horizons, and archaeological landscape elements.

Experts who analyze the radar data should use it to penetrate recent alluvial deposits for depth, distribution, and soil horizons for the areas of deposit in the eastern end of the Western Baray, the alluvial delta of Siem Reap, and the delta of the Tonle Sap.

The study of Angkor's hydrology may also benefit from the SIR-C/X-SAR data. The radar should be used to locate "mineral licks" within the upland terraced slopes, wetland/watering holes that are primarily springs, and ephemeral springs that carry seepage from bedrock stratas. The data set perhaps could define the internal drainage of the rhyolite sandstone deposits and locate springs within the Eastern Baray area.

Many questions exist about the vegetation that supported the Khmer civilization and how that vegetation has changed over time. It would be useful to study the radar data set to define the following:

- Major changes in surface vegetation
- Rice paddies by density of rice and productivity differences
- The dypterocarpus forest -- existing and potential -- the cooperation of existing stands and their soil with unforested zones having the same soil conditions
- Stands of large wood content -- trunk sizes
- Stands with the full four layers of vegetation, those stands with less layers, and the composition of mixed stands

The radar may also help in distinguishing all bamboo crop areas from natural expanses; the location of termite mounds which would help understand where forests had once stood; and the presence of trails within vegetation zones, which might lead to clues to whether they were once human courses or elephant paths. Radar information may also help us understand if there were differences in vegetation use on a daily or seasonal basis.

Examination of the radar data should focus on locating other major ecological developments at Angkor for which there is more surmised than known. Carbon cycle changes and water circulation within the Lake Tonle Sap are examples of such subjects.

Methodology and Communications

Participants: Janos Jelen, Minja Yang, Markus Bela, Pamela Logan, Levente Varga

The Methodology and Communications Group focused on the need to turn the radar data set into useful information and then to make it accessible worldwide. Each of these objectives involves specific steps that must be taken to reach those goals.

To provide value to the immense amount of raw data, it must be converted into useful information appropriate to various fields, such as archaeology, ecology, and land use. The quantity of data produced by SIR-C/X-SAR is too immense to place on-line. Its value comes once it is converted from a digital data set into imagery and that imagery is interpreted to show information. To be able to locate that information from the data, it is necessary to form individual teams of radar image interpretation experts and scholars from the appropriate scientific disciplines. The radar image interpretation expert must use the specialist as his "eyes" to be able to locate an object to be studied by the specialist, or to examine areas of interest. The expert can manipulate the polarizations and filters for each band to enhance certain areas of the image and will be better able to use these techniques once the site expert provides the necessary background information.

In light of the importance of this team, it is important to organize a pool of site specialists from different fields that would be available to join a radar expert to generate information from the core data set. These experts should be sought globally, with the

understanding that there is particular expertise in Southeast Asia, such as at the Asian Institute of Technology, which has a specialty focusing on the region's resources.

It will also be necessary to have access to a radar expert and applicable software. The radar expert should be familiar with physics and the software, after NASA'S Jet Propulsion Laboratory provides the data and a lead to the type of software that should be used for interpretation.

After information is gleaned from the radar data, it should be made available on the Internet via the World Wide Web which will provide access to this set of information and conclusions. The use of electronic bulletin boards can provide an interactive means for peer review and criticism. It would be useful to place the interpreted radar data on a system that is compatible with that used by scientists working on Angkor and the region, in particular those involved in environmental work. It also should be made available to planners and departments of the Royal Cambodian Government, with the understanding that the utility of the radar information is of prime concern. Coordination with UNESCO and with the Royal Cambodian Government's other relevant regional and international bodies would enhance the spirit of cooperation.

This remote sensing data should be co-registered and geo-referenced to a base map to standardize position referencing for Angkor. The radar data can thus be used for GIS overlay and comparison to other remote sensing data (i.e. satellite and aircraft surveys) as well as geodetic data. It is important that once promulgated, this data be provided to other GIS systems, such as the Land Use Mapping Office (LUMO) in Cambodia.

The radar data is not an end in itself, but an important new element in the overall effort to learn more about the Angkor Eco-Site. The effort to use this data should be coordinated with the latest draft of the "Angkor Information Strategy," a product of UNESCO's recently developed ZEMP for Angkor. The Angkor Information Strategy is multi-disciplinary and relates to man's interaction with his environment; as such, it is important to promote the radar imagery as part of a holistic treatment of historic and cultural areas for Angkor and other sites.

Because the use of radar imaging technology for archaeology is new, it is necessary that the archaeology community develop a working relationship with NASA and JPL. By developing synergy, the sharing of information can benefit all. The Methodology

and Communications Group supported the investigation as to whether the Angkor radar imaging project is transferable to other sites in the world. The group also supported the development of remote sensing training programs to assist in this undertaking for Angkor.

Dr. Diane Evans, Project Scientist for SIR-C at NASA'S JPL, interprets radar imaging data from NASA'S JPL's home page on the World Wide Web, for Princeton roundtable members.

RADAR POTENTIAL AT ANGKOR ECO-SITE

During and after the roundtable working sessions of the practitioners, Dr. Diane Evans, SIR-C Project Scientist at NASA'S Jet Propulsion Laboratory, offered suggestions on methods to employ in analyzing the radar data of Angkor. She offered the assistance of NASA'S Jet Propulsion Laboratory in the initial preparation of data from the core data set. Based on the objectives she heard from the roundtable experts, Dr. Evans offered her advice and assistance.

Advice on Methodology

- Begin using the old analog method of comparing images side to side -- using, for example, Landsat and SPOT. Use multiple sensors for an object-oriented approach during classification.
- Look at the seven separate bands: the L-band, C-band, and X-band and their polarizations.
- Experiment with enhancing elements of the image and use existing knowledge of the site to find what you seek.
- The resolution of the image is not the final word. The reflector -- the type of surface -- the radar has bounced from makes a difference. This technique is new to archaeology.
- An additional way of using the radar is to enhance right-angle structures through polarization. You can get a double bounce using a 180 degree base shift. It would just take a small software program to clarify all 180 degree bounces using the whole polarization matrix. This has worked in Brazil and is good for determining stands of trees, making it easy to do biomass research.

NASA'S JPL Assistance

- NASA'S JPL will provide the seven independent bands and the raw radar data.
- NASA'S JPL will offer ideas of what bands and polarizations to use to look for something.

- If the radar brings something out, it doesn't matter what band it is in. If you see something, let NASA'S JPL know and it will explain the physics of the scattering. NASA'S JPL can come up with ideas of what to look for.

- NASA'S JPL can provide images for the generation of bite files. They will be in the same format as SPOT and the Thematic Mapper, so as not to be locked in to the color composite that NASA'S JPL chose. NASA'S JPL will assist in color composition.

- NASA'S JPL can help locate different vegetation types on the radar images. There are computer models on types of trees.

- As with polarizations, NASA'S JPL will assist with filtering advice.

Angkor-Specific Advice

- The radar is good at recognizing linear structures. This feature may be useful for Dr. Elizabeth Moore's proposal for Roluos, Hariharalaya, and prehistoric mounds.

- It may not be possible for the radar to significantly see beneath the soil at Angkor. However, using information, such as the subtle undulation of the soil and the undulation in the top canopy, clues might be found. Visible and infrared data from Landsat may augment the radar data for this purpose. The same advice applies for bodies of water under study, such as Lake Tonle Sap.

- Co-register and geo-reference the Angkor radar data set.

- The radar might distinguish between typologies of buildings.

RADAR WITHIN AN ANGKOR RESEARCH STRATEGY

The UNESCO Zoning and Environment Master Plan was a significant effort in accumulating knowledge on the Angkor region. In 1993, UNESCO adopted a resolution that recognized an Angkor Information Strategy as a major goal. The World Monuments Fund and the Royal Angkor Foundation hope to add to the information from the ZEMP study using the radar data set.

The various imagery of the Angkor site means that no one image alone is authoritative. Rather each image portrays aspects of a reality that is highly dependent on the image-maker and the technology available at the moment. The radar data set may conceptually be used as a reference point to interconnect other data, with the intent to find their interface. This radar data can be overlaid with other satellite and aerial imagery, maps, and other digitalized data. In that way the layers of time might be peeled away to reveal the Angkor Eco-Site at different periods, allowing the analysis of historical changes, such as in the hydrological system. It is therefore important to accumulate as much digital data on the site as possible.

The new radar data must be integrated into geographic information systems. A GIS, as a powerful data management tool, allows the analysis of different environmental and development data by layering that data. Linkages are then revealed among normally disparate subjects. A GIS promotes an integrative approach to management and problem-solving. Most GIS data bases, though, are not interoperable; therefore it is important to ensure that the information from the radar data set is provided to the relevant GIS operators.

It is a key goal of the World Monuments Fund and the Royal Angkor Foundation to make this new and exciting resource available to the Royal Cambodian Government and Cambodians with an interest in the Angkor Eco-Site, as well as to the wider international research community and interested public through various sources including the Internet.

3. FUTURE PLANS & DIRECTIONS

WORLD MONUMENTS FUND/ROYAL ANGKOR FOUNDATION OBJECTIVES

NEXT STEPS

3. FUTURE PLANS AND DIRECTIONS

WORLD MONUMENTS FUND/ROYAL ANGKOR FOUNDATION OBJECTIVES

The following objectives were proposed by the three working groups of specialists with the overall goal of finding the most effective, efficient, and useful application of the radar data set for the benefit of all interested parties.

Architecture and Archaeology

- Use radar imaging data to untangle the various layers of history at Angkor by methods of superimposition, parallel analysis, etc.
- Seek a better understanding of the full extent of the hydrology system and especially how it changed and developed over time.
- Use radar imaging to study areas of Angkor that are not physically accessible due to mines, etc. (e.g. 80% of pre-historic mounds are inaccessible)
- Use the technology to better understand the morphological development of Angkor and changes to site appearances and functions over time.
- Use radar imaging to discover heretofore unknown sites and features at Angkor.
- Use different remote sensing data sets to classify different areas and subjects (e.g., identify all architectural sites and objects; types of biomass; standing water; building typologies; water containment structures, etc.)
- Investigate the water supply and water management system in the Preah Khan, Neak Pean and Ta Som complex.
- Conduct research at the Roluos Study Site and around Ak-yum which may pre-date Hariharalaya (see proposal from Dr. Elizabeth Moore at Appendix B).

