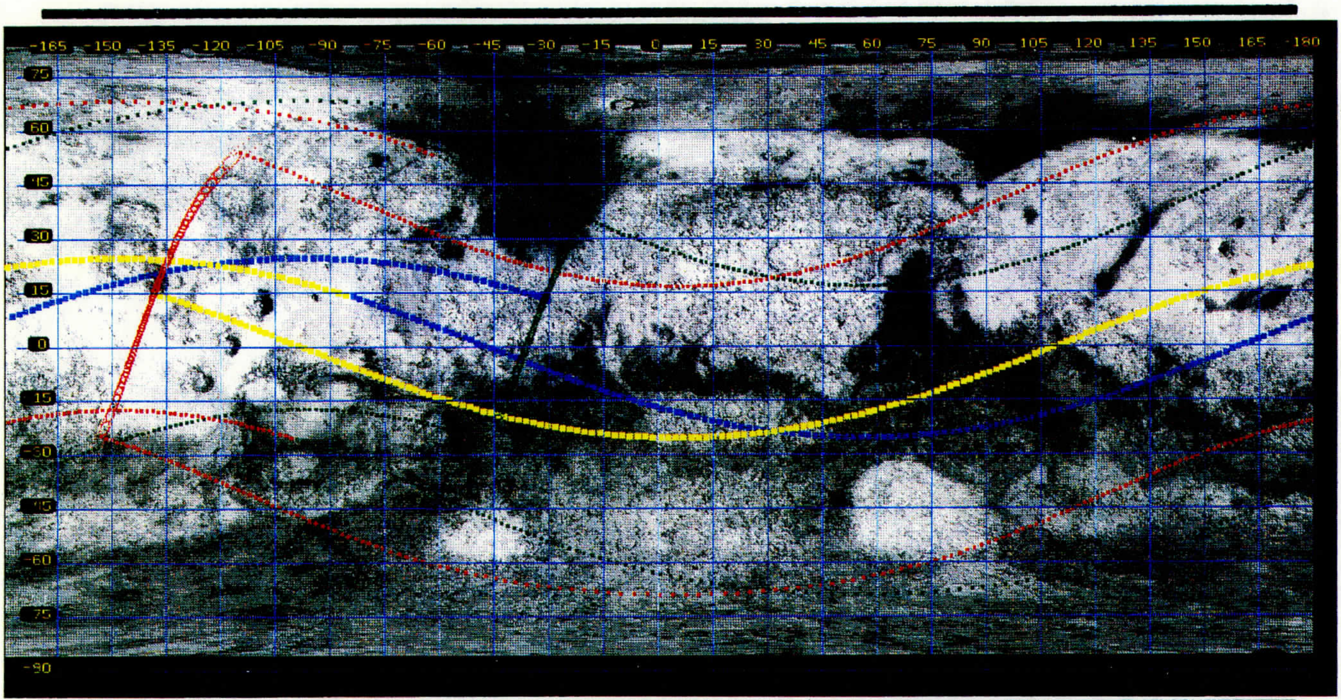
Mars
Operational
Environmental
Satellite

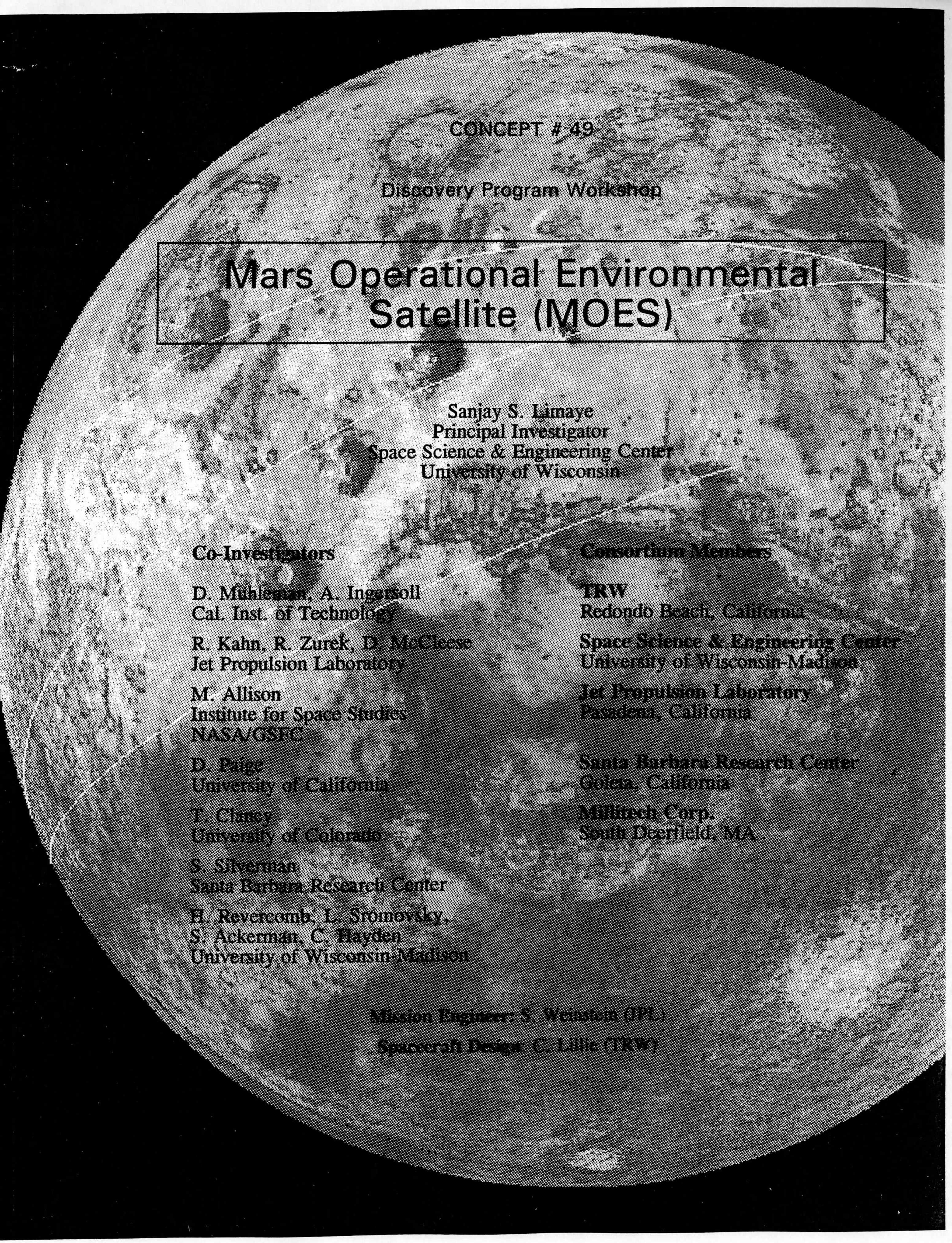
Sanjay S. Limaye
Principal Investigator
Space Science & Engineering Center
University of Wisconsin-Madison



Sub-orbital track from two consecutive 216 minute orbits of MOES around Mars (cyan & yellow). The visible limb location is outlined by green and red dotted lines. Cross track coverage is shown once per orbit for clarity.

TRW U of Wisconsin JPL

September 1992



CONCEPT # 49

Discovery Program Workshop

Mars Operational Environmental Satellite (MOES)

Sanjay S. Limaye
Principal Investigator
Space Science & Engineering Center
University of Wisconsin

Co-Investigators

D. Muhleman, A. Ingersoll
Cal. Inst. of Technology

R. Kahn, R. Zurek, D. McCleese
Jet Propulsion Laboratory

M. Allison
Institute for Space Studies
NASA/GSFC

D. Paige
University of California

T. Clancy
University of Colorado

S. Silverman
Santa Barbara Research Center

H. Revercomb, L. Sromovsky,
S. Ackerman, C. Hayden
University of Wisconsin-Madison

Consortium Members

TRW
Redondo Beach, California

Space Science & Engineering Center
University of Wisconsin-Madison

Jet Propulsion Laboratory
Pasadena, California

Santa Barbara Research Center
Goleta, California

Millitech Corp.
South Deerfield, MA

Mission Engineer: S. Weinstein (JPL)

Spacecraft Design: C. Lillie (TRW)

Table of Contents

REFERENCES
Biography of PI

1. Introduction

The Mars Operational Environmental Satellite (MOES) Mission is designed to observe and understand how Martian weather systems evolve, and how they impact the Martian surface/atmosphere system. It will detect changes globally on time scales down to a fraction of a day. With a single spacecraft in a 25° inclination, 216 minute, 2250-km circular orbit, this mission can investigate the weather systems and diurnal behavior of the Martian atmosphere and surface, by obtaining up to 8 times per sol coverage of the Martian tropics and mid-latitudes. The MOES objectives are similar to those of the fleet of earth orbiting geostationary and polar orbiting satellites and whose observations are routinely used for weather forecasting on a variety of time and spatial scales as well as global climate studies using General Circulation Models (GCMs). For Mars, the GCM capability is now available to begin modest but analogous studies, but there is as yet a gap in existing observational coverage of the planet that will not be filled by any other existing or currently planned missions.

MOES observations would enable us to study in detail, for the first time, the life cycles of rapidly-changing Martian weather phenomena which play an important role in shaping global climatic conditions on the planet. These include cyclones, frontal systems, local, regional, and global dust-storms, as well as short-period wave phenomena such as atmospheric tides. MOES observations are also ideally suited to diagnostic studies with regional- and global-scale models, using data assimilation techniques, and to testing and evaluating Martian weather prediction, using the GCMs that have been developed over the last two decades.

