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THERMOSPHERE-IONOSPHERE-MESOSPHERE ENERGETICS AND DYNAMICS (TIMED)

THE TIMED MISSION AND SCIENCE PROGRAM

REPORT OF THE SCIENCE DEFINITION TEAM

VOLUME I: EXECUTIVE SUMMARY

July 1991

National Aeronautics and
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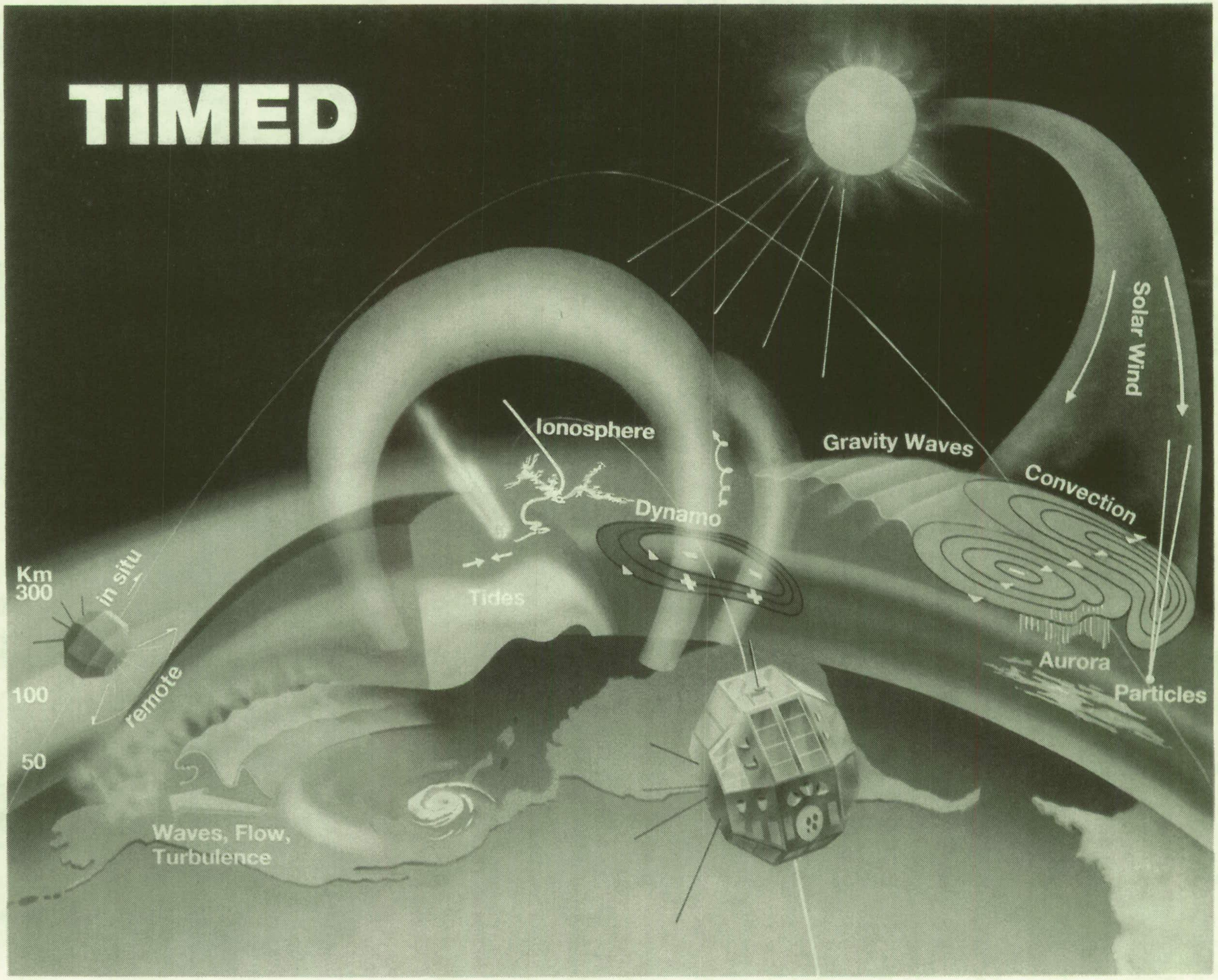
"the Earth's mesosphere and lower thermosphere/ionosphere are the least explored regions in the Earth's atmosphere..."

Space Science in the Twenty-First Century: Imperatives for the Decades 1995-2015, Space Science Board, National Academy of Sciences, 1988.

"a series of space observations is needed to advance understanding of the interesting dynamical, chemical and radiative processes in the mesosphere, stratosphere and thermosphere. One low and one high-inclination spacecraft are first needed to establish basic atmospheric properties and their geographic, diurnal, and seasonal dependencies"

Solar-Terrestrial Research for the 1980's, Committee on Solar-Terrestrial Research, National Academy of Sciences, 1981.



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PREFACE

The work described in this report was performed by the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) Science Definition Team under the cognizance of the Ionospheric Physics Branch of the Space Physics Division of NASA's Office of Space Science and Applications.

THERMOSPHERE-IONOSPHERE-MESOSPHERE ENERGETICS AND DYNAMICS (TIMED)

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SUMMARY

A Science Definition Team was established in December 1990 by the Space Physics Division, NASA, to develop a satellite program to conduct research on the energetics, dynamics, and chemistry of the mesosphere and lower thermosphere/ionosphere. This two-volume publication describes the TIMED (Thermosphere-Ionosphere-Mesosphere, Energetics and Dynamics) mission and associated science program. The report outlines the scientific objectives of the mission, the program requirements, and the approach towards meeting these requirements.

TIMED will carry out the first comprehensive space-borne investigation of the physical and chemical processes acting in the terrestrial mesosphere and lower thermosphere/ionosphere (MLTI) between ~60 and ~180 km. This region represents a "crossroads" in the flow of mass, momentum, and energy through the coupled atmosphere-ionosphere-magnetosphere system. It is a region that is poorly understood due, in part, to its inherent complexity and due, in part, to the difficulty of carrying out *in situ* measurements at these altitudes. It is a "transition" region where atmospheric temperatures and thermal gradients reach extreme values, where turbulent flow changes to diffusive molecular flow, where the composition changes from molecular to atomic, where complex photochemical and electrodynamical processes become predominant, and where these combined effects challenge theoretical description.

TIMED will be an exploratory mission to characterize and understand the interplay of composition, energetics, radiation and dynamics of this region. It will complement the NASA UARS (stratospheric) and ISTP (magnetospheric) missions and contribute to the international STEP program. TIMED will also contribute to the study of anthropogenically–induced changes in the atmosphere. Specifically, the mesosphere is sensitive to increasing levels of methane and carbon dioxide and may be an important harbinger of global change. There is already strong evidence that the mesosphere may be changing on relatively short time scales (~10's of years), and hence it is critical to establish a baseline global description of the region at the earliest possible date.

The satellite and instrument requirements for the TIMED mission are derived from prioritized requirements calling for measurements of the energy and momentum sources, state variables, dynamics, and the related ionospheric structure and electrodynamics. The resulting mission comprises two identical spacecraft in different orbits to provide extensive

coverage of MLTI parameters in latitude, altitude, local time, and season. The spacecraft are launched on separate Delta-class expendable launch vehicles into orbits having inclinations of 95° and 49°. Both spacecraft have on-board propulsion capabilities to allow for circular and eccentric orbits. The operating lifetime of each spacecraft is 48 months.

The TIMED mission requires a dedicated ground-based data system and a science team organization that ensure strong interactions between experiments and theory and appropriate use of the data resource. As such, TIMED represents a natural evolution from previous NASA missions, such as AE, SME, DE, and UARS. It will enable a quantitative exploration of a critical transition region of the Earth's upper atmosphere that has previously proved resistant to experimental study.

The TIMED mission concept was a product of the 1990 Strategy-Implementation Study that brought together scientists from the disciplines in the ionosphere-thermosphere-mesosphere (ITM) community. This document is the final report of the Science Definition Team for the TIMED pre-Phase-A study. Volume I provides an executive summary, while Volume II provides the detailed findings of the team.

With the presentation of this pre-Phase-A study report, the TIMED mission and supporting technology are sufficiently well defined so that, with a one-year Phase-A study, TIMED will be ready as a new-start candidate in the intermediate-class cost category.

I. INTRODUCTION

While our knowledge of the near-Earth space environment has increased enormously since the start of the Space Age, many significant gaps in this knowledge exist and our ability to model the variability of the system as a whole remains rudimentary at best. Furthermore, certain regions of the solar-terrestrial system remain largely *unexplored* and important physical, chemical, dynamical, electrodynamical, and radiative coupling processes which act upon and between different regions have been identified but not investigated in detail.

The desire to investigate and understand our "local" space environment is not only driven by intellectual curiosity, but also by practical societal motivations. In particular, there has been increasing concern and interest in recent years about the variability, both natural and artificial, of the Earth's upper atmosphere and ionosphere. These concerns have been emphasized by the discoveries of anthropogenically-induced changes in the ozone abundance and potential global warming related to increased atmospheric loading of radiatively active minor constituents. In addition, long-term variations in solar activity and large solar storms have led to instances of premature re-entry of orbital vehicles and disruptions in power supply and global communications. These important issues and their societal effects have heightened our appreciation of the complexity of the Earth's upper atmosphere and ionosphere and its sensitivity to external influences. The potential threats to the stability of the near Earth space environment, and the possibility of additional and yet unidentified changes, call for an enhanced long-term program of scientific research directed toward improving our knowledge of the Earth's atmosphere.

The region of the atmosphere about which the *least* is currently known is the mesosphere and the MLTI. This region, between roughly 60 and 180 km altitude, is too high for probing by balloons and too low for direct *in situ* measurements by long-lived satellites without on-board propulsion. As a consequence, it has received much less attention than the more readily accessible regions above and below. In many respects, the MLTI region represents an uncharted "frontier" for upper atmospheric research.

This lack of knowledge and understanding of the MLTI region has been recognized by the various national advisory groups. For example, the Space Science Board of the National Academy of Sciences has stated that:

> *"The Earth's mesosphere and lower thermosphere are the least explored regions of the Earth's atmosphere. They are influenced by varying solar extreme ultraviolet,*

ultraviolet, and X-ray radiation, auroral particles and fields, and upward propagating waves and tides from the lower atmosphere. There are strong interactions between the chemistry, dynamics, and radiation of both the neutral and ionized constituents of this region. It is known that the global structure of this region of the atmosphere can be perturbed during stratospheric warmings and solar-terrestrial events (magnetospheric substorms, solar flares, etc.), but the overall structure and dynamic responses to these effects and even the basic controlling physical and chemical processes of these effects are not understood "

To study this system, the National Academy's Committee for Solar-Terrestrial Research pointed out that :

"A series of space observations is needed to advance understanding of the interesting dynamical, chemical, and radiative processes in the mesosphere, stratosphere, and thermosphere. One low and one high inclination spacecraft are first needed to establish basic atmospheric properties and their geographic, diurnal, and seasonal dependencies"

A list of recent Academy reports calling for the exploration and quantitative investigation of the MLTI region is given in Table 1.

The recent Strategy-Implementation Study (SIS) of the Space Physics Division also recommended a phased program of NASA missions devoted to a comprehensive study of the Ionosphere-Thermosphere–Mesosphere (ITM) system. The first component of this program identified during the SIS is the Thermosphere–Ionosphere–Mesosphere, Energetics and Dynamics (TIMED) mission, which is designed to address the MLTI region and is in the "intermediate class" ($ 200 – 300 M) cost category. This TIMED mission is an important new effort aimed at improving our knowledge and understanding of the atmosphere and ionosphere above the stratosphere and below the upper thermosphere/ionosphere and magnetosphere. In this region, complex physical, chemical, dynamic, radiative, and electrodynamic processes all undergo profound transitions and combine to drive a rich thermal, dynamical, and compositional global morphology. Through a careful balance between comprehensive measurements, theoretical studies of the basic processes, and model analysis, it is now clear that substantial progress can be made in solving the major outstanding problems of this region.

Table 1

National Advisory Reports calling for the exploration of the Mesosphere, Lower-Thermosphere/Ionosphere System

(1) *Solar-Terrestrial Research for the 1980's,* Committee on Solar-Terrestrial Research, National Academy of Sciences, 1981.

(2) *A Strategy for the Explorer Program for Solar and Space Physics,* National Academy Press, Washington D.C.,1984.

(3) *An Implementation Plan for Priorities in Space Physics,* Space Science Board, National Academy of Sciences, 1985.

(4) *Strategic Plan,* NASA Office of Space Sciences, 1988.

(5) *Solar-Terrestrial Sciences,* Report from the Science Strategy Workshop, NASA Space Physics Division, 1988.

(6) *Space Science in the Twenty-First Century,* Solar and Space Physics report of the Study Steering Group, Space Science Board, National Academy of Sciences, 1988.