Site, Landscape, and Botany

- Use radar imaging to develop a better understanding of the geological history of Angkor. Address questions of uplift, plate movement, mound formation, soil types and formation, etc.
- Use radar imaging to analyze forest tree patterns (biomass research).
- Use this technology to study ancient climate and water patterns.
- Describe major surface geology and vegetal features in the Angkor region.
- Identify sub-soil conditions in the temple complex.
- Trace historic drainage systems, tracks, and roads -- both natural and man-made.
- Establish "texture types" for major waterway structures and map their locations.
- Search for signs of historic wooden structures: patterns of stilt house settlements, signature deforestation patterns, etc.

Methodology and Communications

- Convert raw data into useful site specific information appropriate to various fields such as archaeology, ecology, and land use.
- Link experts familiar with radar image interpretation to those in the relevant fields of scholarly research (to achieve the above objective).
- Post interpreted data and conclusions on Internet accessible computer sites, referenced through a World Wide Web home page.
- Establish electronic bulletin boards for peer review and criticism.
- Co-register and geo-reference remote sensing data to a base map to standardize position referencing for Angkor.
- Coordinate the new radar imaging data with the latest draft of the "Angkor Information Strategy" document.
- Use radar technology to enhance other research at Angkor. Extend the notion of multidisciplinary holistic treatment of historic/culture areas to other sites, underscoring the close evolving relationship between human activities and eco-system.
- Work to build more bridges between NASA'S JPL and the archaeological community.
- Establish remote sensing training programs related to this project.
- Examine the transferability of the Angkor radar imaging project to projects elsewhere in the world.

Further Objective

- It is the ambition of the World Monuments Fund and the Royal Angkor Foundation to document the Angkor Eco-Site using radar imaging in the height of the dry season in Cambodia to augment the present record of the site made at the height of the wet season.

NEXT STEPS

Based on the recommendations and objectives set forth by the roundtable participants, and in recognition of the possibilities and limitations of the radar imagery technology, plans were developed to move the Radar Imaging Survey of the Angkor Eco-Site to its next phase. The action items approved are as follows:

- Obtain SPOT images to compare with SIR-C/X-SAR radar images.
- Obtain from NASA'S JPL a printout of the individual band data, in particular the X-band radar data.
- Analyze radar images of Angkor using special techniques of the "double bounce" and "right angle" bounce analytical methods (core data set).
- Learn more of the work of others using radar imaging for archaeological investigation.
- Work with NASA archaeologist Tom Sever to organize a conference of archaeological organizations using spaceborne radar imaging to gain an exchange of views and experiences.
- Use visible and near-infrared Landsat images.
- Seek to obtain other useful related data sets from NASA archives.
- Use different remote sensing data sets to classify different areas and subjects (e.g. architectural signatures).
- Possibly establish alliance with a university remote sensing center.
- Obtain CD-ROM for the Department of Archaeology at the University of Beaux Arts in Phnom Penh from NASA.
- Present results of the First Scientific Roundtable on Radar Imaging of the Angkor Eco-Site at the meeting of the International Coordinating Committee on the Safeguarding and Development of the Historic City of Angkor (ICC) in Phnom Penh, Cambodia on March 30, 1995.
- Engage the team of young Khmers in Phnom Penh in the Angkor radar imaging project at a workshop in late March 1995.

APPENDICES

A. ROUNDTABLE AGENDA

B. PROPOSALS OF DR. ELIZABETH MOORE AND MR. TERRY SCHNADELBACH

C. PROPOSAL OF WORLD MONUMENTS FUND AND ROYAL ANGKOR FOUNDATION TO NASA'S JET PROPULSION LABORATORY

D. EXCHANGE OF LETTERS BETWEEN THE HON. VANN MOLYVANN, SENIOR MINISTER OF STATE FOR CULTURE AND FINE ARTS, COUNTRY AND URBAN PLANNING AND CONSTRUCTION, KINGDOM OF CAMBODIA AND MR. JOHN H. STUBBS, WORLD MONUMENTS FUND

E. PROJECTS OF THE WORLD MONUMENTS FUND AND THE ROYAL ANGKOR FOUNDATION IN CAMBODIA

F. SELECTED MEDIA COVERAGE

G. SIR-C/X-SAR PROJECT SCIENTISTS

H. PARTICIPANT INFORMATION

APPENDIX A

ROUNDTABLE AGENDA

An International
Preservation Organization

WORLD MONUMENTS FUND

174 East 80th Street
New York, New York 10021
Telephone: 212 517 9367
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31 January 1995

Radar Imaging Survey of the Angkor Eco-Site
First Scientific Roundtable at Princeton

The World Monuments Fund, together with the Royal Angkor Foundation, is conducting the first scientific roundtable on its Radar Imaging Survey of the Angkor Eco-Site. The purpose is to assess the data collected by the National Aeronautics and Space Administration (NASA) space shuttle *Endeavour* during its October 1994 mission and determine the criteria for analyzing the information provided. Using NASA's SIR-C/X-SAR Earth Imaging Radar system, the *Endeavour* collected images of specific archaeological sites in Cambodia to assist in the documentation and analysis of the Historic City of Angkor in response to a proposal submitted jointly by WMF and RAF on July 15, 1994.

The roundtable is the first general meeting of the international project team to determine the criteria and a detailed program for analyzing the information provided by NASA. It will occur over a two-day period in facilities at Princeton University in New Jersey. Participants will discuss to potential of the research possibilities afforded by the availability of this new technology and develop a list of objectives for the overall research project. Following this, a plan of action will be formulated, intended to engage other researchers and address possible future collaborations with NASA on the subjects of cultural heritage conservation, historic eco-systems and archaeology. This conference will serve as a significant advancement in an ongoing dialogue between NASA and archaeologists and other researchers with regard to new possibilities in both archaeological research and site conservation.

The roundtable results, published as an illustrated finished report, will be presented at a meeting of the International Coordinating Committee on the Safeguarding and Development of the Historic Site of Angkor (ICC) scheduled for late March 1995 in Phnom Penh.

This conference is made possible by a generous grant from the *Exploration and New Technologies Program* of The J. M. Kaplan Fund in New York.

Program (final)

Day One (Wednesday 1 February)

10:00 AM	Welcome, introductions, agenda review and background of the project. Presentation of materials and other research resources in hand. Presenters: Jelen, Stubbs, Schnadelbach & Moore. *Location:* Bendheim Hall, (at Woodrow Wilson School) Room 012.
12:15	Lunch with film on Angkor.
1:30	Overview of NASA's SIR-C/X-SAR program, its purpose and possibilities. Mention of work being done by others on similar sites. (Logan)
2:15	History of the Historic City of Angkor with emphasis on its morphological development as a city in relation to its geography and ecosystem. (Jelen, Markus, Moore & Schnadelbach)
3:00	Coffee Break
3:15	Presentation on the recently developed Zoning Environmental Management Plan (ZEMP) for Angkor with special emphasis on its Geographical Information Systems (GIS) component. (Jelen, Markus & Moore)
5:00	Brief break followed by special presentation on NASA's SIR-C/X-SAR program followed by discussion. (Dr. Diane Evans, Project Scientist, *Endeavor* Mission)
7:00	Social gathering and dinner at Prospect Club.

Day Two (Thursday 2 February)

9:15 AM	Brief gathering in plenary followed by working session(s) to develop a master list of objectives and methodologies for the Eco-Site of Angkor project. *Location:* Firestone Library.
11:15	Presentation of first synthesis of results and a recommended plan for the overall work program.
12:30	Lunch at Prospect Club.

1:45	Final synthesis of research program, discussions on procedures, team communications, work formats, budgets, etc.
3:00	Break
3:30	Summary session with invited members of the press and others.
5:00	Close of meeting and farewell.

Participants

Roundtable participants include: J. Stubbs (WMF, New York), J. Jelen (RAF, Budapest), Dr. Diane Evans, Project Scientist, (JPL, NASA, Pasadena), P. Davidson, Trustee (J.M. Kaplan Fund, New York), Henry Ng, Director (J.M. Kaplan Fund), Dr. P. Logan (CERS, Los Angeles), J. Sanday (WMF, Nepal)*, Dr. E. Moore (Univ. of London, UK), Dr. B. Markus (Dept. Head GIS, Budapest), L. Varga, Engineer (Budapest), Dr. C. Jest (Paris)*, F. Mayro (WMF, New York), R. Yimsut (Seattle), Susan Sherwood (U.S. National Park Service, Washington, DC), Terry Schnadelbach, landscape architect (New York), K. Eirinberg, rapporteur (CSIS, Washington, DC).

*participation by telephone, if necessary.

Observers

Jamie James, *Science* Magazine
John Noble Wilford, *The New York Times*
Rob Bingham, *The New Yorker*
Tim Folger *Discover*
Claire Whitaker, The Kreisberg Group
Minja Yang, World Heritage List, UNESCO
Mary Hardin, Jet Propulsion Laboratory, NASA, Pasadena
Jon Calame, Columbia University, GSAPP
Katherine Rodway, Columbia University, GSAPP
Professor Archer St. Clair Harvey, American Academy in Rome
Oszkar Fuzef, *Mepszabadsag*

APPENDIX B

PROPOSALS OF DR. ELIZABETH MOORE AND MR. TERRY SCHNADELBACH

ARCHAEOLOGY [HYDROLOGY]

Pilot study of using SIR-C/X

Title:

Hariharalya & Khmer water management
ancestral veneration and the prehistoric-to-historic interface

A. Methodology

My interest is to assess the capability of the radar imagery, on its own as an investigative tool. As well as visually interpretative images, I would like to see spatial and chronological outputs computer.

1. search for the **attributes** through **statistical means** (such as factor or principal components analysis) which were central to the development of the urban area and **rectilinear** water management features such as *barays* , moats, canals and dikes.