Mars atmosphere bears greater similarity to that of the Earth's than any other planet in the solar system, due in part to the general similarity of the length of the day and inclination of its rotation axis. There are also major differences in the respective environments. Mars currently has no oceans and only a thermodynamically weak hydrological cycle; on Earth, these together account for a large fraction of the meridional heat transport. On the other hand, Mars has a thermodynamically active dust cycle, and a carbon dioxide cycle which leads to major seasonal fluctuations in atmospheric pressure. Vigorous weather systems are present, and in the Viking data appear remarkably regular compared to their terrestrial counterparts. Viking and Mariner images of Mars show cyclonic systems, mountain waves, frost, dust devils and other phenomena also seen on the Earth. Comparisons between the two are particularly useful in helping determine the relative importance of underlying mechanisms controlling climate. A key component of such comparisons is the impact of atmospheric opacity at all wavelengths. Thus an increase in atmospheric carbon dioxide increases the infrared opacity on earth leading to concerns of enhanced greenhouse effect. Similarly, the opacities of dust and hazes in both the Martian and earth's atmosphere also have longer term impacts on the climate based on their atmospheric residence times. A key illustration is offered by the presence of layered terrain in Martian polar latitudes which suggests cyclic variations in dust deposition and hence perhaps of climate. How these changes occur is the key question that MOES observations would address.

Achieving a better understanding of the cycles of dust, water vapor, and water ice on Mars requires detailed information about atmospheric transports of water and dust associated with weather systems, particularly those arising in mid-latitudes during fall and winter. It also requires a quantitative understanding of the processes responsible for the onset and development of dust storms at all scales. Long-term, continuous observation of Mars by MOES includes measurement of temporal surface albedo variations, and thereby of another component of the surface-atmosphere interaction related to dust transport.

With its emphasis on short-term weather and time-of-day variations, the MOES Mission complements the polar-orbiting Mars Observer Mission, which is optimized to study seasonal variations. The MOES mission will not observe the polar latitudes, where Mars Observer has excellent coverage, but it will provide comprehensive coverage of local time at lower latitudes where diurnal variations of the meteorological fields tend to be largest, and where dust storms are believed to occur most frequently. This strategy of flying complementary polar and equatorial orbiting satellites is the one used to systematically study global weather and climate on Earth. Thus MOES is a logical follow-on to the Mariner, Viking, and Mars Observer missions.

The nominal Mission life is one Martian year (1.88 Earth years). The payload contains two instruments, which were chosen (1) to acquire high-spatial resolution (≈4x4 km) images of the atmosphere and surface in two visible and three infrared bands, selected to measure condensate, dust, and water vapor distributions, and (2) to obtain associated atmospheric temperature profiles using passive microwave detection. Primary observations would include column dust and water abundance, cloud morphology, surface albedo, and the atmospheric temperatures, which would be used, for example, to derive global wind fields.

2. Scientific Goals and Expected Results

Scientific Goals:

Martian weather, like its terrestrial counterpart, manifests itself on time scales of seconds (as evidenced by Viking lander observations) to hours, days, and months (witness the seasonal cycle) and on spatial scales of few km to global. The recognizable phenomena include frost, wind-blown dust, water-ice clouds, cyclones, polar caps and dust storms. Measuring these on time scales of hours to a year and on spatial scales of a few km to global is the underlying scientific goal of the mission. The basic weather observations required are of wind, temperature, pressure, and moisture and cloud distributions. The same is the case for Mars, except that dust replaces water vapor in priority because of its thermodynamic impact on the atmosphere. Specifically, the observational objectives for MOES are as follows:

- Monitor the time-dependent development and evolution of weather systems and dust storms
- Observe the diurnal behavior of hazes and clouds over many latitudes and seasons
- Determine the atmospheric thermal structure
- Derive winds from atmospheric thermal structure (gradient balance) and passive tracers
- Understand the physical mechanisms important to transport in the atmosphere, dust raising and deposition at the surface, and the life cycle of weather systems

These objectives can be met with frequent global visible and infrared imaging and global atmospheric temperature profiles observations of Mars continuously. Visible and broad band infrared imaging of Mars will provide information about atmospheric features such as clouds, dust storms, frost and surface features. The infrared imaging will provide information during both day and night and is deemed especially useful for dust and water-ice cloud monitoring and atmospheric circulation systems that are radiatively driven. Window channel infrared images of the earth from geosynchronous satellites vividly show the dust storm circulations and land-sea breeze systems over desert areas during late spring and summer months, and the same may be expected on Mars. Whereas Mars Observer will obtain visible images at two wavelengths with a nominal resolution of about 7 km in addition to some very high resolution images of the surface (Malin et al., 1992), MOES imaging emphasis is on investigation of atmospheric features at a nominal pixel size of 4 km in two visible (0.45μ and 0.59μ) and three infrared channels selected for dust, water vapor and surface brightness temperature estimates. This spatial resolution is essential to seeing the detailed morpholgy of weather systems and of dust storms, even though it is achieved with lower vertical resolution than could be provided by a Discovery Class mission using interferometer measurements or limb soundings.

For studies of Martian weather one of the most useful measurement is of the global three dimensional wind field. Thus wind fields will be inferred from thermal structure as well as from the motions of clouds, dust and moisture patterns from the visible and infrared imaging as opportunities allow. Given a spatial resolution offered by this mission and systematic space-time coverage of the thermal field, winds can be objectively inferred from the governing constraints of the equations of motion by assimilation in a numerical weather model. Imaging observations of surface streaks and erosion patterns will offer a further characterization of the wind stress and atmospheric boundary layer.

MOES employes passive microwave observations to derive atmospheric temperature profiles. Remote temperature sounding of the Martian atmosphere can be accomplished by a variety of techniques- microwave or infrared filter radiometers or infrared interferometers by nadir (IRIS on Mariner 9, Hanel et al., 1972, TES on Mars Obsever, Christensen et al., 1992) or limb scanning measurements (PMIRR on Mars Observer, McCleese et al., 1992) in addition to radio occultations (Mariner, Kliore et al., 1972, Viking, Fjeldbo et al., 1977, and Mars Observer); however the resulting coverage is asynoptic and at inadequate spatial or temporal resolution to adequately study weather.

Retrieval of atmospheric temperature profiles using passive measurements is based on observing various spectral signatures. One of the challenges for profiling the Martian thermal structure by such observations is the presence of dust in the Martian atmosphere, particularly during major dust storms as the radiometric effects of dust need to be distinguished from the atmospheric signature. This is particularly difficult for the nadir looking measurements. These problems are however not faced by remote sensing measurements at wavelengths longer than the size of the dust particles (typically 3-40μ). Given temperature profiles unaffected by the presence of dust, the multispectral infrared images can be used to estimate column opacity.

Expected Results

The surface and atmosphere of Mars have been observed to exhibit dynamic temporal behavior over daily, seasonal and interannual time scales. Key parameters that are known to vary include surface and atmospheric temperature (Hanel etal., 1972; Kieffer et al., 1977; Martin and Kieffer, 1979), atmospheric dust and water ice cloud loading (Hanel et al., 1972; Conrath, 1975; Briggs et al., 1979; Martin et al., 1979), surface frost coverage (James et al., 1979), and surface albedo (Christensen, 1988). The highly regular spatial and temporal coverage that will be obtained by the single MOES spacecraft is nearly ideal for observing Martian dynamic behavior in the equatorial and mid-latitude regions. This type of coverage has not been obtained in previous missions.

Regular observations from MOES of daily surface and atmospheric temperature variations will fill an enormous gap in hourly coverage that will be left by the 2am to 2pm Mars Observer orbit. MOES will provide a detailed picture of the diurnal cycle of condensation and sublimation of water ice in the atmosphere and on the surface. This daily cycle plays a key role in determining the exchange of water between surface and atmospheric reservoirs (Flasar and Goody, 1976), and has not been observed previously in a systematic fassion. Similarly, MOES will also observe the daily cycle of mid-latitude CO_2 frost condensation and sublimation, which is predicted during the coldest seasons (Paige, 1992).

From Viking IRTM observations we know that the Tharsis, Arabia and Elysium regions are blanketed by a layer of very fine-grained, bright, low thermal inertia material (Palluconi and Kieffer, 1981). One of the most interesting and unexplained properties of the low thermal inertia regions is a phenomenon which has come to be known as "anomalous afternoon cooling". Unlike in the high thermal inertia regions, observed daily temperature variations in the low thermal inertia regions can not be satisfactorily fit by a simple thermal model that assumes constant soil thermal properties and soil reflectance properties with time of day and depth (Kieffer et al., 1977). It is strongly suspected that this unusual behavior is due to diurnal variations in the radiative and convective heating of the surface by the Martian atmosphere (Haberle and Jakosky, 1991), but other purely surface mechanisms have been proposed (Jakosky, 1979; Dittoen 1982). By providing measurements of surface and atmospheric temperatures throughout an entire diurnal cycle, MOES will provide the data necessary to resolve this problem.

Some of the most valuable coverage that MOES will obtain will be over seasonal and interannual timescales. In the past, nearly continuous observations of specific midlatitude locations for long periods has yielded valuable information concerning the the fallout of dust raised during great dust storms, and its subsequent removal from selected areas (Christensen, 1988). Since our presently available information suggests that no two Mars years are exactly alike, the MOES observations are likely to provide unique insights into the present cycles of dust and volatiles on Mars, and their relation to surface erosional and sedimentary processes.

Strawman Payload

The strawman payload is similar to the basic environmental satellites operated for weather observations of the earth. It provides the required visible and infrared imaging of Mars, atmospheric temperature soundings and dust and water vapor distribution within ± 75° latitude. The candidate instruments are: (i) Mars Imaging Radiometer (MIR) for multispectral day (visible and infrared) and night (infrared) imaging of Mars surface and atmospheric features, (ii) Microwave Atmospheric Sounder (MAS) for obtaining global maps of vertical temperature profiles. The dust and water vapor column distribution can be estimated from the combined infrared radiances and atmospheric temperatures. Finally, it is recognized that the MOES spacecraft will be occulted up to 14 times per sol as seen from the earth, providing opportunities for derivation of atmospheric temperature profiles with a very high vertical resolution similar to those obtained from Mars Observer and past missions to Mars. Both entry and exit occultation temperature retrievals can be accomplished by the X-band communications subsystem incorporating an Ultra Stable Oscillator (USO) and accompanying Deep Space Network (DSN) coverage. If the entry occultations alone are collected then the use of the USO is not essential. The instruments are described below.

