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Final Report

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Spacelab Science Results Study
Volume I: External Observations

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Introduction

Some of the 36 Spacelab missions were more or less dedicated to specific scientific disciplines, while other carried a eclectic mixture of experiments ranging from astrophysics to life sciences. However, the experiments can be logically classified into two general categories; those that make use of the Shuttle as an observing platform for external phenomena (including those which use the Shuttle in an interactive mode) and those which use the Shuttle as a microgravity laboratory. This first volume of this Spacelab Science Results study will be devoted to experiments of the first category. The disciplines included are Astrophysics, Solar Physics, Space Plasma Physics, Atmospheric Sciences, and Earth Sciences. Because of the large number of microgravity investigations, Volume II will be devoted to Microgravity Sciences, which includes Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and Volume III will be devoted to Space Life Sciences, which studies the response and adaptability of living organisms to the microgravity environment.

The team members that contributed to Volume I and their areas of responsibility are:

- Dr. Charles A. Lundquist – Astrophysics
- Dr. Einar Tandberg-Hanssen – Solar Physics
- Dr. James L. Horwitz - Space Plasma Physics
- Dr. Glynn A. Germany – Atmospheric Science
- Dr. James F. Cruise – Earth Observations

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis of the more significant experiments and an extensive list of the publications that were produced. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied.

Our initial intent was to assess the scientific impact of these various investigations on the basis of the number of publications generated and the citations they received. It soon became apparent that this would not be a fair assessment for the following reasons:

- Often the total number of publications is dominated by a small number of highly productive teams that flew the same investigation on multiple shuttle flights.
- Time and fiscal restraints for the study did not allow for an exhaustive reference search; thus there is the possibility that key documents to a particular experiment may have been missed.

- Investigators often publish papers using data from multiple Spacelab missions or combine data from Spacelab with other flights. Therefore, it is not possible to ascribe a particular publication to a specific experiment.
- Often the flight data is only a small part of a much larger ground based investigation. It is difficult to determine which of the ground based papers to include.
- Many of the more exciting results have come on the more recent flights and, therefore, have not had time to collect many citations.

For these reasons, we thought it prudent to simply document the experiments that produced publishable results (even though some were not published in the open literature) by presenting a brief synopsis of their results in context with the state of knowledge in the field (where appropriate) along with the references we have been able to find. The number of references in the peer reviewed literature cited by discipline are listed below:

Table 1. References Cited by Discipline

Discipline	References Cited
Astrophysics	44
Solar Physics	28
Space Plasma Physics	140
Atmospheric Science	220
Earth Sciences	117
Total	549

Only 22 of the Astrophysics references were selected from the 167 papers that were published from the ASTRO missions. Therefore, it is safe to say that the external observational experiments performed on Spacelab missions generated more than 694 papers in archival journals.

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Astrophysics

Charles A. Lundquist

Introduction and Background

Of the scientific disciplines represented on the several Spacelab missions, the astronomical discipline is the most mature, (or is at least as mature as any other discipline). Thus the accomplishments from the astronomical instruments must be viewed against a large body of knowledge from many years of prior investigations. In some cases this means that very specific or detailed questions were posed and answered. In other cases it means that astronomical observing technology was extended into difficult wavelengths or modes not previously used. The most significant data fall into such cases, and will be identified as such in subsequent discussions. There are also of course, instances in which the Spacelab instrumentation produced observations of individual stars or objects which add incrementally to the general astronomical data base. These data are valuable, but typically cannot be addressed in any depth here.

Because the Spacelab missions spanned many years, a further factor in reviewing astronomical results is timeliness. Astronomy is a rapidly moving discipline. Results that were new and important at the time of their release may be superseded by newer results a few years later. This is a general feature of astronomy that must be recognized.

The Spacelab astronomical-astrophysical observations were performed with the instruments on the missions listed in Table 1. Also listed are the Principal Investigators. The Co-Investigators and Guest Investigators are numerous and generally are represented as co-authors in the cited references.

Table 1
Astronomical-Astrophysical Observations

	Principal Investigator
Spacelab 1, November 1983	
Far Ultraviolet Space Telescope (Faust)	C. S. Bowyer
Very Wide Field Camera (VWFC)	G. Courtes
Gas Scintillation Proportional Counter (GSPC)	R. Andresen
Spacelab 2, July 1985	
InfraRed Telescope (IRT)	G. Fazio
Cosmic Ray Nuclei Experiment (CRNE)	P. Meyer
X-Ray Telescope (XRT)	A. P. Willmore
Spacelab 3, April 1985	
Ionization Status of Low Energy Cosmic Rays (IONS)	S. Biswas
Astro 1, December, 1990	
Hopkins Ultraviolet Telescope (HUT)	A. F. Davidson
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE)	A. D. Code
Ultraviolet Imaging Telescope (UIT)	T. Stecher
Broad-Band X-Ray Telescope (BBXRT)	P. Serlemitos
Astro 2, March 1995	
Hopkins Ultraviolet Telescope (HUT)	A. F. Davidson
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE)	A. D. Code
Ultraviolet Imaging Telescope (UIT)	T. Stecher

Spacelab 1

Spacelab 1 carried an eclectic ensemble of instruments and experiments. Because this first mission expected to demonstration diverse uses of Spacelab, the instrumentation represented a broad range of disciplines, including the three astronomical instruments in Table 1. These three instruments were hard mounted to the shuttle structure, so that pointing was accomplished by controlling the attitude of the shuttle.

The two telescope-camera instruments photographed star fields in the far ultraviolet (1) (Faust) and ultraviolet (2) (VWFC). As might be expected, a principal result was an improved understanding of how shuttle borne cameras of this class can best be employed. Also, the photographed fields provided surveys of ultraviolet characteristics of classes of stars that could be selected for future detailed observation and analysis.

The Gas Scintillation Proportional Counter (GSPC) measured X-ray energy spectra in the range 2-80 kev for Cyg X-3, Cen X-3 and the Perseus cluster of galaxies, (3, 4). The first two are well known X-ray sources for which these measurements provided further information.

Spacelab 2

The astrophysical instruments on Spacelab 2 used three distinct signals to probe the universe: Infrared radiation, X-rays and Cosmic Rays.

For the first of these, Spacelab 2 carried a small, helium-cooled infrared telescope (IRT). It was designed to observe diffuse, extended sources of infrared as well as to augment data on discrete infrared sources, many of which were cataloged earlier by the Infrared Astronomical Satellite (IRAS). An operational question addressed was the suitability of the Shuttle as a carrier for Infrared Telescopes. With respect to this question, the IRT background due to emission of gas from the Shuttle was found to be greater than anticipated.

The surveys of the Milky Way Galaxy at 2 and 7 microns were new data, implying that the structure of the Galaxy is broader at these wavelengths than at longer wavelengths (5, 6, 7).

As compared to other instruments carried by Spacelab, the Cosmic Ray Nuclei Experiment (CRNE) was massive. Its mass was nearly 2,000 kilograms. An instrument of this extreme size and complexity was required to extend measurements of rare cosmic rays to energies almost 100 times greater than those previously studied by comparable techniques.

The measurements were successful and extend to energies beyond 1 Tev per amu. The investigators conclude that the cosmic ray flux arriving near earth becomes enriched with heavier nuclei, most notably iron, as energy increases, (8, 9). Another analysis presented energy spectra of the cosmic-ray nuclei boron, carbon, nitrogen and oxygen up to energies around 1 Tev (10), which yield information on the propagation of cosmic rays through the Galaxy. Thus the large carrying power of the Space Shuttle supported a significant advance in cosmic ray astrophysics.

The hard X-ray imaging capability on Spacehab 2 was the result of two associated instruments operating approximately in the 2 to 20 kev energy range but with different resolutions, respectively 12 x 12 arc minutes and 3 x 3 arc minutes. Both of the instruments use a coded, X-ray absorbing mask having many small holes in random locations which produces a shadow pattern on a position sensitive multiwire proportional counter. From the resulting data, an image can be constructed, (11, 12).

The objective was to produce images of clusters of galaxies, particularly, and also other extended X-ray sources. A puzzle was the source of the hard X-rays coming from the direction of clusters of galaxies. Measurement of hot gas between the galaxies of the cluster was an objective (See Section: An Exercise in Implication of Spacelab Results). Spectrally resolved images of the Virgo cluster were obtained in the 2-32KeV energy range, (13). The investigators report that much of the hard X-ray emission previously reported from the cluster actually originates in the single galaxy NGC 4388.

Spacelab 3

Spacelab 3 carried an instrument (IONS) developed in India to measure low energy (30 to 300 MeV/amu) "anomalous" cosmic ray ions, (ACR). The detector used two sets of nuclear track plates (mostly CR-39) slowly rotating relative to each other. Thus arrival time of a given cosmic ray can be obtained from relative track displacement. That time when combined with shuttle position and attitude at the same time yields arrival direction.

These low energy cosmic rays may not have all the electrons stripped from their respective nuclei. The low energy cosmic rays have trajectories that are bent more strongly by the magnetic fields in space, particularly the geomagnetic field. The results of magnetic field interaction and therefore arrival direction depend on the charge of the particle and hence on whether or not all the electrons are stripped.

From the IONS instrument data, the abundances of sub-iron (Sc – Cr) and of iron particles in the low energy interval of 30-300 MeV/amu were determined, (14, 15, 16, 17, 18). The sub – iron to iron abundance ratios were 0.8 to 1.2. These ratios are enhanced by a factor of two compared to interplanetary (high energy) ratios of about 0.5. The investigators conclude that the IONS measurement ratios are probably enhanced inside the earth's magnetosphere due to the degree of ionization of low energy Sc to Cr and Fe ions in galactic cosmic rays and to the filtering effects of the geomagnetic field. This is the suggested explanation of cosmic ray data previously cited as anomalous.

Astro 1 and 2

As the mission names imply, the Astro 1 and 2 flights, using Spacelab pallets, carried an ensemble of astronomical instruments. Three of these, HUT, WUPPE and UIT operated in ultraviolet wavelengths and were on a common Instrument Pointing System. These three were carried on both Astro 1 and 2.

A Broad-Band X-ray Telescope (BBXRT) with its own pointing system was added to
Astro 1 only (19), with the initial motivation to observe a 1987 super nova, SN1987A, in a nearby galaxy. However, Astro 1 did not reach orbit until December 1990. The BBXRT was designed to make moderate resolution spectrophotometry of x-ray sources in the 0.3-12 keV band. It consisted of a pair of coaligned conical foil telescopes, with cryogenically cooled Si (Li) spectrometers as focal detectors.

The BBXRT collected and published data for several astronomical objects. These include Xi Pup, the Puppis A supernova remnant and Cygnus X-2, (20, 21, 22).

The Hopkins Ultraviolet Telescope (HUT) was the largest of the three instruments assembled on the Instrument Pointing System for both Astro 1 and 2. HUT was a 0.9 meter telescope designed to perform moderate resolution spectroscopy in the 850 to 1850 Angstrom region of the far-UV. This spectral range goes farther into the UV than the spectrography on the Hubble telescope, which cuts off sharply at wavelengths below 1200 Angstroms.

The HUT operations, particularly on Astro-2, were similar to that of a major ground based observatory. A list of several hundred observing targets was adopted to provide data to many investigators for a diverse analyses. These, of course, employed in crucial ways the unique far-UV capability of HUT. Hence, it is quite impractical here to even enumerate the results, other than to note that new far-UV observations were obtained for virtually every class of objects in the universe, a remarkable achievement! (23)

The astronomers who conceived and built HUT identified what they felt were particularly important or interesting key objectives for the instrument. One of these was to detect and measure the characteristics of the primordial intergalactic gas. Hydrogen, the most abundant element in the universe should dominate the intergalactic medium. Helium should be the next most abundant residual component from the Big Bang and subsequent condensation of stars and galaxies.

The plan was to observe a very distant quasar in its far ultra violet spectrum and look for absorption lines due to its light passing through the intervening intergalactic gas. For this purpose, HUT was programmed to observe quasar HS 1700 + 64. By good fortune, the redshifted spectrum of this quasar covered an absorption line of partially ionized helium. This was detected and analyzed successfully, (24). (See also section: An Exercise in Implication of Spacelab Results)

A second instrument on the Instrument Pointing System was the Wisconsin Ultraviolet Photo-Polarimeter (WUPPE). It was conceived as a pioneering effort to explore polarization and photometry of astronomical objects in the ultra violet spectrum. As did HUT, WUPPE had a long observation target list of many different types of astronomical objects in the universe.

During the two Astro mission, WUPPE obtained polarimetry and spectra for 121 objects. Most of the observations were unique in extending polarimetry into the UV spectral range not possible from the ground (25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35).

The third instrument on the Instrument Pointing Mount was the Ultraviolet Imaging Telescope, (UIT). It was a 38-cm Ritchey – Chretien telescope equipped for ultraviolet filer and grating imagery over a 40 arcminute field of view with a resolution of about 3 arcsec. It produced ultraviolet (1200-3300 angstroms) images of a variety of astronomical objects, particularly extended objects. The images are recorded on 70 mm film (36, 37, 38).

One product of general utility to the astronomical community is an atlas of spatially – resolved far – UV (1500 Angstroms) and mid – UV (2500 Angstroms) images of 50 nearby galaxies. This set includes ellipticals, disk systems and irregular galaxies (39).

Other extended objects studied include the Large and Small Magellanic Clouds. Star clusters were likewise recorded (40, 41, 42, 43, 44).

Summary

The sequence of astronomical instruments on the Spacelab missions evolved over the years from exploratory, pioneering devices, to more mature, multi-purpose instruments and operations. The very productive and successful Astro 2 mission is the prime example of the latter situation.

The evolutionary progress of instrumentation design afforded by the Spacelab missions is probably as important as the observations obtained. While the space shuttle is not the ideal carrier for many astronomical instruments, it was a valuable test-bed for new observation techniques and opportunities. The resulting insight can subsequently be applied to free-flying observatories if the remaining astronomical issues warrant. The circumstance is illustrated in a following section: An Exercise in Implication of Spacelab Results. Presumably, in the future, the International Space Station may provide a comparable test-bed for instrument concepts yet to be invented.

The surveys and catalogs generated from the Spacelab observations in previously unused frequency and energy ranges will find continuing utility in identifying individual astronomical objects worthy of future detailed study. This will insure a lasting legacy from Spacelab.

References

A complete set of references resulting from the astronomical and astrophysical instruments carried by Spacelab is very voluminous. Those few listed below and cited in the text are representative of this extensive literature. They are selected to illuminate points addressed in the text. For a more complete reference set, the reader is referred to an automated service such as (adsabs.harvard.edu).

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Addendum to Astrophysics:

An Exercise in Implication of Spacelab Results

The earlier text, Introduction and Background, noted how astronomical and astrophysical observations build on earlier results and subsequently motivate still further observations. The observations from the instruments on Spacelab have a place in this ever growing fabric of astronomical knowledge.

Occasionally a notable milestone is reached in this process. Such was the case in 1998 when the magazine Science designated as the science break through of the year the findings by two groups that the general expansion of the universe is accelerating (1, 2, 3). This is a remarkable finding because it has profound implications for cosmology when combined with other information.

In a parallel treatment, Scientific American, in its January 1999 issue, carried a special report on the "Revolution in Cosmology" (4, 5, 6). This three-article series also emphasized the reported accelerated expansion of the universe and its cosmological implications. The latter depend on many observational facts about the universe.

Still further, the American Physical Society held its Centennial Meeting in March 1999. This Centennial Celebration was the largest meeting of physicists ever. One well-attended session of invited papers on the Cosmological Constants (7), covered similar topics to those in Science and Scientific American.

Cosmology usually does not receive such notoriety. Hence it is particularly timely to ask whether, or how, the earlier Spacelab results contributed to the excitement. An attempt to answer this question was undertaken as an instructive exercise. Of course, many similar exercises of less notoriety could be pursued, but one example illustrates the process.

In brief, the current view of the universe envisions that some 70% of the energy of the universe is represented by a cosmological constant in the general theory of relatively. This energy of the cosmological constant or the vacuum is responsible for an accelerated expansion of the universe. About 30% of the energy of the universe is in the form of gravitating matter. Of this 30%, some 5% is in baryon matter and 25% or so in cold dark matter. However, the sum of the cosmological constant energy and matter energy is just sufficient to produce a flat universe in the sense of the general theory of relativity. This is a dramatic revision of the view of the universe a few years ago.

The accelerated expansion of the universe is supported by observations of Type Ia supernovae in distant galaxies (2, 3). Large numbers of such galaxies are monitored from the ground at intervals of a few days to detect promptly any changes in brightness caused by a rare supernova in some distant galaxy. When such an event is detected, large ground telescopes and/or the Hubble space telescope are mobilized to measure first the increasing and then the decreasing luminosity of the supernova over several days or weeks. From the time history of this measured luminosity, the absolute peak luminosity from the supernova can be determined, using established models. The absolute and observed luminosity provides a reliable measurement of the distance to the supernova and its galaxy. Also the redshift of the galaxy provides evidence of its expansion rate. From analysis of several such events, a plot of relative distance vs redshift can be produced for the distant galaxies involved. This yields the basic finding that the expansion of the universe, as determined from redshifts of galaxies at known distances, is accelerating.

Previously, a deceleration had been expected due to mutual gravitation of the galaxies and other massive constituents of the universe. The apparent issue had been whether there is enough mass in the universe to eventually halt the expansion or whether the expansion will continue forever. The recent assessment is that the expansion is instead accelerating, caused by some other factors, such as a cosmological constant, and there is too little gravitating matter to produce deceleration.

In as much as Type 1a supernovae are rare events in distant galaxies and they require dedicated and specialized techniques for their observation, the Spacelab instruments contributed nothing directly to these recent findings, although Spacelab did add to the general understanding of supernovae. However, the instruments did have a role in measuring massive constituents of the universe. Lawrence M. Krauss, for example, has discussed this issue (5, 8).