2. compare this to the core features of the **irregular** prehistoric mounds

3. hypothetically reconstruct the **incremental development** between the historic and prehistoric phases

4. describe the **fluctuating balance** over time between manmade and natural elements

The sites below are well known to me from previous study of other imagery (vertical & oblique aerials 1945,1954,1966,1993; SPOT, etc.) and ground survey. A future phase might compare the results with this other imagery.

B. Scope

a) 9th century AD palaces

The Roluos temple group. 12 kilometres southeast of Angkor. forms the central north-south axis of the 9th century AD city referred to in inscriptions as Hariharalaya. The focus of this study is the rectangular [400x500 metre] temple enclosure of Preah Ko. This moated *enceinte* was dedicated in AD 887, by King Indravarman in honour of his ancestors. One aim of the study is a detailed analysis of this enclosure, in particular to define suspected palace remains. Comparison may be made with the similar enclosure of Prei Monti, another contemporaneous, or slightly earlier temple and palace site lying to the south of Preah Ko.

b) The 9th century AD city

The city of Hariharalaya was abandoned in the 10th century AD, when the capital moved northwest to Angkor. At this new location, layer upon layer of temple building and water management structures were constructed, well into the 13th century AD. We therefore have left today at Angkor a complex palimpsest of remains. In contrast, Hariharalaya was only occupied as a seat of royal power for about 100 years. It is the first urban site of the Khmer erected after the instigation of the god-king or *devaraja* cult. This fact, combined with its short occupation makes the city a unique physical manifestation of the first flowerings of that cult. In particular, we see at Hariharalaya the intimate and essential connection between king, water and ancestral veneration.

c) The prehistoric mounds

The remains of Hariharalaya today are situated in the midst of a number of prehistoric habitation mounds, irregular in shape, with their form derived from the local topography. The dates of the prehistoric occupation have yet to be determined - the mounds may have been occupied for several thousand, or several hundred years, prior to the founding of the new city in the 9th century AD. All are located along

present or past river courses. The site of Phum Stung, on the northeast corner of the Indratataka reservoir or *baray*, is of particular interest for its relationship to Hariharalaya. Just as water control and ancestral veneration were at the heart of historical kingship, veneration of ancestral spirits and manipulation of water courses characterizes the prehistoric mound dwellers.

d) The prehistoric-to-historic interface

As described above, both prehistoric and historic occupation and water management features are present at Hariharalaya. Thus contained within this zone is the moment of change, when in morphological terms, the water management structures shifted from an irregular to rectilinear form. This change in form exemplifies a revolution in cultural and royal contexts, for it represents the adoption of Indic norms of state and kingship. The interest of this study is to demonstrate the extent to which this grew out of existing animistic cults and water management techniques.

C. "Objects" for GIS

a) 9TH c. Palaces

1. * Preah Ko & Preah Monti
   palace
   off set of temple at front of enclosure
2. Stung Roluos canalization

c) Mounds

General

1. presence of moat and earthworks
2. appearance before rectangular water features, eg. old river courses
3. Contour/ elevation to 1 metre

Hariharalaya

1. Phum Stung mound - moat/earthwork presence
2. Phum Roluos Chas and other nearby mounds

d) Ak Yum-- historical urban comparison

1. terrain with only Prei Kmeng
2. terrain with only Ak Yum and associated sites

e) Puok valley -- prehistoric mound comparison

1.relation to old Stung Siem Reap
2. micro elevation/contour
3. seasonal changes
4. Lovea, Reul, Romiet

PROPOSAL OF TERRY SCHNADELBACH
Ecologist/Landscape Architect

Presented at the First Scientific Roundtable
Radar Imaging Survey of the Angkor Eco-Site
February 2, 1995

Geology

Surface Features

Define the exact surface geological features, particularly textural changes.

Specifically, define the bedrock versus alluvial versus sedimentary geological features.

Define the variations in soil type within alluvium stratum/bands.

Define the width of wet phase soils within drainage ways.

Subsoil Conditions

Define the subsoil conditions.

Penetrate the temple complex sands for variations in depth, ground water, soil horizons, and archaeological landscape elements.

Penetrate recent alluvial deposits for depth, distribution, and soil horizons - areas of deposit in the eastern end of the Western Baray, the alluvial delta of Siem Reap, and the delta of the Tonle Sap.

Hydrology

Locate "mineral licks" within the upland terraced slopes. These and wetland/watering holes that are primarily springs and ephemeral springs that carry seepage from bedrock stratas.

Define the internal drainage of the rhyolite sandstone deposits.

Locate springs within the Eastern Baray area.

Vegetation

Define major changes in surface vegetation.

Define rice paddies by density of rice and productivity differences.

Define the dypterocarpus forest -- existing and potential -- cooperation of existing stands and their soil with unforested zones with same soil conditions.

Define stands of large wood content -- trunk sizes.

Define stands with full four layers of vegetation.

Define stands with ground or 3-layer vegetation.

Define composition of mixed stands.

Locate all bamboo crops versus natural areas.

Locate termite mounds.

Define trails within vegetation zones - ascertain if possible.

Differences in use -- (Daily, Seasonal) (Elephant versus human).

Locate, if possible, carbon cycle changes.

Determine water circulation within the Tonle Sap lake.

APPENDIX C

PROPOSAL OF THE WORLD MONUMENTS FUND AND THE ROYAL ANGKOR FOUNDATION TO NASA'S JET PROPULSION LABORATORY

An International
Preservation Organization

WORLD MONUMENTS FUND

174 East 80th Street
New York, New York 10021
Telephone: 212 517 9367
Telefax: 212 628 3146

15 July 1994

Dr. Diane L. Evans
Project Scientist
NASA
180703 Jet Propulsion Laboratory
Pasadena, CA 91109

URGENT

telefax 818-393-1492

Dear Dr. Evans,

Per your request we are providing a more detailed application to NASA for including the Eco-Site of Angkor in north central Cambodia as a SIR-C/X-SAR Supersite in the upcoming August 18th Space Shuttle *Endeavor* mission. The following application serves to supplement previous telephone and fax correspondence on the subject of radar documentation at Angkor since March, the time of the last mission.

The short title of our project is termed *Eco-Site of Angkor Radar Imaging Survey*. The project is part of an on-going investigation which is termed "Eco-historical Cycles of Human Civilization and its Environment: the balance of manmade and natural elements at World Heritage Sites". The four specific study areas are the region referred to as the Eco-Site of Angkor, and three temple sites within: Preah Khan, the Bayon and Preah Ko.

World Monuments Fund (New York) with strengths in architectural monuments conservation, and the Royal Angkor Foundation (Budapest) with special interests in conservation and geographical information systems have specially formed a scientific collaborative for this survey. WMF and RAF strongly believe that SIR-C/X-SAR data would provide an immeasurable aid to a number of recently re-activated archaeological and geographical research programs at Angkor. It would facilitate, for the first time, a coherent and comprehensive analysis of both surface and sub-surface features particularly environmental, archaeological and hydrological anomalies.

The fact that Angkor today is a vast city of stone, over a thousand years old, situated on relatively soft soil makes the possibilities of discovering new surface and sub-surface anomalies using radar imaging a highly likely prospect. Thus the *Eco-Site of Angkor Radar Imaging Survey* could also satisfy the NASA mission objectives concerning the provision of useful geological and ecological development patterns at selected areas of earth's surface in Indochina, an area of the world which received relatively little attention in the March mission.

Some recent medium resolution aerial photogrammetry and infrared documentation of Angkor provided by the French have answered a number of questions pertaining to geography and has raised others. It is felt that the vegetation and

topsoil penetration abilities of SIR-C/X-SAR data will be the perfect complement to the base mapping of the site which is in hand. Such an investigation could revolutionize our present understanding of the archaeological potential of Angkor and questions pertaining to the city's morphological development. For those of us working to conserve and present this World Heritage Site the radar scan data provided by NASA should aid the research efforts of well over 150 scientists, scholars and researchers in the fields of geography, hydrology, archaeology, history, land conservation, architectural conservation, site management, tourism and education. Scientific research using radar images of this significant historic site will present an entirely new research methodology for Angkor, which is generally regarded as the paradigm of its type.

The WMF/RAF collaborative guarantee that research data provided by NASA will be used solely for constructive historic cultural resource management purposes and will be accessible only to qualified individuals making serious scientific inquiries. NASA will always be appropriately and respectfully credited for its generous assistance to the Angkor research project team.

We are most hopeful that NASA will include Angkor as a 'Supersite' on the upcoming mission. If there are any questions, please do not hesitate to contact me or project co-director Janos Jelen in Budapest at tel./fax 011 (361) 122 4270.

Thank you for the cooperation and encouragement you have given us thus far.

Sincerely,

John H. Stubbs
Program Director

encl

An International
Preservation Organization

WORLD MONUMENTS FUND

174 East 80th Street
New York, New York 10021
Telephone: 212 517 9367
Telefax: 212 628 3146

RADAR IMAGING SURVEY OF THE ECO-SITE OF ANGKOR

Introduction

The Eco-Site of Angkor, the historical capital of the Khmer civilization from the 8th to the mid-15th century, extends over an area of approximately 5000 square kilometers in north central Cambodia. Renowned for the beauty of its sculpture, the magnificence of its architecture, and the extraordinary engineering achievement represented in its vast hydrological works, the Eco-Site of Angkor is listed as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization (UNESCO).

Today, after two decades of neglect, there is an ongoing international effort to conserve and present the Eco-Site of Angkor as a unique achievement of man and as a symbol of the history and cultural identity of the Cambodian people.

World Monuments Fund and the Royal Angkor Foundation are conducting two scales of research at Angkor: 1) special investigations of the ancient hydro-engineering system and related historic urban development matters, and 2) detailed above-, at-, and below-grade archaeological research and documentation at the representative temple sites of Preah Khan, Preah Ko and the Bayon. It is strongly felt that remote sensing investigations of these sites using data from NASA's SIR-C/X-SAR Earth Imaging Radar system would provide fruitful results. Some of the questions we seek to answer have vexed archaeologists and others since Angkor was 're-discovered' in 1852.