(7) *Earth System Science, A Closer View,* Report of the Earth System Sciences Committee, NASA Advisory Council, 1988.

(8) *Long-term Solar-Terrestrial Observations,* Panel on long-term observations, Committee for Solar-Terrestrial Research, National Academy of Sciences, 1988.

(9) *Space Physics Strategy-Implementation Study Workshop,* Executive Summary – Report of the Mission Integration and Divisional Science Plan, 1990.

This report (Volume I of the pre-Phase-A study) provides a brief summary of the findings of the TIMED Science Definition Team. Full details of the study may be found in Volume II. The following sections briefly describe the TIMED science rationale and implementation plan.

II. Scientific Objectives

The scientific objectives for the TIMED mission were developed after a thorough review of the current state of knowledge of the field and the development of a prioritized set of key scientific questions. After this review, and in accordance with the mandates of both the Academy of Sciences and the Strategy-Implementation Study, the Science Definition Team adopted the following *Primary Objective* for TIMED:

To perform an exploratory study of the physical and chemical processes acting within and upon the coupled mesospheric, thermospheric, and ionospheric system between ~60 and 180 km.

Figure 1 illustrates the basic thermal and plasma density structure of the MLTI region, together with an indication of the altitude regimes of interest for the UARS and ISTP missions as well as those for balloon and some ground–based experiments.

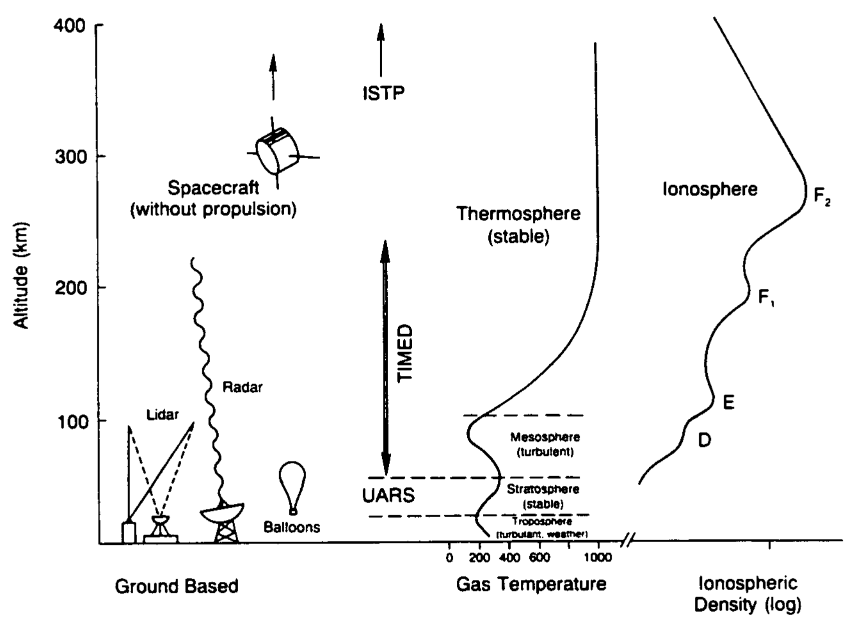


Figure 1. Schematic illustration of the atmospheric thermal structure and electron (ion) content. The primary altitude regimes of scientific investigations for TIMED – as well as those for UARS, ISTP, ballon and some ground–based experiments – are indicated.

The region to be investigated by TIMED is home to a large number of fundamental transitions in atmospheric processes. Perhaps the most fundamental one is the change from turbulent mixing to molecular diffusion. However, there are also many others. The energy balance is marked by a change from radiative control to thermal conductive control. The composition changes from molecular to atomic. The available solar radiation changes spectrally, with EUV important at higher altitudes and UV important at lower altitudes. The dynamics of the region changes from geostrophic control to ageostrophic control, with viscosity and ion drag playing more important roles at higher altitudes. The highly variable heating rates, due to solar EUV/UV absorption, Joule heating, particle heating, tidal, and gravity wave dissipation, *all maximize* in the MLTI transition region. Yet, the lowest temperatures anywhere in the Earth's atmosphere occur near the *summer* polar mesopause. The region also houses the primary atmospheric, ionospheric, and electrodynamical interactions. The influence of the magnetosphere becomes significant, and ionospheric conductivities and currents maximize. Gravity wave breaking and plasma instabilities affect the energy and momentum balances, as turbulence becomes a primary factor in mass, momentum, and energy transfer processes at the lower boundary. Finally, in this region of the Earth's atmosphere, the largest temperature gradients are found – leading to a rapid change in atmospheric stability.

Table 2 summarizes the fundamental and dramatic changes that characterize this transition region. Some of the processes responsible for these effects are schematically illustrated in the frontispiece. *All of these processes occur within the MLTI region that has never been the subject of a comprehensive satellite investigation. It is the general purpose of TIMED to provide such a comprehensive and global study of the interplay between dynamics, energetics, chemistry, radiation, and electrodynamics in this region.*

In addition to the exploratory and investigative motivations for TIMED, there is an important additional need for early measurements of the MLTI region. It is expected that anthropogenic changes will cause the terrestrial mesosphere to experience first–order changes in its chemistry, composition, temperature distribution, and dynamics within the next two to three decades. The projected cooling of the mesosphere from increased amounts of carbon dioxide, for example, will affect the chemistry of important minor constituents. This cooling will also allow high altitude ice clouds (Polar Mesospheric

Clouds) to form at lower attitudes than normally possible. This equatorward spread may influence the climate down to the Earth's surface. It seems very likely that the mesosphere.

Table 2
Characteristics of the 60–180 km Transition Region

(1) Turbulent mixing gives way to molecular diffusive separation and transport.

(2) Radiative processes dominate the thermal balance below and thermal conduction dominates above.

(3) Composition ceases to be dominated by molecules and becomes increasingly dominated by atoms.

(4) Solar EUV is important at higher altitudes and solar UV is important at lower altitudes.

(5) Heating rates due to solar EUV/UV absorption, Joule heating, and particle heating all maximize.

(6) The dynamics of the region change from geostrophic control to ageostrophic control.

(7) The coupling processes between the atmosphere and the magnetosphere become significant, conductivities maximize, and the charged particle population plays an important role in atmospheric energetics.

(8) Gravity wave breaking and plasma instabilities play significant roles in the energy and momentum balances.

(9) The thermal structure shows a fundamental change in lapse rate, leading to rapid changes in atmospheric stability.

(10) Local thermodynamic equilibrium ceases to apply.

(11) The charged particle population changes from one that has positive and negative cluster ions at lower altitudes, to one that has electrons and chemically controlled molecular ions, to one that has electrons and diffusively controlled atomic ions at higher altitudes.

(12) The dynamics of charged particles is controlled by collisions with the neutral atmosphere at lower altitudes and by diffusion and electric as well as magnetic fields at higher altitudes.

of the future will be quite different from what it is now. Due to this high degree of senitivity to anthropogenic effects in temperature and composition, the mesosphere proves to be an ideal region for the early detection of related long-term atmospheric changes.

The anticipated changes can be appreciated from a straight–forward assessment of the effects of a growing abundance of atmospheric carbon dioxide, methane, and water vapor. CO_2, increasing at the rate of 0.5%/yr, will lead to a far stronger cooling of the middle atmosphere than to a warming of the Earth's surface. The expected changes in temperature from a doubling of carbon dioxide will be in the 10's of degrees in the middle atmosphere, compared to fractions of a degree at the surface. Methane is increasing at the rate of 1 – 2%/yr in the middle atmosphere. Its oxidation to water vapor in the middle

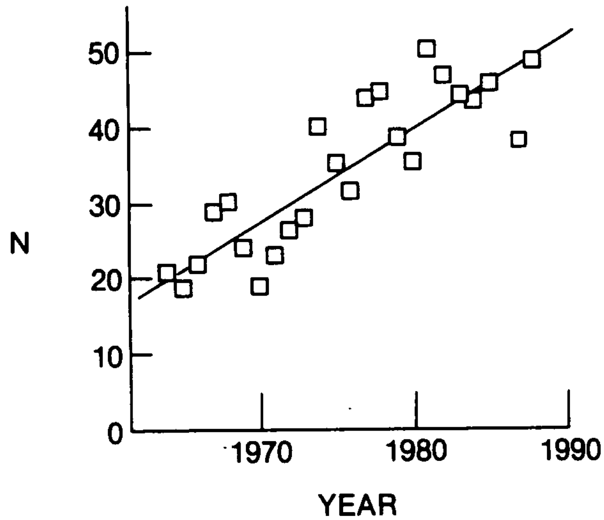


Figure 2. Plot of the number of nights per year, N, on which noctilucent clouds were reported from north–west Europe, with the effect of solar activity removed. This plot (from Gadsden, 1990) provides evidence for secular increases in mesospheric noctilucent cloud occurrence.

atmosphere will drive a stronger odd–hydrogen chemistry, probably resulting in a decrease in the density of ozone in this region. This sensitivity of the mesosphere is exemplified in Figure 2 by the observed increase in noctilucent cloud occurrence, which accounts for no less than a factor of ~2 increase over the past 20 years and has been attributed to the man induced methane increase or, alternately, to the secular decrease in mesopause temperature.

In response to a series of key scientific questions formulated by the Science Definition Team, the five overall objectives for the TIMED mission have been developed and are given in Table 3:

Table 3

TIMED Overall Mission Objectives

(1) *To investigate and quantitatively understand the important physical and chemical processes responsible for the energy and momentum budgets of the MLTI region and the electrodynamic as well as chemical interactions between the neutral and plasma components of the region.*

(2) *To investigate and quantitatively understand the coupling between chemistry, radiation, waves (tides, gravity waves, and planetary waves), unorganized motions, and the large-scale circulation, and the resultant effects on momentum, energy, and mass (species) transfer within, to, and from the mesosphere and lower thermosphere.*

(3) *To investigate and quantitatively understand the lower ionosphere: to elucidate its role in the global electric circuit, to understand the chemistry and energy budget of this region, and to determine how these processes affect the coupling between the lower thermosphere and mesosphere.*

(4) *To investigate and quantitatively understand the odd oxygen, odd nitrogen, and odd hydrogen chemistry within the Mesosphere and Lower Thermosphere*

(5) *To investigate anthropogenically induced changes in the mesosphere and lower thermosphere and establish a baseline for future investigations.*

These objectives, together with the measurement oriented science questions, in turn, were used to derive the measurement requirements, leading to an implementation strategy. Full details of this process can be found in Volume II of this report.

III. TIMED Mission Requirements

III.1 Measurement Requirements

The primary measurements of TIMED include observations of the global and temporal variations in the atmosphere and ionosphere, which are controlled by radiative, chemical, dynamic, thermodynamic, and electrodynamic processes. Measurements of the dynamics of neutral and ionized species will serve to describe, for the first time, the global-scale circulation of the MLTI region, including global wind systems, planetary waves, solar and lunar tides, and a broad spectrum of gravity waves. They will allow fundamental investigations of turbulence and wave breaking, which are known to affect profoundly the mass, momentum, and energy budgets of the region. The measurements will also enable the electrodynamics of the most highly conducting part of the atmosphere to be investigated, leading, in turn, to deeper insights concerning the global electrical circuit, including magnetospheric components.

Measurements of the radiative and corpuscular sources of energy, together with observations of airglow emissions and neutral and plasma temperature distributions, will serve to determine the energy balance of the region. Such observations and associated theoretical work will quantitatively determine, for example, the causes of the extremely low temperatures found in the summer mesopause – the coldest region of the atmosphere.

Measurements of the relative abundances of the major neutral and ionized constituents of the region, together with observations of the altitude profiles of a panoply of photochemically active ionized and neutral trace constituents will enable the first comprehensive and detailed compositional global inventory to be assembled. Such measurements will provide a new window on the extremely complex chemical and radiative processes known to couple the odd oxygen, odd hydrogen, and odd nitrogen chemical families, which collectively control atmospheric ozone.

Table 4 summarizes the needed observations related to the key scientific questions (ref. Volume II), without regard to the ease of measurement. These measurements are *required* to accomplish the five overall scientific objectives.