The standard theory of nucleosynthesis in the big bang predicts that measurement of the production ratios of the lightest isotopes gives a sensitive constraint on the cosmological baryon-to-photon ratio. The cosmic microwave background gives a measure of the photon density at the big bang, which with the baryon to photon ratio, yields the cosmological baryon density, (9).

The deuterium to hydrogen ratio (D/H) in the intergalactic gas has been determined by observing absorption lines in the light from a distant quasars (9, 10). These D/H measurements can be done from the ground, but the corresponding measurement of helium absorption is best measured in ultra-violet wavelengths, which must be done in space. This circumstance motivated Davidson, Kriss and Zheng (11) to use the HUT telescope on Astro II to measure the absorption from singly ionized helium (He II) in the spectrum of the quasar HS 1700+64.

Because the intergalactic clouds have been negligibly affected by nucleosynthesis in stars, measurements of the light isotope abundance ratios in intergalactic space implies the ratios from the big bang. Thus the HUT measurements contribute to estimates of baryonic or ordinary matter generated in the big bang, as cited above.

Another way to obtain information on masses in the universe is to deduce the mass in large clusters of galaxies. These are currently the largest objects in the universe for which total masses can be estimated directly (12, 13, 14). The measurement technique depends on the notion that most of the luminous mass of a large galaxy cluster is in hot intergalactic gas which emits X-rays. The assumption is used, and justified, that the gas is in hydrostatic equilibrium, i.e. gas pressure gradients and gravity are in balance. For a massive galaxy cluster, this requires that the gas be so hot that it emits X-rays. Appropriate theory provides equations from which the mass of a galactic cluster can be determined from measurements of the X-rays from its intergalactic gas.

The X-ray telescope on Spacelab 2 was a pioneering effort to use this technique to assess the masses of galactic clusters (12). It demonstrated the usefulness of the technique, which requires spectral imaging of the clusters studied. Of course the duration and scope of observations from Spacelab 2 was limited by the mission length.

In 1990, five years after Spacelab 2, the ROSAT satellite was launched with X-ray spectral imaging capabilities. Far more comprehensive observations of galactic clusters were obtained and analyzed, (13, 14). These later data, building on the Spacelab

2 experience, currently provide one of the best measurements of observable mass in the universe, since galactic clusters represent a large fraction of the identifiable mass.

The galactic cluster mass data are cited, with the previously noted results from light element nucleosynthesis, as the most telling available information on the matter content in the universe, as mentioned above. This information is central to the present "Revolution in Cosmology". The note worthy point here is that pioneering investigations using Spacelab instrumentation helped move the cosmology discipline to its current exciting state.

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SOLAR PHYSICS INVESTIGATIONS

Einar Tandberg-Hanssen

1 Introduction

Seven different solar physics experiments have been flown on the Spacelab facility. In the following we shall refer to them by their acronymes as follows:

ACRIM = Active Cavity Radiometer Irradiance Monitor (Willson, PI)
SUSIM = Solar Ultraviolet Spectral Irradiance Monitor (Brueckner, PI)
SOLSPEC = Solar Spectrum Measurement from 180 to 3200 Nanometers, (Thuillier, PI)
SOLCON = Measurement of the Solar Constant (Crommelynck, PI)
SOUP = Solar Optical Universal Polarimeter (Title, PI)
CHASE = Coronal Helium Abundance Spacelab Experiment (Culhane and Gabriel, PI's)_
HRTS = Solar Ultraviolet High Resolution Telescope and Spectrograph, (Brueckner, PI)

Note that some of these Spacelab experiments have been flown also on non-Spacelab missions, viz.

ACRIM on SMM (Solar Maximum Mission), 1980 -89
SUSIM on OSS-1 (Office of Space Science-1), 1982, and on UARS (Upper Atmosphere Research Satellite), 1992.
SOLCON on EURECA (European Space Agency's European Retrievable Carrier), 1992.

2. List of Principal Investigators, with experiments and missions.

G. E. Brueckner, Naval Research Laboratory, Washington DC, USA, (SUSIM: ATLAS-1, ATLAS-2, ATLAS-3; HRTS: Spacelab-2)
D. A. Crommelynck, Institut Royal Meteorologique de Belgique, Brussels Belgium, (SOLCON: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3)
J. A. Culhane, University College London, UK (CHASE: Spaceleb-2)
A. H. Gabriel, Rutherford and Appleton Laboratory, Chilton, UK, (CHASE: (Spacelab-2).
G. O. Thuillier, Service d'Aeronomie du Centre National de la Recherche Scientifique, Verrieres-le-Buisson, France, (SOLSPEC: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3)
A. M. Title, Lockheed Solar Observatory, Palo Alto, CA. USA (SOUP: Spacelab-2).
R. C. Willson, Jet Propulsion Laboratory, Pasadena, CA. USA, (ACRIM: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3).

3. Description of Solar Physics Experiments on Spacelab Missions.

3.1 ACRIM

Purpose.

The primary objective is to determine the degree and direction of possible fluctuations in the Sun's total output of optical enegy (X-rays to microwave wavelengths) by measuring the total solar optical irradiance outside the Earth's atmosphere.

Physical Characteristics.

Spectral coverage : 180 to 3200 nm
Effective cavity absorptance: 0.999980 +/- 0.000020
Single sample irradiance precision: +/- 0.012 %
Length of single measurement cycle: ~2 min
Uncertainty for single shutter cycle: less than+/- 50 ppm
Data rate: 256 b/s
Mass 35 kg

Instrument Operation.

The ACRIM contains four cylindrical bays, three of which house independent heat detectors, pyrheliometers. The pyrheliometers are independently shuttered, selfcalibrating
and automatically controlled. Each pyrheliometer consists of two cavities, and the temperature difference between the two is used to determine the solar flux. One cavity is maintained at a constant reference temperature, while the other is heated 0.5 K higher than the reference cavity and is periodically exposed to the Sun. When the shutter covering the second cavity is open, sunlight enters and creates an even greater difference in cavity temperatures. The power supplied to the second cavity by the ACRIM eletronics decreases automatically to maintain the 0.5 K temperature difference between the two cavities, and this decrease is proportional to the solar irradiance entering the cavity. The fourth bay contains a sensor that measures the relative angle between the instrument and the Sun. The cavities have mirror-like black surfaces that reflect light toward the apex of the cavity, where 99.99998 % of the Sun's incoming enegy in the 180-3200 nm wavelength range is absorbed.

3.2 SUSIM

Purpose.

The objective is to determine both long-term and short-term variations of the total ultraviolet flux emitted by the Sun.

Physical Characteristics.

Spectral coverage: 110 to 410 nm
Spectral resolution: 5 nm, 0,15 nm
Accuracy: 5 % absolute.

Inflight calibration source: deuterium lamp
Data rate: 156 b/s
Mass: 69 kg
Power consumption: 53 W

Instrument Operation.

The instrument is composed of two precision ultraviolet spectrometers with two sets of optics and an inflight calibration deuterium lamp. This assembly provides an accurate recording of the solar spectral irradiance from 110 to 410 nm, and is capable of tracking any change in ultraviolet sensitivity. The instrument has seven detectors that allow cross-checks of possible detector changes. One spectrometer operates as the primary unit and makes the solar spectral measurements. The other spectrometer gathers data from the deuterium lamp used to calibrate both this unit as well as the primary unit. Since the second spectrometer is not exposed to solar radiation, its readings can be used as reference information to track any degradation in the first spectrometer.

3.3 SOLCON

Purpose.

SOLCON's purposes are to measure the absolute value of the total solar irradiance and to detect and measure long-term variations that may exist in its absolute value.

Physical Characteristics.

Spectral coverage: integrated over the full wavelength range
Absolute accuracy: better than 0.1 %
Precision: better than +/- 0.01 %
Sensitivity: better than 0.05 %
Field of view: 9 deg
Data rate: 46 b/s
Digital resolution: 22 b
Mass: 13 kg.

Instrument Operation.

The instrument is a true differential, absolute radiometer with a digital processing/ converter unit. Because its electrical, optical, mechanical, and thermal characteristics are known, no radiative calibration source is required. Two openings admit sunlight into two cavities, which are painted black. Each cavity has an independently controlled shutter at the front to block sunlight and a thermopile to measure the heat that is generated electrically as well as by absorbed sunlight. The actual measurements are made by pointing the radiometer to the Sun's center and opening the shutter of one cavity, while the other cavity remains closed. The closed cavity is heated electrically until its heatflux to the heatsink matches the heatflux of the open cavity. The energy required is proportional to the incoming sunlight, and the difference in power applied with the shutter opened and closed is a measure of the solar radiation flux. In an alternative mode of operation a constant electrical power is supplied to the closed cavity, and the heatflux balance is re-established by heating the open cavity.

3. 4 SOLSPEC.

Purpose.

The objective is to measure the solar energy in the ultraviolet, visible and infrared parts of the spectrum, and to determine the amounts of energies in this spectral irradiance, and how they change with time.

Physical Characteristics.

Spectral coverage: 180 to 3200 nm
Bandpass in ultraviolet and visible: 1 nm
Bandpass in infrared: 20 nm
Total number of bandpasses: 1950
Precision of individual bandpass: 0.01 nm
Photometric accuracy: 5 % in ultraviolet, 1 % in infrared and visible
Time to record solar spectrum: 13 min
Number of spectra per orbit: 3
Data rate: 500 b/s
Mass: 32 kg.

Instrument Operation.

The instrument is a double-monochromator using two holographic gratings as dispersive element. It has three spectrometers (one each for the ultraviolet, visible, and near-infrared portion of the spectrum), scanning at 650 different positions. Each position corresponds to a 1 nm bandpass in the ultraviolet and visible ranges, and to a 20 nm bandpass in the infrared, producing a total of 1950 bands. A hollow cathode lamp measures the wavelength scale of the spectrometers. The accuracy in flight is assured by four calibration lamps (two deuterium and two tungsten ribbon lamps). Their light follows the same optical path as the Sun's light. During operation, observations of the Sun alternate with observation of the calibration lamps at 15-minutes interval.

3.5. SOUP

Purpose.

The objectives of the experiment are:

1. to measure magnetic and velocity fields in the solar atmosphere with high spatial resolution and to deduce the small-scale structure and evolution of these fields on the 10- to 20-min time scale of solar granulation;
2. to follow the evolution of solar magnetic structures over periods of several days to determine how magnetic elements couple to the supergranule velocity patterns and by what mechanisms field diffusion and disappearance occur;
3. to study with high temporal and spatial resolution the magnetic field changes associated with transient events, like flares, and to isolate and follow the birth

of sunspots, pores, and ephemeral regions;

4. to provide a test of the pointing accuracy and stability of the Instrument Pointing System (IPS) to sub-arc second accuracy.

Physical Characteriscics.

Dimension (cm): Telescope and focal- plane structure: 40x40x205
Processor: 56x48x36

Total mass: 248 kg

Average power: 150 W at 28 Vdc

Total energy: 22 kWh

Data: Digital:1.4 Mbps
Film : Type SO-115
TV: 4.2 MHz.

Instrument Operation.

The experiment consists of a Solar Optical Universal Polarimeter (SOUP) mounted on the IPS, using a 30-cm Cassegrain telescope designed for diffraction-limited performance in the wavelength region 480 to 700 nm. A gimbal system and a solar limb tracker allow the observation of any point on the solar disk when the IPS is directed within several degrees of the Sun. Two independent focal-plane systems are used; the first being a white-light system which records granulation and pointing data onto film. The other, a tunable filter system, consists of a birefringent filter with selectable bandpass of 30 mA or 70 mA, and associated blocking and polarizing filters to produce monochromatic images in a known state of circular or linear polarization. The wavelength of the resulting image is selectable to within +/- 4 A of any of nine predesigned spectral lines. The resulting filtergrams are recorded on SO-115 film and with a diode array camera. The diode array output is fed into the video processor, which is capable of image storage and also of adding, subtracting, multiplying and dividing images into any or all of its six internal image memories. In this manner, magnetograms and velocitygrams are made in real time.

3. 6. CHASE

Purpose.

The goal of this experiment is to determine accurately the helium abundance of the Sun. In addition, the temperature, density and composition of coronal gases can be derived from measurements of the intensities of ultraviolet emissions.

Physical Characteristics.

Dimension (cm): Instrument: 56x44x115
Microprocessor: 37x36x30
Power supply: 35x33x30

Total mass: 114 kg

Average Power: 72 W at 28 Vdc

Total energy: 11.7 kWh

Data: 8.2 kbps

Instrument Operation.

The experiment utilizes a 1-m grazing-incidence spectrometer with a 1200 lines/mm concave grating. The image of the Sun is focused onto the entrance-slit plane by means of a 28-cm focal length grazing incidence Wolter-type I telescope. Eleven channel-electron multipliers are placed behind individual exit slits that are positioned on the Rowland cycle to accept pre-selected wavelengths. Two such detectors monitor the hydrogen Lyman alpha and the He II, 304 A lines. The other detectors monitor ionized lines of Fe, S, C, and O, for temperature and density determinations.

3. 7. HRTS

Purpose.

The major objectives of the experiment are:

1. to investigate the energy transport and mass balance of the temperature minimum, chromosphere, transition zone, and corona in the quiet Sun as well as in plages, flares and sunspots;
2. to study the velocity field of the lower corona in order to investigate the origin of the solar wind;
3. to investigate the structure of spicules and superspicules;
4. to investigate the structure and dynamics of prominences;
5. to study the preflare and flare phenomena.

Physical Characteristics.

Dimension (cm): Instrument: Diam. 49x365
Electronics: 49x60
Total mass: 326 kg
Average power: 340 W at 28 Vdc
Total energy: 48.6 kWh
Data: Digital: 3.2 kbps
Film: Type S0-652 and Type S0-410
TV: 4.2 MHz.

Instrument Operation.

The instrument consists of a telescope, an ultraviolet spectrograph, an ultraviolet spectroheliograph, and an H-alpha slit-display system, all housed in a thermally controlled canister. The telescope is a concentric Gregorian with a 30-cm primary paraboloid of 90-cm focal length. An occulting mirror at the primary focus reflects away all but a 7x15 arc min portion of the solar image. This portion passes through an aperture in the occulting mirror and strikes the secondary mirror which re-images it at the slit plane of the ultraviolet spectrograph. The telescope resolution is diffraction limited at 0.5 arc sec. The ultraviolet spectrograph of the symmetric tandem Wadsworth type uses two concave diffraction gratings. A stigmatic spectrum with spectral resolution of 50 mA and a spatial resolution of 0.5 arc sec is formed at the film camera. The ultraviolet spectroheliograph photographs the solar image reflected from the front surface of the spectrograph slit-plate. It is tuned to observe the C IV, 1550 A emission line. This instrument is a reversed tandem Wadsworth arrangement with two concave gratings that form a zero-dispersion image at the camera focal plane. The H-alpha filter consists of two tandem Fabry-Perot interference filters with half-width of 0.5 A. The slit-display system forms a photographic and a video image of the solar image reflected from the front surface of the spectrograph slit-plate.

4. Spacelab Missions with Solar Experiments

4.1 Spacelab-1 1983
SOLSPEC
ACRIM
SOLCON

4.2 Spacelab-2 1985
SOUP
CHASE
HRTS
SUSIM

4.3 ATLAS-1 1992
SOLSPEC
SUSIM
ACRIM
SOLCON

4.4 ATLAS-2 1993
SOLSPEC
SUSIM
ACRIM
SOLCON

4.5 ATLAS-3 1994
SOLSPEC
SUSIM
ACRIM
SOLCON

5. Major Scientific Results from Solar Spacelab Missions.

The scientific investigations carried out by solar experiments using the Spacelab facility fall into three main categories, viz.

1. Measurements of the solar irradiance (the solar constant problem);

2. Abundance determinations (the solar helium problem);

3. The dynamic nature of the solar atmosphere.

The ACRIM, SOLSPEC, SOLCON, and SUSIM experiments all addressed the solar constant problem, while CHASE was used to investigate the helium abundance problem. The multifaceted aspect of the nature of the dynamic solar atmosphere was studied in great detail by the SOUP and HRTS experiments.

5.1. Measurements of Solar Irradiance.

The total solar irradiance is the total radiant enegy of the Sun received by the Earth at a distance of one astronomical unit. The absolute value of the solar irradiance is one of the critical factors that determines Earth's absorption and reflection of radiation, the energy balance that governs atmospheric circulation. Solar ultraviolet radiation in the wavelength range 120 to 400 nm is absorbed by the Earth's atmosphere between 20 and 120 km., and even though this radiation constitutes only a small percentage of the total solar output, it is the main source of energy for the middle atmosphere. This ultraviolet component of sunlight varies considerably more than the visible radiation. During an 11-year cycle of the Sun's activity, changes in ultraviolet radiation bring about corresponding changes in a number of atmospheric conditions, and may be responsible for weather and climate changes.

5.1.1. Main Results of the Solar Irradiance Investigations.

Already on the pre-Spacelab SMM the ACRIM experiment had discovered that the models used to estimate the irradiance, underestimate the observed irradiance values at the time of solar activity maximum and at the beginning of the declining phase of solar cycle 22. Furthermore, the 9-year long series of measurements carried out by ACRIM on the SMM revealed both a long-term, and a day-to-day, variation in the value of the irradiance, variations that could be related to the presence of sunspots on the solar disk. The experiment detected an 11-year cycle in the bolometric radiation with a 0.1 % amplitude, (Willson and Hudson, 1991). Note that several, more or less identical, versions of the ACRIM experiment flew - sometimes simultaneously - on different missions. In particular, during the Spacelab-1 and Spacelab-2 missions the first ACRIM flew on the much longer-lasting SMM (Willson, 1991). Many of the ACRIM experiment descriptions and scientific results from the Spacelab missions can be studied in the appropriate literature from the SMM. A comparison of data obtained by the SMM, Spacelab-1, UARS and ATLAS missions was given by Willson (1994), and Woods et al (1996) made a comparison of the UARS irradiance measurements with the ATLAS-1 and ATLAS-2 data, showing the basic consistency between them.