3. Mission Design

Mission Requirements

Truly synoptic global coverage would require a minimum of three satellites in low inclination synchronous orbit around Mars (24h 37m period), and at least one polar orbiting satellite, similar to the current situation where four geostationary weather satellites and two polar orbiting satellites observe the Earth continuously. Such a fleet of aerostationary satellites is clearly outside the cost limitations of the Discovery program. However, the proposed orbit for MOES will obtain near-uniform local time coverage at *each longitude* of the Martian tropics eight times per sol, and less often of the longitudes at higher latitudes. This yields sufficient temporal and spatial coverage to investigate the diurnal behavior of the Martian atmosphere adequately for these purposes and within the Discovery cost constraints.

The basic mission requirement is to deploy a spacecraft in a circular orbit with an inclination of about 155° (retrograde) and a period of about 216 minutes. This orbit, which has an altitude relative to Mars surface of about 2250 km, is expected to precess at the rate of about +2.46°/day. Thus the orbit "walks" around Mars every 49 days or about 14 times per Martian year. The Mars relative period of the orbit is 3.1496h, so that a given longitude is under the spacecraft eight times per sol. The maximum solar and earth occultation times are about 0.74h, requiring storage batteries to provide power for spacecraft operation during the solar eclipses of the spacecraft and charging of the batteries by the solar panels during the sun-lit portion of the orbit.

Imaging data would be acquired continuously in orbit. Observations consist of multispectral (5 bands) imaging and atmospheric temperature soundings. The imaging and the sounding observations are acquired more or less continuously by nadir looking instruments and cross track scanning. Data collected by the instruments is stored in on-board solid state memory for once-per day transmission to the DSN.

Launch Opportunities, flight time

The earliest launch opportunity occurs on 11 Nov 1996. Other opportunities occur in 1999, 2001 and 2003. The trajectory is direct to Mars with a flight time of 303 days, to arrive at Mars on 15 September 1997. The orbit insertion is planned to occur with a single burn into a circular orbit of radius 5646 km (1.66 * R_{Mars}). The launch energy over a 20 day period is 9.5 km^2/sec^2; the arrival V-infinity is 2.8 km/sec. Mars orbit insertion can be achieved with a delta-V = 2.01 km/sec. Considering a statistical delta-V = 100 m/s (including a 40 m/s Delta II figure-of-merit, plus reserve for post-insertion trims), the total post-launch delta-V is 2.11 km/s. The 1999 and 2001 opportunities require a slightly higher additional deltav-V requiring additional propellant, but both are well within the mass margins.

Launch Vehicle, mission propulsion requirements, and margins

Using 7% contingency, the Delta II (7925) can inject 984 kg to a C_3 of 9.5 km^2/sec^2. The allowable spacecraft dry mass is 514 kg if a bipropellant system is used (I_{sp} = 331s for the Orbit Insertion Motor used on the TRW spacecraft described below), or 360 kg for a monopropellant system (I_{sp} = 215 s).

Encounter Geometry and preliminary observational timeline

Due to the relatively large orbit radius and low declination of the final orbit, no plane change into final orbit is required and a single burn for orbit insertion is sufficient. As no transition orbit is necessary, Mars atmospheric monitoring will commence immediately. A nearly constant schedule will be employed to collect global observations every orbit to achieve eight global observations of Mars for a minimum of one Martian year. The observational schedule may be changed somewhat under special circumstances such as the development of regional dust storms, however, given the nature of the data collection, these changes would primarily affect the spatial/temporal resolution at which data is transmitted to earth.

4. Flight System Design

Spacecraft characteristics and requirements

A nadir looking 3-axis stabilized spacecraft is required. The primary power source is a single solar panel that is articulated to orient towards the sun as the spacecraft orbits Mars close to the ecliptic plane. Communications to earth are handled by a 1.5m High Gain Antenna (HGA) and two omnidirectional antennae. Absolute pointing is not as critical as pointing stability and post facto knowledge. Mars disk coverage is to be attained by scanning mirrors (cross-track coverage) while the orbital motion of the spacecraft is employed to accomplish coverage in the along scan direction for the infrared measurements. Due to the low inclination of the orbit the spacecraft will be in Mars shadow for as much as 42 minutes per orbit or up to 4.5 h/day. To maintain the spacecraft operations batteries of sufficient capacity are required. Figure 1 shows the MOES spacecraft schematic configuration.

MOES Spacecraft Configuration

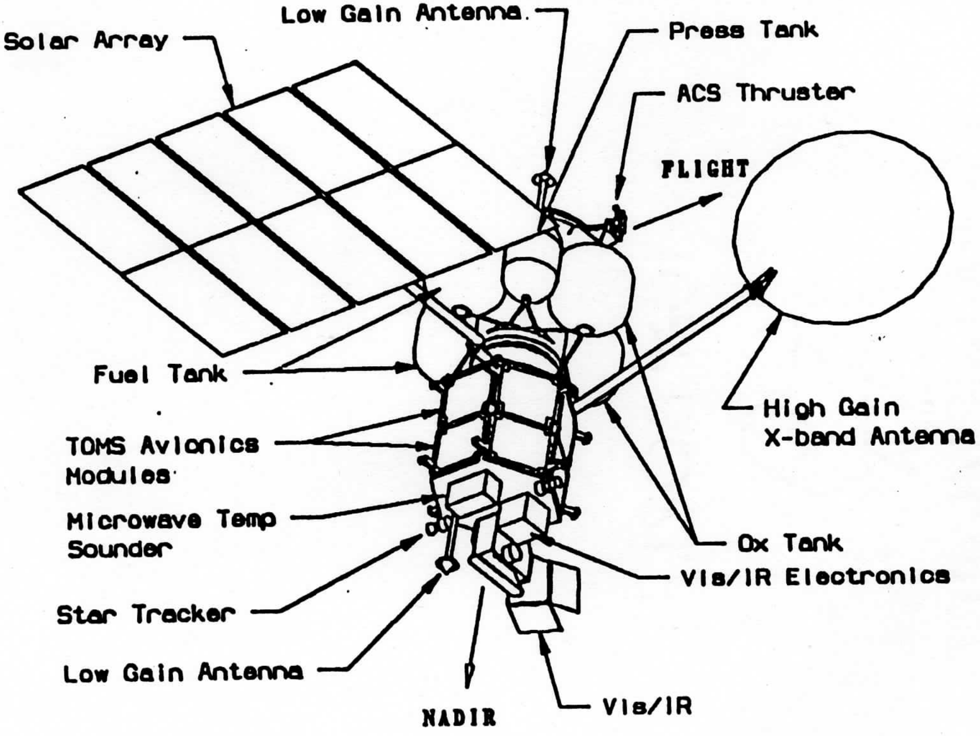


Figure 1.

WEIGHT BUDGET (kg)		
BUS		
STRUCTURE		80.4
THERMAL		10.3
ACDS		29.7
ELECTRICAL		34.2
HARNESS		15.5
C&DH		43.8
PROPULSION		55.6
BUS TOTAL		269.5
CONTINGENCY (15%)		42.1
INSTRUMENTS		43.5
TOTAL DRY WEIGHT		355.1
PRESSURANT (He)		1.9
PROPELLANT		343.4
TOTAL WET WEIGHT		716.4
LIFT CAPABILITY (C_3=9.7)		984.0
MARGIN	37.4%	267.6

POWER BUDGET (W*)		
BUS		
THERMAL		42.0
ACDS		44.3
ELECTRICAL		16.6
C&DH		43.6
PROPULSION		0.0
BUS TOTAL		146.5
INSTRUMENTS		47.0
CONTINGENCY (20%)		38.7
BATTERY CHARGING		83.1
TOTAL REQUIREMENT		315.3
SOLAR ARRAY CAPABILITY		350.4
MARGIN	11.1%	35.1

* ORBITAL AVERAGE POWER IN WATTS AT 1.66 AU

PERFORMANCE

SPACECRAFT CLASS	A/B
POINTING	
CONTROL	0.50°
KNOWLEDGE	0.10°
STABILITY	0.01°/SEC
TT&C	X–BAND
U/L DATA RATE	125 bps
D/L DATA RATE	16 Kbps @ 2.7 AU (VIA DSN 34–M ANTENNA)
DATA STORAGE	1 Gigabit

DIMENSIONS (STOWED)	
BUS DIAMETER	1778 MM
BUS HEIGHT	2172 MM
TOTAL HEIGHT	3084 MM

Design inheritance and existing hardware

The TRW design for the MOES spacecraft is based on the TOMS-EP spacecraft designed by TRW. The modifications are limited to adapting the spacecraft for operation in Mars orbit, increasing battery and data storage capacity and the addition of star tracker in the attitude control system.

Spacecraft mass and power estimates

Figure 1 provides and mass and power estimates for the spacecraft subsystem. The Mass and power budgets and performance are also indicated.

5. Instrument Description and Requirements

The key requirements for MOES are to obtain (i)imaging and vertical temperature profile coverage within ± 60° latitude from the MOES orbit, and (ii) simultaneous estimates of dust and water vapor distribution, and (iii) observations at all local times. The latitude range is a compromise that reflects use of a single spacecraft to obtain both local time and near global coverage and also reflects the fact that over this latitude range the diurnal coverage would be missed from Mars Observer in its 2am - 2pm sun-synchronous orbit. The imaging observations enable qualitative and quantitative monitoring of atmospheric phenomenon while the thermal structure observations enable simulations of the Martian atmospheric circulation. The orbit chosen for MOES actually provides coverage up to ± 75° latitude.

The payload instruments are chosen to provide the required atmospheric temperature sounding and mapping of dust and water vapor capability over the Martian globe (40km nadir spatial resolution) and visible and infrared imaging (4 km resolution at nadir) for clouds, dust and surface imaging. Visible imaging of Mars has either been acquired by vidicons (Mariners, Vikings) or by a CCD camera (Mars Observer). The need to monitor the atmospheric processes diurnally dictates the use of infrared observations. Multispectral imaging is therefore proposed to be acquired by a Mars Imaging Radiometer (MIR), a nadir looking cross-track scanning instrument with 2 visible and 3 infrared bands, similar to those now currently being deployed on spacecraft in earth orbit for terrestrial meteorological observations (e.g. the AVHRR on NOAA polar orbiting satellites).

Near global coverage of temperature profiles that are not affected by the presence of dust can be obtained by passive nadir looking microwave measurements. The proposed Microwave Atmospheric Sounder (MAS) is expected to provide such temperature profiles with slightly better than a scale height vertical resolution. The candidate instruments are described below.