Table 4
TIMED Science-driven measurement requirements

Science Question(s)	Measurements	Approx. Alt. Range (km)	Accuracy	Spatial scales	Temporal scales
	Composition				
3,5,8,10,20,23, 24,25	major species abundance N_2, O_2, O.	50 - 400	5%	1/2 scale height (vertical) 10 km (gravity waves) 100's km (tides, planetary waves)	~1 min (gravity waves) ~1 hr (tides) ~ 1hr (planetary waves) 1 month (seasonal)
2,3,4,5,6,8,9, 10,12,13,24	minor species abundance CO_2, O_3, Ar, Mg, CO, NO, OH, N, Fe, NO_2, H_2O, CH_4, Na, H, He	50 - 180 < 600	5%	1/2 scale height (vertical) 10 km (gravity waves) 100's km (tides, planetary waves) (1 km Na, Fe)	~1 min (gravity waves) ~1 hr (tides) ~ 1hr (planetary waves) 1 month (seasonal) (match frequency of measurements with solar flux for photochemical studies)
2,4,5,9,11,12, 13,23,	excited states $N(^2D)$, $O(^1D)$, $O(^1S)$, $O_2(^1\Delta)$, $O_2(^1\Sigma)$, OH^*, O_3^*, N_2^*, O_2^*, CO_2^*	45 - 300 (species dependent)	10%	1/4 scale height 10 km horizontal (gravity waves)	1 min (photochemical studies and gravity waves)
2,11,13,21,22, 23,24,25	charged species e, O^+, NO^+, O_2^+, N_2^+, H^+, He^+, N^+, metallics	90 - 400	5%	1 km (vertical) 1 km (horizontal) 1 m (n_e)	1 min (phenomenology) < 1 sec(instabilities)
	Temperatures				
1-7, 9, 13-21 23-24	neutral kinetic temperature	40-400	2% (100 km) 5% (>150 km)	1/4 scale height 10 km (gravity waves) 100 km (tides, planetary waves)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
4,12 4,12,23	rotational vibrational	55-200	2% (100 km) 5% (>150 km)	1/4 scale height 10 km (gravity waves) 100 km (tides, planetary waves)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)

Table 4 (cont.)
TIMED Science-driven measurement requirements

2,19,22,23,24	ion and electron temperatures	80-400	5%	1 km (vertical) 1 km (horizontal)	1 min (phenomenology) <1 min (instabilities)
	Dynamics				
2,5,6,10,11,14-18,21	global circulation	50-400	1 m/sec	100 km	<1 min
2,6,11-13,15-17,19,20,21,23-25	tides and planetary waves	50-400	1 m/sec	100 km	1 hr (tides and planetary waves)
2-4,6,11-18,21,24	gravity waves	50-400	1 m/sec	10 km (horizontal) 1/4 scale height (vertical)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
2,5,11,14,16,19-25	ion drifts	90-400	5 m/sec	10 km (horizontal) 1/4 scale height (vertical)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
	Energetic particles				
2,4,11,12,21,23,24	<100 eV electrons and ions	110-200	ΔE/E 10%	10 km	1 min
2,3,5,9,10,12,16,19,20-25	10 eV - 50 keV electrons and ions	80-250 >300	ΔE/E 30%	10 km	1 sec
4,9-12	>50 keV electrons and ions, REPS	>300	30%	2 km	1 sec
2,14,19-22,24,25	**Electric fields**	150-400	5%	1 m	1 min (phenomenology) <1 sec (instabilities)
19,20,22,25	**Magnetic fields**	125-400	1 nT	1km	<1 sec
1,2,5,8-13	**Solar EUV** (λ<1050-Å)	≥300	10%	specral resolution 10-Å	10/day
1,2,5,11-15,17,18	**Solar UV** (λ>1050-Å)	≥300	10%	spectral resolution 1-Å	10/day

III.2 Orbital Requirements

The three principal orbital requirements for the mission are:

(1) *The need for global coverage, including in particular the high-latitude regions.*

(2) *The need for rapid local time precession of the orbit to enable tidal structures to be mapped with a resolution of (at a minimum) 24 hrs LT per month.*

(3) *The need for remote measurements down into the mesosphere and in situ measurements down into the lower thermosphere and ionosphere.*

These requirements point to the need for 3-axis stabilization of the vehicles (for accurate remote sensing), propulsion capability (for phased orbital adjustments), and a combination of elliptical orbits (to provide low altitude *in situ* measurement capability) and circular orbits (to optimize the remote sensing measurement capability). A scenario designed to meet the measurement and orbital requirements is discussed below.

IV. IMPLEMENTATION PLAN

IV.1 Mission Scenario and Orbit Selection

No single orbit is suitable for separating the spatial and temporal variations of the mesosphere and lower thermosphere. A configuration with two spacecraft (TIMED-H and -L) is required to provide the complementary coverage. TIMED-H will be placed into in a high–inclination, nearly sun-synchronous 95°orbit, while TIMED-L will be in a 49° orbit. The slowly precessing orbit of H will provide essentially full global coverage, while the rapidly precessing orbit of L will provide full diurnal coverage each month at middle and low latitudes. From these orbits, a combination of remote and *in situ* devices will cover the entire altitude region of interest in both latitude and local time.

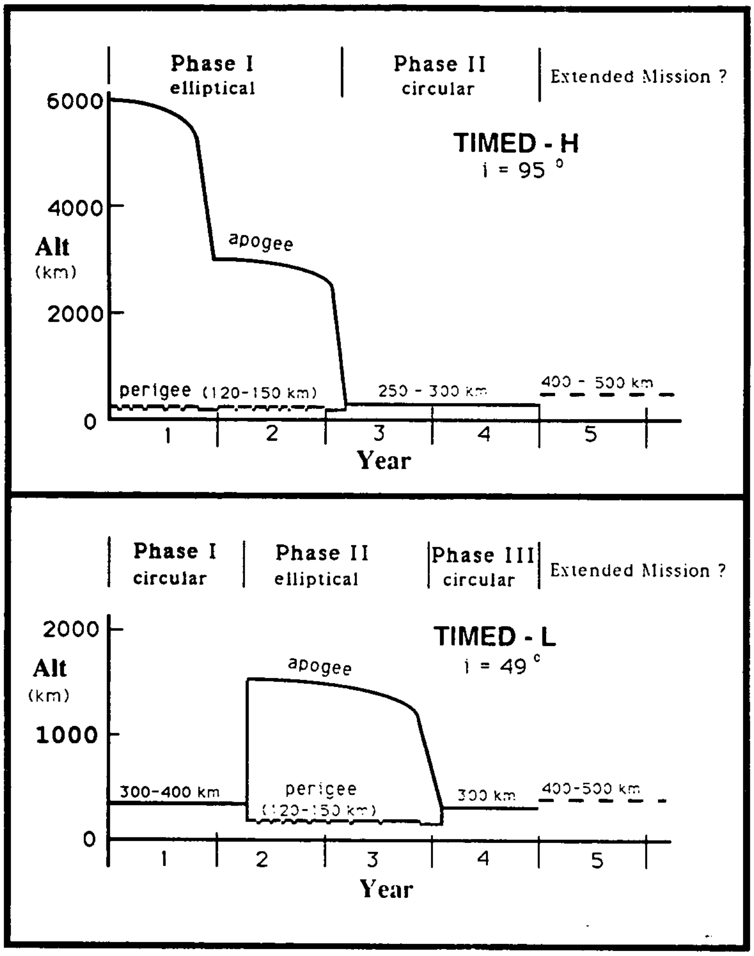


Figure 3. Apogee and perigee scenarios for TIMED-H and -L

A strawman phased mission scenario is illustrated in Figure 3. The length of each mission phase will be selected to provide optimum geophysical coverage by combining the measurements from the two spacecraft. TIMED-L begins in circular orbit at altitudes between 300 and 400 km (Phase I) where both remote and *in–situ* global coverage will be obtained. TIMED-H starts in a high elliptical orbit (Phase I) that favors "deep diving" into the lower thermosphere and ionosphere where *in–situ* measurements will be stressed. In Phase II, the roles of TIMED-H and -L will be reversed. TIMED-L will be maneuvered into an elliptical orbit for deep diving, while the orbit of TIMED-H will be circularized through the use of aerodynamic drag. Onboard propulsion capability will provide the sampling advantages of both elliptical and circular orbits. A 4-year mission lifetime is adequate to permit full separation of latitude, local time, and seasonal variations in the mesosphere and lower thermosphere.

IV.2 Strawman Instrument Complements

Table 5 identifies a total of 15 instruments for the Core Strawman Payload of the two spacecraft, although each spacecraft would carry only a subset of these. Most of these instruments are required on both spacecraft, but a few are restricted to one. The infrared limbscanning is best done from the lower inclination TIMED-L orbit because it precesses rapidly enough to permit measurement of the very important diurnal and semidiurnal tides in the mesosphere. The fields and particle measurements are more appropriate for the higher inclination orbit of TIMED-H.

IV.3 Spacecraft Design

The instrument complements and mission plans of the two spacecraft led to a common spacecraft design, and Figure 4 shows a suggested configuration.

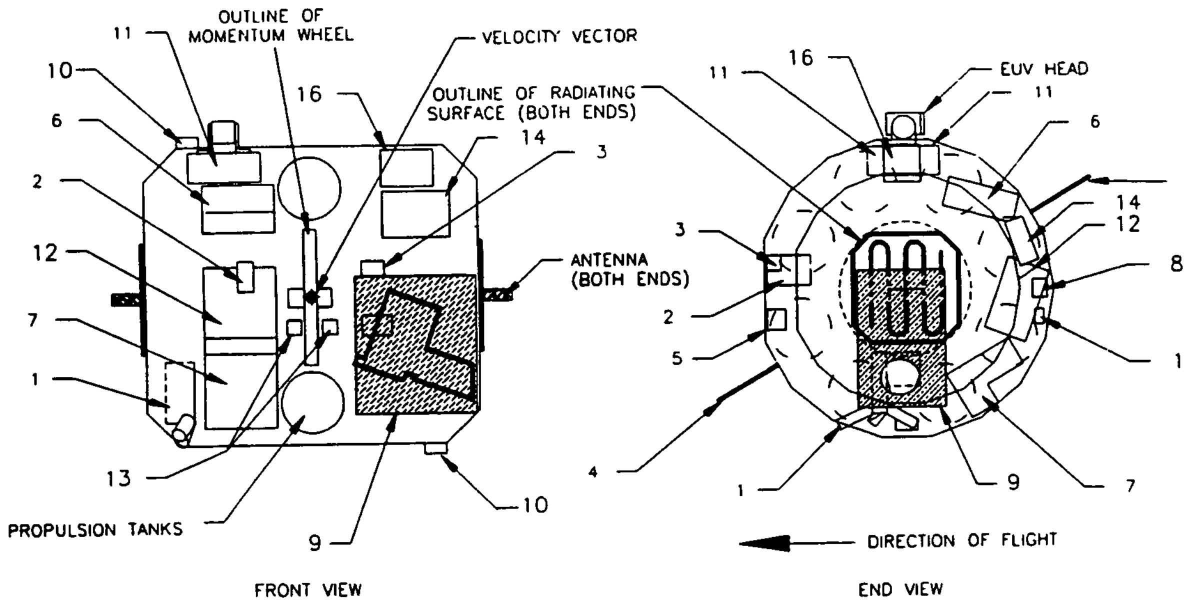
Both spacecraft require a substantial onboard propulsion capability to permit survival for 4 years in the relatively high drag environment to which they will be exposed. There must be adequate fuel capacity to attain and maintain the desired orbital eccentricities and altitudes given in the strawman mission scenario. They must also provide the capability to acquire and store data at any remote point about the orbit and to dump those data once or twice a day during passages over a NASA tracking station. The battery capacity should be adequate to permit continuous operation of all instruments for at least one full orbit, and its solar cell capacity should be adequate to recharge the battery quickly enough to permit full orbit operation for one out of every four orbits. In an elliptical orbit, the spacecraft should be designed to operate for at least 25 minutes during every perigee passage.

The spacecraft thermal design and the layout of the solar cells must accommodate both high and low inclination orbital geometries with widely varying Sun angles. The spacecraft must also support simultaneous *in–situ* and remote measurements from both orbits. This means that they must employ a method of attitude stabilization which simultaneously points the limb scanners at the limb, the ram lookers into the velocity vector, the airglow imagers appropriately downward to view the underlying atmosphere, and the Solar EUV Spectrometer at the Sun. The deep diving requirement precludes the use of a deployed solar array which would add unacceptably to the total spacecraft drag coefficient. Such arrays are also incompatible with the need to avoid the scattering of light and particles into the sensors, and to avoid producing a wake that could affect the *in–situ* measurements at certain combinations of solar and velocity directions.