SOLCON results from the Spacelab-1 mission determined the value of the solar constant at the time to be 1361.5 +/- 2.3 Watts/m2 (Crommelynck et al., 1986). The first SOLCON results from the ATLAS-1 mission were published by Crommelynck et al (1994). Then, from the ATLAS-1 mission SOLCON results indicate a correlation between the number of sunspots and the fluctuation of the values of the solar irradiance. Hence, both the ACRIM and the SOLCON experiments established the important link between the occurrence of sunspots and the value of the solar constant. Crommelynck et al (1994, 1995) described in some detail the observations from the ATLAS-1 and the ATLAS-2 missions, and Mecherikunnel (1996) compared the irradiance measurements from SOLCON on the ATLAS missions with the ACRIM data from UARS.

The solar spectrum was measured by the SOLSPEC experiment on Spacelab-1 (Labs et al. 1987), and by the SUSIM experiment on Spacelab-2, and the spectra obtained agreed within 3 percent in the 200 to 3500 nm range. The SOLSPEC data showed that the solar irradiance is spectrally similar to sun-like stars down to at least 240 nm. The experiments showed that while the differential irradiance at 200 nm is less than 10 mW/m2.nm, it increases strongly toward longer ultraviolet wavelenghts, and reaches 1000 mW/m2.nm at 3500 nm. These results are of prime importance for the study of the influence of solar radiation on the Earth's atmosphere. Already on the SMM the SOLSPEC X-ray data had also revealed a time-dependent line broadening that was to be further studied in later missions (Doschek et al, 1980).

5.2. Helium Abundance Determination.

Helium is a major contributor to opacities and radiative loss effects, and its abundance is important to all aspects of stellar evolution and stellar modeling. In the Sun helium contributes about 10 per cent to the mass and plays therefore a crucial role in models of the solar interior.

However, because of their high excitation potential, He I lines are formed in the Sun at high temperatures in the chromosphere where the situation is complicated due to inhomogeneities associated with the chromospheric network and spicules. As a consequence, normal methods of determining abundances from photospheric absorption lines cannot be applied. Instead the CHASE experiment can observe the hydrogen (1216 A) and the ionized helium (304 A) resonance lines formed by photoexcitation of the coronal plasma, i.e. in a region where the hydrogen and helium line emissions are due mainly to the resonance scattering of the intense chromospheric emission. The experiment observes both the light source (solar disk) and the scattering region (corona above solar limb), and since the two principal lines are common in both cases, the results are independent of instrument intensity calibration.

5.2.1 Main Results of the Abundance Determination.

No comprehensive report concerning scientific data obtained by CHASE on the Spacelab-2 mission seems to have been published in any of the major astronomical journals.

5.3 The Dynamic Nature of the Solar Atmosphere.

The SOUP and HRTS instruments have provided a host of new results concerning the nature of the solar atmosphere. From observations with the SKYLAB and the SMM we know that solar magnetic fields play THE crucial role in determining the state and development of the ionized solar atmosphere, but many aspects of the physics involved have been clarified by the SOUP and HRTS investigations, and new discoveries have been made.

5.3.1 Results From the SOUP Experiment.

In-depth studies of both solar granulation and super-granulation have been made, using SOUP data from Spacelab-2. In particular, the horizontal flow field in the solar atmosphere was observed and analyzed by Title et al (1986), and the statistical properties of the granulation were investigated by Simon et al (1989). Simon et al (1993) modeled the supergranulation diffusion (from the observed horizontal flow pattern), and Simon and Weiss (1989) and Simon et al (1991) produced models of exploding granules.

The important transport of magnetic fields in the horizontal flows was treated by Simon et al (1988), while the general properties of the horizontal velocities were delineated by Tarbell et al (1992). Interesting results from the SOUP measurements also were the discoveries of a 600 - 1000 m/s outflow from the penumbra of sunspots, and the reduced horizontal flow in regions with many magnetic pores, (November et al, 1987).

5.3.2. Results From the HRTS Experiment.

The spectroscopic investigations using the HRTS experiment on Spacelab-2 furnished high-resolution (1 arcsec spatial, 0.05 A spectral) spectra of the 1170 - 1710 A region in the quiet, as well as in the active, solar atmosphere. In particular, several new lines were identified, (Sundlin et al, 1986 a, b).

The HRTS spectra further revealed some up-, but mainly strong, down-flows over sunspots in the transition region between the chromosphere and the corona, (Brueckner et al, 1986; Kjeldseth-Moe et al, 1988). The down-flows cover most of the sunspot area and are supersonic in nature, with velocities, for the C IV, 1548 A line, of 40 - 80 km/s. The C IV line furthermore reveals large non-thermal line-broadening in areas of emerging magnetic flux, (Brueckner et al, 1986; Cook et al, 1987). Detailed studies of the transition region revealed a multiple-flow regime around sunspots; some of the flows being supersonic in nature (Kjeldseth-Moe et al 1993). Furthermore, on Spaceleb-2 the HRTS experiment discovered macrospicules inside a polar coronal hole (Dere et al, 1989), and other Spacelab-2 data have been used to check theoretical calculations. In particular, the effect of non-Maxwellian electron-distribution functions on S III line ratios were calibrated against HRTS observations (Keenan et al 1989).

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6.2. Helium Abundance.

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6.3 Dynamic Nature of Solar Atmosphere.

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S2-75

Shuttle-Based Space Plasma Physics Science Accomplishments

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In this report, we attempt to provide a perspective and summary of published science accomplishments in the areas of Shuttle-based studies of Space Plasmas, having at least to some connection with the charged particle environment. We have chosen to employ a mixed itemization/classification/groupings of the science accomplishments, in some cases based on the scientific nature of the effort or the phenomenon, in some cases based on the technique or experimental method, and in one case, the science accomplishments for that particular mission.

I. Measurements of Natural Energetic Particles from the Shuttle

Although most of the Shuttle based space plasma science was oriented towards actively stimulated effects, Lieu et al.[1988] used an electron spectrometer experiment aboard Spacelab 1 to measure fluxes of low-energy(0.1-12.5 keV) electron precipitation at low latitudes, $\pm 30^o$. They found generally two components, one being a low-energy component in the range 0.1-1 keV which had a power law spectrum, and the other being a high-energy component showing a tail "flattening" at higher energies. This latter spectral component occasionally showed a peak in the spectrum, and at times showed temporal flaring with time scales of about 1.5 hours. This higher-energy(1-12.5 keV) component in some cases exhibited very large fluxes, e.g., > 3. x 10^5 el cm^{-2} s^{-1} sr^{-1}, and also showed peaks straddling the equator, where a flux minimum was observed. Lieu et al.[1988] were unable to adequately determine the likely acceleration mechanism for these electrons.

II. The Shuttle-Based Creation and Use of "Ionospheric Holes"

One of the important investigations from Spacelab 2 was of the creation of "artificial holes" in the F-region ionosphere, which earlier theoretical and precursor experiments[cf., Mendillo and Forbes, 1978,Bernhardt et al., 1979, Mendillo et al., 1980]had suggested.
A review of the theory and experimental results ionospheric holes was given by Mendillo[1988]. Mendillo discussed the effects of rocket launches as well as shuttle engine burns supplying various contaminants in large amounts to react with the ambient O^+, producing a new ion and neutral in this reaction, and the ions subsequently rapidly recombine with electrons to form neutral molecules and airglow. Hence the plasma density is rapidly depleted, creating a hole in the ionosphere.

In his schematic presentation of the ionospheric hole creation process, some of the potential consequences noted in various simulations would include: triggering equatorial plasma instabilities, enhancement of photo-electron escape to the conjugate ionosphere, plasma flow into depletion region, overall plasmaspheric flux tube depletion, airglow excitation by thermal electrons, and thermal expansion. The artificially-induced airglow burst in the O^+ line 630 nm was observed over New England on July 29, 1985 and described by Mendillo[1988].

These artificially-created holes were also used for enabling radio astronomy observations[Ellis et al., 1988], owing to the reduced plasma frequency cutoff of such radio emissions during such hole events. Ellis et al.[1988] were able to make observations of the galactic radio background emission at a number of frequencies between 0.51 MHz and 2.75 MHz. The observations were conducted at a time when the ambient F-region peak electron density corresponded to an foF2 plasma frequency cutoff of 1.99 MHz, meaning that no astrophysical emissions below that frequency should have been observable. However, on this flight over the Hobart observatory in Australia on August 5, 1985, during the Spacelab-2 mission, the Shuttle engine burn, which produced rapid recombination and depletion of the plasma density, resulted in a dramatic drop in the foF2, creating a "window" which allowed much lower than normal frequencies to be observed from the ground observatory. Such observations were described as being useful in permitting much improved mapping of the galactic radio distribution, particularly at frequencies below 1.6 MHz.A survey of the galactic background radio emission derived from the radio studies provided by these burns was presented by Ellis and Mendillo[1987. Mendillo et al[1987] also discussed these Spacelab-2 burn/depletion experiments and the associated ionospheric and radio astronomy investigations.

III. Shuttle Glow

Another area of important Space Plasma investigations was of the so-called "Shuttle glow". Observations from the third launch of the space shuttle(STS-3) published by Banks et al.[1983] reported diffuse optical emissions surrounding the Shuttle surfaces interacting with the atmosphere in the ram direction. It was found that this glow emission had intensities which were comparable to that of the Earth's airglow, and also is comparable to the brightness of stars in TV cameras. Banks et al.[1983] estimated that the layer where the glow emission was occurring around the Shuttle was probably in the range of 5-10 cm thick. These glows appeared to have generally similar features to the glow observed on the Atmospheric Explorer-C spacecraft[cf. Torr, 1983]. Mende et al.[1983] also reported Shuttle glow, from STS-4 observations, and estimated the total glow intensity in their observational range to be 100-300 Rayleighs, which was much less than the glow estimated for the STS-3 flight, perhaps because STS-4 was at a higher altitude where the atmospheric density was smaller, and also because the angle of interaction was more oblique in the latter case. Mende et al.[1984] distilled some of the observed consistent properties of the Shuttle glow from observations on the STS-3, STS-4, and STS-5 missions.

Among other suggestions, Slanger[1983] suggested that the glow was generated by the Shuttle surface interaction with 5 eV $O(^3P)$ atoms at the high altitudes of the Shuttle. Alternatively, Papadopoulos[1984] suggested that the Critical Ionization Velocity(CIV) phenomenon could be involved. In this concept, although the shuttle velocity was nominally too low, at 8 km/s compared to the CIV velocity for oxygen, which is 12.7

km/s, Papadopoulos suggested that specular reflection of a small fraction of the ion population would give a relative ion-neutral velocity of 16 km/s, which cold excite the CIV effect, which in turn could provide the Shuttle glow effect.

IV. Use of the Plasma Diagnostics Package for Space Plasma Investigations

A special feature of Spacelab 2 was that the Shuttle released a separate satellite, the Plasma Diagnostics Package(PDP) in order to probe the plasma, field and wave environment of the Shuttle[e.g., Shawhan, 1982; Shawhan et al., 1984aF; Reasoner et al., 1986, Kurth and Frank, 1990]. The instrumentation on this PDP satellite included an electron/ion plasma analyzer, known as a LEPEDEA[e.g. Frank et al., 1978], a Langmuir probe, an ion mass spectrometer, a retarding potential analyzer, a differential ion flux probe[Stone et al., 1985], a plasma wave receiver and electric field detector suite, an electrometer, a neutral pressure gauge, and radio receivers. Further discussion of the PDP and the associated instrumentation can be found in Shawhan [1982], Shawhan et al.[1984a,b], Reasoner et al.[1986] and Kurth and Frank[1990], with the Kurth and Frank[1990] providing also a brief review of some of the results.

The first active beam-plasma experiments with the Shuttle were performed during March 1982 on the third Shuttle flight, STS-3, and the properties of waves generated by continuous and modulated electron beams were described by Shawhan et al.[1984b], making the use of the Plasma Diagnostic Package. It was found that during the continuous beam experiments, the waves were dominantly electrostatic and had peaks of the order $4x10^{-3}$ V^2 m^{-2} Hz^{-1} in the 300-500 Hz range, and were unpolarized. With modulated beams, strong emissions near the electron gyrofrequency and plasma frequency were observed at times, and the emissions at near the modulation frequency had more of an electromagnetic character, with more intense with electric field strengths sometimes attaining levels up to 1 V/m.

Aspects of electron velocity distributions and the associated plasma waves were also investigated by Frank et al.[1988] based on Spacelab 2 observations with the PDP. They observed from behind the shuttle with a particle spectrometer on the PDP, a magnetically aligned "sheet" of electrons returning back opposite to the direction of the injected electrons. The thickness of the electrons was estimated to be about 20 meters. They also observed concomitant intensifications of electrostatic noise within the electron sheet, which they attribute to an ion acoustic instability, which they suggested might also be responsible for the returning electrons through the process of quasi-linear diffusion. Spacelab proved to be an excellent laboratory for investigating controlled generation of wave emissions in dilute large-scale plasmas which were not possible to study on confined terrestrial plasma laboratories.

An interesting phenomenon observed by the PDP was whistler mode radiation detected during periods when the PDP and the Shuttle were magnetically connected, and an electron generator injected a 1-keV, 50 milliAmpere electron beam into the environment. As reported by Gurnett et al.[1986] and by Farrell et al.[1988, 1989], the generated whistler radiation had some interesting characteristics: the evidence suggested that it was quasi-electrostatic, with little magnetic component of the waves, and the wave power was "funnel-shaped" when presented on a gray-scale frequency-time spectrogram. From natural auroral region emissions studies it is known that such a shape results from a propagation effect of the whistler waves having normal angles near the resonance cone.

The power in the detected whistler waves was estimated to be about $2x10^{-5}$ of the electron beam's total power[Farrell et al., 1988]. Although this fraction is seemingly low, it was determined by Farrell et al. [1988] that a process of *incoherent* Cerenkov radiation should produce radiation that is even much lower, about 10^7 too small, to explain the detected radiation. These authors then turned their attention toward *coherent* Cerenkov radiation[Farrell et al., 1988, 1989]. In this framework, the injected beam becomes modulated by a beam-plasma electric field wave instability which causes the beam electrons to bunch up into periodically-spaced density perturbations which allow coherent, and thus much stronger, radiation to occur. In a detailed model of the process, Farrell et al[1989] showed that a one-dimensional line source beam/wave radiator was calculated to be expected to produce more than enough power(40 times as much, in fact) to explain the observed waves. It was concluded that the PDP was indeed probably observing coherent Cerenkov radiation during these electron beam injections, and that the actual smaller power was probably associated with the finite spread of the beam, and other complicating factors not included in their simulation.

During the OSS/STS-3 mission, the PDP was also employed to investigate the plasma-electrodynamics interactions around the Space Shuttle[Stone et al., 1986]. The PDP included the instruments noted above, as well as a Differential Ion Probe(DIFP) for measuring and deconvolving multiple ion streams/directions[Stone et al., 1985]. For the OSS/STS-3 mission, it was found by Stone et al.[1986] that the measured ion flow directions and energies indicated that the interaction region between the Shuttle orbiter and the ionospheric plasma is confined to 10 m in thickness in the forward/ram direction, with a boundary layer thickness of about 2 m. Stone et al.[1986] also indicated a close correlation between the ion and neutral gas densities, and finally that the interactions between secondary ion streams at high inclinations to the basic flow direction of the ambient plasma probably generate the broad-band electrostatic noise found by the PDP wave instruments. Siskind et al.[1984] examined forward/ram conditions around the Space Shuttle from the same STS-3 flight chiefly using a Spherical Retarding Potential Analyzer(SPRA) and Langmuir probe(LP) on the orbiter itself(not the PDP measurements in this case). They found a rather larger than expected plasma turbulence, with a strong component at 2.2 kHz. Siskind et al.[1984] also detected unusually large densities of molecular ions, with masses of 30-32 amu, and elevated ion temperatures in the range 2000-3000 K, and coincident with even higher electron temperatures of about 5000 K. They also discussed these measurements as evidence for a plasma instability associated with the outgasses from the moving Shuttle interacting with the ionosphere. Additional discussion of the results from these thermal plasma environment measurements on STS-3 was given by Raitt et al.[1984].

Also observed with the PDP on the Challenger Spacelab 2 mission were substantial densities of hot ions, with energy spectra in the PDP frame showing characteristic peaks near 18 eV, and substantial fluxes of such ions out to about 60 eV[Paterson and Frank, 1989]. It was found that these ions also exhibited "pancake-shaped" velocity distributions, in which the ion distribution was peaked around velocities directed perpendicular to the magnetic field. Such ions were seen by the PDP as far away as at least 280 km from the Shuttle.

The analysis of these ions by Paterson and Frank[1989] determined that these ions were mainly molecular ions including H_2O^+, H_3O^+, CO^+, CO_2^+, and others. The dominant species was the water molecules, ranging from densities of 30 to 10^4 H_2O^+ ions/cm^{-3}. These were concluded to have characteristic energies of 18 eV, which was twice the energy associated the relative motion between the spacecraft and the ambient atmosphere. Paterson and Frank[1989] constructed a model in which water and other vapor molecules from the Shuttle surrounded the orbiter and charge-exchanged with the ambient ionospheric O^+ ions. By a "pickup ion" process similar to processes occurring in cometary comas, the Io torus, and other settings involving relative motion between neutral gases and magnetized plasmas, the ions were concluded to have been trapped in gyration orbits immediately after the charge-exchange formation by the magnetic field with twice the relative motion velocity contained in the gyration speed. It was further shown that such ions exhibited a strong diurnal variation in their densities, being large in the daytime and small at night, which is consistent with the controlling factor in their formation being the similarly-varying ambient ionospheric O^+ ions which the originally-neutral water molecules would charge exchange with. Paterson and Frank[1989] estimated that the Space Shuttle was producing a water vapor cloud with densities of the order of perhaps 10^9 H_2O molecules/cm^3 at approximately 50 m from the Shuttle.