MARS IMAGING RADIOMETER (MIR)

MIR is essentially a the Visible InfraRed Scanner (VIRS) currently in Phase C/D for the Tropical Rainfall Measurement Mission (TRMM) and is being built by the Santa Barbara Research Center (SBRC). TRMM is in a similar orbit to MOES and the instrument requirements are very similar and differ only in spectral bands, scan mirror spin rate and field of view. For Mars applications the single visible and four infrared channels of VIRS are replaced by two visible (0.45μ and 0.59μ) and three infrared channels (6.9, 7.7, and 9.3μ for surface, water vapor and dust respectively). The three infrared channels use HgCdTe detectors cooled with a passive radiator for increased performance. Cross-tack coverage is provided by a continuously rotating double sided scan mirror (14.5 rpm) with an active field of view (FOV) of $\pm 37.5^{0}$. A 9.0 cm telescope provides the 4 km x 4464 km scan. In-flight calibration is provided by an on-board black body and a solar diffuser and space view for the solar and infrared channels. As VIRS was designed for terrestrial applications, mass minimization was not a key-issue in the design and according to the vendor some savings is possible by choice of different fabrication materials. Similarly, the power quoted is matched to the much higher data rate (50 kbps) of the earth instrument and as the scan rate is much lower for MIR, the power required for the data handling is expected to be less than the 34 W consumed by VIRS. A cutaway view is shown in Figure 2.

Table 1.
MIR Description
(Based on VIRS Design)

Channels:	5 (2 vis, 3 infrared) (0.45, 0.59, 6.9, 7.7, 9.3μ)
IFOV:	1.8 mr or 0.1034° (4 km @ nadir)
Scan:	±37.5°
# samples:	750
Quantization:	12 bits/sample
Data rate:	21.9 kbps uncompressed
Size:	38 x 79 x 42 cm (scanner) 25 x 33 x 22 cm (Electronics Module)
Mass:	25 kg (scanner), < 9 kg (electronics)
Det. Cooling:	A.D. Little Radiative Cooler
Det. Temp.:	120 K
Scanning:	360°, double sided, 14.5 rpm
Power:	< 34 W

Table 2
MAS Mass and Power Estimates

Mass	
Millimeter radiometer:	1.5 kg
Ref. Osc. System:	2.0 kg
Spectrometer:	2.0 kg
Data Proc. Unit:	1.5 kg
Optics : (excl. obj mirror)	0.5 kg
Mirror & Calib. load:	0.5 kg
Main mm inst. module:	1.5 kg
Total:	9.5 kg
Power	
Millimeter radiometer:	4 Watts
Spectrometer:	4 Watts
Data Processing Unit:	2 Watts
Mm freq. ref. Elect.:	5 Watts
Total:	15 Watts
Size	
Radiometer:	15 x 15 x 19 cm
Electronics:	15 x 15 x 19 cm
Data Rate	
10 bit quantization:	< 1 kbps

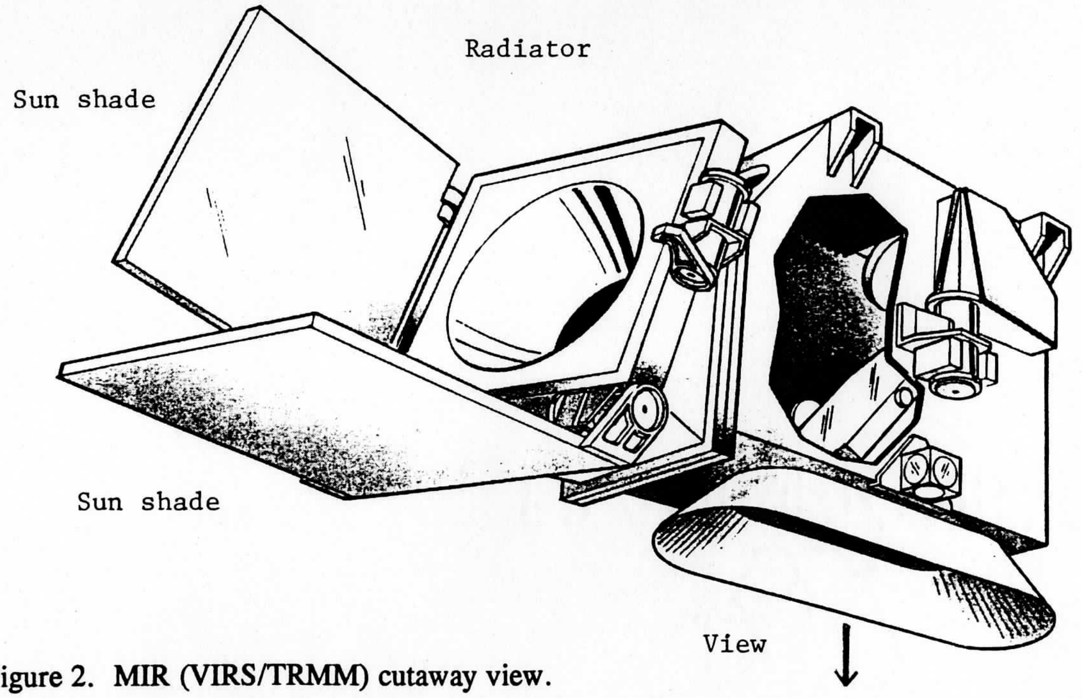


Figure 2. MIR (VIRS/TRMM) cutaway view.

MICROWAVE ATMOSPHERIC SOUNDER (MAS)

MAS obtains Martian atmospheric temperature profiles by passive microwave observations which are immune to the presence of dust. It is known that carbon monoxide is ubiquitous in the Martian atmosphere as both theory and existing measurements suggest that it is uniformly mixed from the surface to at least 100 km (Rosenquist et al., 1992 present analysis of some observations from Phobos 2 that suggest that the 2.35μ indicate either a CO "hole" over Martian volcanoes, or likely presence of some mineral at the high altitudes that mimics the spectral signature of CO). The lifetime of CO molecule in the Martian atmosphere is estimated to be 3 years, and due to the much smaller vertical mixing time, CO must be vertically uniformly mixed over the planet. In fact, ground-based microwave CO measurements resolving the disk of Mars have indicated that, on hemispheric scales, CO is vertically well-mixed (Lellouch et al., 1991). Ground-based microwave CO measurements have also been analyzed to derive low-to-mid latitude averaged temperature profiles (0-70 km) for the Mars atmosphere between 1975 and 1989 (Clancy et al., 1990). The molecule has a reasonable dipole moment and very strong rotational transitions: (0-1) 115.3 GHz, (1-2) 230.5 GHz, (2-3) 345.8 GHz, etc. Even the first rotational line is nearly optically thick in the line center and the transitions above 230GHz are too opaque for Mars sounding; however, the (1-2) transition is ideal. An 8 cm mirror would yield a footprint of nearly 40 km at nadir from the MOES orbit altitude and useful spectra can be obtained to within ± 37.5° of nadir by cross-track scanning. Each IFOV of the MAS thus consists of approximately 10 x 10 IFOV's of MIR. The global coverage obtained from the MAS per sol (7 orbits) is illustrated by footprints on Mars surface by cross-track scanning (shown every other scan for one orbit only for clarity) for the MAS IFOV in Figure 3. The CO line has a pressure broadening coefficient of 3 MHz/mb and the total line width on Mars will therefore be less than ± 20 MHz. The radiances are measured in as many as 20 discrete spectral channels sensitive to different levels of the Martain atmosphere. Such spectra can be measured with a Chirp Transform Spectrometer using Surface Acoustic Waves (SAW) chips.

Through pressure broadening, altitude information is encoded into each spectrum. Such spectra then can be inverted in the same manner as the infrared filter radiometer observations, to yield atmospheric temperature profiles with a slightly better than a scale height vertical resolution. Because of the very long wavelength (1.3 mm), the temperature sounding is completely immune to any particles or aerosols that can be supported in the Martian atmosphere, unlike broadband infrared observations. In fact, the infrared measurements (MIR) in addition to the temperature profile measurements yield the dust distribution over the mapped disk. Mass and power estimates for the microwave portion of the instrument are given in Table 2. Dr. D.O. Muhleman is the Instrument PI and the instrument contractor is Millitech, Corp. of South Deerfield, MA.

Calibration of Microwave Temperature Profiles

Due to the low inclination of the MOES orbit, the spacecraft is occulted as seen from the earth as many as seven times per sol, enabling a total of 14 entry and exit profiles. These occur within ±25° latitude and at all local times. Monitoring of the received carrier frequency allows the vertical temperature profile to be obtained with a resolution as high as 100-200m. These temperature profiles serve as independent verification of the MAS retrieved profiles.

The MIR data can be subjected to 5:1 compression thereby reducing the rate to 7.3 kbps. The data collected per orbit is about 280 mbits, so that the on-board storage is about capable of storing nearly 10 orbits, or about 2.5 sol's data in compressed format. One orbit's data can be transmitted at maximum range in about 57 minutes, so that 7 orbits worth of data can be received at maximum range in as little as 6.6h assuming 5:1 compression using the 34-m station. At closest range (0.36 AU), the DSN coverage required is only a few minutes.