Table 5
Core Strawman Instruments for TIMED-H and -L

No*	Instruments	Acronym	Measured Parameters	Spacecraft H	Spacecraft L
	A. Remote Sensing				
6	UV Spectrometer	UVS	O_3, NO_x, and other minor constituents	X	X
14	Near Infrared Spectrometer/Photometer	NIRSF	$O_2(^1\Delta)$, (O_3), OH rot., and H_2O	X	1
1	Fabry-Perot Interferometer	FPI	Wind, temperature, and emission rate profiles	X	X
7	Imaging Photometer	IP	Wave structures	X	X
12	Global UV Airglow Imager	GUVI	Global Imaging of atmospheric UV emissions	X	1
9	Infrared Limb Sounder[2]	IRLS	Mesospheric CO_2, O_3, OH, and NO	1	X
11	Solar EUV Spectrometer[3]	SEUVS	Spectral Solar EUV and X-ray fluxes	X	-
	B. In situ				
2	Neutral Mass Spectrometer/Wind and Temperature	NMSWT	Local gas composition, winds, and temperature	X	X
3	Ion Mass Spectrometer	IMS	Ion composition	X	X
4	Langmuir Probe	LP	Electron/ion density, and electron temperature	X	X
10	Energetic Particles Analyzer	EPA	Auroral electron and ion energy fluxes	X	1
5	Ion Drift Meter Retarding Potential Analyzer	IDM/RPA	Ion drift/electric fields, and ion temperature	X	X
17	Magnetometer	MAG	Currents	X	1
8	Accelerometer[4]	ACC	Total air density	X	X
15	Electric Field Detector/Plasma Wave Experiment[5]	EFD/PWE	Three-axis AC and DC electric fields	X	1

The Fast Electron Spectrometer (13) and Energetic Particle Spectrometer (16) are secondary instruments.
1 Secondary Instrument
2 Low duty cycle due to high power requirements
3 Not needed on TIMED if done simultaneously on other mission(s)
4 Non-PI class instrument.
5 Contingent on feasiblity of booms at low perigee altitude
* Numbers referred to in Figure 4.



Instrument numbers are defined in Table 5

Figure 4. TIMED conceptual spacecraft configuration

IV.4 Data System

The TIMED project will employ a distributed data system that will connect the Principal Investigator teams with both the project at GSFC and with ground-based investigators around the world. The system builds on the experience gained in the AE and DE missions by providing rapid access and exchange of processed geophysical data among the investigators. Figure 5 shows the system as it is currently envisioned. It will consist of a Spacecraft Control Center node and a Data Distribution Center node (both part of Code 500 at GSFC), and investigator nodes at the home institutions of the Principal Investigators. The NSSDC will also become a node for acquiring and disseminating final geophysical data. These units will be networked to: (1) facilitate communication of the information needed to operate the spacecraft and instruments; (2) permit rapid transmission of telemetry and orbital data to the investigator sites; (3) support the early and continuous exchange of geophysical data between the TIMED investigators; and (4) provide for access and the exchange of correlative data from Guest Investigators and other scientists indirectly connected to the TIMED project.

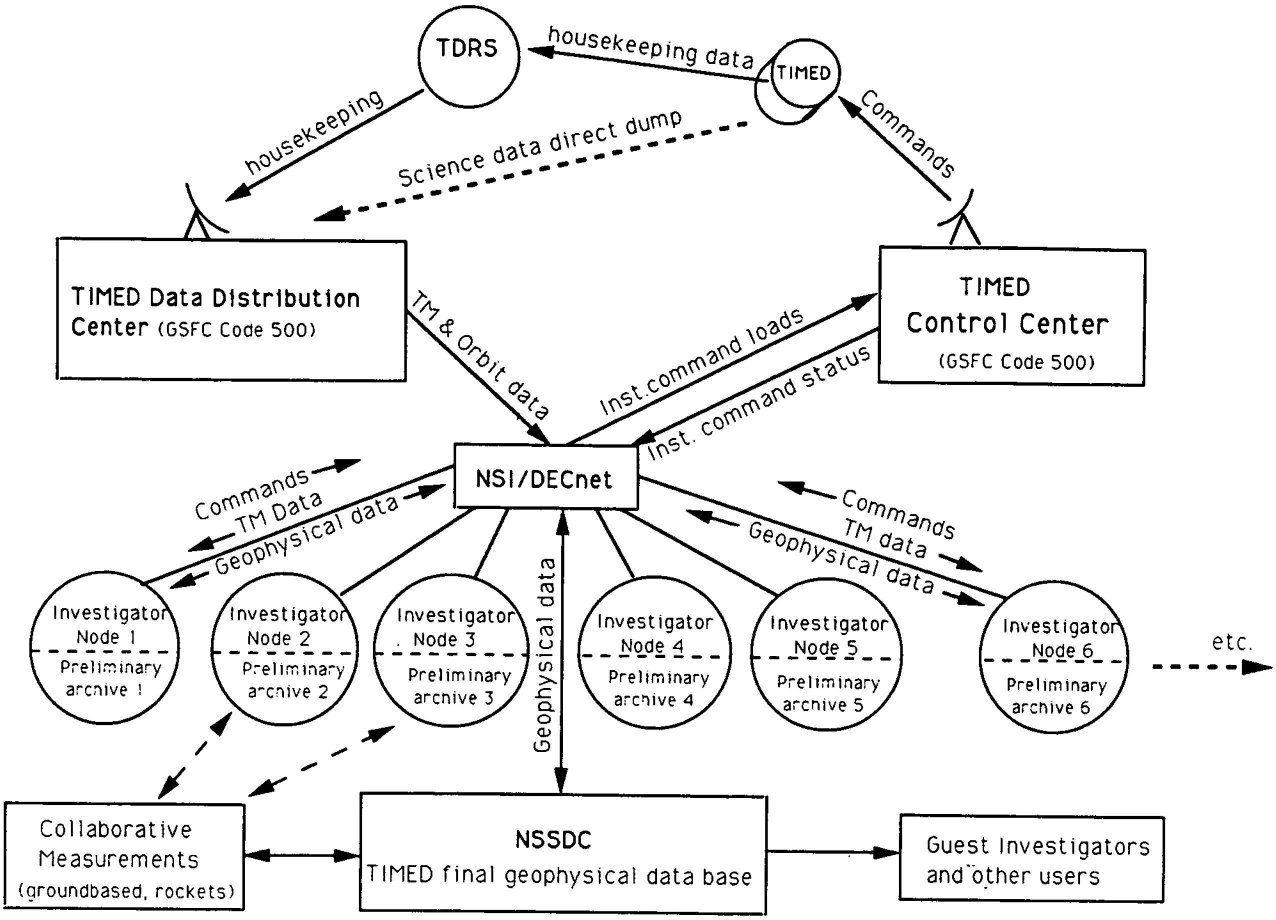


Figure 5. Distributed data system for TIMED

V. Scientific Merit

Scientific Objectives and Significance

The key scientific issues addressed by the TIMED mission have been briefly described above. The mission will provide the first comprehensive spaceborne investigation of an important region of the Earth's near-space environment – a complex transition region that may well be susceptible to rapid anthropogenic change. Since the mission has a real exploratory aspect, new discoveries are to be expected. It is possible, however, to identify various significant scientific issues that will definitely be resolved by the mission. Specifically, TIMED will:

- *Determine the temperature and wind structure of the mesosphere and lower thermosphere, delineating the seasonal/latitudinal variations and tidal components.*

- *Determine the relative importance of the major sources and sinks of energy for the thermal structure of the mesosphere and lower thermosphere.*

- *Examine anthropogenically induced changes in the mesosphere and lower thermosphere.*

- *Determine the roles of CO_2 and NO cooling in the lower thermosphere and the importance of O in enhancing these cooling rates.*

- *Determine the roles of exothermic chemical reactions, involving HO_x and O_x, for the energetics and radiative budget of the mesosphere and lower thermosphere.*

- *Advance our understanding of the radiative and dynamical processes that produce the cold and warm mesopause temperatures in the summer and winter hemispheres, respectively.*

- *Shed light on the effects of albedo changes and radiation associated with noctilucent and polar mesospheric clouds and their importance for the energy balance of the mesosphere.*

- *Determine the global distribution of the major constituents N_2, O_2, and O in the upper mesosphere and lower thermosphere as well as that of CO_2, which is important for the energy budget of the region.*

- *Determine the spatial and temporal variations in odd oxygen [O and O_3], odd hydrogen [OH, H_2O, CH_4, and HO_2], and odd nitrogen compounds [NO, NO_2, $N(^2D)$, and $N(^4S)$].*

- *Determine how the large-scale circulation in the mesosphere and thermosphere affects the distribution of chemically active and radiatively important species (such as H_2O, CO_2, CO, NO, and O).*

- *Advance our understanding of the photochemical, dynamical, and radiative processes that control the basic structure of the mesosphere and lower thermosphere.*

- *Determine the spatial and temporal variations of radiatively significant minor species in the mesosphere and lower thermosphere [CO_2, NO, O_3, OH, $O_2(^1D)$, and $O_2(^1S)$] .*

- *Determine the mean global circulation (meridional and zonal) in the mesosphere and lower thermosphere in response to annual forcing cycles and its geographic and short-term variability.*

- *Determine the diurnal tidal structures, their annual and height variations, and their effects on the mean large-scale circulation.*

- *Determine the sources and magnitudes of gravity waves and planetary waves in the mesosphere and thermosphere, and their spatial and temporal variability.*

- *Determine the effects of gravity waves and planetary waves on the large-scale circulation, thermal structure, and composition.*

- *Provide an understanding of the interactions that occur among different wave motions (tidal, gravity, and planetary) and the extent, causes, and consequences of their variability.*

- *Provide data to study the effects of gravity wave and tidal dissipation on turbulent transport of energy, mass, and momentum.*

- *Determine the dynamical effects of magnetospheric coupling and the depth to which they penetrate.*

- *Help delineate the electric field components of the magnetosphere, the disturbance dynamo, and the tidal dynamos that control the electrodynamics at middle and equatorial latitudes.*

- *Help to determine the roles of neutral winds and electric fields affecting the small- and large-scale variability in the ionospheric density and composition.*

- *Contribute significantly to our understanding of the coupling between E- and F- region plasma structures.*

- *Contribute significantly to our understanding of the ionization sources and the metastable ion chemistry responsible for the molecular ion inventory in the lower ionosphere.*

- *Significantly advance our understanding of the ion and neutral chemistry in the lower thermosphere which is important for the partitioning of energy.*

- *Significantly advance our understanding of the global composition, temperatures, and transport velocities of neutrals and ions in the lower thermosphere by providing, for the first time, simultaneous observations of these variables.*

- *Significantly advance our understanding of tides and related dynamo electric fields, as well as gravity waves and traveling ionospheric disturbances, by performing simultaneously in situ and remote measurements in the thermosphere, ionosphere, and mesosphere.*

- *Significantly advance our understanding of magnetic storm effects in the neutrals and ions by performing simultaneous measurements of temperatures, densities, transport velocities, and electric as well as magnetic fields.*

Generality of Interest

These scientific issues addressed by TIMED are of considerable general interest, since they are related to important sub-disciplines. These include: gas kinetics; turbulence; plasma physics; fluid dynamics; photochemistry; spectroscopy; atomic and molecular collision physics; thermodynamics; etc. Issues of practical concern include: satellite drag; shuttle re-entry; aerobraking in planetary atmospheres; communication–disruption; and global change.

The adapted technology used for the TIMED program will also be of considerable general interest. New stereoscopic remote sensing techniques will be developed to probe planetary atmospheres, and new tomographic techniques will be used to interpret the results. *In–situ* sensors will be used in the challenging low altitude regime. The combination of remote and *in–situ* measurements from two closely coordinated spacecraft will provide for new methods of resolving temporal and spatial ambiguities. New numerical models and global time dependent simulation techniques will be developed.

TIMED has great potential for new discoveries, because the MLTI regime represents a unique laboratory for the study of transitional fluid dynamics and gas kinetics. Unexpected atmospheric linkages that couple the lower atmosphere to the MLTI and magnetosphere, may be discovered. Important new chemical schemes may be discovered, others elucidated, involving constituents or compounds that are key species for atmospheric evolution. New insights may be gained into the role played by turbulent processes in controlling the natural world.

TIMED bridges a major gap in Solar-Terrestrial Science, connecting lower and upper atmospheric physics, magnetospheric physics and planetary aeronomy. Global understanding of the MLTI region requires a *spaceborne* measurement program – the knowledge to be provided by TIMED could not be gained using ground-based or sub-orbital techniques.

Feasibility and Readiness

The results of the pre-Phase-A study have shown that the TIMED mission is feasible and cost effective. The scientific community is ready for this mission, having anticipated it for some time. TIMED is built on the strong foundation of successful previous missions, such as AE, SME, and DE. The community has demonstrated its ability to coordinate efforts to solve global-scale problems, as evidenced by the successful NSF CEDAR program. Strong international participation, both in the mission development phase and in the data analysis phase, is anticipated. Two international colleagues (one from Germany and one from Canada) participated in the pre-Phase-A study and their respective national agencies have already expressed an interest in the mission. TIMED is well poised to contribute importantly to the international STEP program.

The scale of the TIMED mission is well suited for participation by a spectrum of institutions; including universities, NASA centers, and industry.