Additional observations of water and other ions during Spacelab 2 were obtained with a Bennett RF ion mass spectrometer on the PDP[Grebowsky et al., 1987]. They found that the concentrations of the water ions decreased with distance from the Shuttle in the orbiter wake, and fell below the concentrations of ambient O^+ ions at wake distances of about 30 m. These and other similar measurements raised serious questions about the viability of making reliable natural or ambient ion measurements in the Shuttle environment.

These water molecules can be the result of specific water releases which are needed to eject the excess water produced by fuel cells, or other types of wastewater production by the Shuttle. As an evident consequence of the presence of such ions, Pickett et al.[1989] examined observations by the PDP Langmuir probe of plasma density fluctuations, which showed that that such fluctuations and turbulence increased markedly during these water dumps. They found that these water dump-associated plasma density fluctuations occurred over a frequency range from the lowest detectable, a few Hertz, up to the local lower hybrid frequency. They concluded that such would be produced by the interaction of the aforementioned charge-exchange produced water ions with the ambient ionospheric plasma. Two mechanisms for producing the waves were considered by Pickett et al.[1989]. In the first, the "free energy" in the relative motion between the water ions and the oxygen ions of the ionosphere would initiate a beam-plasma interaction. For the second, the ring-shaped velocity distribution of the water ions would itself be unstable and thus contain free energy for the excitation of the waves.

Murphy et al.[1986] also used the above Langmuir probe for the PDP on the STS-3 flight to determine electron densities, temperatures and the plasma potential surrounding the Shuttle. As consistent with observations described elsewhere within this report, they find similar wake effects as for small satellites and laboratory experiments, but exaggerated in the case of the Shuttle, with orders of magnitude decreases in density, and factor of five temperature enhancements. They also observed strong turbulence, with strong power up to and through the lower hybrid frequency. Similar Langmuir probe measurements of the Shuttle Orbiter wake were obtained with the PDP during Spacelab 2 by Murphy et al.[1989].

Shawhan et al.[1984b] used experiments on the Plasma Diagnostics Package(PDP) to measure the plasma environment of the Shuttle Orbiter. Occasionally, somewhat energetic ions and electrons were observed with energies of 10's of eV. It was also found that the Shuttle primary and vernier thrusters usually induce a temporary enhancement of the electron density.

Intense broadband waves around the Shuttle as observed by the PDP were also reported from both the OSS 1 and Spacelab 2 missions by Cairns and Gurnett[1991]. In their characterization of these waves, they found it useful to view the waves in terms of 3 relatively distinct components below 10 kHz, together with a high-frequency tail of the power which declined with frequency about 10 kHz. The first component could be characterized as a quasi-uniform relatively intense level of waves extending over 31-10,000 Hz range. On top of this broad spectrum are two components which have about twice the primary's electric field values. One of them has a low-frequency peak in the frequency range 100-178 Hz, while the other occurs near the local lower hybrid frequency

One of the most interesting findings by Cairns and Gurnett[1991 was that the observed waves were strongly modulated in both amplitude and frequency location by the angle between the magnetic field and the shuttle's velocity vector, which they characterized in terms of $V_{\parallel}/V_T$, where V_T is the total shuttle speed and $V_{\parallel}$ is the component parallel to the magnetic field. They found that as the shuttle moves to regions where it is moving close to parallel to the magnetic field($V_{\parallel}/V_T \sim 1$), the wave amplitudes and frequency spreads become very small. Because of this directional dependence, Cairns and Gurnett[1991] concluded that waves were most likely driven by water pickup ions. They also suggested that their findings have important consequences for trying to observe waves from the Shuttle, namely, that the preferred Shuttle orbits should have directions close to the magnetic field(i.e., $V_{\parallel}/V_T > 0.7$) so as to inhibit waves of such origin such that experiments designed to probe naturally-occurring waves and waves produced by active perturbations. Such comments imply a preference for polar orbits and against equatorial orbits.

Also from the Spacelab 2 mission and making use of the PDP capabilities were the findings of Reeves et al.[1988a,b; 1990], who studied the VLF wave emissions produced during both pulsed and DC electron beam injections. The electron beam injections were done with the Vehicle Charging and Potential(VCAP) experiment[Banks et al., 1987]. This experiment included a Fast Pulsed Electron Generator(FPEG) which could inject an electron beam of 50 or 100 mA of current in 1-keV electrons. Additional discussion of the waves and the return currents for these experiments was presented by Neubert et al.[1988].

During these experiments, it was found that the injection of a continuous or DC, or square-wave modulated beams elicited a broadband electromagnetic spectrum of waves, whereas pulsed beams produced narrowband emissions. Owing to the manuevering of the PDP, it was possible to probe the wave amplitudes and frequency ranges variation as a function of distance from the center of the beam and Reeves et al.[1988a,b; 1990] found that the waves amplitudes and frequency extents declined with such increasing perpendicular distance to the beam. Many of the properties of the narrowband waves were found to be consistent with the linear theory of Harker and Banks[1987], and are consistent with Cerenkov radiation for certain wave normal angles. Other relevant calculations to the radiation from pulsed electron beam trains in space plasmas were performed by Harker and Banks[1985], for both short and long pulse trains.

Steinberg et al.[1988] attempted to use a double-probe potential experiment onboard the PDP for Spacelab-2 to measure the electric fields in the vicinity of electron beams injected. Although they observed large differential voltages between the two probes, they concluded that these measurables were not due to ambient electric fields, but rather due to other effects, including shadowing of the probes from streaming electrons by the PDP chassis. One conclusion Steinberg et al.[1988] did obtain was that at greater than 80 meters downstream from the electron beam injection location, the energetic electron flux is opposite to the injection direction, as would be expected if those energetic electrons were basically a secondary return electron caused by scattering of the primary beam electrons.

A further electrostatic potential-related observation made on the Spacelab 2 mission with the PDP was the observation of large changes in the electrostatic potential on the PDP satellite when a pulsed, high-voltage source is operated, with the magnitude of the PDP voltage variations being dependent on the high-voltage source orientation relative to the plasma flow, among other effects[Tribble et al., 1988].

V. Investigations of the Near Shuttle Environment

The plasma environment of the wake of the Space Shuttle for Spacelab 2 mission was investigated by Raitt et al.[1987]. This was an opportunity to examine the plasma structure in the wake of a very large spacecraft, after previous investigations of the wakes of small spacecraft. Raitt et al.[1987] used the Spherical Retarding Potential

Analyzer(SRPA) for ion measurements together with a Langmuir probe for electron measurements to determine plasma properties. They found that the plasma densities decrease within the deep wake much faster than the rates predicted by previous theoretical models. The densities were, for some regions, an order of magnitude or perhaps more lower than the theoretical predictions. They also found that in certain angular ranges and periods, two wake electron populations may be deduced. They concluded that one of these electron populations was the electrical filtering of the high-energy tail of the ionospheric population, while the other was from photo-electrons ejected from the payload bay surface, during certain daytime periods when that surface was illuminated by the Sun.

Large fluxes of such ions as O^+, H_2O^+ and H_3O^+ were also detected in the vicinity of the Shuttle by the quadrupole ion-neutral mass spectrometer(QINMS) on shuttle flight STS-4, the fourth flight of the Shuttle in June-July 1982[Hunton and Calo, 1985]. The energies for these ions were generally below 1.5 eV relative to the orbiter. Hunton and Calo[1985] identified the outgassing neutral flux from the Shuttle surfaces, interacting with the ambient ionosphere through ion-molecule reactions and non-reactive scattering processes, as the main sources for the observed ions. The reactions include the charge-transfer process $O^+ + H_2O \rightarrow H_2O^+ + O$, and the possible subsequent reaction $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$.

VI. Shuttle Charging Effects

Shuttle charging in association with electron beam injections was investigated with Spacelab 1 measurements by Myers et al.[1989]. Also, Watermann et al.[1988a,b] used several experiments on the Spacelab-1 mission to investigate effects such as shuttle charging during electron beam injections. During these injections, the SEPAC experiment fired electron beams of currents up to 280 mA and maximum energies of 5 keV, and the electron spectrometer 1ES019A observed electron fluxes in the energy range 0.1-12.5 keV. Watermann et al.[1988a] suggested that for beam injection intensities above 100 mA, there must be beam-plasma discharge phenomena operating, and argued that high-charging events during the electron beam injections were not supported by their observations. Further aspects of the suprathermal electron return flux seen during these Spacelab-1 experiments was discussed in Watterman et al.[1988b] and Wilhelm et al.[1984].

Banks et al.[1987] reported charging of the Shuttle during the STS-3 mission using instrumentation of the Vehicle Charging and Potential(VCAP) experiment. Charging measurements using thermal plasma probes were obtained during passive events as well as periods when a 100 mA/1 keV electron beam was emitted. Banks et al.[1987] found that during the short pulsed charging events, an upper limit of about 1 mF was obtained for the Shuttle's capacitance. For steady-state charging events the electrical potential only reached a few volts ordinarily, although during some nighttime conditions, potentials of over 40 Volts were detected.

VII. Attempted Remote Detection of Shuttle-Generated Waves

An attempt was made to detect whistler radiation possibly generated by the electron beams injected with the FPEG experiment on Shuttle flight STS-3 during the latter part of March, 1982, remotely out along the field lines threading the plasmasphere, with wave detectors on the Dynamics Explorer-1 satellite[Inan et al., 1984]. No evidence of such propagation of such radiation from the FPEG to the DE-1 satellite was seen; however, it was noted that the geometric conditions of the Shuttle were such that either the electrons emitted by FPEG struck the Shuttle main body or the possible wave propagation was otherwise blocked from reaching the DE-1 satellite.

VIII. Uses of the Space Experiments with Particle Accelerators(SEPAC) and Phenomena Induced by Charged Particle Beams(PICPAB) Experiments

Waves generated by the artificially-injected electron beams during Spacelab 1 were reported by Neubert et al.[1986], who utilized the SEPAC(Space Experiments with Particle Accelerators) experiment, which injected electrons with current levels of up to 300 mA and energies of 5 keV. Neubert et al.[1986] found that during these electron beam injections the waves in the VLF range, 0.75-10 kHz range have basically power-frequency relation that follows a power law, f^{-n}. The strongest emissions are observed when the beams are injected parallel to the magnetic field. The observed waves were interpreted as being driven by a drift wave instability. Further discussion of the waves, wave-particle interactions, and electron energization, as well as a fairly complete discussion of the SEPAC experiment, was given by Taylor et al.[1985].

An additional feature of interest from the Space Experiments with Particles Experiments(SEPAC) on Spacelab-1 was the initiation of a beam-plasma discharge by the injection of a strong electron beam into a planned release of a dense nitrogen gas plume or cloud[Sasaki et al., 1985], which also made use of the Phenomena Induced by Charged Particle Beams(PICPAB) experiment[Beghin et al., 1984]. In these experiments, a gas cloud of about 10^{23} N_2 molecules was released over a 100 ms interval, and then an electron beam of 8 kV energy, 10 or 100 milliAmps of current, was injected for periods of 20 or 40 msec. These experiments were conducted at altitudes of 245 km at night. Making use of video observations, as well as plasma-field diagnostics from Langmuir probe, and VLF/HF receivers, Sasaki et al.[1985] concluded that plasma was produced outside the beam as well as inside it, and that there was an optimum range of gas density for this outside plasma production. They found that the rate of plasma production was greater than expected from the simple beam-neutral gas ionization effects, and that there must have existed suprathermal electrons outside the beam, so as to excite the observed 3914 Angstrom light emissions. Kawashima[1988] reviewed the results of various electron beam experiments conducted with SEPAC, and discussed problems and future possibilities.

Pulsed electron beam experiments using PICPAB on Spacelab-1 showed almost immediate return electron fluxes, within 1ms of the beam injection[Torkar et al., 1988]. The electron beams had energies of 8 keV, 10-100 mA, and durations of 20-40 ms, and the electron flux measurements were for the energy range 0.1 to 12.5 keV, using the 1ES019A experiment. Although much of the return flux was found at the lower energy ranges, the return flux spectrum did extend up to the beam energy. Beghin et al.[1984] also investigated the strong wave emissions in the electron gyrofrequency and plasma frequency ranges produced by these electron beams with PICPAB, finding electromagnetic components that could be used for mode identification

Sasaki et al.[1986] and Sasaki[1988] also used the SEPAC facility to investigate the effects of injection of a high-speed plasma into the atmosphere. In this experiment, an Argon gas of about 10^{19} atoms was ionized by a chamber with discharging electrodes, creating a plasma of about 10^{19} electron-ion pairs. This plasma was then accelerated and ejected into space with a velocity in the range 18-28 km/sec. Such a fast plasma will have a large flow velocity relative to the neutral gas around the Shuttle. It was found that this surrounding neutral gas was ionized for several tens of ms after the injection. Also observed were waves in the lower hybrid frequency range. Sasaki et al.[1986] and Sakai[1988] concluded that they were observing the so-called Critical Ionization Velocity(CIV) effect, first proposed by Alfven[1954], in which it was suggested that if the energy of relative motion between a neutral gas and ions exceeded the ionization energy for this gas, it might be ionized. Papadopolous[1986] and several others have suggested that this process operates indirectly by first driving lower hybrid waves in the initial plasma which heat electrons which can then in turn further ionize the neutral gas. SEPAC was also used on the Atlas-1 mission to conduct experiments on the Critical Ionization Velocity(CIV) effect by Marshall et al.[1993], also finding evidence for CIV occurrence during high-speed plasma injections. In the Atlas-1 experiments, the plasma injection at supersonic speeds of about 20 km/s was accomplished by using the Xenon plasma contactor, hence using the gas originally proposed for the Shuttle experiments. A brief review of experiments on the production of artificial auroras and the CIV experiment with SEPAC was given by Burch et al.[1994].

Another related experiment conducted on Spacelab-1 with the SEPAC experiment was the injection of a plume of neutral nitrogen gas into space, which led to a large amount of plasma being detected by a plasma instrument[Sasaki et al., 1985]. This plasma was above the ambient plasma density level, and the amount of the plasma density was strongly influenced by the orbiter attitude. Sasaki et al.[1985] suggested that this was not a CIV effect, because the supplied orbiter/neutral velocity was too low(7.5 km/sec) compared to the relative ion-neutral speed nominally needed for CIV ionization, about 10.4 km/sec for nitrogen. Instead, Sasaki et al.[1985] considered that the enhanced neutral densities performed the role of collisionally-scattering ionospheric ions into the wake region where the measurements were taken.

Sasaki et al.[1986] investigated positive charging of the Shuttle during electron beam injections with SEPAC on the Spacelab-1 mission. The charging levels were detected by means of data from a Langmuir probe, a floating probes, an electron energy analyzer and a low-light-level TV camera. It was found that the level of charging was highly dependent upon the attitude of the Shuttle. Sasaki et al.[1986] found that whenever the beam accelerating potential exceeded 1 kV, the Shuttle's potential attained that level as well whenever the conducting portions of the orbiter lay within the thicker part of the Shuttle's wake, and stayed well below 1 kV when the orbiter was in the thinner part of the sheath.

Still another related experiment, in this case involving plasma injection to neutralize a electron-emitting Shuttle, was performed by Sasaki et al.[1987], using the SEPAC experiment on Spacelab-1. In these experiments, electron beams were injected with as much as 5 keV of beam energy and 300 mA of current. The electron beam injection of course charges the Shuttle positive. However, it was found that when a plasma of 10^{19} Argon ion-electron was subsequently injected, the potential decreased and had attained nearly zero potential by 6-20 ms following this injection. It then recovered to the initial high level of charging over a period of 10-100 ms. Sasaki et al.[1987] discussed this relatively long charging recovery time in terms of a model of cold plasma, produced in the charge exchange between neutral argon atoms and energetic argon ions during plasma injection, and then diffusion away from the orbiter.

IX. Artificial Auroras

Artificial aurora observations by high-resolution TV imaging of electron beam firings onto the upper atmosphere were conducted by Burch et al.[1993a,b], on the basis of ATLAS 1 experiments.

The Atlas-1 mission was conducted between March 24 and April 2, 1992. A brief summary of the scientific objectives of this mission is given in Torr[1993], as well as a tabular description of the experiments onboard. Although the focus of the scientific mission was toward the atmosphere, there were also significant space plasma physics experiments conducted.

Since the dawning of the Space Shuttle age, one of the space plasma experiments most discussed has been the creation of artificial auroras by means of electron beam injections fired down upon the atmosphere by electron accelerators on the Shuttle orbiter. Burch et al.[1993] described the production of artificial auroras via the SEPAC experiment which was also carried on Atlas-1. In this case, in order to neutralize the spacecraft in order to allow the beam to leave the spacecraft sheath and not be reflected back, SEPAC utilized three conducting spheres for charge collection, and a hollow-cathode Xenon plasma contactor. This permitted the injection of electron beams at high currents, of up to 1.2 Amps. It was found that without the operation of the charge collection by these spheres as well as the plasma contactor, as was the case on Spacelab 1, the Shuttle was charged to the beam potential for beam currents above 100 mA.

The auroras created by the injection of these beams toward the atmosphere below the Shuttle were imaged on Atlas-1 by Atmospheric Emissions Photograph Imaging(AEPI) instrument[Mende et al,, 1993]. The emissions were in white light images as well as in a narrow wavelength band centered around 427.8 nm, which corresponds to the first negative band of the ionized diatomic molecule, N_2^+. Owing to an extended tail in the imaged distribution distribution together with the very short lifetime of this band, it was concluded that the emissions produced were coming from both high and low altitudes below the orbiter. The peak intensity of the emissions was about 5 kiloRayleighs.