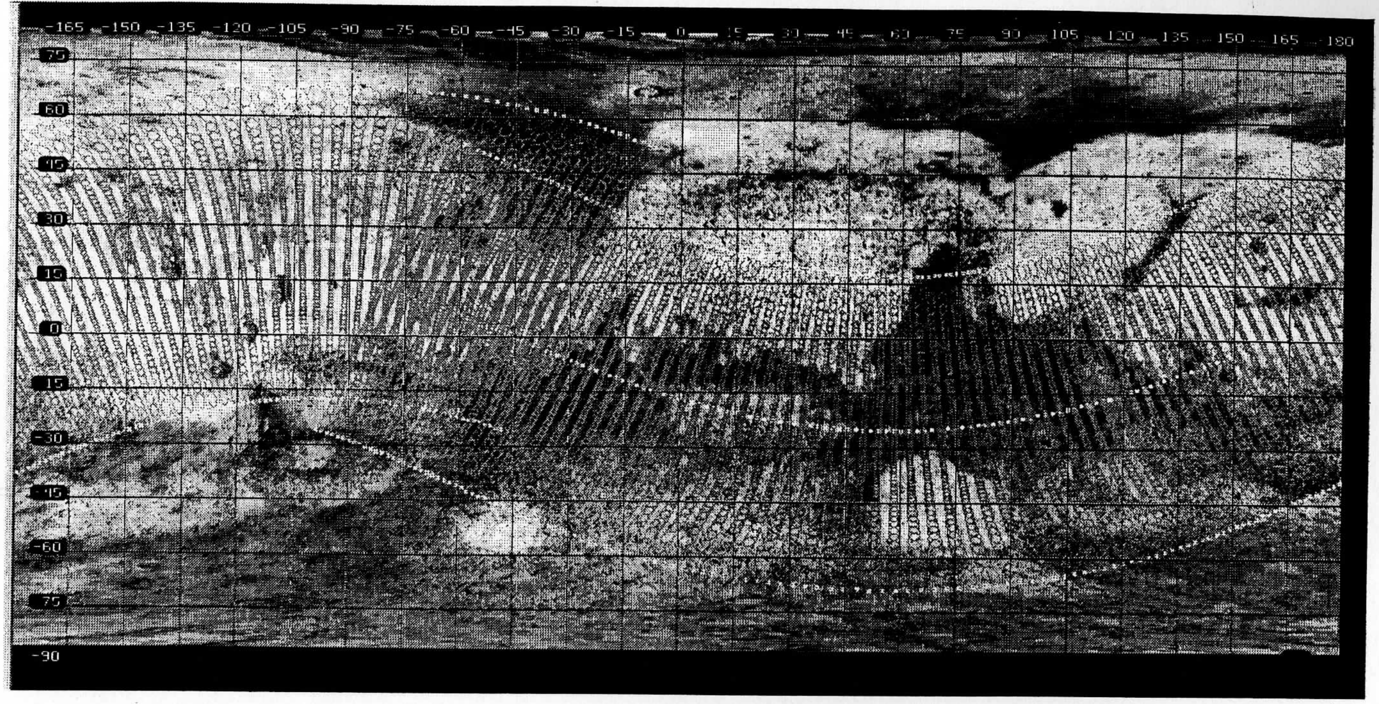


Figure 3. Illustration of the spatial coverage from MAS. Only every other cross-track scan is shown for clarity for one whole orbit.

6. Mission Operations concept

Spacecraft communications requirements

Global microwave soundings and multispectral imaging observations are acquired continuously in orbit. Only the infrared observations are returned on the night side through on-board editing of the data stream. The total daily volume is about 246 mbytes/day. The instruments observe continuously and as there is no pointing required, no commands to the instruments need to be uplinked regularly. Data is stored in the on-board gigabit memory, sufficient to store nearly 3 sols worth of continuous data.

Deep Space Network usage

One DSN pass daily DSN coverage required is to receive data from MOES. Throughout the mission life the maximum data rate supported by the 34-m DSN stations varies from 918 to 16.57 kbps for the HGA. With the 70-m stations the rates range from 3.08 mbps @ 0.36 AU to 55.5 kbps @ 2.68 AU for the HGA and 354 to 6.4 bps for each of the omnidirectional antennae.

The real-time data collected by the instruments is stored on the spacecraft in the gigabit solid state memory at 5:1 compression. The data is played back in a single 34-m DSN pass lasting 6.6 hrs, longer than the 216 minute orbital period. The spacecraft thus gets occulted during the data collection pass, allowing the very high vertical resolution temperature profile to be retrieved from the radio data. This once per sol occultation temperature profile is used as an independent measure of the microwave temperature profile retrievals. About once per week or as continuous DSN coverage is available for about a day, the occultations that occur would be covered to obtain not only the latitudinal but the local time data coverage.

Control center location and ground communications

Spacecraft control will be managed by the Jet Propulsion Laboratory. Telemetry acquisition from the spacecraft and command communications are to be handled by the DSN. It is expected that near continuous coverage will be available from the 34m stations. Decoded raw data will be forwarded to the JPL and from there to SSEC using Internet.

Science data collection, distribution, and archiving

The science data collection, distribution and archiving activities would be performed at the Space Science and Engineering Center (SSEC) of the University of Wisconsin-Madison, utilizing the existing capabilities. These capabilities for most weather satellites are available through McIDAS (Suomi et al., J. Appl. Meteor., 1983). McIDAS (Man Computer Interactive Data Access System) is a hardware software system developed at SSEC in the mid 1970's to ingest and conventional (i.e surface and upper air stations) and satellite observations of weather. Currently it is the prime facility in the world into which routine high data rate observations from GOES, METEOSAT, GMS and the two NOAA polar orbiting satellites are ingested in real time and made available to the scientists locally and globally for research, operational and educational use. McIDAS is used at KSC, JSC, MSFC and VAFB as heart of the weather information support system for all STS launches. It is also used routinely by other national weather facilities in the US such as NMC, NHC, NSSFC as well as those in other countries (European Center for Medium Range Weather Forecasts (England), Australia, Spain, China) for routine weather operations and even by private companies such as Federal Express. Additionally, through a joint project with UCAR, McIDAS also makes satellite and conventional observations available for use by educational institutions for classroom use through UNIDATA. This system is more than adequate for handling the data from MOES.

The implementation of the analysis, archiving and distribution of MOES observations will be patterned after the existing earth weather satellite data. No new software or hardware development is required for the collection (after receipt of data at SSEC), distribution or archiving. The only software development required is for instrument specific analysis. The data would be made available to the science team via Internet for routine (operational) analysis and entered into the Planetary Data System (PDS) as soon as practical for archival and use by other scientists. Analysis capability would be provided by the existing McIDAS workstations or UNIX workstations running McIDAS-X software that has already been developed.

Formation and Activities of Science Team

The science objectives are pursued by the Science Team consisting of the PI and Co-investigators. The co-investigators are: Drs. M. Allison (NASA/GISS), T. Clancy (U. Colorado), D. McCleese, R. Kahn and R. Zurek (JPL), D. Muhleman (CalTech), D. Paige (UCLA), S. Silverman (SBRC), L. Sromovsky, H. Revercomb and S. Ackerman (UW-Madison), and C. Hayden (NOAA). The Science Team would meet quarterly prior to launch and during the mission life.

Drs. D. McCleese, T. Clancy, L. Sromovsky and H. Revercomb share the responsibility for temperature and dust retrievals from the MAS and MIR observations. All have considerable experience in remote sounding of atmospheres.

Drs. Paige and Kahn would primarily investigate the surface/atmosphere interaction and surface changes.

Drs. M. Allison, A. Ingersoll and C. Hayden will be responsible for the assimilation and objective analysis of thermal sounding measurements and infrared dust retrievals using a numerical model (Mars GCM) routinely. Prof. Ingersoll also brings the Mars Observer experience to the team. Dr. Allison will produce daily weather maps and numerical forecasts for use by the rest of the science team, using models now under development for his

Participating Scientist investigation on Mars Observer. Routine data products will include twice-daily (simulcast) global maps of retrieved winds, interpreted daily forecasts, and "monthly"-mean compilations of height-latitude sections of zonal wind and meridional stream function. Dr. C. Hayden is an expert in the use of of the earth satellite observations in terrestrial forecast models operationally will participate jointly with Dr. Allison on the modelling effort.

Drs. R. Kahn, R. Zurek and Ackerman will monitor the weather processes on Mars on a routine basis, evaluate forecasts and investigate general circulation properties of the Martian atmosphere.

MOES Science Group

Just like the earth, Mars weather is expected to be a rich source of investigation topics. In view of the larger scientific community interest in the investigation of Mars as well as the longevity of the mission, we visualize the formation of a MOES Science Group. Scientists who have expressed interest and agreed to participate in pursuing the MOES science objectives would form the core of this group along with the MOES investigation team, and currently include Drs. R. Haberle and J. Pollack (NASA/Ames), C. Leovy (U. Washington), P. James (U. Toledo) and G. Schubert (UCLA). It would be possible to make the data routinely available to this group for educational and research use through an appropriate agreement with the investigation team and NASA. This approach parallels the one where the earth satellite data is routinely available to the researchers and the academic community.

7. Program Management

The philosphy for program management is efficiency and economy and best use of the expertise. MOES program management is therefore split into spacecraft procurement and instrument procurement activities. A MOES Program Manager (PM) at the University of Wisconsin oversees the overall MOES Program and Instrument in particular while a Program Office at JPL oversees the spacecraft specific activities including instrument integration and launch support.

Organizational structure and hierarchy

The organizational structure is shown in Figure 2. The overall responsibility for the success of the mission lies with the Principal Investigator (PI). The management support is provided by the MOES Program Manager at UW-Madison.

Responsibilities and activities of consortium partners

The consortium partners are TRW (spacecraft prime contractor for assembly, and integration and testing), SBRC (MIR instrument design, fabrication, calibration jointly done by SBRC and UW), and JPL (spacecraft management, spacecraft control and DSN communications) and Millitech Corp. (MAS fabrication, calibration) and UW (Data System).