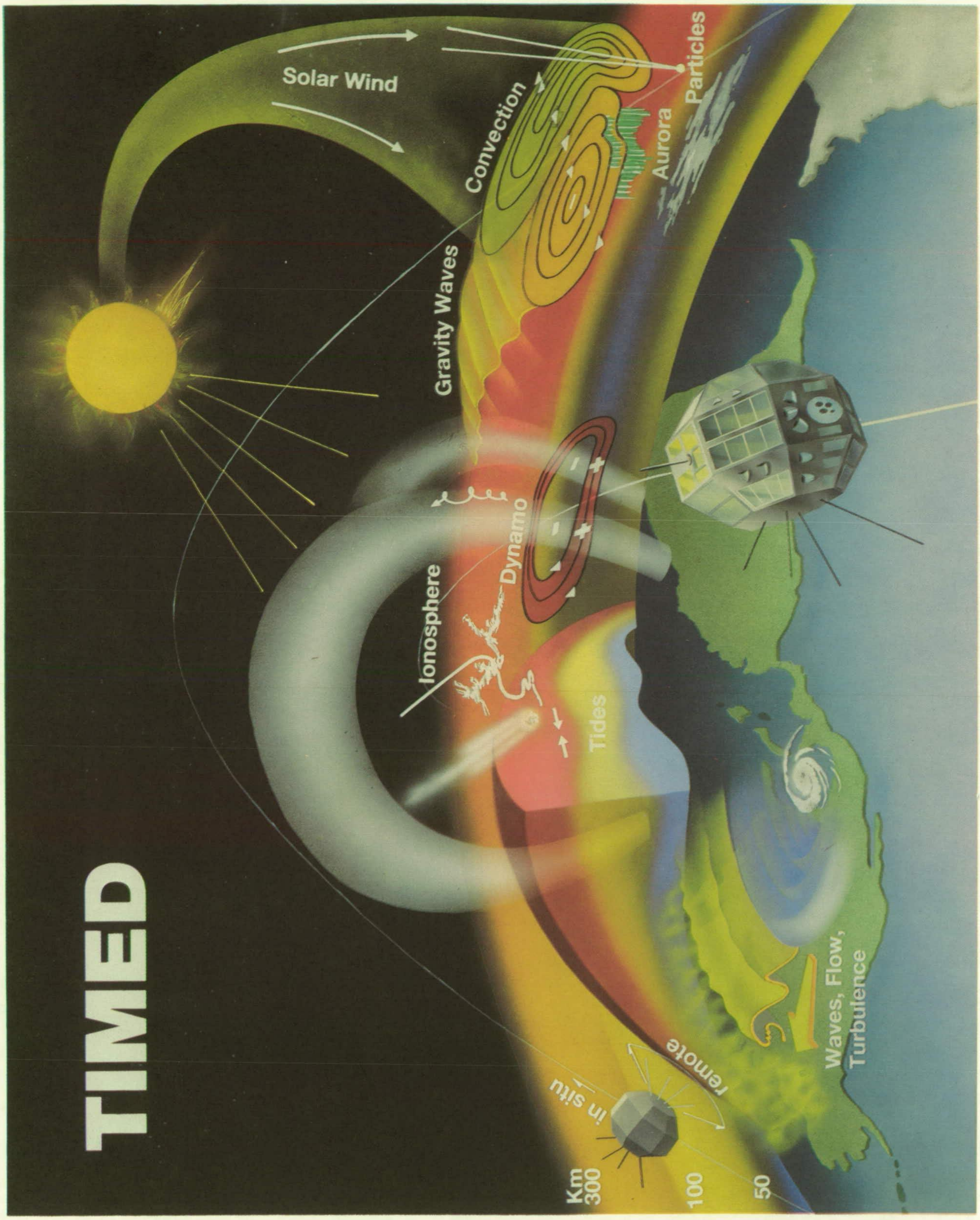
Finally, and perhaps most importantly, we reiterate that TIMED will *explore* the mesosphere and lower thermosphere/ionosphere, termed by the Academy of Sciences, "*the least understood region in the Earth's atmosphere*." It is thought that this region of our near Earth space environment, which is closer to us than Baltimore is to Washington, may be highly susceptible to global change. The TIMED Science Definition Team considers it to be important that this broad, exciting, and well balanced research program is carried out at the earliest possible date.

"the Earth's mesosphere and lower thermosphere/ionosphere are the least explored regions in the Earth's atmosphere..."

Space Science in the Twenty-First Century: Imperatives for the Decades 1995-2015, Space Science Board, National Academy of Sciences, 1988.

"a series of space observations is needed to advance understanding of the interesting dynamical, chemical and radiative processes in the mesosphere, stratosphere and thermosphere. One low and one high-inclination spacecraft are first needed to establish basic atmospheric properties and their geographic, diurnal, and seasonal dependencies"

Solar-Terrestrial Research for the 1980's, Committee on Solar-Terrestrial Research, National Academy of Sciences, 1981.



Frontispiece

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PREFACE

The work described in this report was performed by the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) Science Definition Team under the cognizance of the Ionospheric Physics Branch of the Space Physics Division of NASA's Office of Space Science and Applications.

THERMOSPHERE-IONOSPHERE-MESOSPHERE ENERGETICS AND DYNAMICS (TIMED)

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SUMMARY

A Science Definition Team was established in December 1990 by the Space Physics Division, NASA, to develop a satellite program to conduct research on the energetics, dynamics, and chemistry of the mesosphere and lower thermosphere/ionosphere. This two-volume publication describes the TIMED (Thermosphere-Ionosphere-Mesosphere, Energetics and Dynamics) mission and associated science program. The report outlines the scientific objectives of the mission, the program requirements, and the approach towards meeting these requirements.

TIMED will carry out the first comprehensive space-borne investigation of the physical and chemical processes acting in the terrestrial mesosphere and lower thermosphere/ionosphere (MLTI) between ~60 and ~180 km. This region represents a "crossroads" in the flow of mass, momentum, and energy through the coupled atmosphere-ionosphere-magnetosphere system. It is a region that is poorly understood due, in part, to its inherent complexity and due, in part, to the difficulty of carrying out *in situ* measurements at these altitudes. It is a "transition" region where atmospheric temperatures and thermal gradients reach extreme values, where turbulent flow changes to diffusive molecular flow, where the composition changes from molecular to atomic, where complex photochemical and electrodynamical processes become predominant, and where these combined effects challenge theoretical description.

TIMED will be an exploratory mission to characterize and understand the interplay of composition, energetics, radiation and dynamics of this region. It will complement the NASA UARS (stratospheric) and ISTP (magnetospheric) missions and contribute to the international STEP program. TIMED will also contribute to the study of anthropogenically–induced changes in the atmosphere. Specifically, the mesosphere is sensitive to increasing levels of methane and carbon dioxide and may be an important harbinger of global change. There is already strong evidence that the mesosphere may be changing on relatively short time scales (~10's of years), and hence it is critical to establish a baseline global description of the region at the earliest possible date.

The satellite and instrument requirements for the TIMED mission are derived from prioritized requirements calling for measurements of the energy and momentum sources, state variables, dynamics, and the related ionospheric structure and electrodynamics. The resulting mission comprises two identical spacecraft in different orbits to provide extensive

coverage of MLTI parameters in latitude, altitude, local time, and season. The spacecraft are launched on separate Delta-class expendable launch vehicles into orbits having inclinations of 95° and 49°. Both spacecraft have on-board propulsion capabilities to allow for circular and eccentric orbits. The operating lifetime of each spacecraft is 48 months.

The TIMED mission requires a dedicated ground-based data system and a science team organization that ensure strong interactions between experiments and theory and appropriate use of the data resource. As such, TIMED represents a natural evolution from previous NASA missions, such as AE, SME, DE, and UARS. It will enable a quantitative exploration of a critical transition region of the Earth's upper atmosphere that has previously proved resistant to experimental study.

The TIMED mission concept was a product of the 1990 Strategy-Implementation Study that brought together scientists from the disciplines in the ionosphere-thermosphere-mesosphere (ITM) community. This document is the final report of the Science Definition Team for the TIMED pre-Phase-A study. Volume I provides an executive summary, while Volume II provides the detailed findings of the team.

With the presentation of this pre-Phase-A study report, the TIMED mission and supporting technology are sufficiently well defined so that, with a one-year Phase-A study, TIMED will be ready as a new-start candidate in the intermediate-class cost category.

I. Introduction

While our knowledge of the near-Earth space environment has increased enormously since the start of the Space Age, many significant gaps in this knowledge exist and our ability to model the variability of the system as a whole remains rudimentary at best. Furthermore, certain regions of the solar-terrestrial system remain largely *unexplored* and important physical, chemical, dynamical, electrodynamical, and radiative coupling processes which act upon and between different regions have been identified but not investigated in detail.

The desire to investigate and understand our "local" space environment is not only driven by intellectual curiosity, but also by practical societal motivations. In particular, there has been increasing concern and interest in recent years about the variability, both natural and artificial, of the Earth's upper atmosphere and ionosphere. These concerns have been emphasized by the discoveries of anthropogenically-induced changes in the ozone abundance and potential global warming related to increased atmospheric loading of radiatively active minor constituents. In addition, long-term variations in solar activity and large solar storms have led to instances of premature re-entry of orbital vehicles and disruptions in power supply and global communications. These important issues and their societal effects have heightened our appreciation of the complexity of the Earth's upper atmosphere and ionosphere and its sensitivity to external influences. The potential threats to the stability of the near Earth space environment, and the possibility of additional and yet unidentified changes, call for an enhanced long-term program of scientific research directed toward improving our knowledge of the Earth's atmosphere.

The region of the atmosphere about which the *least* is currently known is the mesosphere and the MLTI. This region, between roughly 60 and 180 km altitude, is too high for probing by balloons and too low for direct *in situ* measurements by long-lived satellites without on-board propulsion. As a consequence, it has received much less attention than the more readily accessible regions above and below. In many respects, the MLTI region represents an uncharted "frontier" for upper atmospheric research.

This lack of knowledge and understanding of the MLTI region has been recognized by the various national advisory groups. For example, the Space Science Board of the National Academy of Sciences has stated that:

> *"The Earth's mesosphere and lower thermosphere are the least explored regions of the Earth's atmosphere. They are influenced by varying solar extreme ultraviolet,*

ultraviolet, and X-ray radiation, auroral particles and fields, and upward propagating waves and tides from the lower atmosphere. There are strong interactions between the chemistry, dynamics, and radiation of both the neutral and ionized constituents of this region. It is known that the global structure of this region of the atmosphere can be perturbed during stratospheric warmings and solar-terrestrial events (magnetospheric substorms, solar flares, etc.), but the overall structure and dynamic responses to these effects and even the basic controlling physical and chemical processes of these effects are not understood "

To study this system, the National Academy's Committee for Solar-Terrestrial Research pointed out that :

"A series of space observations is needed to advance understanding of the interesting dynamical, chemical, and radiative processes in the mesosphere, stratosphere, and thermosphere. One low and one high inclination spacecraft are first needed to establish basic atmospheric properties and their geographic, diurnal, and seasonal dependencies"

A list of recent Academy reports calling for the exploration and quantitative investigation of the MLTI region is given in Table 1.

The recent Strategy-Implementation Study (SIS) of the Space Physics Division also recommended a phased program of NASA missions devoted to a comprehensive study of the Ionosphere-Thermosphere–Mesosphere (ITM) system. The first component of this program identified during the SIS is the Thermosphere–Ionosphere–Mesosphere, Energetics and Dynamics (TIMED) mission, which is designed to address the MLTI region and is in the "intermediate class" ($ 200 – 300 M) cost category. This TIMED mission is an important new effort aimed at improving our knowledge and understanding of the atmosphere and ionosphere above the stratosphere and below the upper thermosphere/ionosphere and magnetosphere. In this region, complex physical, chemical, dynamic, radiative, and electrodynamic processes all undergo profound transitions and combine to drive a rich thermal, dynamical, and compositional global morphology. Through a careful balance between comprehensive measurements, theoretical studies of the basic processes, and model analysis, it is now clear that substantial progress can be made in solving the major outstanding problems of this region.

Table 1

National Advisory Reports calling for the exploration of the Mesosphere, Lower-Thermosphere/Ionosphere System

(1) *Solar-Terrestrial Research for the 1980's,* Committee on Solar-Terrestrial Research, National Academy of Sciences, 1981.

(2) *A Strategy for the Explorer Program for Solar and Space Physics,* National Academy Press, Washington D.C.,1984.

(3) *An Implementation Plan for Priorities in Space Physics,* Space Science Board, National Academy of Sciences, 1985.

(4) *Strategic Plan,* NASA Office of Space Sciences, 1988.

(5) *Solar-Terrestrial Sciences,* Report from the Science Strategy Workshop, NASA Space Physics Division, 1988.

(6) *Space Science in the Twenty-First Century,* Solar and Space Physics report of the Study Steering Group, Space Science Board, National Academy of Sciences, 1988.

(7) *Earth System Science, A Closer View,* Report of the Earth System Sciences Committee, NASA Advisory Council, 1988.

(8) *Long-term Solar-Terrestrial Observations,* Panel on long-term observations, Committee for Solar-Terrestrial Research, National Academy of Sciences, 1988.