X. The Tether Mission TSS-1R

Early on, it was recognized that the use of a tether connecting a sub-satellite to the Shuttle could enable some intriguing electrodynamic and space plasma experiments, using a long conducting wire[e.g., Banks et al., 1981; Banks, 1989]. The Tethered Satellite System(TSS) was a partnership venture between NASA and the Italian Space Agency(ASI). The second flight of the TSS hardware was the TSS-1R mission, which was launched February 22, 1996 into a 300-km circular orbit with 28.5 °inclination[Stone and Bonifazi, 1998]. This mission involved the deployment of a 1.6 m diameter spherical, conducting satellite, connected by a electrically-conducting tether, the tether being insulated from the ionospheric plasma. As described by Stone and Bonifazi[1998], there were twelve science investigations, several of which were designed to explore space plasma-electrodynamic processes, particularly involved in the generation of ionospheric currents. A major source of potential in this system is the electromotive force $\phi_{emf}=\underline{v}x\underline{B}*\underline{L}$, where v is the velocity of the tether relative to the plasma, B is the geomagnetic field, and L is the displacement from the orbiter to the satellite.

One of the major surprises of the TSS-1R mission was in the current collected by the TSS versus the voltage and the ionospheric plasma parameters[Thompson et al., 1998], which exceeded those from previous theoretical expectations by factors of 2-3. It was found that the collected current varies approximately with the square root of the voltage over the range 10 to 1200 V. In these experiments, the tether current was controlled by the ASI Electron Gun Assembly(EGA)[Bonifazi et al., 1994]. The orbiter potential was measured by the Shuttle Potential and Return Electron Experiment(SPREE)[Oberhardt et al., 1994]. The fact that the currents were significantly larger than expected pointed to the need for developing new, more sophisticated models of the three-dimensional plasma behavior under such conditions.

For the TSS-1R mission, the relative energy of the ambient O^+ ions to the orbiter was 5 eV. Wright et al.[1998] investigated the behavior of ions on the front hemisphere of the TSS satellite while that satellite's potential was changed from below to above 5 Volts. The primary instrument used in this investigation was the Research on Orbital Plasma Electrodynamic(ROPE) experiment[Stone et al., 1994]. It was found that for satellite potentials < 5 V, no ions were observed on the ram side of the satellite. However, when the satellite potential was raised to be greater than 5 V, ions were seen to be flowing from the forward portion of the satellite. The reflected ions were observed to have larger temperatures than those of the ambient ionosphere.

Significant currents through a plasma such as the ionosphere can often be sources of free energy which can produce plasma instabilities and waves. Since TSS produced large currents through the ionospheric plasma, it was natural to expect plasma wave activity as a result. Iess et al.[1998] used the wave sensors of the Research on Electrodynamic Tether Effects(RETE) to measure electromagnetic wave power spectra in the frequency range 180 Hz to 12 MHz. Iess et al.[1998] examined the wave activity during three intervals in which the currents were at 50, 190 and 55 mA, which corresponded to periods of positive satellite potentials of 9, 200 and 2 V. They found that large power occurred between 2 and 4 kHz, which was close to the lower hybrid frequency, and that the electric field amplitudes were extremely large, at times up to 12 V/m. For this particular range of frequencies, the waves observed were determined to be electrostatic and circularly polarized.

Winningham et al.[1998] used the Soft Particle Electrostatic Spectrometer(SPES) onboard the TSS-1R satellite to measure charged particles with energies up to 27 keV. Since the TSS satellite developed a positive potential owing to the $\underline{v}\times\underline{B}$ Lorentz force with the tether, it was expected that ambient electrons would be accelerated to the satellite-borne detectors, and thus the measurements could be used to determine the satellite's potential, as well as the current. However, it was observed that the cold ionospheric electrons were only observed when they were accelerated to less than about 70 eV. For these cases, the accelerated energies agreed with the satellite potentials as observed by other independent techniques. However, when higher satellite potentials were observed, sometimes as high as 1.5 kV, with such other diagnostics, the expected accelerated ionospheric electrons were not observed. At the same time as these expected accelerated cold ionospheric electrons were not observed, it was found that there was a separate population of suprathermal electrons whose flux increased. Winningham et al.[1998] tentatively concluded that the accelerated ionospheric cold electrons were still present, but that the observation of them was made impossible by the dominating presence of these suprathermal electron fluxes.

These suprathermal electrons had energies typically centered around 200 eV, and their fluxes jumped by 4 orders of magnitude when the satellite potential exceeded the satellite ram energy. The origin of these suprathermal electrons was suggested to be a wave-driven acceleration of the ionospheric electrons, in which the electron-energizing waves might be the observed lower hybrid waves[Iess et al., 1998], which in turn could be driven by an ion stream-stream instability associated with the forward reflected ions seen when the satellite potential exceeds the ram energy[Wright et al., 1998], or alternatively with an electron-ion stream instability.

Magnetic fields associated with the intense currents through the tether wire system were measured by the TEMAG instrument on TSS-1R[Mariani et al., 1998]. With TEMAG, magnetic field components were observed parelle to the short satellite boom and to the spin axis, having a strong peak when the boom pointing direction was near the ram direction. Part of the explanation of the observed magnetic field signatures is in a toroidal current flowing on the ram side of the plasma sheath.

TSS-1R was apparently the first Shuttle mission to encounter strong negative Shuttle charging[Gentile et al., 1998]. These negative shuttle charging events were detected by the SPREE experiment, which measured ion spectral peaks indicative of strongly accelerated ionospheric ions into the Shuttle. These occurred when a 15 Ω and 25 k Ω resistors were arranged to connect the tether to the Shuttle ground. It was found during operations with the 15 Ω shunt that the potential changed from -17 to -245 Volts as the tether extended to 2.6 km, and that the current density detected was controlled also by the ionospheric density. Using the 25 k Ω resistor, it was found that the potential could goto -300 Volts in the nighttime ionosphere with the tether at 5.1 km, and could get to -600 Volts near the dawn terminator, with and without thruster firings.

Near the time of the tether breaking on TSS-1R, very large electric currents on the tether were detected[Gilchrist et al., 1998]. This happened with 19.7 km of the tether deployed at an electromotive force(emf) of 3482 Volts. Approximately 0.97 Amps went through the tether to the Shuttle electrical ground, which in turn maintained electrical contact with the ionosphere via its main engine surfaces. It was found that as the broken end of the tether was in the ambient ionospheric plasma, the current was enhanced to 1.1 A and stayed high for 75 seconds after the break. It was concluded that the enhancement was due to a gas-enhanced electrical discharge which must have provided an electrical emission source.

Gough et al.[1998] also used the SPREE to measure plasma responses to electron beams being emitted from the Shuttle with 1 keV energies and 100 mA currents, at magnetic pitch angles of 90 °. They measured resulting time-modulations of the electron fluxes in the MHz range which could be considered within two types. One of these was a narrow bands near the electron gyrofrequency and its harmonics, while the other was at frequences between the harmonics, and the modulation frequencies varied with electron energy. Gough et al.[1998] concluded that strong plasma interactions near the emission aperture caused large time-varying electric fields to modulate the electrons, and suggested an analogy with the electron cyclotron maser process thought to be involved in auroral kilometric radiation.

The TSS-1R tether system was also used as an electrodynamic double probe to measure vertical ionospheric electric fields[Williams et al., 1998]. These measurements were conducted in the mid to low-latitude F-region ionosphere, and were consistent with other measurements of such ionospheric electric fields in those regions, and suggested that the scales of such electric fields can be at least 20 km.

XI. Conclusions

Clearly, through the uses of various active experiments as described here, it has been possible to probe the responses of the surrounding ionospheric plasma environment to these pertubations. It has also been possible to probe the physics of the Shuttle's interaction with this environment. It has also been possible to enable experiments not ordinarily feasible by actively modifying this environment, i.e., the ionospheric hole experiments which permitted radio astronomy studies at lower frequencies.

Reliable passive studies of the space plasma environment have been much more limited to date. However, one obvious area where Shuttle-based studies should lead to advances in our understanding of the ionosphere, as well as the upper atmosphere, is in the deployment of tethered probes both upward and downward from the nominal Shuttle orbital altitude. For example, if it is possible to troll a probe below the Shuttle down toward the E-region, say 120 km or lower, we will be able to investigate a region which remains only explored by remote radars and rapidly moving rockets at this time. It would permit advanced exploration of a region where important currents flow and unique instabilities and wave-particle interactions occur. Such experiments would be very exciting future uses of the Shuttle for space plasma studies.

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Spacelab Scientific Impact: Atmospheric Science Investigations

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Executive Summary

1. The principal scientific contributions to atmospheric science from the Spacelab missions are...

- a greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone. The contribution from these investigations can be grouped into four catagories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.

- increased knowledge of the impact of human activities on the lower atmosphere. Examples include transport of pollutants (both industrial and from biomass burning) across continents and oceans. This category can also include the studies of the optical glow environment of the space shuttle, since this must be understood and corrected for in any shuttle-based remote sensing investigation.

- unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

2. The majority of investigations (6 of 10 in Table 2 below) have focused on the lower atmosphere (troposphere to mesosphere). Only 4 investigations have focused on the middle to upper atmosphere (mesosphere to thermosphere). Virtually all investigations (9 of 10 in Table 2) are spectrometers/spectrophotometers. The lone exception in Table 2 is AEPI, a two-dimensional imager. Also, some lightning surveys were conducted with television cameras.

3. Based on the number of papers published, five Spacelab missions (Spacelab-1, -3 and Atlas-1, -2, -3) have made significant contributions to atmospheric science. Two additional missions (OSTA-1, -3) have made smaller contributions. A summary of these missions and their relative contribution is given in Table 1. With the exception of Atlas-2, there is no significant difference in productivity between the Spacelab-1, -3, and Atlas missions. The lower publication rate from Atlas-2 is probably due to its being scheduled between the Atlas-1 and Atlas-3 missions with approximately one year between successive launches. It is possible that the Atlas-2 data was published in conjunction with Atlas-1 and Atlas-3 data and not properly allocated by mission in this study. (See Caveats and Methodology discussion below).

4. When individual investigations are examined a clear difference in productivity is found. The two most productive missions, both in total papers and papers per flight, are

ATMOS and ISO. Other principal missions are listed in Table 2, where the investigations are ranked by the number of published papers per shuttle flight.

The paper count for several missions includes initial calibrations and orbital intercalibrations between other instruments and missions. About 20% of the ATMOS papers and 70% of the SSBUV papers fall into this category.

Table 1. Summary of the most productive Spacelab missions in atmospheric science.

Year	Mission	Papers
1981	OSTA-1	4
1983	Spacelab-1	50
1984	OSTA-3	9
1985	Spacelab-3	49
1992	Atlas-1	37
1993	Atlas-2	14
1994	Atlas-3	36

5. Both the Spacelab-1 and Spacelab-3 missions had periods of productivity that lasted about 8 years from mission launch. (See Table 4 below.) OSTA-1, and OSTA-3 also seemed to follow this pattern, though it was not as apparent due to the lower number of publications.

Table 2. Summary of the most productive Spacelab investigations in atmospheric science.

Team	Papers	Flights	Papers/Flight
ATMOS	102	4	25.5
ISO	36	2	18
CRISTA	11	1	11
GRILLE	16	2	8
MAPS	11	2	5.5
MAHRSI	5	1	5
MAS	12	3	4
AEPI	6	2	3
SSBUV	24	8	3
ALAE	5	2	2.5

Spacelab Scientific Impact: Atmospheric Science Investigations

1.0 Introduction to study

1.1 Questions to be addressed

The question of assessing the scientific impact of the Spacelab series of shuttle missions is necessarily a subjective one. For the purposes of this discussion, we will attempt to quantify this question in terms of the impact of scientific issues addressed as well as the relative significance of individual Spacelab missions and individual investigations.

What scientific questions are addressed?

The ultimate judgement of scientific impact is not given by the number of shuttle mission flown, by the number of papers published, or even by the total number of citations to published work. Rather, the scientific impact is judged by how a single investigation or mission changed our understanding of the atmosphere. Therefore, this measure of significance is addressed below.

What is the relative significance of individual Spacelab missions?

The Spacelab missions had varying scientific goals which impacted the relative importance of each mission to studies of the atmosphere. For example, a mission devoted to life sciences or microgravity experiments would not be expected to yield much new insight into atmospheric processes. Therefore the first approach is simply to determine which missions produced the most publications related to atmospheric studies. Unfortunately this is not as straightforward as it may seem, since published papers may combine data from multiple Spacelab missions. Nevertheless, an attempt is made to assess relative importance on a mission-by-mission basis.

What is the relative significance of individual investigations?

On examination of the Spacelab atmospheric publications, we find that the total number of publications is dominated by a small number of highly productive teams that flew the same investigation on multiple shuttle flights. Therefore, the publications by instrument team are also presented.

1.2 Caveats & Methodology

Caveats

Scientific productivity, as presented here, is most easily quantified by the number of papers published and by an examination of the published studies. The author is keenly aware that failure to properly locate published material will adversely affect the conclusions of this study. Unfortunately, resources did not allow a more complete review of the publications. However, it is felt that the results presented here, while not necessarily as comprehensive as desired, are representative of the scientific productivity trying to be assessed.

Because this study is limited to Spacelab contributions only, the tables of publications listed below cannot be used to judge an investigator's total scientific productivity. Some investigators with an otherwise significant and active publication record have published few papers with Spacelab data and are listed among the less productive Spacelab investigations. This is not intended to reflect on their overall scientific contribution.

A potential bias in the results of this study is the difficulty of tracking publications of an individual researcher as compared to those of a team of researchers. An individual may work with multiple data sets from multiple missions, making it difficult to find all publications and properly associate them with single missions. A team of researchers, on the other hand, will typically be identified by an acronym that is included in paper titles and abstracts. This makes finding publications much easier. Teams also tend to maintain web sites with online listings of publications.

Resources did not allow a detailed investigation of all publications from all investigators. Mission identification was made from paper title, paper abstract, previous reviews (especially M. Torr, [1995]; see below), and review of selected papers.

Investigators often publish papers using data from multiple Spacelab missions. For the results of Table 2 of the Executive Summary, estimates of the mission data used were made from paper title, abstract, and previous reviews. In cases where multiple mission data was used each mission was credited with a publication. If it was not clear which mission data was used then no credit was given in Table 2. Consequently, the total number of papers in Tables 1 and 2 will not agree with each other or with the bibliography given for each mission.

Atmospheric Investigations Only

Only investigations and publications relating to the Earth's atmosphere are included in this study. The investigations in Table 3 were provided by Dr. Naumann as relevant investigations and were the basis of all publications searches. Where appropriate, additional investigations were added to the survey. Earth observations, e.g. radar mapping, were not included nor were studies of the Earth's radiation budget since this topic is so closely related to solar studies. Also, auroral studies that do not directly relate to atmospheric studies are omitted.

Sources: Journals & Technical Reports

The following journals and technical reports were used, in part, to identify investigators and their contributions.

Torr, M., The Spacelab scientific missions: A comprehensive bibliography of scientific publications, NASA Technical Memorandum 108487, Marshall Space Flight Center, April 1995.

Craven, P. D. Spacelab Mission 1 experiment descriptions, NASA Technical Memorandum 82537, Marshall Space Flight Center, July 1978.

Craven, P. D., and M. R. Torr, Atmospheric Laboratory for Applications and Science Mission 1, NASA Technical Memorandum 4101, Marshall Space Flight Center, October 1988.

Kaye, J. A., and T. L. Miller, The ATLAS series of shuttle missions, *Geophys. Res. Lett.*, *23*, 2285, 1996.

Torr, M. R., The scientific objectives of the ATLAS-1 shuttle mission, *Geophys. Res. Lett.*, *20*, 487, 1993.

Only publications in peer-reviewed publications are considered. Technical reports and meeting proceedings are not included in this study. Scientific impact is gauged by total number of publications and by the nature of the investigation topics.