Radar Scan Location Requests

WMF and RAF respectfully request that NASA conduct SIR-C/X-SAR scans of the following four locations:

Project supersite:
The Eco-Site of the Angkor region (an approximate 5000 km area)
13°04' - 13°45' Latitude, 103°35' - 104°15' Longitude

Proposed swath centers:
The temple of Preah Khan
13°27'36.6" Latitude, 103°52'30.6" Longitude

The temple of Preah Ko
13°20'28.8" Latitude, 103°58'30" Longitude

The temple of Bayon
13°26'20" Latitude, 103°51'25" Longitude

Polarimetric requirements: NASA, please advise. The WMF/RAF team seeks highest imagry resolution which is technically possible for the three (3) above mentioned temple sites. The same is needed for the vastly larger 'Supersite' of the general Eco-Site of Angkor.

Executing agencies: World Monuments Fund, New York, USA, and Royal Angkor Foundation, Budapest, Hungary

Investigators: J. Stubbs (WMF, New York), J. Jelen (RAF, Budapest), Dr. P. Logan (CERS, Los Angeles), J. Sanday (WMF, Nepal), Dr. E. Moore (Univ. of London, UK), Prof. J. Allan (Univ. of London, UK), I. Klinghammer (ELU, Budapest), Dr. C. Jacques (Ecole Pract. des Hautes Etudes, Paris), Dr. C. Jest (Paris), Kevin Sarring (Chicago), R. Yimsut (Seattle).

Affiliations: School of Oriental and African Studies, and Geography Department, University of London; Eotvos Lorand University, Faculty of Science, Institute of Environmental Physics, Dept. of Cartography, Budapest; the Schools Archaeology and Architecture, University of Beaux Arts, Phnom Penh; and the Ministry of Culture, Royal Cambodian Government, Phnom Penh.

Project Description and Objectives: The main purpose of the investigation is to identify environmental change in the Supersite's Quaternary geomorphology and its biomass, and artifactual gaps which have been suspected but not confirmed, ranging from sculpture to monuments, canals and roads. Included are not only the superimposition of temples, but important earlier settlements destroyed in the construction of enormous *barays* or reservoirs.

The construction of Angkor was an immense technological achievement. While cities are generally sustained by an already established agricultural prosperity, Angkor was conceived to create its own prosperous agriculture. Because the land beyond Angkor is not well watered naturally, gigantic barays were built to store water, fill the moats and canals in the city and irrigate the fields beyond. From these great reservoirs, navigable canals conveyed water to moats encircling the temple complexes and provided a mode of transportation for people and goods. Water flowed south from the high points where the barays were located to the Tonle Sap (a great lake). These irrigated tracts provided fertile land where several crops were grown each year, which supported the strength and prosperity of the Khmer empire. Today the vast hydrological system of Angkor is almost entirely in disuse and its original system of operation is little understood.

In examining change in form and vegetation, critical features are found in the south to north progression of lake, plain, and mountain zones which comprise the setting of Angkor. These incorporate variations of the perimeter and depth of the Tonle Sap, the present classification of the plain into recent and ancient alluvial zones, natural and manmade diversions of river courses, and the effects of constructing the four major barays.

The data generated by the project would provide an unprecedented lever enabling us to 'lift up' the present setting of Angkor and its remains, so as to expose its roots or origins. If the balance of natural and man-made alterations to the Angkor zone at regular intervals over the last seven thousand years could be charted, both the evolution of the urban center ('Angkor' means 'The City') and its demise would revolutionize our knowledge about the history of Angkor. It could also

provide a more supple framework for conceptualizing the site: more than a palimpsest of temporal layers, we could begin to comprehend and interpret the overlapping geographical and cultural microzones, and thereby uncover not just the effects, but the forces which led to the remarkable concentration of man-built cultural patrimony and current human activity which we call 'Angkor' today.

The data from SIR-C/X-SAR could be integrated into the existing Angkor database, the Geographical Information System (GIS), developed by Royal Angkor Foundation and further expanded by the Zoning and Environmental Management Plan (ZEMP) for the site of Angkor, organized by the UNESCO. If it is possible to calculate temporal changes from the data then it should be feasible to extrapolate historical cycles first at Angkor and later at other World Heritage Sites elsewhere in the world.

The GIS, which the Royal Angkor Foundation established through ZEMP is primarily 'present time' data: population, roads, rivers. Some elements have begun to construct a temporal framework: aerial photos from 1945, 1954, 1992; satellite images; maps from 1907, 1927, 1973; etc. The chronology of Khmer civilization and its antecedents has preoccupied many researchers for over a century, though for the present purpose, the temporal framework labels of 'prehistoric', 'early' and 'late Angkorian' suffice. Of key importance is the relation of some of the over 1000 archaeological sites at Angkor to water features over time.

Concerning geomorphological change, certainly the lake bed, the soils of the plain, at the present and past river courses are the easiest to document, but if data were collected over a period of time, say five years, perhaps that could be used to project change over 500 years. Here we enter unknown territory, stretching the possibilities of SIR-C/X-SAR data and our hypotheses to their limits. The future of such a methodology is just breathtaking, a retrospective assessment of great human interventions into nature based on 'real-time' archaeo-environmental measurements.

Description of Organizations and Key Personnel

World Monuments Fund Established in 1965 the World Monuments Fund is a not-for-profit private organization based in New York, USA whose purpose is to assist in the preservation of man's most significant artistic and architectural heritage through research, planning, development and funding of major conservation projects worldwide. WMF has worked at Angkor since 1989. For the past four years WMF has worked to conserve and present the monastic complex of Preah Khan which is considered to be among the most significant of the temple complexes at Angkor. In March of 1994 the Royal Cambodian Government asked WMF to oversee conservation activities at four other major temple sites and for WMF field personnel to play a major role as advisors to the government in the planning of conservation interventions throughout the entire archaeological park.

Royal Angkor Foundation The Royal Angkor Foundation is a recently established not-for-profit organization based in Budapest, Hungary whose purpose is to revitalize the material and intellectual heritage of the ancient culture of Angkor. To achieve its goals the Foundation advocates increased international acknowledgment of the culture and civilization of Angkor through scientific research. RAF's activities to date have concentrated mainly on an eco-cultural hydrological history of the Khmer Empire, comparative cartography of the Angkor region and the consolidation of all available information on Angkor into a Geographical Information System (GIS). RAF personnel played a major role in the development of a Zoning and Environmental and Management Plan (ZEMP) for Angkor.

Principal project personnel comprising the WMF/RAF collaborative include:

John Stubbs - Program Director, World Monuments Fund
At the headquarters of WMF in New York, John Stubbs is coordinator of the various campaigns of work at Angkor. He has participated in field work at Angkor since March 1992 where he has contributed to the development of project planning and conservation policies on site. Trained as a conservation architect he has been in practice for over 20 years. He presently teaches part time as Adjunct Associate Professor at Columbia University's School of Architecture and Historic Preservation. His educational experiences included serving as surveyor and illustrator on archaeological excavations in Italy and Egypt. Graduate and post graduate training included a masters thesis on conserving and presenting 'in situ' archaeological remains and course work in archaeological prospecting at the Lerici Foundation in Rome.

Janos Jelen - Chairman, Royal Angkor Foundation
Janos Jelen is a career diplomat with a long-standing interest in the political and cultural history of Indochina. Over the past five years he has directed the incorporation of Angkor on the Geographical Information System, which is the first of its kind.He was also responsible for incorporating the mapping of Angkor as an integral research activity of the Division of Geography at Lorand Eotvos University in Budapest. He founded the Royal Angkor Foundation in 1992. His recent book *Angkor and the Khmers* is considered one of the very best of the modern overviews of Angkor available. Janos Jelen has served as emissary for Hungary in several countries and received high acclaim for his work as Deputy Director of United Nations Transitional Authority operations in the Siem Reap province in Cambodia where Angkor is located.

Dr. Pamela Logan - Science Director
Dr. Logan presently holds a similar post as science director at the China Exploration & Research Society (CERS) in Los Angeles. Her role in the Eco-Site of Angkor Radar Imaging Survey is to use photographic and aerial imaging to help identify man-made constructs at Preah Khan, Preah Ko, the Bayon and other sites. She has worked with John Sanday, WMF Preah Khan Project Director, in Tibet and at the Palpung Monastery near Derge (a CERS project). Dr. Logan holds a doctorate in Aerospace Science from Stanford University and received her Bachelors and Masters degrees in Mechanical Engineering from the California Institute of Technology.

John Sanday - Conservation Architect
Since the inception of the WMF program in Cambodia in 1989, John Sanday has been involved in promoting and managing the project for WMF and has led all the missions. His main skills are in the planning and development of the special sub-projects and in the mobilization of the site activities and workforce. John Sanday has over 25 years experience conserving historic buildings and sites. He established his architectural practice in Katmandu, Nepal in 1972 and has since conserved several dozen sites in Southeast Asia. His career accomplishments include serving as Program Officer for the J. Paul Getty Trust in Los Angeles.

Corneille Jest - Environmental Scientist
Dr. Jest is Maitre de Recherche Centre National de Recearche Scientifique and oversees CNRS's general research program for the Himalaya and the Karakoram. Dr. Jest was a member of the first WMF team to Cambodia in 1989. He has contributed widely to WMF's understanding of the environmental aspects of the Preah Khan project as well as being a liaison between Cambodian officials and the French contingent with common interest in Angkor.

Dr. Elizabeth Moore - Archaeologist
Dr. Moore is a specialist in Khmer art and in remote sensing in archaeology in Cambodia. Dr. Moore is on the faculty of the Department of Art and Archaeology at the School of Oriental & African Studies at the University of London. She has written widely on the topics of hydrology and urban development at Angkor and served as the archaeological consultant to Unesco's Zoning & Environmental Management Project. Her special contributions to the ZEMP were in the areas of habitation and hydraulic features and the development of the GIS database. She has also participated in a wide range of projects concerning archaeology and hydrologic development in various locations in Thailand and Myanmar.

Professor J. Anthony Allan - Geography
Professor Allan teaches in the Department of Geography at the School of Oriental & African Studies at the University of London. His specialties include water management, land evaluation, remote sensing and global monitoring and he has published articles and reports including "The value of Earth observation data in Logica Space and Communications" in *Issues in Earth Observation data Policy for Europe* (Report for DG XII of the Community for the European Communities, London. 1993). Professor Allan serves not only as a member of the Governing Body and Academic Board of SOAS but also the Chairman of the Computing Committee.