(9) *Space Physics Strategy-Implementation Study Workshop,* Executive Summary – Report of the Mission Integration and Divisional Science Plan, 1990.

This report (Volume I of the pre-Phase-A study) provides a brief summary of the findings of the TIMED Science Definition Team. Full details of the study may be found in Volume II. The following sections briefly describe the TIMED science rationale and implementation plan.

II. Scientific Objectives

The scientific objectives for the TIMED mission were developed after a thorough review of the current state of knowledge of the field and the development of a prioritized set of key scientific questions. After this review, and in accordance with the mandates of both the Academy of Sciences and the Strategy-Implementation Study, the Science Definition Team adopted the following *Primary Objective* for TIMED:

To perform an exploratory study of the physical and chemical processes acting within and upon the coupled mesospheric, thermospheric, and ionospheric system between ~60 and 180 km.

Figure 1 illustrates the basic thermal and plasma density structure of the MLTI region, together with an indication of the altitude regimes of interest for the UARS and ISTP missions as well as those for balloon and some ground-based experiments.

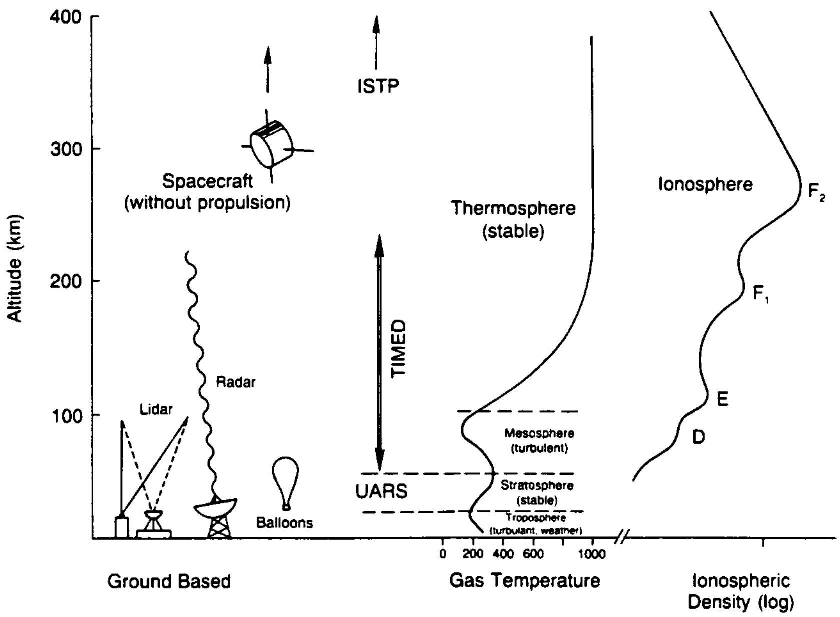


Figure 1. Schematic illustration of the atmospheric thermal structure and electron (ion) content. The primary altitude regimes of scientific investigations for TIMED – as well as those for UARS, ISTP, ballon and some ground-based experiments – are indicated.

The region to be investigated by TIMED is home to a large number of fundamental transitions in atmospheric processes. Perhaps the most fundamental one is the change from turbulent mixing to molecular diffusion. However, there are also many others. The energy balance is marked by a change from radiative control to thermal conductive control. The composition changes from molecular to atomic. The available solar radiation changes spectrally, with EUV important at higher altitudes and UV important at lower altitudes. The dynamics of the region changes from geostrophic control to ageostrophic control, with viscosity and ion drag playing more important roles at higher altitudes. The highly variable heating rates, due to solar EUV/UV absorption, Joule heating, particle heating, tidal, and gravity wave dissipation, *all maximize* in the MLTI transition region. Yet, the lowest temperatures anywhere in the Earth's atmosphere occur near the *summer* polar mesopause. The region also houses the primary atmospheric, ionospheric, and electrodynamical interactions. The influence of the magnetosphere becomes significant, and ionospheric conductivities and currents maximize. Gravity wave breaking and plasma instabilities affect the energy and momentum balances, as turbulence becomes a primary factor in mass, momentum, and energy transfer processes at the lower boundary. Finally, in this region of the Earth's atmosphere, the largest temperature gradients are found – leading to a rapid change in atmospheric stability.

Table 2 summarizes the fundamental and dramatic changes that characterize this transition region. Some of the processes responsible for these effects are schematically illustrated in the frontispiece. *All of these processes occur within the MLTI region that has never been the subject of a comprehensive satellite investigation. It is the general purpose of TIMED to provide such a comprehensive and global study of the interplay between dynamics, energetics, chemistry, radiation, and electrodynamics in this region.*

In addition to the exploratory and investigative motivations for TIMED, there is an important additional need for early measurements of the MLTI region. It is expected that anthropogenic changes will cause the terrestrial mesosphere to experience first–order changes in its chemistry, composition, temperature distribution, and dynamics within the next two to three decades. The projected cooling of the mesosphere from increased amounts of carbon dioxide, for example, will affect the chemistry of important minor constituents. This cooling will also allow high altitude ice clouds (Polar Mesospheric

Clouds) to form at lower attitudes than normally possible. This equatorward spread may influence the climate down to the Earth's surface. It seems very likely that the mesosphere.

Table 2

Characteristics of the 60–180 km Transition Region

(1) Turbulent mixing gives way to molecular diffusive separation and transport.

(2) Radiative processes dominate the thermal balance below and thermal conduction dominates above.

(3) Composition ceases to be dominated by molecules and becomes increasingly dominated by atoms.

(4) Solar EUV is important at higher altitudes and solar UV is important at lower altitudes.

(5) Heating rates due to solar EUV/UV absorption, Joule heating, and particle heating all maximize.

(6) The dynamics of the region change from geostrophic control to ageostrophic control.

(7) The coupling processes between the atmosphere and the magnetosphere become significant, conductivities maximize, and the charged particle population plays an important role in atmospheric energetics.

(8) Gravity wave breaking and plasma instabilities play significant roles in the energy and momentum balances.

(9) The thermal structure shows a fundamental change in lapse rate, leading to rapid changes in atmospheric stability.

(10) Local thermodynamic equilibrium ceases to apply.

(11) The charged particle population changes from one that has positive and negative cluster ions at lower altitudes, to one that has electrons and chemically controlled molecular ions, to one that has electrons and diffusively controlled atomic ions at higher altitudes.

(12) The dynamics of charged particles is controlled by collisions with the neutral atmosphere at lower altitudes and by diffusion and electric as well as magnetic fields at higher altitudes.

of the future will be quite different from what it is now. Due to this high degree of senitivity to anthropogenic effects in temperature and composition, the mesosphere proves to be an ideal region for the early detection of related long-term atmospheric changes.

The anticipated changes can be appreciated from a straight–forward assessment of the effects of a growing abundance of atmospheric carbon dioxide, methane, and water vapor. CO_2, increasing at the rate of 0.5%/yr, will lead to a far stronger cooling of the middle atmosphere than to a warming of the Earth's surface. The expected changes in temperature from a doubling of carbon dioxide will be in the 10's of degrees in the middle atmosphere, compared to fractions of a degree at the surface. Methane is increasing at the rate of 1 – 2%/yr in the middle atmosphere. Its oxidation to water vapor in the middle

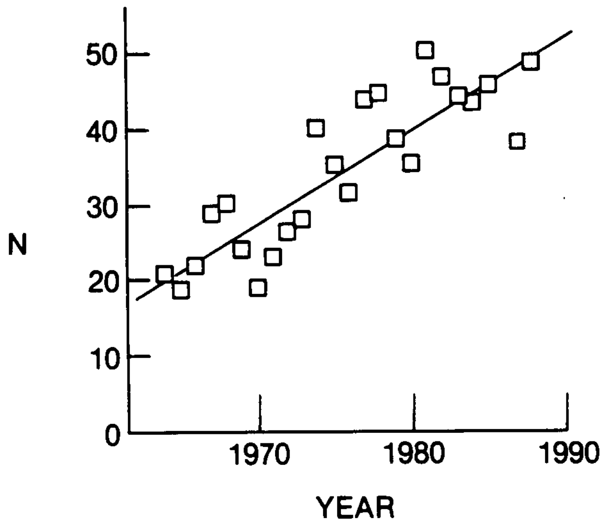


Figure 2. Plot of the number of nights per year, N, on which noctilucent clouds were reported from north–west Europe, with the effect of solar activity removed. This plot (from Gadsden, 1990) provides evidence for secular increases in mesospheric noctilucent cloud occurrence.

atmosphere will drive a stronger odd–hydrogen chemistry, probably resulting in a decrease in the density of ozone in this region. This sensitivity of the mesosphere is exemplified in Figure 2 by the observed increase in noctilucent cloud occurrence, which accounts for no less than a factor of ~2 increase over the past 20 years and has been attributed to the man induced methane increase or, alternately, to the secular decrease in mesopause temperature.

In response to a series of key scientific questions formulated by the Science Definition Team, the five overall objectives for the TIMED mission have been developed and are given in Table 3:

Table 3
TIMED Overall Mission Objectives

(1) *To investigate and quantitatively understand the important physical and chemical processes responsible for the energy and momentum budgets of the MLTI region and the electrodynamic as well as chemical interactions between the neutral and plasma components of the region.*

(2) *To investigate and quantitatively understand the coupling between chemistry, radiation, waves (tides, gravity waves, and planetary waves), unorganized motions, and the large-scale circulation, and the resultant effects on momentum, energy, and mass (species) transfer within, to, and from the mesosphere and lower thermosphere.*

(3) *To investigate and quantitatively understand the lower ionosphere: to elucidate its role in the global electric circuit, to understand the chemistry and energy budget of this region, and to determine how these processes affect the coupling between the lower thermosphere and mesosphere.*

(4) *To investigate and quantitatively understand the odd oxygen, odd nitrogen, and odd hydrogen chemistry within the Mesosphere and Lower Thermosphere*

(5) *To investigate anthropogenically induced changes in the mesosphere and lower thermosphere and establish a baseline for future investigations.*

These objectives, together with the measurement oriented science questions, in turn, were used to derive the measurement requirements, leading to an implementation strategy. Full details of this process can be found in Volume II of this report.

III. TIMED Mission Requirements

III.1 Measurement Requirements

The primary measurements of TIMED include observations of the global and temporal variations in the atmosphere and ionosphere, which are controlled by radiative, chemical, dynamic, thermodynamic, and electrodynamic processes. Measurements of the dynamics of neutral and ionized species will serve to describe, for the first time, the global-scale circulation of the MLTI region, including global wind systems, planetary waves, solar and lunar tides, and a broad spectrum of gravity waves. They will allow fundamental investigations of turbulence and wave breaking, which are known to affect profoundly the mass, momentum, and energy budgets of the region. The measurements will also enable the electrodynamics of the most highly conducting part of the atmosphere to be investigated, leading, in turn, to deeper insights concerning the global electrical circuit, including magnetospheric components.

Measurements of the radiative and corpuscular sources of energy, together with observations of airglow emissions and neutral and plasma temperature distributions, will serve to determine the energy balance of the region. Such observations and associated theoretical work will quantitatively determine, for example, the causes of the extremely low temperatures found in the summer mesopause – the coldest region of the atmosphere.

Measurements of the relative abundances of the major neutral and ionized constituents of the region, together with observations of the altitude profiles of a panoply of photochemically active ionized and neutral trace constituents will enable the first comprehensive and detailed compositional global inventory to be assembled. Such measurements will provide a new window on the extremely complex chemical and radiative processes known to couple the odd oxygen, odd hydrogen, and odd nitrogen chemical families, which collectively control atmospheric ozone.

Table 4 summarizes the needed observations related to the key scientific questions (ref. Volume II), without regard to the ease of measurement. These measurements are *required* to accomplish the five overall scientific objectives.