Table 3 Principal Spacelab atmospheric science investigations

Acronym	Mission	PI	Description/Title
ALAE	SL-1, ATL-1	J. Bertaux	Investigation of Atmospheric H and D Through the Measurement of Their Lyman-a Emissions
ATMOS	OSTA-3, SL-3, ATL-1,2,3	C. Farmer, M. Gunson	Atmospheric Trace Molecule Spectroscopy - absorption profiles of molecular species in the stratosphere and mesosphere.
CRISTA	ATL-3	K. Grossman	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere - middle atmospheric IR emissions.
GRILLE	SL-1, ATL-1	M. Ackerman	Grille Spectrometer - absorption and emission profiles of molecular species in the stratosphere and mesosphere.
ISO	SL-1, ATL-1	M. Torr	Imaging Spectrometric Observatory - emission profiles of atomic and molecular, ion and neutral species in the mesosphere and thermosphere.
MAHRSI	ATL-3	R. Conway	Middle Atmosphere High Resolution Spectrometric Investigaton - middle atmosphere OH and NO UV solar fluorescence.
MAPS	OSTA-1,3	H. Reichle	Measurement of Air Pollution from Satellites
MAS	ATL-1,2,3	G. Hartmann	Millimeter-Wave Atmospheric Sounder - limb profiles of temperature, pressure, and selected molecules in the stratosphere and mesosphere.
SSBUV	ATL-1,2,3		Shuttle Solar Backscatter Ultraviolet - calibrated ozone profiles and solar UV
	OSTA-1	B. Vonnegut	"Optical Survey of Lightning"
	SL-1	M. Herse	"Waves in the OH Emissive Layer"
	SL-1	G. Dieterle	"Microwave Remote Sensing"
	OSTA-3	T. Hallinan	"Auroral Imaging Experiment"
	SL-2	G. Brueckner	"Atmospheric Physics"

Table 3 Principal Spacelab atmospheric science investigations

Acronym	Mission	PI	Description/Title
ALAE	SL-1, ATL-1	J. Bertaux	Investigation of Atmospheric H and D Through the Measurement of Their Lyman-a Emissions
ATMOS	OSTA-3, SL-3, ATL-1,2,3	C. Farmer, M. Gunson	Atmospheric Trace Molecule Spectroscopy - absorption profiles of molecular species in the stratosphere and mesosphere.
CRISTA	ATL-3	K. Grossman	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere - middle atmospheric IR emissions.
GRILLE	SL-1, ATL-1	M. Ackerman	Grille Spectrometer - absorption and emission profiles of molecular species in the stratosphere and mesosphere.
ISO	SL-1, ATL-1	M. Torr	Imaging Spectrometric Observatory - emission profiles of atomic and molecular, ion and neutral species in the mesosphere and thermosphere.
MAHRSI	ATL-3	R. Conway	Middle Atmosphere High Resolution Spectrometric Investigaton - middle atmosphere OH and NO UV solar fluorescence.
MAPS	OSTA-1,3	H. Reichle	Measurement of Air Pollution from Satellites
MAS	ATL-1,2,3	G. Hartmann	Millimeter-Wave Atmospheric Sounder - limb profiles of temperature, pressure, and selected molecules in the stratosphere and mesosphere.
SSBUV	ATL-1,2,3		Shuttle Solar Backscatter Ultraviolet - calibrated ozone profiles and solar UV
	OSTA-1	B. Vonnegut	"Optical Survey of Lightning"
	SL-1	M. Herse	"Waves in the OH Emissive Layer"
	SL-1	G. Dieterle	"Microwave Remote Sensing"
	OSTA-3	T. Hallinan	"Auroral Imaging Experiment"
	SL-2	G. Brueckner	"Atmospheric Physics"

2.0 Detailed Descriptions

2.1 Investigations

Table 3 lists the principal investigations examined for this study. Of these investigations, the more productive ones are discussed in more detail below. The investigations are ranked in the order of Table 2, i.e. by the number of published papers per mission. Where possible, instrument descriptioins and objectives have been taken from documents prepared by the investigators.

Published papers are grouped, somewhat arbitrarily, into three categories: science, technical, and general/programmatic. The general category includes descriptions of investigation objectives, of instrument design, and surveys intended for the community at large. Technical papers include details of instrument design, operation, and calibration, as well as data analysis techniques. This category also includes calibration/validation of other instruments via coincident observations. Papers not included in the general or technical are counted as science papers. The designations were made from examination of the paper title and, when available, the paper abstract.

2.2 Descriptions

Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS)

URL: http://remus.jpl.nasa.gov/atmos/atmos.html
Missions: Spacelab 3, Atlas 1, Atlas 2, Atlas 3
Investigators: M. R. Gunson, PI

Objective of experiment(s):

"The primary objective for the ATMOS experiment is to make simultaneous measurements of as many trace atmospheric constituents as possible, providing height-volume mixing ratio profiles of these gases... under all seasonal and global conditions.... [A] secondary goal was to obtain a set of reference spectra characterizing the background infrared response of the upper atmosphere" --'An overview of the relevant results from the ATMOS missions of 1985 and 1992', by M. R. Gunson and R. Zander, in NATO ASI Series 'The role of the Stratosphere in Global Change', M.-L. Chanin, ed. (Springer-Verlag 1993).

Techniques:

"ATMOS is an infrared spectrometer (a Fourier transform interferometer) that is designed to study the chemical composition of the atmosphere. Since the molecules of interest to the ATMOS investigation must be measured remotely (i.e., from outside the atmosphere itself), solar spectroscopy was the method of choice for making the measurements, using those periods during each orbit of the spacecraft when the atmosphere is between the Sun and the instrument (i. e., at sunrise and sunset as seen from the spacecraft). During sunset, for example, the tangent point of the ray path to the instrument penetrates deeper and deeper into the atmosphere until it is blocked by the surface of the Earth (or clouds); as seen from a typical shuttle orbit, the height of the tangent point changes at about 2 kilometers per second so that, to be able to distinguish changes in the composition with altitude, successive measurements of the spectrum must be made very rapidly. By analyzing the absorptions due to a given molecule in each successive spectrum, the variations in its concentration with altitude can be determined. " --http://remus.jpl.nasa.gov/atmos/instrument.html

Observations:

Absorption profiles of molecular species in the stratosphere and mesosphere.

Significance:

"Today we are aware of some 40 different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun's radiation. Some of these gases are present only as a result of our activities and are a sensitive indicator of the extent to which the environment is being perturbed. The fact that these gases have the potential for seriously changing the conditions at the surface of our planet, reinforces the realization that we can no longer view humanity and its environment as separate entities. While our primary concern in the past may well have been to protect ourselves from the environment, today we must also be concerned with protecting the environment from the detrimental effects of our own activities.

In the past decade, research into many interrelated questions about the Earth's atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability. "

--http://remus.jpl.nasa.gov/atmos/study.html

Notes:
ATMOS studied chemistry and transport of stratospheric trace gases, including ozone. Observations were made in and near both the Arctic and Antarctic polar vortices. Studies of long-term trends were performed as well as effects of atmospheric perturbations such as the eruption of Mt. Pinatubo. Many correlative and validation experiments were performed with other instruments.

Publication Summary: Total papers: 102 (82 Science, 19 Technical, 1 General/Programmatic)

<u>Imaging Spectrometric Observatory (ISO)</u>

URL: none
Missions: Spacelab 1, Atlas 1
Investigators: M. R. Torr, D. G. Torr

Objective of experiment(s):
Measure thermospheric emissions over a broad wavelength range (extreme ultraviolet to near infrared).

Techniques:
"[The instrument] is comprised of an array of five half-meter grating spectrometers which utilize two-dimensional intensified CCD array detectors to simultaneously record spectral and spatial information. Altitude is imaged in the dimension parallel to the slit when placed perpendicular to the horizon, and spectral information normal to the slit. In addition, the instrument has a front scan mirror." --Geophys. Res. Lett. 20, 515, 1993.

Observations:
Emission profiles of atomic and molecular, ion and neutral species in the mesosphere and thermosphere.

Significance:
"[ISO obtained] the first spectra of dayglow over several thousand angstroms, but it obtained these spectra as a function of altitude, providing valuable data for comparison with models of the source and sink functions. By obtaining a large number of emissions simultaneously, a diverse set of production and loss mechanisms can be tested, providing valuable multiple constraints on the theory." Geophys. Res. Lett., 20, 519, 1993.

Notes:
ISO studied the chemistry/photochemistry of the mesosphere and thermosphere. It was also used in several studies that helped quantify the initially baffling problem of identifying the source of the 'shuttle glow' that interfered with remote sensing investigations from space.

The instrument development effort for this investigation lead to new instruments, including a compact spectrometer and the Ultraviolet Imager (UVI), currently operational on the GGS POLAR spacecraft.

In the delay following the Space Shuttle Challenger accident, the ISO was used as a ground observatory from McDonald, Texas.

The ISO science and development team disbanded shortly after the Atlas 1 mission, which limited the study and dissemination of the ISO Atlas 1 data. The author was a member of the ISO science team and has recently been funded by NASA to restore the ISO Atlas-1 data and make it available to the science community. This work should be completed within two years.

Publication Summary: Total papers: 36 (27 Science, 8 Technical, 1 General/Programmatic)

CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)

URL: http://www.crista.uni-wuppertal.de/crista_index.shtml
Missions: Atlas 3
Investigators: D. Offermann, K. Grossmann

Objective of experiment(s):
"Prime CRISTA science objective is the study of small scale dynamical structures seen in the global trace gas distributions. The data are also used to test 3-D chemical-dynamical model predictions."
--http://www.crista.uni-wuppertal.de/crista_index.shtml

Techniques:
"CRISTA... is a limb scanning satellite experiment, designed and developed by the University of Wuppertal to measure infrared emissions of the Earth's atmosphere. Equipped with three telescopes and four spectrometers and cooled with liquid helium, CRISTA acquires global maps of temperature and atmospheric trace gases with very high horizontal and vertical resolution. The design enables the observation of small scale dynamical structures in the 15-150 km altitude region.

CRISTA is mounted on the free flying ASTRO-SPAS satellite by Daimler-Benz Aerospace which is named then CRISTA-SPAS, together with MAHRSI, an ultraviolet spectrograph from Naval Research Laboratory in Washington, DC. The CRISTA-SPAS platform is launched with the U.S. Space Shuttle. In orbit it is released from the cargo bay by the manipulater arm and retrieved at the end of the mission."

--http://www.crista.uni-wuppertal.de/crista_index.shtml

Observations:
Global maps of temperature and trace gases in the stratosphere and mesosphere.

Significance:
"CRISTA-SPAS has now successfully completed two missions: CRISTA 1 was launched on November 3, 1994 with STS-66 Atlantis. Atmospheric measurements were obtained in the free flying phase from November 4-12, 1994, travelling 50-100 km behind the shuttle. On November 12 the satellite was retrieved and two days later returned to Earth. The STS-66 payload also included the SSBUV experiment and the ATLAS-3 instrument package. CRISTA 2 was launched on August 7, 1997 with STS-85 Discovery. Atmospheric measurements were made between August 8, 05:21 UT and August 16, 09:30 UT. The Space Shuttle landed on August 19, 11:08 UT at NASA Kennedy Space Center, Florida.

The CRISTA/MAHRSI Campaign encompasses the mission and complements it with ground truth and other coordinated measurements including monitoring of the atmospheric background by ground based, aircraft, balloon, rocket and satellite experiments. The first campaign took place from October 27 - November 25, 1994 and included over 32 rockets, 56 balloons, and ground based experiments at 42 locations. The second CRISTA/MAHRSI Campaign was from July 31 until August 30, 1997. "

--http://www.crista.uni-wuppertal.de/crista_index.shtml

Notes:
Like ATMOS, CRISTA monitors trace gases and ozone, but it has the capability of extending its observations from the mesosphere into the lower thermosphere. Note that CRISTA is a part of a free-flying satellite that is launched and then retrieved by the Shuttle. CRISTA is one of the most recent investigations.

Publication Summary: Total papers: 11 (8 Science, 1 Technical, 2 General/Programmatic)

GRILLE Spectrometer

URL: none
Missions: Spacelab 1, Atlas 1
Investigators: M. Ackerman

Objective of experiment(s):
Study on a global scale atmospheric parameters between 15 and 150 km altitude.

Techniques:
Infrared absorption spectrometry during sunrise or sunset periods, with the sun as the source of light

Observations:
Absorption and emission profiles of molecules in the stratosphere and mesosphere.

Significance:

Notes:
GRILLE was also capable of emission spectrometry, but this observing mode was canceled on Atlas-1 and possibly on Spacelab 1, as well.

Publication Summary: Total papers: 16 (8 Science, 7 Technical, 1 General/Programmatic)

Measurement of Air Pollution from Satellites (MAPS)

URL: http://stormy.larc.nasa.gov/overview.html
Missions: OSTA 1, OSTA 3, Earth-Observing Space Shuttle mission (1994)
Investigators: H. G. Reichle, Jr., V. Conners

Objective of experiment(s):
The MAPS experiment measures the global distribution of carbon monoxide (CO) mixing ratios in the free troposphere.

Techniques:
"The MAPS instrument is based on a technique called gas filter radiometry. Thermal energy from the Earth passes through the atmosphere and enters the viewport of the downlooking MAPS instrument. Carbon monoxide and nitrous oxide (N2O) in the atmosphere produce unique absorption lines in the transmitted energy. The energy which enters the MAPS instrument is split into three beams. One beam passes through a cell containing CO and falls onto a detector. This CO gas cell acts as a filter for the effects of CO present in the middle troposphere. A second beam falls directly onto a detector without passing through any gas filter. The difference in the voltage of the signals from these two detectors can be used to determine the amount of CO present in the atmosphere at an altitude of 7-8 km.

A third beam of the incident energy passes through a cell containing N2O and falls onto a detector. This N2O gas cell acts as a filter for the effects of N2O present in the atmosphere. The global distribution of N2O is well known, so the N2O signal can be used to detect the presence of clouds in the field of view and to correct the simultaneous CO measurement for systematic errors in the data. "

--http://stormy.larc.nasa.gov/overview.html

Observations:
Distribution of middle tropospheric carbon monoxide.

Significance:
"Because of MAPS' previous flights on board the Space Shuttle, Earth system scientists now know that carbon monoxide concentrations in the troposphere are highly variable around the planet, and that widespread burning in the South American Amazon Basin and southern cerrados, the African savannahs, and the Australian grasslands and ranches are major sources of carbon monoxide in the southern hemisphere and tropical troposphere."

--http://stormy.larc.nasa.gov/overview.html

Notes:
Of all the investigations surveyed here, MAPS most closely monitors the results of human activity via industrial and biomass pollutants.

Publication Summary: Total papers: 11 (8 Science, 2 Technical, 1 General/Programmatic)

MAHRSI

URL: http://uap-www.nrl.navy.mil/mahrsi/mahrsi.html
Missions: Atlas 3
Investigators: R. R. Conway, PI

Objective of experiment(s):
MAHRSI's primary objective is to measure limb intensity profiles of the resonance fluorescent scattering of sunlight by hydroxyl (OH) in the altitude region from 38 to 90 km, and by Nitric Oxide (NO) in the region from 48 to 160 km.

Techniques:
MAHRSI is a high spectral resolution (0.018 nm) imaging spectrometer sensitive in the wavelength region from 190 nm to 320 nm.

Observations:
"From these intensity profiles, global vertical density profiles of OH and NO with a vertical resolution of 2 km and a downtrack resolution of 8 - 12 degrees are inferred. By measuring Rayleigh scattering intensity profiles, the experiment also provides precise knowledge of the neutral density and temperature in the mesosphere"

--http://uap-www.nrl.navy.mil/mahrsi/mahrsi.html

Significance:.
"MAHRSI was designed and developed by the Upper Atmospheric Physics Branch UAP, within the Space Science Division of the U.S. Naval Research Laboratory (NRL). MAHRSI flew in November 1994 on the German Space Agency's Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere/Shuttle Pallet Atmosphere Satellite (CRISTA/SPAS), as part of NASA's flight of the Atmospheric Laboratory for Applications and Science ATLAS-3. The CRISTA/SPAS satellite was deployed from the Space Shuttle Atlantis STS-66 on November 4, 1994 for 8 days of free flight. During these 8 days the MAHRSI instrument observed latitudes from 53° S to 63° N, and acquired 80 orbits of OH profiles, composing nearly 5 global maps, and 24 orbits of NO profiles. MAHRSI flew again successfully on Space Shuttle Discovery STS-85 in August of 1997."

--http://uap-www.nrl.navy.mil/mahrsi/mahrsi.html

Notes:

Publication Summary: Total papers: 5 (4 Science, 0 Technical, 1 General/Programmatic)

Millimeter-wave Atmospheric Sounder (MAS)

URL: http://www.informatik.uni-bremen.de/~gunnar/?
Missions: Atlas 1, Atlas 2, Atlas 3
Investigators: G. Hartmann

Objective of experiment(s):
Measure emissions from six mm-wave transitions of four molecular species: O3, H2O, ClO, and O2.

Techniques:
MAS is a shuttle-based, limb-scanning spectrometer. From these measurements are deduced abundance profiles and temperature.

Observations:
Limb profiles of temperature, pressure, and selected molecules in the stratosphere and mesosphere

Significance:

Notes:

Publication Summary: Total papers: 12 (9 Science, 2 Technical, 1 General/Programmatic)

Atmospheric Emissions Photometric Imager (AEPI)

URL none
Missions: Spacelab 1, Atlas 1
Investigators: S. Mende

Objective of experiment(s):
To provide two-dimensional imaging in support of magnetospheric electron bounce experiments by the SEPAC investigation and to study natural auroras.

Techniques:
Dual channel UV/visible video with filter wheels mounted on two-axis gimbal for pointing.

Observations:
Observed E and F region Mg+, lower thermospheric $O(^1S)$ and O_2 airglow, and topside images of gravity waves in airglow

Significance:

Notes:
AEPI was able to conduct only limited observations (~4 hours on Spacelab 1) and was viewed primarily as a companion to SEPAC, a space plasma investigation. Consequently, it's contribution to atmospheric science was limited. At least two papers on auroral imaging not included in this survey.

AEPI is the only non-spectrometric instrument included in this survey.

Publication Summary: Total papers: 6 (4 Science, 0 Technical, 2 General/Programmatic)

Shuttle Solar Backscatter Ultraviolet (SSBUV)

URL http://ssbuv.gsfc.nasa.gov/
Missions: STS-32, -41, -43, -72, Atlas 1, Atlas 2, Atlas 3, USMP-2
Investigators: E. Hilsenrath, PI

Objective of experiment(s):
"The primary objective of the [Atlas 1] SSBUV instrument was to transfer accurate absolute calibrations to the SBUV/2 instrument on the NOAA operational satellite used for global ozone measurement." --Geophys. Res. Lett., 20, 487, 1993.

"SSBUV supports the long-term global stratospheric ozone and solar UV monitoring programs by providing repeated checks on the calibrations of UV ozone and solar monitoring instruments flying on US and international satellites." --Geophys. Res. Lett, 23, 2289, 1996.

Techniques:
"The theoretical basis for backscattered ultraviolet (buv) measurements of stratospheric ozone was developed in the late 1960's, and buv-type instruments have made regular observations from satellites since 1970. The basic instrument design is a nadir-viewing Ebert-Fastie spectrometer, which measures the terrestrial radiance at 12 discrete channels between 250-340 nm with ~1.1 nm resolution. These instruments are flown in Sun-synchronous orbits, so that a diffuser plate can be deployed as the satellite crosses the terminator in order to make solar irradiance measurements at the same wavelengths that are used to measure the backscattered terrestrial radiance. The spectral albedo of the Earth, derived from the ratio of these two measurements, is then inverted to calculate the total column amount of ozone and the distribution of ozone with altitude in the stratosphere."