Claude Jacques - Historian
Dr. Jacques is one of the most prominent historians and epigraphers to have studied the Khmer Kingdom and Angkor. His contributions to the World Monuments Fund's work at Angkor have ranged from advising on the chronological development of the site to translation of the famous Preah Khan Stele. Professor Jacques is presently Directeur d'Etudes at l'Ecole Practique des Hautes Etudes, Paris. He has published widely on the subject of Angkor and the Khmers and serves as advisor to nearly all important scientific and governmental authorities with interests in Angkor.

Kevin Sarring - Architect/ Archaeologist
Kevin Sarring is an architect and archaeologist who has worked on important excavations is Pompeii and Rome. His role in WMF's Angkor missions is to document the sites in their 'as found'state and to record the progress of the various conservation sub-projects. To date he has produced numerous drawings with the help of archaeological students from the Department of Archaeology, University of Beaux Arts in Phnom Penh. Mr. Sarring's accomplishments as a restoration architect include serving as restoration coordinator for the Raffles Hotel in Singapore. He is a graduate of Columbia University's Graduate Program in Historic Preservation.

Ronnie Yimsut - Landscape Architect and Forester
Ronnie Yimsut, a Cambodian-American, whose chief responsibilities include surveying and planning for the conservation of the ecology of the five sites at Angkor where WMF is working. For WMF and for numerous other scientific teams working at Angkor he has opened a series of new perspectives with regard to the environmental context of the various man-built structures. Ronnie Yimsut holds degrees in Forestry and Landscape Architecture from the Universities of Oregon and Washington.

APPENDIX D

EXCHANGE OF LETTERS BETWEEN THE HON. VANN MOLYVANN, SENIOR MINISTER OF STATE FOR CULTURE AND FINE ARTS, COUNTRY AND URBAN PLANNING AND CONSTRUCTION, KINGDOM OF CAMBODIA AND WORLD MONUMENTS FUND/ROYAL ANGKOR FOUNDATION

KINGDOM OF CAMBODIA

ROYAL GOVERNMENT

NATION - RELIGION - KING

No : ...326.....

To : Mr. John H. STUBBS
Program Director, World Monuments Fund
174 East 80th Street, NEW YORK, U.S.A.

FAX : (212) 628 3146

Phnom Penh, 22 July 1994

Dear Mr. Stubbs,

Mr. John Sanday, Project Director of the Preah Khan Conservation Project, informed me of your recent contact with NASA's space shuttle Endeavor, in an attempt to obtain a radar scan of the whole of Angkor, as well as Preah Khan and Prah Ko.

The Royal Government of Cambodia sincerely thanks the World Monuments Fund for its generous efforts, of which it entirely approves. It hereby presents a request for NASA to consider the possibility to perform such radar scans of the entire Monumental Site of Angkor, which has been classified in the list of the World Heritage in December 1992.

The results obtained will be of utmost importance for our country for the updating of all data related to the Monumental Site of its patrimony and for the implementation of the international campaign for the preservation, conservation and development of this rich archeological Site.

With best regards,

Yours sincerely,

Yann Molyvann
Minister of State
for Culture and Fine Arts,
Country and Urban Planning
and Construction.

Office of the Council of Ministers

Phone : (855-23) 27895/855 18810552 / Fax : (855 23) 26 127

"A VISION WITHOUT A TASK IS BUT A DREAM,
A TASK WITHOUT A VISION IS A LEAD OFFICE,
A VISION WITH A TASK IS THE HOPE OF THE WORLD."

THE
ANGKOR
FOUNDATION

CONCORDE PROGRESS
H.E. SOCIAL CONCORD,
DEVELOPMENT OF THE REPUBLIC OF FRENCH AND
PROGRAMME SEVEN OF HIS MAJESTY NORODOM SIHANOUK,
KING OF CAMBODIA

20 February 1995

H.E. Vann Molyvann
Senior State Minister
for Culture and Fine Arts,
Country and Urban Planning
and Construction

Your Excellency,

We are pleased to write you at the close of a symposium held at Princeton, the First Scientific Roundtable on the Radar Imaging Survey of the Angkor Eco-Site, hosted jointly by the Royal Angkor Foundation (Budapest) and the World Monuments Fund (New York).

Scientists from the National Aeronautics and Space Administration (NASA), in Pasedena, California presented the technology. Assessment on the part of Dr. Elizabeth Moore (SOAS, University of London), Dr. Bela Markus (Head of Geoinformatics at the University of Forestry and Land Survey, Szekesfehervar, Hungary) and Mr. Terry Schnadelbach (landscape architect and ecologist, New York), may suggest that we have an extremely exciting new tool for investigating the archaeology, hydrology and ecology of Angkor as well as a teaching tool for the new generation of Khmer GIS experts. A report on the proceedings is underway and we plan make it available for your perusal very soon.

Dr. Moore and Mr. Jelen plan to be in Cambodia at the end of March thru early April to attend the Technical Committee Meeting of the ICC. After the meeting we would like to propose to you that a Radar Imaging Workshop be held at the documentation center of the Institute of Khmer Culture within the Angkor Conservation compound, if it is available at that time (or in any other convenient place that is appropriately equipped). The group of GIS fellows educated during the last six months in Siem Reap could be introduced to the new technology. Their level of knowledge could also be identified for further training and related activities. We envisage the participants would be by invitation and include Cambodian computer experts, plus selected foreign technical and archaeological experts.

We believe strongly that the new NASA data and technology should be implemented quickly within Cambodia, by experts there, working where appropriate with foreign counterparts. We would hope very much that you might consent to serve as Honorary Chairman of this workshop. Your position and experience would help to steer the proper course for use of this tool for Cambodia.

We hope this proposal meets with your approval and satisfies some of the issues you raised in your letter dated February 1, 1995.

Sincerely yours,

Janos Jelen
Chairman of the Board of Trustees
Royal Angkor Foundation

John Stubbs
Program Director
World Monuments Fund

APPENDIX E

PROJECTS OF THE WORLD MONUMENTS FUND AND THE ROYAL ANGKOR FOUNDATION IN CAMBODIA.

World Monuments Fund in Cambodia

The World Monuments Fund, based in New York City, is a private non-profit organization that sponsors worldwide preservation activity. Its goal is to bring together both public and private sponsors to assure the survival of the world's most outstanding artistic and architectural treasures. This work focuses on the conservation of monuments and works of art that are in danger of loss or destruction. Through funding from its membership and philanthropic sponsors, WMF contributes technical and financial support to help save these works. Founded in 1965, WNF has completed more than 100 major projects in 29 countries around the world.

The World Monuments Fund sent its initial field mission to Angkor in December 1989, among the first western experts to visit Cambodia after almost two decades of civil war, chaos, and genocide. WMF's first mission surveyed Angkor and evaluated the damage suffered by some of the world's most sublime architectural treasures during the years of horror. Contrary to expectations, the team found that the temples had been relatively unaffected – frozen in a kind of majestic stasis, with only minimal random damage attributable to the war. It was rather the people of Cambodia who had suffered the greatest deliberate destruction, The entire educated population had been eliminated, and also the universities and libraries. Those with specialized training in architectural conservation had perished, and only a handful of the former workers at the site had survived. Angkor was virtually unattended, the French conservation facility in shambles. WMF's team recommended that all future work at Angkor should emphasize training Cambodians to enable them to care for their great treasures.

As the country emerged from isolation, the Cambodian government urged WMF to organize a pilot program to address some of the key problems in preserving Angkor. The site selected by WMF was Preah Khan, a large temple complex at the perimeter of the Angkor archeological zone, engulfed in a lush jungle. In particular, the site was appropriate to WMF's objectives – the training of young Cambodians architects for the task of preserving Angkor, the development of standard techniques for on-site work, and the preparation of Angkor to receive international visitors.

One of several magnificent 12th-century temple cities built during the reign of Jayarvarman VII (who also constructed the incomparable Bayon temple, the gates of Angkor Thom, and the sites of Banteay Kdei and Ta Prohm), the monastic complex of Preah Khan – meaning "sacred sword" – commemorates an important victory in c. 1180. This site of triumph was to become a place of learning and syncretic religion, with individual chapels dedicated to Buddhism, Saivism, Vaisnavism and ancestor worship. Five hundred and fifteen divinities were installed among the teachers and pupils in the complex, according to a famous stele recording the dedication of the temple. The walled site occupies fifty-six hectares (approximately one-third the size of central Park), and included living quarters, independent pavilions, a central enclosure with a tower, and surrounding porticoes which contain a stupa. The impressive, grandly proportioned architectural remains are graced with beautiful sculpture and bas-reliefs of divinities and dancing apsaras.

WMF's annual missions to Preah Khan began in the autumn of 1990. Each year, five of the ten international experts spend three to four months in the field, occupied with training students in survey and architectural inventory, conducting scientific and technical studies, reinforcing collapsing buildings, and overseeing the Cambodian workers (now numbering around one hundred). In the four seasons since the work began, the entrance causeways have reemerged from the underbrush, revealing long axial vistas; fallen stones have been cleared from passageways and courtyards; major sculptures have been discovered; areas threatened by imminent collapse have been stabilized. In the winter of 1993, an entire pavilion (the Dharmasala) was discovered in the jungle, establishing a new priority for conservation at the site. During the winter of 1994, a precariously balanced portico at the eastern entrance was repaired under the direction of a Macedonian engineer. The continuing work enables visitors, now numbering several thousand a year, to understand and enjoy the site.

The goal of the WMF's ten-year program is to conserve Preah Khan as a partial ruin. The time-worn qualities of the site are to be respected and preserved as much as possible, new interventions limited to supporting the existing architectural fabric, and the natural environment sustained. During the course of the work, WMF's field team will consult with the Cambodian Government on broader issues, ten Cambodian students will receive otherwise unavailable training and experience as future conservation architects, and a new generation of architects and craftsmen will learn the traditional means of preserving the Angkor sites.