Table 4
TIMED Science-driven measurement requirements

Science Question(s)	Measurements	Approx. Alt. Range (km)	Accuracy	Spatial scales	Temporal scales
	Composition				
3,5,8,10,20,23, 24,25	major species abundance N_2, O_2, O.	50 - 400	5%	1/2 scale height (vertical) 10 km (gravity waves) 100's km (tides, planetary waves)	~1 min (gravity waves) ~1 hr (tides) ~ 1hr (planetary waves) 1 month (seasonal)
2,3,4,5,6,8,9, 10,12,13,24	minor species abundance CO_2, O_3, Ar, Mg, CO, NO, OH, N, Fe, NO_2, H_2O, CH_4, Na, H, He	50 - 180 < 600	5%	1/2 scale height (vertical) 10 km (gravity waves) 100's km (tides, planetary waves) (1 km Na, Fe)	~1 min (gravity waves) ~1 hr (tides) ~ 1hr (planetary waves) 1 month (seasonal) (match frequency of measurements with solar flux for photochemical studies)
2,4,5,9,11,12, 13,23,	excited states $N(^2D)$, $O(^1D)$, $O(^1S)$, $O_2(^1\Delta)$, $O_2(^1\Sigma)$, OH^*, O_3^*, N_2^*, O_2^*,CO_2^*	45 - 300 (species dependent)	10%	1/4 scale height 10 km horizontal (gravity waves)	1 min (photochemical studies and gravity waves)
2,11,13,21,22, 23,24,25	charged species e, O^+, NO^+, O_2^+, N_2^+, H^+, He^+, N^+, metallics	90 - 400	5%	1 km (vertical) 1 km (horizontal) 1 m (n_e)	1 min (phenomenology) < 1 sec(instabilities)
	Temperatures				
1-7, 9, 13-21 23-24	neutral kinetic temperature	40-400	2% (100 km) 5% (>150 km)	1/4 scale height 10 km (gravity waves) 100 km (tides, planetary waves)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
4,12 4,12,23	rotational vibrational	55-200	2% (100 km) 5% (>150 km)	1/4 scale height 10 km (gravity waves) 100 km (tides, planetary waves)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)

Table 4 (cont.)
TIMED Science-driven measurement requirements

2,19,22,23,24	ion and electron temperatures	80-400	5%	1 km (vertical) 1 km (horizontal)	1 min (phenomenology) <1 min (instabilities)
	Dynamics				
2,5,6,10,11,14-18,21	global circulation	50-400	1 m/sec	100 km	<1 min
2,6,11-13,15-17,19,20,21,23-25	tides and planetary waves	50-400	1 m/sec	100 km	1 hr (tides and planetary waves)
2-4,6,11-18,21,24	gravity waves	50-400	1 m/sec	10 km (horizontal) 1/4 scale height (vertical)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
2,5,11,14,16,19-25	ion drifts	90-400	5 m/sec	10 km (horizontal) 1/4 scale height (vertical)	~1 min (gravity waves) 1 hr (tides) 1 hr (planetary waves) <1 month)season)
	Energetic particles				
2,4,11,12,21,23,24	<100 eV electrons and ions	110-200	ΔE/E 10%	10 km	1 min
2,3,5,9,10,12,16,19,20-25	10 eV - 50 keV electrons and ions	80-250 >300	ΔE/E 30%	10 km	1 sec
4,9-12	>50 keV electrons and ions, REPS	>300	30%	2 km	1 sec
2,14,19-22,24,25	**Electric fields**	150-400	5%	1 m	1 min (phenomenology) <1 sec (instabilities)
19,20,22,25	**Magnetic fields**	125-400	1 nT	1km	<1 sec
1,2,5,8-13	**Solar EUV** (λ<1050-Å)	≥300	10%	spectral resolution 10-Å	10/day
1,2,5,11-15,17,18	**Solar UV** (λ>1050-Å)	≥300	10%	spectral resolution 1-Å	10/day

III.2 Orbital Requirements

The three principal orbital requirements for the mission are:

(1) *The need for global coverage, including in particular the high-latitude regions.*

(2) *The need for rapid local time precession of the orbit to enable tidal structures to be mapped with a resolution of (at a minimum) 24 hrs LT per month.*

(3) *The need for remote measurements down into the mesosphere and in situ measurements down into the lower thermosphere and ionosphere.*

These requirements point to the need for 3-axis stabilization of the vehicles (for accurate remote sensing), propulsion capability (for phased orbital adjustments), and a combination of elliptical orbits (to provide low altitude *in situ* measurement capability) and circular orbits (to optimize the remote sensing measurement capability). A scenario designed to meet the measurement and orbital requirements is discussed below.

IV. Implementation Plan

IV.1 Mission Scenario and Orbit Selection

No single orbit is suitable for separating the spatial and temporal variations of the mesosphere and lower thermosphere. A configuration with two spacecraft (TIMED-H and -L) is required to provide the complementary coverage. TIMED-H will be placed into in a high–inclination, nearly sun-synchronous 95°orbit, while TIMED-L will be in a 49° orbit. The slowly precessing orbit of H will provide essentially full global coverage, while the rapidly precessing orbit of L will provide full diurnal coverage each month at middle and low latitudes. From these orbits, a combination of remote and *in situ* devices will cover the entire altitude region of interest in both latitude and local time.

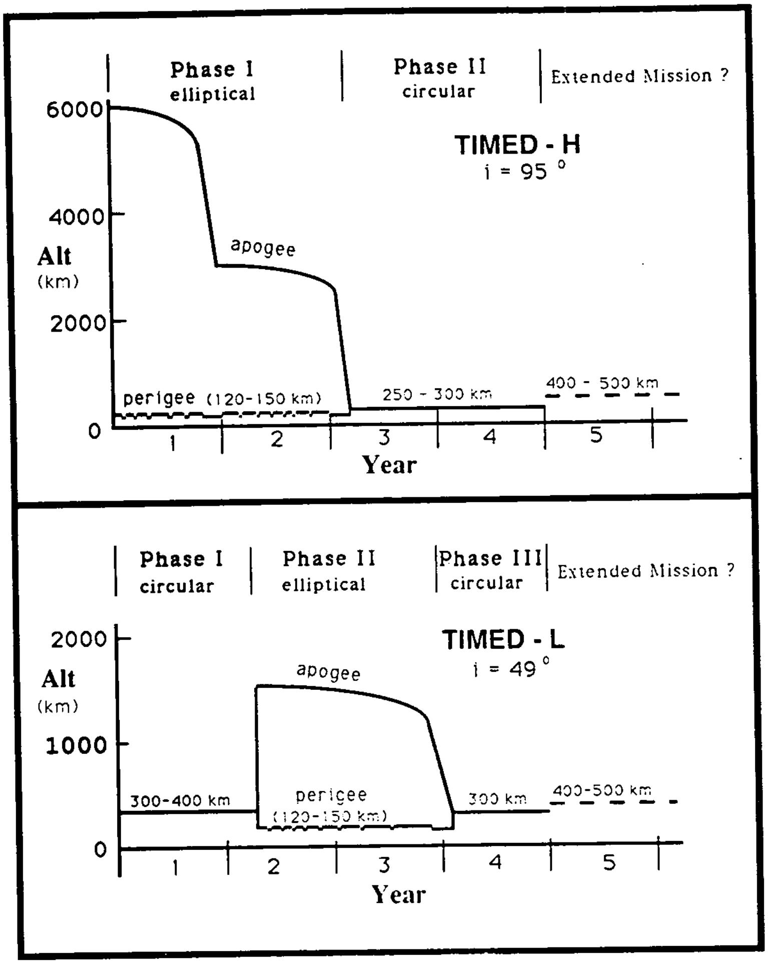


Figure 3. Apogee and perigee scenarios for TIMED-H and -L

A strawman phased mission scenario is illustrated in Figure 3. The length of each mission phase will be selected to provide optimum geophysical coverage by combining the measurements from the two spacecraft. TIMED-L begins in circular orbit at altitudes between 300 and 400 km (Phase I) where both remote and *in–situ* global coverage will be obtained. TIMED-H starts in a high elliptical orbit (Phase I) that favors "deep diving" into the lower thermosphere and ionosphere where *in–situ* measurements will be stressed. In Phase II, the roles of TIMED-H and -L will be reversed. TIMED-L will be maneuvered into an elliptical orbit for deep diving, while the orbit of TIMED-H will be circularized through the use of aerodynamic drag. Onboard propulsion capability will provide the sampling advantages of both elliptical and circular orbits. A 4-year mission lifetime is adequate to permit full separation of latitude, local time, and seasonal variations in the mesosphere and lower thermosphere.

IV.2 Strawman Instrument Complements

Table 5 identifies a total of 15 instruments for the Core Strawman Payload of the two spacecraft, although each spacecraft would carry only a subset of these. Most of these instruments are required on both spacecraft, but a few are restricted to one. The infrared limbscanning is best done from the lower inclination TIMED-L orbit because it precesses rapidly enough to permit measurement of the very important diurnal and semidiurnal tides in the mesosphere. The fields and particle measurements are more appropriate for the higher inclination orbit of TIMED-H.

IV.3 Spacecraft Design

The instrument complements and mission plans of the two spacecraft led to a common spacecraft design, and Figure 4 shows a suggested configuration.

Both spacecraft require a substantial onboard propulsion capability to permit survival for 4 years in the relatively high drag environment to which they will be exposed. There must be adequate fuel capacity to attain and maintain the desired orbital eccentricities and altitudes given in the strawman mission scenario. They must also provide the capability to acquire and store data at any remote point about the orbit and to dump those data once or twice a day during passages over a NASA tracking station. The battery capacity should be adequate to permit continuous operation of all instruments for at least one full orbit, and its solar cell capacity should be adequate to recharge the battery quickly enough to permit full orbit operation for one out of every four orbits. In an elliptical orbit, the spacecraft should be designed to operate for at least 25 minutes during every perigee passage.

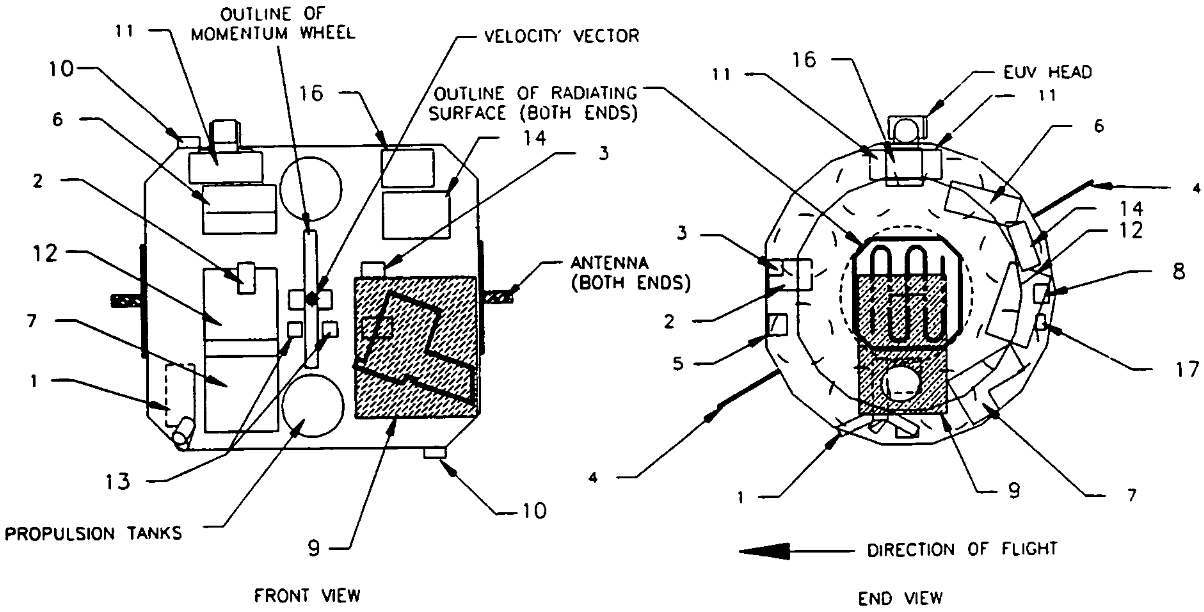
The spacecraft thermal design and the layout of the solar cells must accommodate both high and low inclination orbital geometries with widely varying Sun angles. The spacecraft must also support simultaneous *in–situ* and remote measurements from both orbits. This means that they must employ a method of attitude stabilization which simultaneously points the limb scanners at the limb, the ram lookers into the velocity vector, the airglow imagers appropriately downward to view the underlying atmosphere, and the Solar EUV Spectrometer at the Sun. The deep diving requirement precludes the use of a deployed solar array which would add unacceptably to the total spacecraft drag coefficient. Such arrays are also incompatible with the need to avoid the scattering of light and particles into the sensors, and to avoid producing a wake that could affect the *in–situ* measurements at certain combinations of solar and velocity directions.