--http://ssbuv.gsfc.nasa.gov/

Observations:
Calibrated ozone profiles and solar UV from 180 to 405 nm

Significance:
"SSBUV's value lies in its ability to provide highly accurate ozone measurements. The instrument is calibrated to a laboratory standard before flight, then is recalibrated during and after flight to ensure its accuracy. These laboratory standards are calibrated routinely at the National Institute of Standards and Technology. The rigorous calibration has been maintained since the beginning of the SSBUV flight series.

SSBUV's impact on NASA's ability to detect ozone trends accurately was realized after approximately four flights. Data from the first flight with an earlier satellite already have been used to estimate ozone trends in the upper stratosphere since 1980. These results show a depletion of about 8 percent over 10 years, which is consistent with predictions of ozone depletion.

SSBUV has achieved one of it's primary objectives using data from the first three flights, flown in 1989, 1990 and 1991. These data have been used to update the calibration of the NOAA-11 SBUV/2 ozone instrument which has been in orbit since late 1988. The NOAA ozone data have been reprocessed with a refined algorithm and new calibration factors based on SSBUV and SBUV/2 in- flight calibration data, which were provided by NASA. The latest reprocessing covers the period 1989 to 1995. The reprocessed data have been checked against ground-based ozone observations, and these comparisons show very good agreement. There is also now excellent consistency between the refined NOAA-11 SBUV/2 data and the Nimbus-7 SBUV/TOMS data set, which goes back to

1978. The combined 15-year data set represents an excellent resource for ozone climate and trend studies.

SSBUV detected and verified a significant decrease in the amounts of total Northern Hemisphere between the STS-45/ATLAS-1 (March 1992) and STS-56/ ATLAS-2 (March 1993) missions. This depletion also was detected simultaneously by satellites and ground-based observations. Indications are that total ozone decreased during the same period on the order of 10 to 15 percent at mid- latitudes in the Northern Hemisphere. Scientists believe that this significant depletion resulted from the combined residual effects of Mt. Pinatubo aerosols in the stratosphere and cold stratosphere temperatures during the winter of 1992/ 93. "

--http://ssbuv.gsfc.nasa.gov/

Notes:

Publication Summary: Total papers: 24 (8 Science, 16 Technical, 0 General/Programmatic)

Atmospheric Lyman Alpha Emissions (ALAE)

URL
Missions: Spacelab 1, Atlas 1
Investigators: J. Bertaux

Objective of experiment(s):
To study various sources of Lyman-alpha emission in the atmosphere.

Techniques:
The instrument is a spectrophotometer with two absorption cells, one filled with hydrogen, the other with deuterium. Either cell, when in use, absorbs the associated radiation. By modulating the cells the absolute intensity of the deuterium emissions can be determined.

Observations:
Spacelab 1: Lyman alpha deuterium emission was observed for the first time along long slant path distances on the limb. Nadir viewing was not possible due to the limited sensitivity of the detector.

Atlas 1: Nadir emission detected from the mesosphere.

Significance:
"...measuring the nadir Lyman a emission of deuterium atoms offers a new possibility to sound the chemically very active region where H2O (and HDO) is photodissociated, the D atoms servings as the most appropriate proxy to the H atoms which cannot be observed themselves directly." Geophys. Res. Lett. 20, 507, 1993.

Notes:
Bertaux published several (non atmospheric) papers on interplanetary Lyman alpha and solar physics (with the Prognoz instrument), but no more on atmospheric studies with the ALAE instrument.

Publication Summary: Total papers: 5 (5 Science, 0 Technical, 0 General/Programmatic)

3.0 Science Impact

3.1 Summary of Scientific Contributions

The nature of atmospheric science contributions from Spacelab missions can be placed in context with a quote from the ATMOS team:

> "Today we are aware of some 40 different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun's radiation.... In the past decade, research into many interrelated questions about the Earth's atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability. " --http://remus.jpl.nasa.gov/atmos/study.html

This need for additional studies and global measurements has been at the core of the investigations surveyed here. The contribution from these investigations can be grouped into four catagories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.

Observational 'Firsts'

The number of observational 'firsts' that have been accomplished during the Spacelab missions is staggering and every investigation can rightly cite examples from their work. A few examples (not comprehensive) can be listed. They include the observations of vertical profiles of stratospheric trace gases not previously measured, including N_2O_5, $ClONO_2$, HO_2NO_2, CH_3Cl, COF_2, and SF_6 by ATMOS. In the thermosphere, ISO obtained the first spacebased measurement of ground state OH in the mesosphere, the first dayglow altitude profiles of $N(^2P)$ at 346.6 nm (which provided the first examination of photochemical sources and sinks in normal daytime thermosphere uncontaminated by auroral emissions), and the first simultaneously acquired altitude images of NO gamma band temperature and intensity in the thermosphere. In addition to observing new emissions, old emissions were examined in new ways as well. For example, MAS performed the first measurements of latitudinal variation of mesospheric nighttime O_3 and H_20, an accomplishment that is also an example of the next class of observations: observations conducted on an extended scale.

Extended Observations

Investigations that were included in multiple missions had the opportunity to make observations over extended geographical ranges or to monitor temporal trends between missions. ATMOS, with 4 missions, for example, made observations throughout the tropics and mid-latitudes, in both hemispheres and over two seasons, and both inside and outside the Arctic and Antarctic polar vortices. Between missions ATMOS was able to study trends in trace gases between 1985 and 1994 as well as the effects of stratospheric aerosol injection from the Mt. Pinatubo eruption in 1991. Similarly, SSBUV reported a 12% ozone decrease between successive flights in 1992 and 1993.

MAPS made observations of biomass burning to demonstrate that forest burning in remote locations can contribute to enhanced CO and O_3 levels that can be transported large distances from the burn sites. As noted above, MAS produced latitudinal maps of O_3 and H_20, as well as ClO. CRISTA similarly obtained high resolution global maps of temperature and atmospheric trace gases. AEPI also provide observations of gravity waves, not by building up data, but by two-dimensional imaging of the airglow emissions.

Detailed Observations

With the exception of AEPI, every investigation surveyed here employs some type of spectrometer to return spectral information about the atmosphere. (MAPS and ALAE use spectrophotometers, which can be viewed as a limited form of spectrometer.) This emphasis on spectral information is significant and underscores the high information content available from spectral observations. Such observations provide multiple simultaneous constraints on atmospheric models.

Correlative Studies

A significant component of all the Spacelab missions was the large number of correlative studies based on simultaneous observations from multiple observing platforms. A brief survey of the papers listed in the appendix lists the following illustrative studies: ATMOS/MAS, ATMOS/UARS, ATMOS/ER-2 aircraft, ATMOS/MAS/ SSBUV, MAS/UARS, MAS/MLS, MAPS/TOMS. Studies such as these enable examination of different aspects of common atmospheric features, as well as calibration/validation of observations. This latter accomplishment is especially important, in view of the low level, long term changes that are often the subject of quantitative study.

3.2 Scientific Publications

Table 4 lists the number of publications from selected Spacelab missions from 1980 through 1997. Missions with no significant publication history are not included in the table. Boxes indicate mission launch, before which publications are not generally expected. The only exception to this would be publications detailing instrument development or general papers describing a mission or investigation.

The publications for each mission are divided into three categories, labeled at the bottom of the table as 'T', 'S', and 'G', representing papers devoted to instrument development, observing, or analysis techniques (T), scientific papers (S), and programmatic or review papers (G).

Beginning in 1995, it becomes increasingly difficult to associate publications with single missions, as studies combined data from multiple investigations and missions. Best estimates were made as described in Section 1.2 above.

Table 5 lists publications by investigation. The nomenclature used is the same as that in Table 4, with publications identified with the labels 'T', 'S', and 'G'. Shuttle missions are noted with a border and principal Spacelab missions are noted at the top of the table.

3.3 Scientific Citations

A classic method of measuring scientific productivity is by measuring the total number of citations to an investigation's work, rather than the total number of publications. This has the advantage of allowing the scientific community assess the importance of the work being done and is not easily skewed by publication choices made by the investigation team. To be of most use, however, a citation search must guard against bias from such sources as self-citation by authors or participants in correlative studies. Also, citation sources are best used to measure the impact of a single study or publication by a single author. Unfortunately, the nature of the investigations surveyed here make an meaningful citation source difficult.

The first difficulty is the total number of papers to be surveyed. The ATMOS, ISO, and SSBUV teams produced 159 publications included in this survey, none of which can easily be labeled as a seminal paper that would be a potential target for a citation search. The second difficulty is the number of potential authors. The most productive investigations were conducted by teams of scientists. For teams like ATMOS, that were active for long periods, the team composition changed with time. Finally, the caveats discussed above about the dangers of missing publications are greatly amplified in a citation search under these conditions.

For these reasons, it was decided that current resources did not permit a comprehensive citation search to be performed.

Table 4. Atmospheric science publications by Spacelab mission. Data is taken from the publications in the Appendix for which a mission is known.

	AT1			AT2			AT3			SL1			SL3			OSTA1			OSTA-3		
1980																					
1981																					
1982										5							1				
1983										2	1	1				1					
1984										3	6	2							1	1	
1985										3	7			1							
1986										2	4			5						2	
1987											3		1	6							
1988											3		1	2			1			1	
1989											2			6			1				
1990										1	2			6						2	
1991											1		3	7						1	
1992		1	2								1			4					1		
1993		11												1							
1994	1	5		1	1																
1995		2							1		1										
1996	1	11	1	1	10	1		24	2					5	1						
1997		2					1	8													
TOTAL	**2**	**32**	**3**	**2**	**11**	**1**	**1**	**32**	**3**	**16**	**31**	**3**	**5**	**43**	**1**	**1**	**3**	**0**	**2**	**7**	**0**
	T	S	G	T	S	G	T	S	G	T	S	G	T	S	G	T	S	G	T	S	G
		37			**14**			**36**			**50**			**49**			**4**			**9**	

4.0 Conclusions

So we now return to the central questions this study was designed to answer. What has been the impact of the Spacelab shuttle missions on atmospheric science? How do we view the atmosphere differently now in light of the Spacelab missions? What conclusions, if any, can we draw about the relative success of the different missions and investigations?

When viewed as a whole, we can see that the Spacelab missions and their associated investigations studied virtually the entire atmosphere, from the troposphere near the Earth's surface to the thermosphere in which the space shuttle orbited. These observations included mesospheric studies which are very difficult to conduct from the ground and for which, consequently, there is a general dearth of data and concomitant understanding. This does not mean that the entire atmospheric range was covered in equal detail. In fact, the stratospheric regions received by far the most attention while the thermospheric regions received much less. It is in the stratosphere, of course, that the Earth's ozone layer resides, along with all its attendant questions about its impact on human activities, and vice versa. These questions were addressed by focusing on the details, studying the chemistry and transport of over 40 trace gases previously unstudied, or studied only in a cursory fashion. These were quantitative studies which required careful calibrations of the sensors and assurance that the rigors of spaceflight did not seriously degrade those same sensors. This assurance was obtained by correlative studies involving simultaneous observations from the ground, aircraft, and other spacebased detectors. A large percentage of the papers published during this period fall into this category which underscores the importance the atmospheric community places on correlative studies. This emphasis is necessary because the climatological effects examined are quite small.

The study of the troposphere and stratosphere is intimately linked with human activities, and several studies focused on the detection of and monitoring of transport of atmospheric pollutants on a global scale. We now know, for example, that widespread burning of grasslands and forests in South America, Africa, and Australia are major sources of carbon monoxide and ozone in the southern hemisphere, observed to travel between continents and across oceans. Spacelab investigations also tracked the spread of industrial pollutants between continents as well, underscoring the global nature of these problems.

Do we now view the atmosphere in a fundamentally, or revolutionarily different manner because of the Spacelab investigations? In the large picture, probably not much. But in the details, undoubtedly so. Atmospheric models, and our understanding, are now constrained to match a new wealth of observations. This is the principal contribution of the Spacelab atmospheric investigations.

Which of the missions was most important?

This is a question that is dependent on many variables and is only addressed obliquely here, because of the caveats cited above about the publication searches associated with this survey. What can be said without hesitation is that most of the contributions to atmospheric science came from five missions: Spacelab 1, Spacelab 3, and the three Atlas missions. To a lesser extent, the OSTA1 and OSTA3 missions also made significant contributions. Spacelab 1 and 3 produced more total papers than did the Atlas missions, but they flew earlier and have had more time for publications. Both of these missions had a period of productivity that lasted roughly eight years. The first Atlas mission flew seven years before this date of this report. This survey reports that Atlas 2 had about half the publications of the other Atlas missions but, as discussed above, this is probably a shortcoming of the survey methodology.

Which of the investigations was most important?

This is a question the author is manifestly unwilling to address, due to the dangers of an incomplete literature search compounded by the fact that the author is experienced in thermospheric studies while the emphasis on tropospheric and stratospheric studies in the Spacelab era has already been noted. Despite this reluctance, a number of conclusions can be made. First of all, the ATMOS team is clearly in a class by itself. No other investigation comes close to matching their total number of papers or the number of papers per mission. It is highly unlikely that a more comprehensive literature search would change this fact. ISO and SSBUV represent a 'second tier' of productivity, after ATMOS, when total number of papers are considered. If the criterion is switched to number of papers per flight, then the second tier is composed of ISO and CRISTA. It is interesting to speculate on what the ISO publication level would have been had the instrument team not disbanded, or what effect the upcoming rerelease of the instrument data to the science community will have. While the status of these first and second tier investigations would probably be unchanged by a more comprehensive literature search, that is clearly not the case for the remainder of the investigations. Take, for example, the investigation entitled "Optical Survey of Lightning" on Spacelab 1 by B. Vonnegut. Only three publications are cited in Table 5, a considerably low value. The literature search, however, turned up multiple references to lightning studies by Vonnegut but only three of them using the Spacelab data. It appears that the Spacelab 1 flight served as a prototype development for instruments that have found wide use on non-Spacelab missions. Once again the caveats of relative comparisons based on this survey must be emphasized.

In summary, the principal scientific contributions to atmospheric science from the Spacelab missions are...

- a greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone. The contribution from these investigations can be grouped into four catagories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.
- increased knowledge of the impact of human activities on the lower atmosphere. Examples include transport of pollutants (both industrial and from biomass burning) across continents and oceans. This category can also include the studies of the optical glow environment of the space shuttle, since this must be understood and corrected for in any shuttle-based remote sensing investigation.
- unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

Table 5. Atmospheric science publications by investigation

OST1		SL1	OST3	SL3							AT1	AT2	AT3									
81	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**Total**		**Altitude**	**Notes**		
				S(1)	S(5)	T(1) S(6)	T(1) S(2)	S(6)	S(6)	T(3) S(8)	S(5)	S(3)	T(1) S(7)	S(6)	T(13) S(25) G(1)		T(19) S(80) G(1)	**100**	20-80		ATMOS	JPL
							T(1)	T(1)	T(2)	T(1)	S(1)	T(2)	T(1) S(1)	S(2)	T(4) S(3)	T(2) S(1)	T(15) S(8)	**23**	20-100	1	SSBUV	
														G(1)	S(2) G(1)	T(1) S(6)	T(1) S(8) G(1)	**11**	15-180		CRISTA	K. Grossman
											G(1)	T(1) S(1)		T(1)	S(8)		T(2) S(9) G(1)	**12**	20-90		MAS	G. Hartmann
	S(1)	T(1)			S(2)		S(1)	S(1)	S(2)	S(1) G(1)	T(1)						T(2) S(8) G(1)	**11**		2	MAPS	H. Reichle
	T(2)	T(1)	T(2)	T(1) S(2)	T(1)	S(2)	S(1)		S(1)		G(1)	S(1)					T(7) S(7) G(1)	**15**	20-140		GRILLE	M. Ackerman
														G91)	S(2)	S(2)	S(4) G(1)	**5**	40-145		MAHRSI	R. Conway
	T(3)	T(1)	S(2) G(1)	T(2) S(4)	T(1) S(2)	S(3)	S(2)		T(1) S(1)	S(1)	S(1)	S(6)	S(3)	S(2)			T(8) S(27) G(1)	**36**	>60		ISO	M. Torr
		S(1) G(1)	G(1)	S(1)				S(1)					S(1)				S(4) G(2)	**6**	>80		AEPI	S. Mende
			S(3)					S(1)				S(1)					S(5)	**5**	>80		ALAE	J. Bertaux
			T(1) S(1)														T(1) S(1)	**2**			Waves in the OH Emissive Layer	M. Herse
											S(2)			S(1)			S(3)	**3**			Optical Survey of Lightning	B. Vonnegut
													S(1)				S(1)	**1**			Auroral Imaging Experiment	T. Hallinan

NOTES: 1 SSBUV flew twice in 1994
2 MAPS flew in 1994, but not on AT3

Spacelab Scientific Impact: Atmospheric Science Investigations

Appendix: Bibliographies

Before each reference below, a code is inserted in square brackets stating the paper type (S: Science, T: Technical, G: General/survey/programmatic) and mission (Spacelab 1,3: SL1, SL3; Atlas 1,2,3: AT1, AT2, AT3) assigned to each paper. If the mission is not known, no mission code is provided.

This bibliography was compiled from a number of sources, included web downloads and scanned documents. This accounts for differences in format and possible typographic errors. The references are ordered as in Table 2 of the report, which sorts investigations by the number of papers per mission.