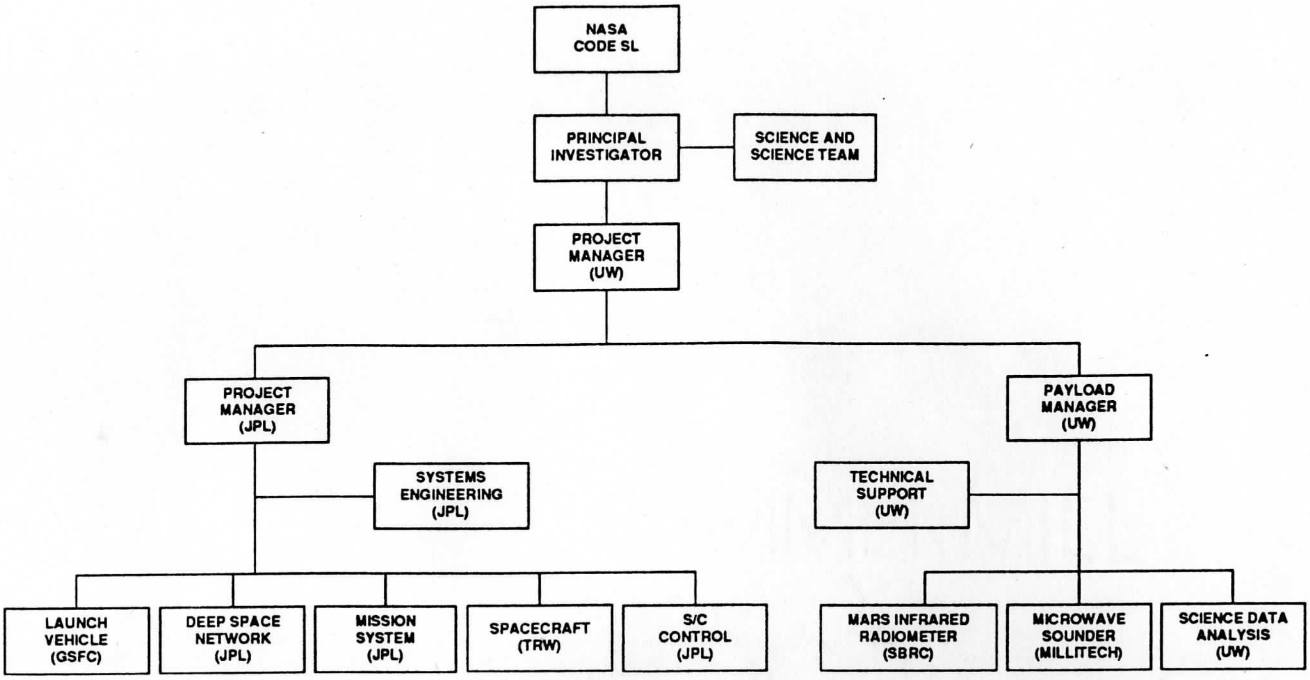
Procurement activities

The spacecraft procurement will be handled by JPL. Based on preliminary communications with TRW fixed price procurement is possible.

Development Schedule

The MOES spacecraft could be launched within 36 months of contract. The MIR instrument is a design copy with different filters and requires essentially no development as the only changes from the existing design are the filters.

MARS OPERATIONAL ENVIRONMENTAL SATELLITE (MOES)
PROJECT ORGANIZATION



8. Preliminary Project Development Budget

Based on preliminary mission design and vendor communications, the cost estimates are as follows:

MOES Cost Estimates (Launch + 30 days) in M$

	Year 1	Year 2	Year 3	Total
PI & Sci Team (UW)	0.4	0.6	0.8	1.8
Program Management (UW)	0.3	0.4	0.4	1.1
Data System (UW)	0.2	0.3	0.4	0.9
Project Office (JPL)	0.8	1.0	1.0	2.8
M/O Development (JPL)	1.0	1.0	1.0	3.0
M/A Engineering (JPL)	0.5	0.8	1.0	2.3
MIR (SBRC)	9.0	9.0	2.0	20.0
MAS (Millitech)	2.5	2.5	1.0	6.0
Spacecraft (TRW)	27.7	11.7	2.0	41.4
Sub Total	42.4	27.3	9.6	79.3
Reserves (30% except 10%, MIR)	10.9	6.4	2.5	18.0
TOTAL	53.3	33.7	12.1	99.1

Options for cost reduction

By opting for use of as much existing instrument designs, specifically the multispectral imager (MIR), MOES has already achieved substantial cost savings. Additional cost savings can be realized if the MOES version (MIR) of VIRS is fabricated concurrently by SBRC.

Spacecraft procurement is another area where cost savings are possible if other Discovery programs are able to utilize the spacecraft design. A second, identical spacecraft is estimated to cost $26M.

Discussion of heritage and maturity in cost estimation

MIR

MIR is basically the Visible Infrared Radiometer Scanner (VIRS) being built by the Santa Barbara Research Center (SBRC) for the Tropical Rainfall Measurement Mission (TRMM) to be launched in 1997 to orbit the earth. The current cost estimate is based on the design currently under Phase C/D for the TRMM mission.

MAS

The design of MAS is based on the heritage of SWAS being built by the Millitech Corp. to do spectroscopy of astrophysical objects. The heritage also follows from LMS now in earth orbit and performing limb sounding with millimeter wavelength spectral lines. The technology used in MAS is also very similar to that used in the Cosmic Background Explorer (COBE) which continues to measure the microwave background with 3 microwave radiometers.

Operational Data System

The mission data system is the existing McIDAS facility of the University of Wisconsin which enables routine access and analysis of earth weather data from satellites and other sources operationally. The MOES is essentially a weather satellite that just happens to return data from another planet. As far as the data ingestion and analysis capabilities are concerned, the only difference is in the small volume of data returned by MOES compared to even a single polar orbiting weather satellite such as NOAA 12. The two MOES instruments are analogous to AVHRR and HIRS with similar data coverage and focus. The MOES data can be ingested into McIDAS and made available to the users routinely using existing capabilities.

9. Benefits to the Discovery Program and Solar System Exploration

Importance of scientific goals

By enabling the first systematic nearly synoptic global observations of weather and rapidly varying phenomenon on Mars, the door is opened to a deeper investigation of processes important in Martian weather and climate, thus providing some insight into its past. Such weather observations would be the first of a planet other than our own and would allow the skill of the weather forecast models to be tested for a planet whose atmosphere is dynamically most similar to earth.

Utilization of and benefits to university, industry, and NASA communities

The proposed mission represents an excellent utilization of the Discovery Program resources. By fostering development by the industry and utilization by the scientists of small, capable spacecraft systems, MOES opens a path to more innovative and challenging missions. By sharing the expertise of universities and NASA centers, the mission provides previously non-existent opportunities for a wider body of students and scientists to participate.

Human exploration of Mars has oft been proposed as an appealing national and international endeavor. For the safety of those future explorers, it will be essential to provide a more accurate characterization of the Martian environment, including the practised forecast of the onset, evolution, and decay of dust storms. MOES would pave the way towards achieving that understanding and would provide the first data set with time and spatial resolution adequate to test forecast skills for Mars in a practical way.

Relationship to past and future planetary missions

MOES is a natural complement to the Mars Observer mission. MOES emphasizes local time coverage and rapidly changing phenomenon; it does so by choosing a near-equatorial orbit and trading vertical resolution for horizontal resolution consistent with time and space scales of the weather phenomenon it will characterize. Mars Observer emphasizes the seasonal time scales, the volatile cycles and the characterization of planetary-scale phenomenon; it does so by systematic mapping form a polar orbit and aiming for high vertical resolution by limb sounding.

If there are working meteorological stations on the surface of Mars, embraced by MESUR or foreign Mars missions (e.g., MARS 94/96, MARSNET), the MOES data would provide the interior atmospheric structure and circulation information otherwise unavailable from only a surface network. At a minimum, MOES could provide the regional and local context of surface measurements of temperature, pressure and wind. Certain phenomenon, such as the passage of cold fronts--thought to have initiated much of the dust movement that occurred at Viking Lander 1 site,-- could be studied in greater depth given the combination of remote sensing and surface in-situ data.

Major accomplishments and public perceptions of the missions

MOES is a logical step following the Mariner and Viking missions of the past, is highly complementary to the Mars Observer mission soon to be launched, and would be highly synergistic with MESUR, currently in planning phase. Representation of Mars weather phenomenon in a format highly familiar to the general public would have long-standing popular and educational appeal. It is quite feasible to provide visible and infrared images of Mars in near real-time, suitable for weather information distribution channels; the data handling system at the University of Wisconsin has demonstrated such capability and a tradition of student involvement that would make this happen. The detailed, quantitative analysis of dust opacity, derivation of winds, and analyses designed to understand the physical processes will take longer, of course, but would be foster in an academic environment.

10. Miscellaneous

The nominal mission lifetime is one Martian year. However, an extended mission would provide an opportunity to study the marked interannual variability of global weather on Mars. The observations from Mariner, Viking and Hubble Space Telescope indicate the variability of Martian weather. In recent years the episodes of global dust storms have not been as frequent as previously expected, and short term climatic variations are to be expected on Mars. Extended mission would provide the opportunity to monitor and characterize the interannual Martian weather variability.

The scientific payload has been kept to a minimum to constrain costs. Certainly other measurements can be made to further enhance the science return.

The MOES mission concept bears many similarities to the earth satellite observing programs. By making spacecraft operations routine and simple, systematic observations of Martian environment can be obtained in a manner similar to that used for the earth. Further, the existing tools and data handling systems can be used for the analysis and exchange of data very efficiently and cost effectively.

References

Albee, A.L., R.E. Arvidson, and F.D. Palluconi,Mars observer mission. *J. Geophys. Res.*, **97**, 7665-7680, 1992.

Briggs, G. A., W. A. Baum, and J. Barnes, Viking Orbiter imaging observations of dust in the Martian atmosphere, *J. Geophys. Res.* **84**, 2795-2820, 1979.

Christensen, P. R., Global albedo variations on Mars: implications for active aeolian transport, deposition and erosion, *J. Geophys. Res.*, **93**, 7611-7624, 1988.

Christensen, P.R., D.L. Anderson, S.C. Chase, R.N. Clark, H. H. Kieffer, M.C. Malin, J.C. Pearl, J. Carpenter, N. Bandiera, F. G. Brown, and S. Silverman, Thermal emission spectrometer experiment: Mars Observer Mission. *J. Geophys. Res.*, **97**, 7719-7734, 1992.

Conrath, B. J. Thermal structure of the Martian atmosphere during the dissipation of the dust storm of 1971, *Icarus*, **24**, 36-46, 1975.

Ditteon, R., Daily temperature variations on Mars, *J. Geophys. Res.*, **87**, 10,197-10,214, 1982.

Flasar, F. M. and R. M. Goody, Diurnal behaviour of water on Mars, *Planet. Space. Sci.*, **24**, 161-81, 1976.

Haberle, R. M. and B. M. Jakosky, Atmospheric effects on the remote determination of thermal inertia on Mars, *Icarus*, **90**, 187-204, 1991.

Hanel, R., B. Conrath, W. Hovis, V. Kunde, P. Lowman, W. Maguire, J. Pearl, J. Pirraglia, C. Prabhakara, B. Schlachman, G. Levin, P. Straat and T. Burke, Investigation of the Martian environment by infrared spectroscopy on Mariner 9, *Icarus*, **17**, 423-42, 1972.