Table 5

Core Strawman Instruments for TIMED-H and -L

No*	Instruments	Acronym	Measured Parameters	Spacecraft H	Spacecraft L
	A. Remote Sensing				
6	UV Spectrometer	UVS	O_3, NO_x, and other minor constituents	X	X
14	Near Infrared Spectrometer/Photometer	NIRSF	$O_2(^1\Delta)$, (O_3), OH rot., and H_2O	X	1
1	Fabry-Perot Interferometer	FPI	Wind, temperature, and emission rate profiles	X	X
7	Imaging Photometer	IP	Wave structures	X	X
12	Global UV Airglow Imager	GUVI	Global Imaging of atmospheric UV emissions	X	1
9	Infrared Limb Sounder[2]	IRLS	Mesospheric CO_2, O_3, OH, and NO	1	X
11	Solar EUV Spectrometer[3]	SEUVS	Spectral Solar EUV and X-ray fluxes	X	-
	B. In situ				
2	Neutral Mass Spectrometer/Wind and Temperature	NMSWT	Local gas composition, winds, and temperature	X	X
3	Ion Mass Spectrometer	IMS	Ion composition	X	X
4	Langmuir Probe	LP	Electron/ion density, and electron temperature	X	X
10	Energetic Particles Analyzer	EPA	Auroral electron and ion energy fluxes	X	1
5	Ion Drift Meter Retarding Potential Analyzer	IDM/RPA	Ion drift/electric fields, and ion temperature	X	X
17	Magnetometer	MAG	Currents	X	1
8	Accelerometer[4]	ACC	Total air density	X	X
15	Electric Field Detector/Plasma Wave Experiment[5]	EFD/PWE	Three-axis AC and DC electric fields	X	1

The Fast Electron Spectrometer (13) and Energetic Particle Spectrometer (16) are secondary instruments.
1 Secondary Instrument
2 Low duty cycle due to high power requirements
3 Not needed on TIMED if done simultaneously on other mission(s)
4 Non-PI class instrument.
5 Contingent on feasiblity of booms at low perigee altitude
* Numbers referred to in Figure 4.



Instrument numbers are defined in Table 5

Figure 4. TIMED conceptual spacecraft configuration

IV.4 Data System

The TIMED project will employ a distributed data system that will connect the Principal Investigator teams with both the project at GSFC and with ground-based investigators around the world. The system builds on the experience gained in the AE and DE missions by providing rapid access and exchange of processed geophysical data among the investigators. Figure 5 shows the system as it is currently envisioned. It will consist of a Spacecraft Control Center node and a Data Distribution Center node (both part of Code 500 at GSFC), and investigator nodes at the home institutions of the Principal Investigators. The NSSDC will also become a node for acquiring and disseminating final geophysical data. These units will be networked to: (1) facilitate communication of the information needed to operate the spacecraft and instruments; (2) permit rapid transmission of telemetry and orbital data to the investigator sites; (3) support the early and continuous exchange of geophysical data between the TIMED investigators; and (4) provide for access and the exchange of correlative data from Guest Investigators and other scientists indirectly connected to the TIMED project.

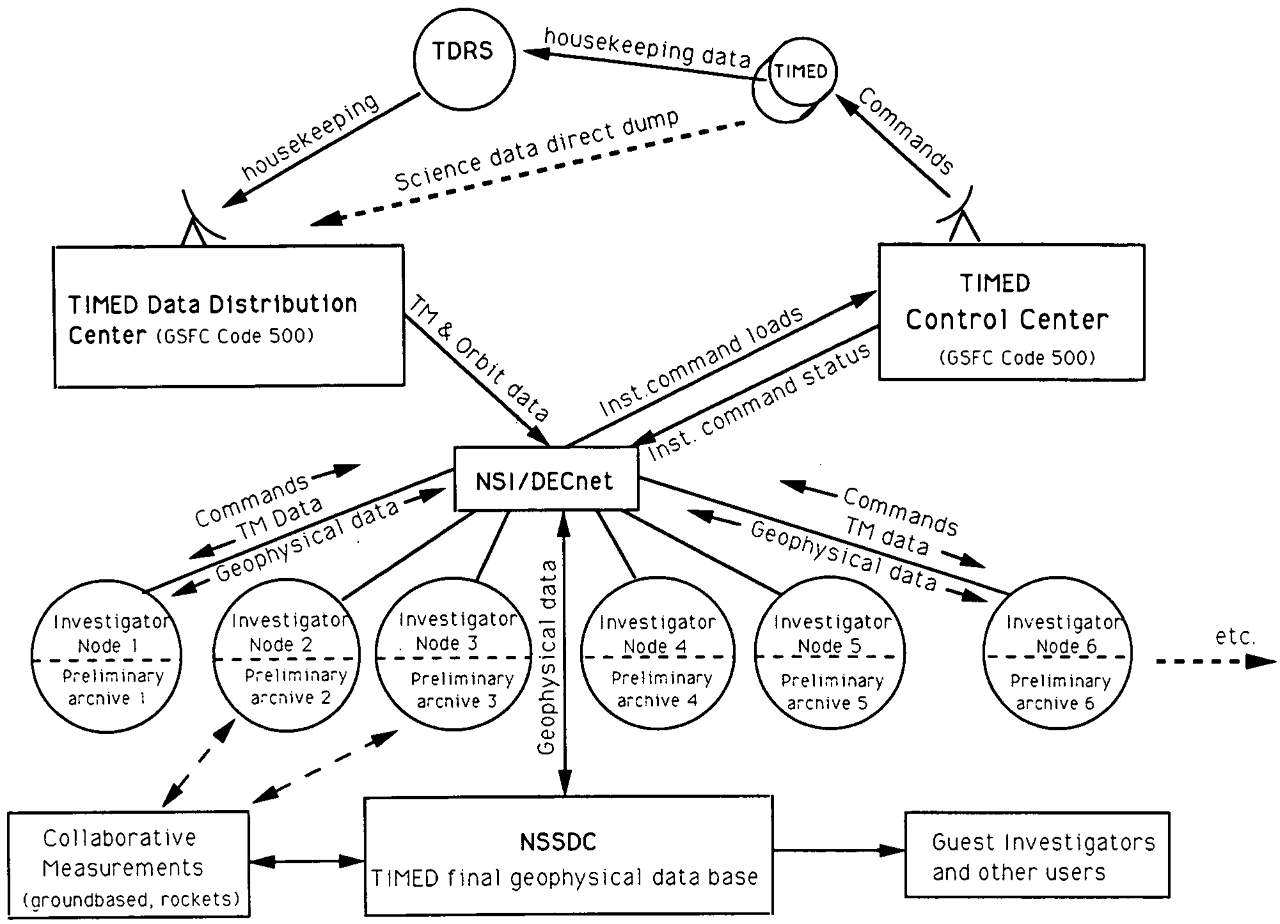


Figure 5. Distributed data system for TIMED

V. Scientific Merit

Scientific Objectives and Significance

The key scientific issues addressed by the TIMED mission have been briefly described above. The mission will provide the first comprehensive spaceborne investigation of an important region of the Earth's near-space environment – a complex transition region that may well be susceptible to rapid anthropogenic change. Since the mission has a real exploratory aspect, new discoveries are to be expected. It is possible, however, to identify various significant scientific issues that will definitely be resolved by the mission. Specifically, TIMED will:

- *Determine the temperature and wind structure of the mesosphere and lower thermosphere, delineating the seasonal/latitudinal variations and tidal components.*
- *Determine the relative importance of the major sources and sinks of energy for the thermal structure of the mesosphere and lower thermosphere.*
- *Examine anthropogenically induced changes in the mesosphere and lower thermosphere.*
- *Determine the roles of CO_2 and NO cooling in the lower thermosphere and the importance of O in enhancing these cooling rates.*
- *Determine the roles of exothermic chemical reactions, involving HO_x and O_x, for the energetics and radiative budget of the mesosphere and lower thermosphere.*
- *Advance our understanding of the radiative and dynamical processes that produce the cold and warm mesopause temperatures in the summer and winter hemispheres, respectively.*
- *Shed light on the effects of albedo changes and radiation associated with noctilucent and polar mesospheric clouds and their importance for the energy balance of the mesosphere.*
- *Determine the global distribution of the major constituents N_2, O_2, and O in the upper mesosphere and lower thermosphere as well as that of CO_2, which is important for the energy budget of the region.*
- *Determine the spatial and temporal variations in odd oxygen [O and O_3], odd hydrogen [OH, H_2O, CH_4, and HO_2], and odd nitrogen compounds [NO, NO_2, $N(^2D)$, and $N(^4S)$].*

- *Determine how the large-scale circulation in the mesosphere and thermosphere affects the distribution of chemically active and radiatively important species (such as* H_2O*,* CO_2*, CO, NO, and O).*

- *Advance our understanding of the photochemical, dynamical, and radiative processes that control the basic structure of the mesosphere and lower thermosphere.*

- *Determine the spatial and temporal variations of radiatively significant minor species in the mesosphere and lower thermosphere [*CO_2*, NO,* O_3*, OH,* $O_2(^1D)$*, and* $O_2(^1S)$*] .*

- *Determine the mean global circulation (meridional and zonal) in the mesosphere and lower thermosphere in response to annual forcing cycles and its geographic and short-term variability.*

- *Determine the diurnal tidal structures, their annual and height variations, and their effects on the mean large-scale circulation.*

- *Determine the sources and magnitudes of gravity waves and planetary waves in the mesosphere and thermosphere, and their spatial and temporal variability.*

- *Determine the effects of gravity waves and planetary waves on the large-scale circulation, thermal structure, and composition.*

- *Provide an understanding of the interactions that occur among different wave motions (tidal, gravity, and planetary) and the extent, causes, and consequences of their variability.*

- *Provide data to study the effects of gravity wave and tidal dissipation on turbulent transport of energy, mass, and momentum.*

- *Determine the dynamical effects of magnetospheric coupling and the depth to which they penetrate.*

- *Help delineate the electric field components of the magnetosphere, the disturbance dynamo, and the tidal dynamos that control the electrodynamics at middle and equatorial latitudes.*

- *Help to determine the roles of neutral winds and electric fields affecting the small- and large-scale variability in the ionospheric density and composition.*

- *Contribute significantly to our understanding of the coupling between E- and F- region plasma structures.*

- *Contribute significantly to our understanding of the ionization sources and the metastable ion chemistry responsible for the molecular ion inventory in the lower ionosphere.*

- *Significantly advance our understanding of the ion and neutral chemistry in the lower thermosphere which is important for the partitioning of energy.*

- *Significantly advance our understanding of the global composition, temperatures, and transport velocities of neutrals and ions in the lower thermosphere by providing, for the first time, simultaneous observations of these variables.*

- *Significantly advance our understanding of tides and related dynamo electric fields, as well as gravity waves and traveling ionospheric disturbances, by performing simultaneously in situ and remote measurements in the thermosphere, ionosphere, and mesosphere.*

- *Significantly advance our understanding of magnetic storm effects in the neutrals and ions by performing simultaneous measurements of temperatures, densities, transport velocities, and electric as well as magnetic fields.*

Generality of Interest

These scientific issues addressed by TIMED are of considerable general interest, since they are related to important sub-disciplines. These include: gas kinetics; turbulence; plasma physics; fluid dynamics; photochemistry; spectroscopy; atomic and molecular collision physics; thermodynamics; etc. Issues of practical concern include: satellite drag; shuttle re-entry; aerobraking in planetary atmospheres; communication–disruption; and global change.

The adapted technology used for the TIMED program will also be of considerable general interest. New stereoscopic remote sensing techniques will be developed to probe planetary atmospheres, and new tomographic techniques will be used to interpret the results. *In–situ* sensors will be used in the challenging low altitude regime. The combination of remote and *in–situ* measurements from two closely coordinated spacecraft will provide for new methods of resolving temporal and spatial ambiguities. New numerical models and global time dependent simulation techniques will be developed.

TIMED has great potential for new discoveries, because the MLTI regime represents a unique laboratory for the study of transitional fluid dynamics and gas kinetics. Unexpected atmospheric linkages that couple the lower atmosphere to the MLTI and magnetosphere, may be discovered. Important new chemical schemes may be discovered, others elucidated, involving constituents or compounds that are key species for atmospheric evolution. New insights may be gained into the role played by turbulent processes in controlling the natural world.

TIMED bridges a major gap in Solar-Terrestrial Science, connecting lower and upper atmospheric physics, magnetospheric physics and planetary aeronomy. Global understanding of the MLTI region requires a *spaceborne* measurement program – the knowledge to be provided by TIMED could not be gained using ground-based or sub-orbital techniques.

Feasibility and Readiness

The results of the pre-Phase-A study have shown that the TIMED mission is feasible and cost effective. The scientific community is ready for this mission, having anticipated it for some time. TIMED is built on the strong foundation of successful previous missions, such as AE, SME, and DE. The community has demonstrated its ability to coordinate efforts to solve global-scale problems, as evidenced by the successful NSF CEDAR program. Strong international participation, both in the mission development phase and in the data analysis phase, is anticipated. Two international colleagues (one from Germany and one from Canada) participated in the pre-Phase-A study and their respective national agencies have already expressed an interest in the mission. TIMED is well poised to contribute importantly to the international STEP program.

The scale of the TIMED mission is well suited for participation by a spectrum of institutions; including universities, NASA centers, and industry.

Finally, and perhaps most importantly, we reiterate that TIMED will *explore* the mesosphere and lower thermosphere/ionosphere, termed by the Academy of Sciences, "*the least understood region in the Earth's atmosphere*." It is thought that this region of our near Earth space environment, which is closer to us than Baltimore is to Washington, may be highly susceptible to global change. The TIMED Science Definition Team considers it to be important that this broad, exciting, and well balanced research program is carried out at the earliest possible date.