WMF's work at Preah Khan is not just the preservation of an architectural jewel. Reestablishing the process of care for the site is strengthening the sense of stability and security in the local population, providing jobs, new expertise, and contact with the outside world. For the larger Cambodian community, Angkor is at once a symbol of identity, a touchstone of the past, and a basis on which to build the future. Restoring these monuments becomes, in this context, a fundamental step in the restoration of peace and prosperity to the country.

The work of WMF at Angkor is supported entirely through contributions. The Cambodian government provides in-kind support for WMF's work at Angkor through improvement of access to the site and through the provision of security and coordination. The Preah Khan program is part of the international campaign for Angkor organized under the auspices of UNESCO.

Milestone Donors

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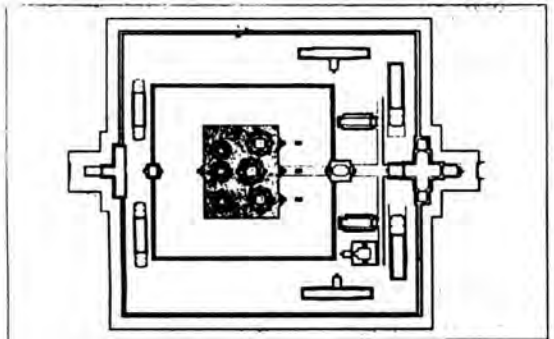
THE FOUNDATION

The Royal Angkor Foundation is a non-profit organisation that is unique in the world by its exclusive focus on the ancient Khmer civilisation of Angkor.
The Foundation is based in Budapest, the capital city of Hungary, a small state in the heart of Europe. It was established in 1992 following the signature of a Letter of Intent, first signed by His Majesty Norodom Sihanouk, King of Cambodia and later by Árpád Göncz, President of the Republic of Hungary.
In February of 1994, with the kind approval of His Majesty Norodom Sihanouk, King of Cambodia the name of "The Angkor Foundation" (TAF) was changed to "Royal Angkor Foundation." (RAF).
Both countries, despite their geographical remoteness, have rich historical cultures and share a determination to survive under the most destructive conditions.
The main objective of the Royal Angkor Foundation is to revitalise the material and intellectual heritage of the ancient culture of Angkor. To achieve its goal, the Foundation advances a better international acknowledgement of the culture and civilisation of Angkor and encourages further scientific research. By that the Foundation wishes to nurture the national identity of the Cambodians.
The activities of the Royal Angkor Foundation until now have been concentrated mainly on three areas: an eco-cultural, hydrological history of the Khmer Empire, a comparative cartography of the Angkor region, and the consolidation of all available information on Angkor into a modern GIS (Geographical Information System).
All results reached by the experts of the Royal Angkor Foundation have been contributed to UNESCO in the interest of furthering international intellectual cooperation for research in and the preservation of Angkor.
The system design of the Angkor GIS, its basic equipment in the Siem Reap sub-Office of UNESCO, as well as the initial data input together with the first comprehensive study of historical hydrology ever written on the Angkor region has laid the ground for a new approach to the scientific interpretation, safeguarding and development of the Angkor region. Together with contributions of other experts, the work of the Royal Angkor Foundation has been instrumental in the formulation of the Zoning and Environmental Management Plan for Angkor (ZEMP) under the auspices of the Royal Government of Cambodia, the World Heritage Committee and UNESCO.
The small and hardly noticeable contribution of the Royal Angkor Foundation represents the creative, diligent and ambitious way in which small and remote nations can and, in fact, should help each other.



Chairman of the Board of Trustees: János JELEN
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THE PREAH KO PROJECT 1994

"A VISION WITHOUT A TASK IS BUT A DREAM,
A TASK WITHOUT A VISION IS A DRUDGERY,
A VISION WITH A TASK IS THE HOPE OF THE WORLD."

ROYAL ANGKOR FOUNDATION

The Project

Preah Ko (Sacred Cow) is situated near the modern town Roluos, 12 km east from Siem Reap city, as part of of the Angkor World Heritage Site in Cambodia. The project entails an urgent intervention by saving on the six central brick towers the remaining 60-80 m² of stucco, cleaning and consolidation of sandstone elements, repair of brickworks and removal of encroaching plants.

Training of the employees of the Angkor Conservation Office in the treatment and restoration of stucco and sandstone works is one of the most important parts of the project. They should take over the highly specialised work to be carried on at other similar sites by technics applied and material used in Angkor.

The project proposal was introduced by the German government and endorsed by the Technical Advisory Committee of the Supreme National Council of Cambodia on 17 May 1993 with the active participation and support of UNESCO within its general programme to preserve and protect Cambodia's cultural heritage. The proposal was confirmed again during the first meeting of the newly established International Coordinating Committee on 21 December 1993 and was approved by H. E. Vann Molyvann, state minister, President of the National Council of Culture on 9 February 1994.

The project duration is one year. This includes preparatory work in Hungary, Germany, Italy, Thailand and Cambodia. The most urgent conservation itself will take place in 1994 from mid January until the end of March with the participation of an international team of architects, restorers and surveyors from France, Guatemala, Hungary, Italy and the United Kingdom. The task is under way. It is organized by the Royal Angkor Foundation (Budapest, Hungary) and financed by the German Government with a generous grant of about 127 000 USD.

The Royal Angkor Foundation is performing the task in close cooperation with the Angkor Conservation Office, the representatives of EFEO (École Française d'Extrême Orient) and the UNESCO sub-office in Siem Reap and Phnom Penh. Valuable help came from the Ministry of Culture and Fine Arts, the National Museum and its Library in Phnom Penh. A student from the Royal University of Fine Arts has joined the Preah Ko Team as well.

The History

Indravarman I ruled this part of Cambodia between 877 and 889, some years prior to the date when the Hungarian people conquested the Carpathian Basin in Central Europe, the region where Hungary is situated now. Indarvarman I was a king who showed extraordinary capabilities and was able to consolidate and push forward the achievements of his predecessors by a remarkable development programme, which included:

- the sponsorship of irrigation works in honour of his subjects and the watery divinities of the soil: "In five days, I will begin to dig."
- the installation of statues of his parents and other ancestors in the guise of gods: Indravarman I sponsored statues of his parents, his mother's parents and of Jayavarman II and his wife, depicted as embodiments of Shiva and his consort in the stuccoed brick temple complex known today as Preah Ko (The Sacred Cow)
- the erection of a temple-mountain in the form of a stepped pyramid – known today as Bakong – most probably, it served as a mausoleum after his death.

The charming temple of Preah Ko was completed and inaugurated in 879. It represents the so-called "Roluos style" of Cambodian architecture. It includes several features that became important later (e.g. enclosing temples in a series of concentric moats and walls) appeared here for the first time. The sophisticated carving and the fine floral motifs suggest that these skills had been developed earlier by carving wood.

APPENDIX F

SELECTED MEDIA COVERAGE

THE NEW YORK TIMES, TUESDAY, FEBRUARY 7, 1995

Space Radar to Study Khmer Temples at Angkor

By JOHN NOBLE WILFORD

PRINCETON, N.J.

ARCHEOLOGISTS, who make a practice of demystifying exotic cultures of the long ago, had their hands full here last week comprehending a very modern one that could be a valuable ally in their investigation of the distant past.

At first, it was one of those awkward encounters between two cultures — not across the wide gulf between science and the humanities, as elucidated by the scientist-writer C. P. Snow in the 1960's, but between two quite different sciences: archeology and the technology of remote sensing from space.

After two days of deciphering each other's arcane language, the archeologists managed to recognize how their needs could be met in part by the new technology's capabilities. The result was a plan for using space radar to advance the study of one of the world's most magnificent archeological sites, the Khmer temples of Angkor in the remote jungle of northern Cambodia.

The archeologists hope that a detailed analysis of radar pictures, taken of the Angkor region by an American space shuttle last October, will open their eyes to more ruins hidden in the jungle and will give them a better understanding of the total environment that supported this sacred and administrative capital of the Khmer civilization from the 9th through the 13th centuries. Many of the palaces, temples, moats and waterworks were constructed at the time Europe was building its great cathedrals.

"I came here mildly curious, and a little skeptical," said Dr. Elizabeth Moore, a University of London archeologist who is directing excavations at Angkor. "Now I'm quite excited. This is a new methodology. We can develop new research goals and new ways of looking at the site."

Scientists at the Jet Propulsion Laboratory in Pasadena, Calif., where the imaging radar system was developed, came away from their encounter with archeologists with a greater awareness that their technology has more potential uses, and eager users, than they had originally conceived. The primary purpose of the experimental flights by the National Aeronautics and Space Administration was to test the radar's ability to monitor natural and human-induced environmental changes taking place on Earth.

Dr. Diane L. Evans, chief scientist of the radar project, promised to supply the archeologists with the raw data from which the radar images were produced and advise them on how to filter and analyze the data to extract information not immediately obvious in the pictures. If a proposal for another shuttle flight with the radar is approved, she said, the needs of archeologists working at many places around the world would be carefully considered.

Until now, the application of space imaging radar to archeology has been an afterthought. "There has been sort of a language and idea barrier between the radar people and their users," said Dr. Pamela Logan, science director of the China Exploration and Research Society in Altadena, Calif., which will be using the technology to search for ruins along the legendary Silk Road in the desert of northwestern China.

The meeting, held at Princeton University, was the first formal attempt to bridge the gap between these two sciences. It was organized by the World Monuments Fund in New York City, which specializes in the conservation of architectural monuments, and the Royal Angkor Foundation of Budapest, which conducts research at the Cambodian site. The J. M. Kaplan Fund, a New York philanthropy, supported the meeting as part of its new efforts o encourage the application of new technologies to archeology.

Interest in exploring the ruins of Angkor, covering 125 square miles, has increased after an interruption of two decades caused by warfare and civil strife. Some of the temples of brick, sandstone and limestone have fallen into disrepair, some being overgrown by jungle vines. Looting has occurred, and gunfire can still be heard in the hinterlands.