Jakosky, B. M. The effects of nonideal surfaces on the derived thermal properties of Mars, *J. Geophys. Res.* **84**, 8252-8262, 1979.

Kieffer, H. H., T. Z. Martin, A. R. Peterfreund, B. M. Jakosky, E. D. Miner, and F. D. Palluconi, Thermal and albedo mapping of Mars during the Viking primary mission, *J. Gephys. Res.*, **82**, 4249-4291, 1977.

Kliore, A.J., D.L. Cain, G. Fjeldbo, B.L. Seidel, M.J. Sykes, and S.I. Rasool, The atmosphere of Mars from Mariner 9 radio occultation measurements. *Icarus*, **17**, 484, 1972.

Lelouch, E., G. Paubert, and T. Encrenaz, Mapping of CO millimieter wave lines in Mars' atmosphere: the spatial variability of carbon monoxide on Mars. *Planet. Space Sci.*, **39**, 219-224.

Martin, T. Z., A. R. Peterfreund, E. D. Miner, H. H. Kieffer and G. E. Hunt, Infrared properties of the Martian atmosphere 2. Global behavior at 7,9,11, and 20 microns, 1979.

Martin, T. Z. and H. H. Kieffer, Thermal infrared properties of the Martian atmosphere 2. The 15 micron band measurements, *J. Geophys. Res.*, **84**, 2843-2852, 1979.

McCleese, D.J., E.D. Hoskins, J.T. Schofield, R.W. Zurek, C.B. Leovy, D.A. Paige, and F.W. Taylor, Atmospherie and climate studies of Mars using the Mars observer Pressure Modulator Infrared Radiometer. *J. Geophys. Res.*, **97**, 7735-7757, 1992.

Muhleman, D.O. and R.T. Clancy, 1992: Microwave spectroscopy of the Mars atmosphere. *J. Opt. Soc., July 1992, in press.*

Paige, D. A. The thermal stability of near-surface ground ice on Mars, *Nature*, **356**, 43-45, 1992.

Palluconi, F. D. and H. H. Kieffer, Thermal inertia mapping of Mars from 60°S to 60°N, *Icarus*, **45**, 415-426, 1981.

Rosenqvist, J., P. Drossart, M. Combes, T. Encrenaz, E. Lellouch, J.P. Bibring, S. Erard, Y. Langevin, and E. Chassefiere, Minor constituents in the Martian atmosphere from teh ISM/Phobos experiment. *Icarus*, **98**, 254-270.

Suomi, V.E., R.J. Fox, S.S. Limaye, and W.L. Smith, McIDAS III: A Modern Interactive Data Access and Analysis System. *J. Clim. Appl. Meteor.*, **22**, 766-778, 1983.

SANJAY S. LIMAYE
Associate Scientist

Education

Ph.D. in Meteorology, 1977, University of Wisconsin-Madison
M.S. in Physics, 1971, Indian Institute of Technology, Kanpur, India
B.S. (Honors) in Physics, 1969, University of Bombay, India

Work Experience

Dr. Limaye began his career with the research on the atmosphere of Venus from Mariner 10 observations with Ph.D. thesis, "Venus stratospheric circulation: a diagnostic study" which was completed at the University of Wisconsin-Madison in 1977 with Prof. Verner E. Suomi. He was a National Research Council Resident Research Associate at the Institute for Space Studies, National Aeronautics and Space Administration, Goddard Space Flight Center, New York, during 1978-1980 where his effort led to the determiniation of Venus atmospheric circulation from Pioneer Venus Orbiter Cloud Photopolarimeter observations. He joined the Space Science and Engineering Center at the University of Wisconsin-Madison in 1980 to continue research on Planetary atmospheres, begining with the investigation of the Jupiter's atmospheric circulation from Voyager images. He has been a Guest Investigator on Pioneer Venus Orbiter mission. Significant among his contributions to Planetary Atmospheres include the discovery of the hemispheric vortex organization of the Venus atmospheric circulation, the detection of the thermal support for the mid-latitude jet on Venus, the high spatial and temporal resolution cloud level circulation of Jupiter and most recently, the atmospheric circulation of Neptune and the the detection of the regional climatic impact of the extensive smoke plumes resulting from the Kuwaiti oil field fires.

Most recently he has been monitoring the wide scale dispersal of smoke from the Kuwait Oil fires set during the Persian Gulf conflict of 1991 and accompnaying atmospheric effects. Currently he is also directing the development of software tools for planetary image data analysis via the creation of a planetary version of the PC-McIDAS software system.

Teaching Experience

Teaching Assistant, 1972-1973, 1974-1975, Department of Meteorology, University of Wisconsin-Madison for undergraduate and graduate level courses (Introduction to Weather and Climate (MET 100), Dynamic Meteorology II (MET 502) and Satellite Meterology (MET 822).

Several guest lectures to atmospheric science graduate and undergraduate students at the university level and to elementary and middle school students.

Awards and Affiliations

National Science Talent Scholarship, Government of India, 1966-1971.

NASA Public Service Award in 1980 for contribution in the Pioneer Venus Orbiter Cloud Photopolarimeter experiment.

NASA Group Achievement Award in 1990 for contribution to the Voyager Science Investigation of Neptune.

Member of the American Meteorological Society
Affiliate member of the American Astronomical Society (Division of Planetary Sciences).

Member of the JPL/Multi-Mission Image Processing Laboratory (MIPL) User Steering Group, NASA.

Member, COSPAR Sub-Commission (C.3) on Planetary Atmospheres and Aeronomy

Member, COSPAR ISC Task Group on Venus International Reference Atmosphere

PUBLICATIONS AND CONFERENCE PRESENTATIONS

Limaye, S.S., P.M. Fry, S.A. Ackerman, M. Isa, G. Ali, A. Wright, and A. Rangno, 1992: Satellite monitoring of smoke from the Kuwait oil fires. *J. Geophys. Res., in press.*

S.S. Limaye, 1992: Satellite Monitoring of Kuwait's Effluent: smoke from the oil fires. In **Global Climate Change: Implications, Challenges and Mitigations,** S.K. Majumdar, L.S. Kalkstein, B. Yarnel, E.W. Miller, and L.M. Rosenfeld, Eds., Pennsylvania Academy of Science. *In press.*

Limaye, S.S., P.M. Fry, S.A. Ackerman, 1992: PC-McIDAS in satellite monitoring of oil-fires in Kuwait expedition, *Preprint Volume of the Joint Session of the Eighth International Conference on Interactive Information and Processing* Systems for Meteorology, Oceanography, and Hydrology, and the Sixth Conference on Satellite Meteorology and Oceanography, January 5-10, 1992, Atlanta, Georgia, American Meteorological Society, J85-J86.

Limaye, S.S., and L.A. Sromovsky, 1991: Winds of Neptune: Voyager observations of cloud motions, *J. Geophys. Res., 96,* 18,941-18,960.

Limaye, S.S., V.E. Suomi, C.S. Velden, and G. Tripoli, 1991: Satellite observations of smoke from oil fires in Kuwait, *Science*, **252,** 1536-1539.

W.B. Hubbard, W.J. Nellis, A.C. Mitchell, N.C. Holmes, and S.S. Limaye, 1991: Interior structure of Neptune: comparison with Uranus, *Science, 253*, 648-651.

Suomi, V.E., S.S. Limaye, and D. R. Johnson, 1991: High winds of Neptune: a possible mechanism, *Science*, **251**, 929-932.

Limaye, S.S., 1990: Observed Cloud level circulation on Venus: temporal variations and solar longitude dependence. **Middle Atmosphere of Venus**, *Veroffentlichungen des Forschungsbereichs Geo- und Kosmoswissenschaften*, K. Schafer and D. Spankuch, eds., **18**, Akademie-Verlag, Berlin, 121-140. (Paper presented at the International Workshop on the Middle Atmosphere and Clouds of Venus, Heinrich Hertz Institute, Akademie der Wissenschaften der DDR, Potsdam, E. Germany, June 22-27, 1987).

Limaye, S.S., L.A. Sromovsky, and V.E. Suomi, 1990: Cloud motions on Neptune: Voyager observations. *Advances in Space Research,* in press.

Smith, B.A., L.A. Soderblom, D. Banfield, C. Barnet, A.T. Basilevsky, R.F. Beebe, K. Bollinger, J.M. Boyce, A. Brahic, G.A. Briggs, R.H. Brown, C. Chyba, S.A. Collins, T. Colvin, A.F. Cook II, D. Crisp, S.K. Croft, D. Cruikshank, J.N. Cuzzi, G.E. Danielson, M.E. Davies, E. De Jong, L. Dones, D. Godfrey, J. Gougen, J. Grenier, V.R. Haemmerle, H. Hammel, C.J. Hansen, C.P. Helfenstein, C. Howell, G.E. Hunt, A. P. Ingersoll, T.V. Johnson, J. Kargel, R. Kirk, D.I. Kuehn, S. Limaye, H. Masursky, A. McEwen, D. Morrison, T. Owen, W. Owen, J.B. Pollack, C.C. Porco, K. Rages, P. Rogers, D. Rudy, C. Sagan, J. Schwartz, E.M. Shoemaker, M. Showalter, B. Sicardy, D. Simonelli, J. Spencer, L.A. Sromovsky, C. Stoker, R.G. Strom, V.E. Suomi, S.P. Synnot, R.J. Terrile, P. Thomas, W.R. Thompson, A. Verbiscer, and J. Veverka, 1989: Voyager 2 at Neptune: Imaging science results. *Science***,** **246**, 1422-1454.

Limaye, S.S., 1989: High latitudinal resolution profile of Saturn's average zonal flow. *Bull. Amer. Astron. Soc.,* **21**, 952-953.

Hammel, H.B., R.F. Beebe, E.M. De Jong, C.J. Hansen, C.D. Howell, A.P. Ingersoll, T.V. Johnson, S.S. Limaye, J.A. Magalhaes, J.B. Pollack, L.A. Sromovsky, V.E. Suomi, C.E. Swift, 1989: Neptune's wind speeds obtained by tracking clouds in Voyager images. *Science*, **245**, 1367-1369.

Limaye, S.S., 1988: Venus atmospheric circulation: known and unknown. *Adv. Space Res.*, **10**, 91-101. *Paper presented at COSPAR, Helsinki, Finland, July 18-29, 1988.*

Limaye, S.S., C. Grassotti, and M.J. Kuetemeyer, 1988: Venus: Cloud level circulation during 1982 as determined from Pioneer Cloud Photopolarimeter images. I. Time and zonally averaged circulation. *Icarus*, **73**, 193-211.

Limaye, S.S., 1988: Venus: Cloud level circulation during 1982 as determined from Pioneer Cloud Photopolarimeter images. II. Solar longitude dependent circulation. *Icarus*, **73**, 212-226.

Limaye, S.S., 1987: Color differences in cloud level circulation on Jupiter. *Bull. Amer. Astron. Soc.*, **19**, 836.

Limaye, S.S., 1987: Jupiter: Short term variations of the mean zonal flow at the cloud level. Paper presented at the International Workshop on Time Variable Phenomenon in the Jovian System, Flagstaff, Arizona, USA, August 25-27, 1987, Available as NASA SP-494, 1989.

Limaye, S.S., 1987: Atmospheric Dynamics on Venus and Mars. *Adv. Space Res*, Planetary Studies, Eds. G.M. Keating, R.W. Shorthill, H. Masursky, and L.S. Elson, Vol 7, No. 12, 39-53. Invited paper presented at 26th COSPAR meeting, Toulouse, France, 30 June-11 July 1986.

Limaye, S.S., 1986: Jupiter: New estimates of the mean zonal flow at the cloud level, *Icarus*, **65**, 335-352.

Limaye, S.S., 1986: Jupiter: Erratum, New estimates of the mean zonal flow at the cloud level, *Icarus*, **67**, 342-343.

Limaye, S.S., C. Grassotti, and M.J. Kuetemeyer, 1986: Cloud level circulation during 1982: Pioneer Venus manual tracking results. *Bull. Amer. Astron. Soc.* **18**, 824.

Limaye, S.S., 1985: Venus Atmospheric Circulation: Observations and Implications of the Thermal Structure, *Adv. Space Res.* **5**, No. 9, 51-62. Invited paper presented at the Venus International Reference Atmosphere (VIRA) Workshop, COSPAR, Graz, Austria, 25-28 June 1984.

Kerzhanovich, V.V., and S.S. Limaye, 1985: Dynamics of the atmosphere from surface to 100 km. Venus International Reference Atmosphere, *Adv. Space Res.*, **5**, No. 11, 59-83.

Seiff, A., J.T. Schofield, A.J. Kliore, F.W. Taylor, S.S. Limaye. H.E. Revercomb, V.V. Kerzhanovich, V.I. Moroz and M. Ya. Marov, 1985: Models of the structure of the atmosphere of Venus from the surface to 100 km. Venus International Reference Atmosphere (VIRA), COSPAR, *Adv. Space Res.*, **5**, No. 11, 3-58.

Limaye, S.S., 1985: Jupiter: New estimates of the mean zonal flow at the cloud level, NASA Conference Proceedings, M.J. Allison and L.D. Travis, eds., NASA SP-2401, Conference on the Jovian Atmospheres, Institute for Space Studies, NASA/GSFC, New York, pp. 124-128.

Limaye, S.S., 1984: Morphology and movements of polarization Features on Venus, *Icarus*, **57**, 362-385.

Limaye, S.S., 1984: Mean thermal structure and balanced zonal circulation in the middle atmosphere of Venus. *Bull. Amer. Astron. Soc.*, **16**, 706-707.

Kliore, A.J., S.S. Limaye, and H.E. Revercomb, 1984: Mean thermal structure of the Venus atmosphere from Pioneer Venus radio occultation data. *Bull. Amer. Astron. Soc.*, **16**, 695-696.

Suomi, V.E., R.J. Fox, S.S. Limaye, and W.L. Smith, 1983: McIDAS III: A Modern Interactive Data Access and Analysis System. *J. Clim. Appl. Meteor.*, **22**, 766-778.

Limaye, S.S, 1983: Venus atmospheric circulation from near cloud level to the surface. Paper presented at the Hamburg. W. Germany Workshop for Venus International Reference Atmosphere (VIRA), IUGG-IAMAP, Hamburg, W. Germany, August 1983.

Limaye, S.S., 1982: Polarization features on Venus, *Bull. Amer. Astron. Soc.*, **14**, 740-741.

Limaye, S.S., C.J. Grund, and S.P. Burre, 1982: Zonal mean circulation at the cloud level of Venus: spring and fall 1979 OCPP observations, *Icarus*, **51**, 416-439.

Limaye, S.S., H.E. Revercomb, L.A. Sromovsky, R.J. Krauss, D.A. Santek V.E. Suomi, S.A. Collins, and C.C. Avis, 1982: Jovian winds from Voyager 2. Part I: Zonal mean circulation, *J. Atmos. Sci.*, **39**, 1413-1432.

Sromovsky, L.A., H.E. Revercomb, V.E. Suomi, S.S. Limaye, and R.J. Krauss, 1982: Jovian winds from Voyager 2. Part II: Analysis of eddy transports, *J. Atmos. Sci.*, **39**, 1433-1445.

Limaye, S.S., V.E. Suomi, L.A. Sromovsky, R.J. Krauss, D.S. Santek, and H.E. Revercomb, 1981: Jovian circulation from Voyager 2 cylindrical mosaics. *Bull. Amer. Astron., Soc.*, **13**, 742.

Sromovsky, L.A., V.E. Suomi, J.B. Pollack, R.J. Krauss, S.S. Limaye, T. Owen, H.E. Revercomb, and C. Sagan, 1981: Implications of Titan's north-south brightness asymmetry, *Nature*, **292**, 698-702.

Sromovsky, L.A., H.E. Revercomb, V.E. Suomi, S.S. Limaye, and R.J. Krauss, 1981: Effects of sampling strategy on Jovian eddy transport measurements. *Bull. Amer. Astron., Soc.*, **13**, 743.

Limaye, S.S., and V.E. Suomi, 1981: Cloud motions on Venus: Global structure and organization, *J. Atmos. Sci.*, **38**, 1220-1235.

Schubert, G., C. Covey, A. Del Genio, L.S. Elson, G. Keating, A. Seiff, R.E. Young, J. Apt, C.C. Counselman, A.J. Kliore, S.S Limaye, H.E. Revercomb, L.A. Sromovsky, V.E. Suomi, F. Taylor, R. Woo, and U. von Zahn, 1980: Structure and circulation of Venus atmosphere, *J. Geophys. Res.*, **85**, 8007-8025.

Rossow, William B., Anthony D. Del Genio, Sanjay S. Limaye, and Larry D. Travis, 1980: Cloud morphology and motions from Pioneer Venus images, *J. Geophys. Res.*, **85**, 8107-8123.

Travis, L.D., D.L. Coffeen, A.D. Del Genio, J.E. Hansen, K. Kawabata, A. A. Lacis, W.A. Lane, S.S. Limaye, W.B. Rossow, and P.H. Stone, 1979: Cloud images from the Pioneer Venus Orbiter, *Science*, **205**, 74-76.

Travis, L.D., D.L. Coffeen, J.E. Hansen, K. Kawabata, A.A. Lacis, W.A. Lane, S.S. Limaye, and P.H. Stone, 1979: Orbiter Cloud Photopolarimeter investigation, *Science*, **203**, 781-784.

Limaye, S.S., 1978: Venus: Clouds, Waves and Spectra, *Bull. Amer. Astron. Soc.*, **10**, 546. Abstract of a paper presented at the meeting of Division of Planetary Sciences, American Astronomical Society, Pasadena, CA, 27 October-1 November 1978.

Suomi, V.E. and S.S. Limaye, 1978: Venus: Further evidence of vortex circulation, *Science*, **201**, 1009, 1011.

Limaye, S.S. and V.E. Suomi, 1977: Possible detection of an atmospheric planetary wave, *Bull. Amer. Astron. Soc.*, **9**, 509. Abstract of a paper presented at the meeting of Division of Planetary Sciences, American Astronomical Society, Boston, MA, 27 October-1 November 1977.

Tomasko, M.G., R. Boese, A.P. Ingersoll, A.A. Lacis, S.S. Limaye, J.B. Pollack, A. Seiff, A.I. Stewart, V.E. Suomi, and F.W. Taylor, 1977: The Thermal balance of the atmosphere of Venus, *Space Science Reviews*, **20**, 389-412.

Schubert, G., C.C. Counselman, J. Hansen, S.S. Limaye, G. Pettengill, A. Seiff, I.I. Shapiro, V.E. Suomi, F. Taylor, L. Travis, R. Woo, and R.E. Young, 1977: Dynamics, winds, circulation and turbulence in the atmosphere of Venus - contribution of Pioneer Venus Science Steering Group on Dynamics, *Space Science Reviews*, **20**, 357-387.

Limaye, S.S., 1977: Venus: Global scale inertial oscillations, *Bull. Amer. Astron. Soc.*, **9**, 467. Abstract of a paper presented at the meeting of the Division of Planetary Sciences, American Astronomical Society, Honolulu, HI, 19-22 January 1977.

Limaye, S.S., and V.E. Suomi, 1977: A normalized view of Venus, *J. Atmos. Sci.*, **34**, 206-215.

Limaye, S.S., 1976: "On the possibility of obtaining the three dimensional wind from geosynchronous measurements of temperature and moisture profiles", in *Studies of Sounding and Imaging Measurements,* Final Scientific Report on NASA Contract NAS5-21798, Space Science and Engineering Center, University of Wisconsin-Madison.

Limaye, S.S., and V.E. Suomi, 1976: A normalized view of Venus. Abstract of the paper presented at the Division of Planetary Sciences Meeting, American Astronomical Society, Austin, TX, 30 March-3 April 1976, *Bull. Amer. Astron. Soc.*, **8**, 550-551.

Suomi, V.E., S.S. Limaye, and R.J. Krauss, 1976: Upper wind observations on Venus. Abstract of the paper presented at the Division of Planetary Sciences Meeting, American Astronomical Society, Austin, TX, 30 March-3 April 1976, *Bull. Amer. Astron. Soc.*, **8**, 552.