The danger of land mines makes large areas inaccessible. Archeologists suspect that these areas contain evidence of settlements where the builders of the temples lived and also clues to prehistoric occupation, perhaps going back to 5000 B.C. More than 60 prehistoric mounds have already been identified, and villagers often dig up stone tools, but few of the mounds have been scientifically excavated.

The centerpiece of the conference was the blowup of a color picture, which NASA scientists had just processed from radar data gathered in a shuttle pass over Southeast Asia. Targeting Angkor had been a last-minute addition to the mission, after an official of the World Monuments Fund read a newspaper account and sent an urgent request to NASA.

Huddling around the picture, archeologists saw all the old familiar places. There was the principal temple complex, Angkor Wat, as a large green rectangle. It was surrounded by a moat in straight black lines. Dr. Moore pointed to Preah Ko, a cluster of ninth-century palaces that to her "contains evidence of the moment of change with the introduction of Indian culture" by the Khmer kings.

Dark rectangles denoted the large reservoirs that some archeologists think were reflecting pools to accentuate the temple splendors, as well as sources of water for the people and for rice cultivation. A landscape architect could make out the courses of ancient rivers, now dry, and other geological features that could be important in understanding regional development.

"Angkor is all about water," said John H. Stuffs, program director of the World Monuments Fund. "It seems to be of paramount importance to understand the old hydrological systems, if they are to be properly restored. Water in the old moats separated the outer world from those sacred precincts. And waterways were probably necessary to bring in the limestone for construction."

Some of the archeologists came to the meeting with unrealistic expectations. No, Dr. Evans said, the radar could not directly expose the presence of buried temple ruins. In deserts, the microwave signals can penetrate the arid sand to depths of 15 feet, which has revealed ancient riverbeds and apparent artifacts in the Egyptian desert. But radar does not penetrate moist soils, although surface textures and variations in vegetation recorded in the images could provide clues to where something is buried, especially if the images are analyzed in conjunction with aerial or space remote-sensing surveys in visible and infrared light.

The space imaging radar system, tested on two shuttle missions last year, transmits pulses of microwave energy in three different wavelengths toward Earth and measures the strength and time delay of the energy that is scattered back to the antenna. The returning signals can be read in ways to show the shape and nature of the surface. A composite of the data is used to produce photograph-like images of the terrain and structures on it.

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SCIENCE

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RESEARCH NEWS

ARCHAEOLOGY

Shuttle Radar Maps Ancient Angkor

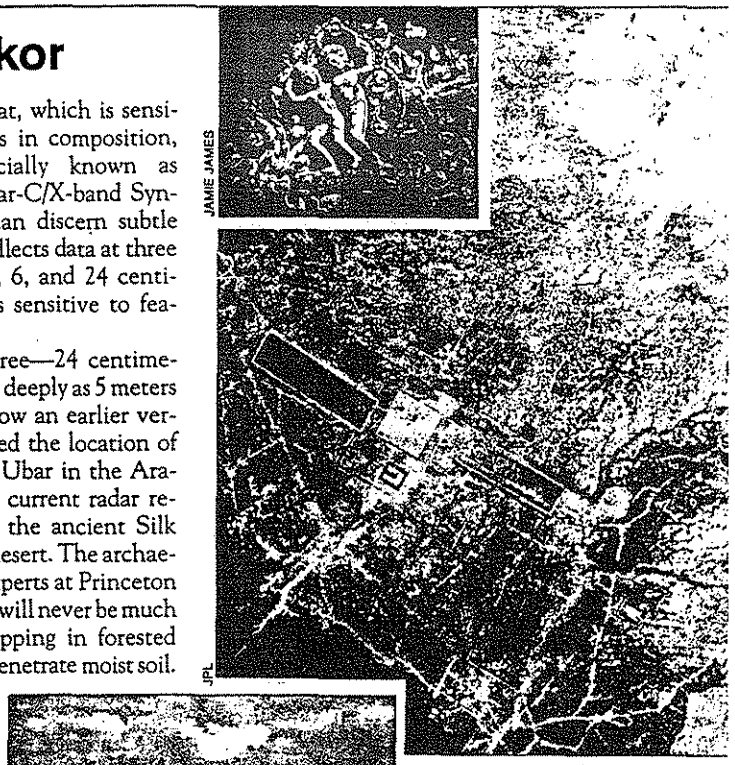
One morning last April, John Stubbs, program director for the World Monuments Fund (WMF) in New York, was leafing through the *New York Times* as he rode the subway to work, when his eye fell on a story about a new earth-imaging radar aboard the Space Shuttle. The story described how the radar had led to the rediscovery of an ancient city in the Arabian desert. Stubbs was so excited by what he read that he got off the subway at the next stop and put in a call to the National Aeronautics and Space Administration.

Stubbs was excited because the WMF has been working since 1989 at the ancient Cambodian city of Angkor, capital of the Khmer empire that ruled much of Southeast Asia from the 9th to the 13th centuries. Much of the site, however, is hidden in jungle, and some lies in territory controlled by the Khmer Rouge. Stubbs realized that the shuttle radar offered a way around these obstacles. NASA agreed, and on 30 September, the Space Shuttle Endeavour passed over Angkor, its radar on.

The resulting image was released last week by NASA's Jet Propulsion Laboratory (JPL) and discussed at a symposium at Princeton University sponsored by the WMF, the Royal Angkor Foundation, and the J. M. Kaplan Fund. The image lives up to Stubbs' hopes. It reveals new clues to the system of canals and reservoirs that sustained ancient Angkor—and has convinced archaeologists that the radar's sensitivity to slight variations in vegetation pattern could be a boon at Angkor and other poorly surveyed forest sites. It's "an unprecedentedly flexible research tool," says Elizabeth Moore, a specialist in Cambodian art and archaeology at the University of London.

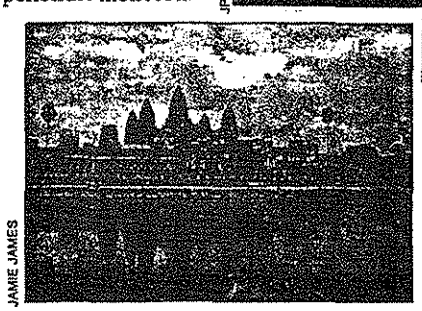
The radar, developed by space scientists from JPL and the German and Italian space agencies, combines data collected over a long exposure from the moving spacecraft to simulate an antenna many miles long. The maps that result show features as small as a few meters. That's no better than the resolution of satellite photographs, such as Landsat images. But unlike Landsat, which is sensitive mainly to differences in composition, the shuttle radar, officially known as Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar, can discern subtle variations in texture. It collects data at three different wavelengths—3, 6, and 24 centimeters—each of which is sensitive to features of a particular size.

The longest of the three—24 centimeters—can also penetrate as deeply as 5 meters into dry ground. That's how an earlier version of the system disclosed the location of the 4800-year-old city of Ubar in the Arabian desert, and how the current radar revealed new details along the ancient Silk Road in the Taklamakan desert. The archaeologists and space radar experts at Princeton agreed that the instrument will never be much use for below-ground mapping in forested areas, because radar can't penetrate moist soil. But the Angkor image shows off the value of the radar's sensitivity to texture. Long after a forest has regrown to cover ancient fields, paths, or canals, subtle alterations of vegetation pattern trace the disturbed areas—clues that the space radar is adept at detecting.



JAMIE JAMES

JPL



JAMIE JAMES

Views of Angkor. The main temple complex of Angkor Wat *(left)* is the bright square near the center of the space radar image; dark rectangles are ancient reservoirs. At top is a relief of a mythological scene.

When Stubbs analyzed the new radar image, he saw linear features to the north of Angkor that Diane Evans, the JPL project scientist, suggested were "residual tracks or paths that hadn't grown over by exactly the same amount as the surrounding areas." Moore, meanwhile, saw evidence of a dam she hadn't noticed in satellite images and aerial photographs. The dam, perhaps part of the ancient kingdom's irrigation scheme, could not have been detected on the ground either, she adds, as it lies in an area controlled by the Khmer Rouge.

Moore is eager to extract more information about ancient Angkor from the space radar image. She has asked Evans and her JPL team to manipulate the data to suppress the rectilinear structures characteristic of classic Angkor, which was under the influence of Indian civilization, and enhance preexisting native circular forms. Stubbs, meanwhile, is hoping to enlist NASA to do more high-tech archaeology, at WMF sites as far-flung as Easter Island, the 2600-year-old city of Butrint in Albania, and the Katmandu Valley in Nepal.

–Jamie James

Jamie James is collaborating on a book about the archaeology of Southeast Asia with anthropologist Russell Ciochon of the University of Iowa.

REMOTE SENSING

AND EARTH SCIENCES

Archaeologists Use Shuttle Radar To Study Angkor Site

By WARREN FERSTER
Space News Staff Writer

WASHINGTON — A New York City-based archaeological organization is using radar imagery taken by NASA's space shuttle to study the ruins of an ancient settlement in the remote jungles of Cambodia.

Researchers with the World Monuments Fund are pouring over data taken by the international Space Radar Laboratory flown aboard space shuttle Endeavour last October to learn more about the ancient Cambodian city of Angkor.

Preliminary analysis indicates that the settlement and surrounding infrastructure are far more extensive that previously thought.

Covering an area of 4,800 square kilometers (a square kilometer is about 0.4 square miles), Angkor is a complex of more than 60 Bhuddist temples dating back to the 9th century, including the monuments of Angkor Wat and the Banyan. It is believed to have been home to more than 1 million people before being abandoned in the 16th century.

An interesting feature of the site, which has been overgrown by vegetation and ravaged by war, weather and looters, is an extensive hydrological system of reservoirs and canals whose stone remnants can be detected through the jungle canopy by shuttle-based radars.

The Space Radar Laboratory, a joint program of NASA and the German and Italian space agencies, has two complementary sensors: a Space Imaging Radar-C (SIR-C); and an X-band Synthetic Aperture Radar (X-SAR). The instruments, which collect imagery at different wavelengths, flew for the first time aboard Endeavour in April 1994.

Four days into that mission, John Stubbs, program director for the World Monuments Fund, called NASA to suggest that the shuttle astronauts target their radars on Angkor. Stubbs, whose group is dedicated to preserving human-made monuments throughout the world, had read about possible archaeological objectives of the mission in the *New York Times*.

Although unable to fully accommodate Stubbs' request during the April mission, NASA included Angkor on its list of objectives for the October 1994 flight of the radar lab.

Both Space Radar Laboratory flights were dedicated to the Earth science disciplines of ecology, geology, oceanography and hydrology, said Jeff Plaut, SIR-C experiment scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif. Other objectives included calibrating the radars and related engineering experiments, he said.

Archaeology was a spinoff application, Plaut told *Space News* Feb. 21. During the April flight, for example, particular attention was focused on the lost city of Ubar in Oman, he said. Another area of interest was Giza in Egypt, home of the Pyramids.

In arid regions such as the Sahara in Africa and the Middle East, radar signals can penetrate into the sand to find evidence of previous human habitation, Plaut said. While not equally suited to detecting subsurface features in tropical areas, radar can still penetrate cloud cover and vegetation to detect human-made structures.

"We think it is the right technology at the right time," Stubbs told *Space News* Feb. 21.

Although Angkor was publicized in the late 19th century, decades of war in Cambodia have prevented researchers from exploring the site on the ground.

Now, with the fighting winding down and radar imagery in hand, the world archaeological community is set to resume exploration of the site, although land mines were placed around the area during the war and it is still considered dangerous.

The private, not-for-profit World Monuments Fund held a workshop earlier this month in Princeton, N.J., to review the imagery collected during the October Endeavour mission.

Grant money from the J.M. Kaplan Fund paid for the workshop, Stubbs said. The radar imagery was provided by NASA free of charge.

A second workshop is planned for March during which the new information will be presented to Cambodian authorities.

Stubbs' organization is interested in using radar technology to explore other sites of archaeological interest, including Easter Island, Tetra in Jordan and monuments left by Native Americans in what is now the United States.

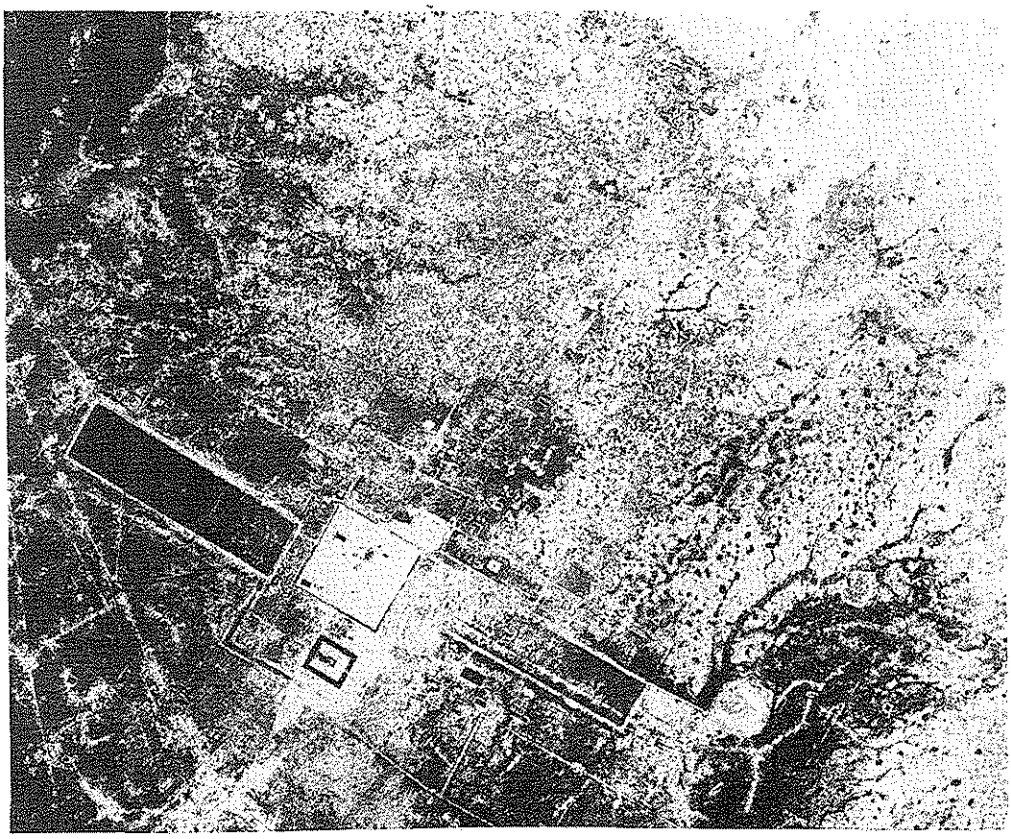
Several groups representing interests including archaeology and mineral exploration have contacted NASA asking that specific sites be targeted in future shuttle flights, Plaut said.

No more flights of the Space Radar Laboratory are scheduled and construction of the international space station looms on the shuttle manifest, so the future of the laboratory is uncertain.

The possibility of adding a third mission is under discussion, but such a flight would not likely take place before 1997.

Further, that mission would likely be dedicated to collecting stereo imagery for the creation of topography maps, according to Plaut.

Global Snapshot



Location: Angkor, Cambodia

Data gathered by: Shuttle Radar Laboratory aboard orbiter Endeavour

Image prepared by: Jet Propulsion Laboratory

Instrument: Spaceborne Imaging Radar-C, X-band Synthetic Aperture Radar

Project: World Monuments Fund archaeological research

Uses of information:

Archaeologists from the New York-based World Monuments Fund intend to expand their studies of the civilization at Angkor, which is situated in a dense Cambodian rain forest.

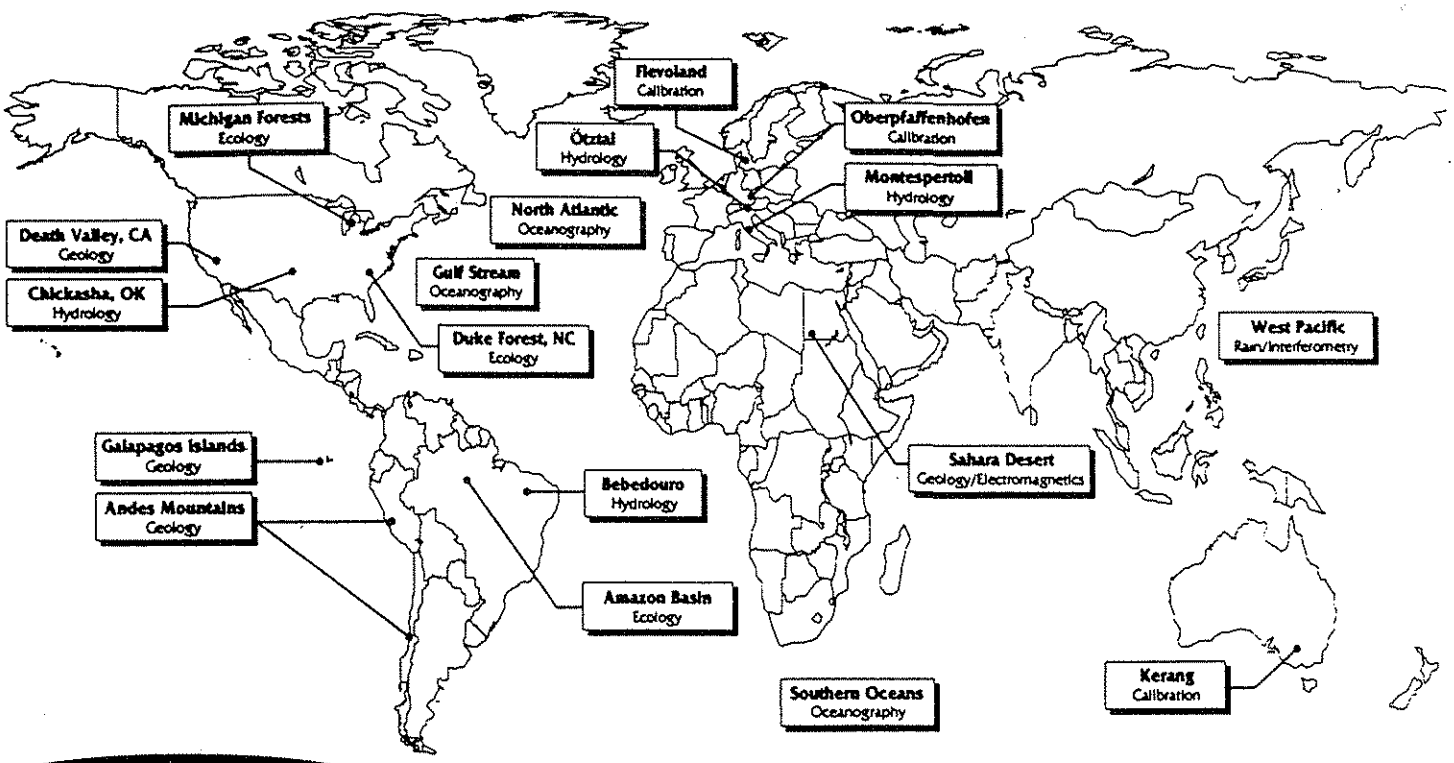
Imagery collected by the Shuttle Radar Laboratory (the example at left is from Sept. 30, 1994) offers clues to the existence of undiscovered structures that may have been part of the Khmer Empire settlement in its heyday, which dates back to the 9th century. The radar-frequency signals penetrate cloud cover and foliage and are reflected by the Earth's surface, revealing structures that would be invisible to orbiting sensors using visible light.

At bottom center in this image, the bright square surrounded by a dark band is the most publicized of the ancient city's dozens of temples, Angkor Wat. Smooth surfaces appear dark in the radar imagery and more jagged terrain is bright; the dark band visible around Angkor Wat is a reservoir or mote. The larger light-colored square above Angkor Wat is the Angkor Thom temple. Archaeologists reviewing this image suspect that the purplish region above Angkor Thom may contain structures that have not yet been examined.

The bright lines throughout the image show the locations of modern roads as well as ancient roads and canals that served Angkor's residents until the city was abandoned in the 16th century.

APPENDIX G

SIR-C/X-SAR PROJECT SCIENTISTS



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