ATMOS

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Evaluation of Results of SIR-C/X-SAR Missions (STS 59 and STS 68) for Earth Science Applications

S4-42

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Introduction

The dual Spaceborne Imaging Radar-C (SIR-C)/X-band Synthetic Aperture Radar (X-SAR) was flown aboard the Shuttle Endeavour during the April and October 1994 missions (STS 59 and STS 68). The SIR-C system records data at both L (23.5 cm) and C (5.8 cm) wavelengths (1.25 GHz and 5.3 GHz frequencies, respectively) with full polarimetric scattering; while the X-SAR is capable of recording data in the X-band (3.1 cm, 10 GHz) with copolar polarization only (Kasischke, *et al.*, 1997). The integrated system records data simultaneously at incidence angles ranging from 15-60° with image resolution varying from 10 to 50 m depending on system configuration (Evans, *et al.*, 1997). The SIR-C/X-SAR is the most advanced airborne imaging radar system ever flown in earth orbit in comparison to satellite mounted instruments such as the European Remote Sensing Satellites (ERS-1,2), the Japanese Remote Sensing Satellite (JERS-1) or the Canadian RADARSAT. Current satellite systems are limited in number of channels, polarization, incidence angle and spatial resolution. For example, the ERS-1, launched in 1991 records data in the C-band, copolar (VV) configuration only with a spatial resolution of 50 km and an incidence angle of 23°, while the JERS-1 records observations in the L-band copolar (HH) configuration at an incidence angle of 35° and a spatial resolution of 80 km. In contrast, the SIR-C/X-SAR is capable of numerous combinations of frequency/polarization configurations over a range of incidence angles and thus can produce enhanced images for a wide variety of earth science applications.

The impact within the remote sensing and earth science communities of the two SIR-C/X-SAR missions was demonstrated early on by the large number of sessions and papers devoted to the subject at the 1995 International Geoscience and Remote Sensing Symposium (IGARSS'95) sponsored by IEEE. Significant interest carried over to the subsequent IGARR Symposia in 1996, 1997 and 1998 as well. Subsequently, three major journals within the earth science and remote sensing communities devoted special issues to presentation of the results of the missions. These issues were *IEEE Transactions on Geoscience and Remote Sensing*, 33(4), 1995; *Journal of Geophysical Research*, 101(E10), 1996; and *Remote Sensing of Environment*, 59(2), 1997. In addition, most of the investigators associated with the missions have published significant articles in journals within their specific disciplines and dozens of other scientists not directly associated with the original missions have incorporated the data into their research and continue to publish results (see bibliographic listing).

Following the flights of the SIR-C/X-SAR in 1994, NASA requested the Space Studies Board of the National Research Council (NRC) to evaluate the utility of a third SIR-C/X-SAR mission and to provide guidance in developing a strategy for a space-based, science-oriented interferometric small SAR. The NRC report has been summarized by

Kasischke, *et al.* (1997). As a result of this report, and the apparent success of the SIR-C/X-SAR missions, NASA has issued a call for proposals for investigators to participate in mission planning and design of the Lightweight Synthetic Aperture Radar (Lightsar) to be launched in 2001 or 2002. Lightsar will be a low orbiting imaging radar satellite operating in the L-band with full polarimetric scattering, and possibly in C- or X- band as well. Thus, the parametric design standards and mission goals of Lightsar builds directly on the results of the SIR-C/X-SAR investigations (Schmullius and Evans, 1997).

The earth science applications associated with SIR-C/X-SAR data can be grouped into six broad categories: 1) Oceanography (including wave observations); 2) Ecology (forestry, agriculture, wetlands); 3) hydrology; 4) geology and geomorphology (including volcanology); 5) precipitation and climate (including glaciology); and 6) surface mapping and topography. Some studies (and investigators) may combine elements of two or more categories. In the following sections, the contributions made in each of these areas by the investigators associated with these missions will be discussed in detail.

Oceanography

The oceanographic studies associated with the SIR-C/X-SAR missions consisted of investigations of the capability of the system to measure important wave properties such as significant wave height (SWH), wave number and propagation direction; and to observe surface frontal boundaries separating cold and warm water masses (Monaldo and Beal, 1995a; Keyte, *et al.*, 1995; Flament, 1995). An on-board processor developed at Johns Hopkins University produced real time images of ocean wave spectra from the C-band signal (Monaldo and Beal, 1995a). A primary goal of the wave study was to incorporate these real time observations into a numerical wave model in order to correct and update model predictions in real time (Monaldo and Beal, 1995a,1995b; Monaldo, 1996). Radar observations were also compared to surface measurements provided by buoy observations (Keyte, *et al.*, 1995). Another important goal of this study was to compare the C-band images from the SIR-C radar to those from the ERS-1 in order to development relationships for Doppler smearing that might be employed in future analysis of ERS-1 images (Plaut, *et al.*, 1995). Frequency-polarization combinations were also studied in order to determine optimal configurations for future satellite systems (Keyte, *et al.*, 1995).

The results of these studies appear to be promising in some cases. The wave properties obtained from the radar data agreed fairly closely with predictions from the model and with the buoy measurements (Monaldo and Beal, 1995a; Monaldo, 1996; Keyte, *et al.*, 1995). The raw radar-estimated times agreed to +/- 3 hours to model predicted times while location agreed to +/- 2° lat/long. These estimates were further corrected using polynomial interpolation of SAR values. Correlation between radar-derived wave direction and model predicted direction was 0.74, with the largest mean difference of -1° (Monaldo, 1996). The on-board processor made these data available in real time and they were successfully incorporated into the wave forecasting model. However, in terms of longer range benefits, the results were not as favorable. Comparison with satellite images revealed that the currently available satellite data could probably not be sufficiently corrected with the airborne data (Plaut, *et al.*, 1995), and it was found that the dependence of wave images on radar frequency-polarization configurations is probably too subtle to finalize development of satellite configurations at this time (Keyte, *et al.*, 1995). The principal development of the wave studies appears to be the conclusion that low orbit radar data can sufficiently distinguish important wave properties in real time such that they can be used to improve numerical wave forecast models (Monaldo and Beal, 1995b). Improved wave forecasting would be very valuable in many instances, including severe weather situations such as hurricanes, or in cases of waves generated by tsunamis.

Another result of the ocean studies was that frontal boundaries were identified on the SAR images during the October flight and that these boundaries closely agreed with field observations and data obtained from conventional thermal and infrared satellite sources (Flament, 1995). Boundary movement was also successfully observed by using images from successive shuttle overpasses (Flament, 1995). Frontal boundary location and movement can have important consequences in terms of weather occurrence and fisheries productivity as well as on water quality issues such as hypoxia and algal blooms. However, the advantages of observing frontal characteristics from microwave radar measurements in lieu of currently available thermal and infrared instruments is unclear.

Ecological Investigations

The ecological studies associated with the SIR-C/X-SAR missions can be grouped into three categories: forestry, wetlands, and forest/nonforest land use classification. The forestry studies consisted primarily of classification and mapping forest spatial structure (Sun and Ranson, 1995; Ranson and Sun, 1997; Keil, *et al.*, 1995; Souyris, *et al.*, 1996; Ranson, 1998), classification of growth stages (Yanasse, *et al.*, 1995; Soares, *et al.*, 1997) and above ground biomass estimation (Souyris, *et al.*, 1995; Ranson and Sun, 1997; Ranson, 1997; Dobson, *et al.*, 1995a, Dobson, *et al.*, 1995b). Forestry studies were focused on both northern latitude hardwoods in Michigan (Dobson, *et al.*, 1995), Maine (Ranson, *et al.*, 1995), and Germany (Keil, *et al.*, 1995) as well as southern rainforests of Brazil (Saatchi, *et al.*, 1997). Attempts were also made to combine forest growth models with a radar backscatter model to improve image analysis (Floury, *et al.*, 1997; Ranson, 1997; Wang, *et al.*, 1998).

Reported results using the SAR data for forest spatial classification were decidedly mixed. One investigating team was able to distinguish forest classes with accuracy ranging from 70% (hardwoods) down to only 50% for mixed classes (Sun and Ranson, 1996). In a more general classification scheme, Keil et al. (1995) used L-HH and L-VV polarizations to distinguish between deciduous and coniferous classes in the Harz mountains of Germany. Souyris, *et al.* (1996) used C-band data with unsupervised classifications to distinguish forest stands lower than 33 ton/ha with an accuracy greater than 85%. Pierce, *et al.* (1995) and Pierce, *et al.* (1998) used multiple frequency-polarization combinations to classify hardwood forests to accuracies of 97% for short vegetation (few large trees) and 98% for tall vegetation. Saatchi, *et al.*(1997) employed copolar and cross polarized L- and C-band data to distinguish primary forest, agriculture and disturbed forest areas to an accuracy of 92%. Combinations of L-, C-, and X-band data allows for the differentiation of spatial features down to areas as small as 10 km^2, which would not be possible with the resolution of satellite SAR data (Keil, *et al.*, 1995). Fractal dimensions were used to examine the spatial patterns of forest growth stands with the ability to discriminate between forest patch perimeters (Sun and Ranson, 1995; Ranson, *et al.*, 1995). The spatial structure recognized on the SAR images was successfully related to forest management practices such as logging (Sun and Ranson, 1995) or storm damage (Keil, et al., 1995). The range of results on classification and spatial mapping of forest types is at least partially due to the different physical and environmental conditions at the various sites (Dobson, *et al.*, 1996; Bergen, *et al.*, 1997). Some sites were in cold regions, others were in southern rainforests; some were in flat terrain while others were in mountainous regions, in some cases snow covered the canopies while in others it did not. These results appear to show that classification and mapping algorithms for SAR data can accurately distinguish broad classes, but that algorithms that would be generally applicable over a range of conditions may be difficult to develop.

Growth stage classification for both forest and agricultural areas was performed by Soares, *et al.* (1997) and Yanasse, *et al.* (1997). Soares, *et al.* (1997) employed L- and C-band data (both copolar and cross polar) to discriminate 15 agricultural texture measures as an aid in the classification of 7 agricultural land classes. A kappa verification statistic of 0.90 was obtained in this effort. Yanasse, *et al.* (1997) found that L-band cross polar data could be used to distinguish second growth and successional stages of canopy in the Amazon rainforest. However, large samples were necessary in order to obtain suitable statistics, *i.e.*, the algorithm must be applied over large spatial areas. Using mean statistics, differences in class means of 5 dB were observed between successional growth stages.

The results for biomass estimation from SIR-C/X-SAR data were fairly consistent even though environmental factors are known to affect these estimates as well (Ranson and Sun, 1997; Dobson, *et al.*, 1996). Biomass estimates are obtained by developing regression equations relating plant biomass to the L-band backscatter or the L/C ratios. In these studies, the regression equations generally explained a fairly high degree of the variance in biomass (Souyris, et al., 1995). Ranson (1997) and Ranson, *et al.* (1995) obtained r^2 of around 0.7 in relating L-HV/ C-HV ratios to biomass in northern hardwood forests. Dobson, *et al.* (1995a, 1995b) related L-band backscatter to biomass estimates for five different vegetation stand heights with r^2 values up to 0.95 with relatively small root mean square error. These results appear to show that forest biomass can be predicted using SAR data (particularly L-band) with sufficient accuracy over a variety of environmental conditions to allow radar data to be used as a significant forest management tool. Forests cover a substantial portion of the earth's surface and the carbon contained in their biomass is an important component of the global carbon budget. The success of the SIR-C/X-SAR mission in predicting forest biomass clearly indicates the importance of active microwave measurements in analysis of the global carbon cycle.

Radar backscatter models were incorporated with forest canopy models by Floury, *et al.* (1997), Ranson (1997) and Wang, *et al.* (1998). The purpose of these integrated models is to allow a theoretical model of tree growth to be incorporated with the radar backscatter model in order to enhance the backscatter image and thus strengthen the relationship between forest biophysical parameters and radar backscatter. In all cases, integration of the models was successful to some degree when compared to the observed SAR data. Wang *et al.* (1998) were able to discriminate between total canopy scattering relationships using L- and C- band copolar scattering models (< 0.5 dB) and cross polar scattering models (1.7-2.3 dB for L-HV and 2.9-3.4 dB for C-HV).

Wetland analyses were carried out by only one investigative team (Pope, et al., 1997). The research focused on identification of wetland flooding cycles during the dry (April) mission compared to the wet (October) mission over the Yucatan Peninsula. The L- and C- band SIR-C data were used with various frequency-polarization combinations to determine which combination would be more appropriate under the two sets of antecedent conditions. Another objective of the experiment was to determine if some combinations of existing satellite data might also be used to detect seasonal flooding of wetlands. It was found that C-band phase differences (H-V) were most effective in detecting increased wetland flooding. Changes from dry or partially flooded to complete inundation could be easily detected; however, changes from dry to partially flooded could not be detected by any configuration. Based on the radar configurations tested, it was concluded that a combination of ERS-1 and 2, and Radarsat might function to detect seasonal flooding of most wetlands, excluding partial flooding.

Land use classification investigations focused primarily on discrimination between forest and non forested areas (Saatchi, *et al.*, 1997; Souyris, *et al.*, 1996; Ranson and Sun, 1997; Pierce, *et al.*, 1997). In all of these analyses, under differing environmental and physical conditions, the SAR data were uniformly successful in separating forest from non forest areas. Accuracies ranged from 87 % (Souyris, et al., 1996) to nearly 100% (Ranson and Sun, 1997; Pierce, et al., 1997). The ability of active microwave measurements to discriminate forested areas, as well as forest classes, and to accurately estimate forest biomass and carbon storage, makes this technology extremely promising as a tool in global change analysis.

Hydrology

The hydrologic investigations associated with the subject missions dealt with the capability of the SIR-C/X-SAR data to estimate soil moisture under a variety of soil types, surface roughness, and moisture conditions (Pultz, *et al.*, 1995; Wang, *et al.*, 1997; Taconet, *et al.*, 1996), and to map the spatial structure and estimate equivalent water content of non-glacial snow pack (Shi and Dozier, 1995, 1996; Matzler, *et al.*, 1997). The estimation of soil moisture content from remote sensing sources has thus far been an intractable problem in hydrology and has become a major focus of research (Jackson, *et al.*, 1996). Most of this research has focused on the use of visible-near IR or passive microwave instruments (Jackson, *et al.*, 1996). Problems with this approach include the ability of these instruments to only sense the surface moisture and their relatively coarse spatial resolution. Active microwave instruments do not exhibit these problems, and consequently, their employment in hydrology is one of the most promising developments in recent years (Mattikalli, *et al.* 1998). The SIR-C/X-SAR missions offered the first opportunity to use multi-frequency, multi-polarization airborne data to study soil moisture signals over a variety of climates, vegetation and soil types ranging from Manitoba, Canada (Pultz, *et al.*, 1995) to Oklahoma, USA (Wang, *et al.*, 1997) to Orgeval, France (Taconet, *et al.*, 1996; Zribi, *et al*, 1997). For this reason, it potentially represented a major step in the development of algorithms to relate vertical soil moisture profiles to radar backscatter.

The shuttle missions coincided with major field campaigns to measure soil moisture in Manitoba, Canada, the Little Washita basin in Oklahoma and the Orgeval watershed in the Brie region of France. Given the ability of the longer wave length radar signals to penetrate the soil surface, active microwave instruments have the potential to measure not only surface soil moisture content, but vertical soil moisture profiles as well. Unfortunately, observed backscatter signals are influenced not only by the soil properties of the surface under investigation, but also by the surface topography, roughness and vegetation characteristics. Past research has focused on the use of these data to estimate moisture profiles primarily on bare soil under relatively smooth surface conditions. Effective algorithms have yet to be developed to correct the radar backscatter signal for variations in surface roughness or vegetation (Jackson, *et al.*, 1996; Wang, *et al.*, 1997).

The two SIR-C/X-SAR missions had the potential to lead to significant improvements in current methodologies; however, this potential does not seem to have been fully realized as of yet. Two investigating teams (Pultz, *et al.*, 1995, 1997; Zribi, et al., 1997) studied the effect of surface roughness and moisture content on the backscatter at different frequencies in an attempt to possibly account for the roughness effects. However, the study reported by Pultz, et al. (1996) again concerned only bare soil conditions. The French study team (Taconet, *et al.*, 1996; Zribi, et al., 1997) did investigate both roughness and vegetation effects; however, only the surface moisture content was obtained. The American team (Dubois, *et al.*, 1995; Wang, *et al.*, 1997) focused entirely on the near surface (5 cm) of bare soil conditions with no attempt to account for either roughness or vegetation effects.

In all of these efforts, considerable success was realized within the narrow confines of the objectives. Pultz, et al. (1995, 1997) were able to obtain relationships between backscatter at both the C and L-band copolar (HH) configurations and moisture profile to a depth of 15 cm over bare soils at the Manitoba test site. The r^2 values of these expressions ranged from 0.84 for the top 2.5 cm layer to 0.77 for the 15 cm layer. The relationships worked well for both spring (April) and fall (October) environmental conditions and the authors found that surface roughness and soil texture do not play significant roles in measuring short term soil moisture (Pultz, *et al.*, 1997). Likewise, Wang, et al. (1995, 1997) found that two inversion algorithms currently used to relate radar backscatter to soil moisture in the top 5 cm of bare soil columns worked well with the C and L-band data (standard error = .05 cm^3/cm). However, in both cases, the algorithms completely failed to capture soil moisture in vegetated environments. A further weakness of both algorithms was that they failed to converge to a solution for a significant number of pixels.

Limited success was also realized over vegetated environments by Taconet, *et.al.* (1997) who were able to estimate surface soil moisture from the C-band measurements to a precision on the order of 0.05 cm^3/cm when the soil column was overlain with a wheat canopy. A correction was applied to the soil moisture inversion algorithm to correct for the vegetation effects on the radar backscatter measurements. The authors demonstrated that even single band satellite data (ERS-1) could be employed for this purpose. As the data collected during the missions are obviously still available, it is hoped that some of the more important problems associated with remote sensing of soil moisture, *i.e.*, vertical profile estimation throughout the active zone and correction for vegetative cover and surface roughness will continue to be addressed in future research. Until this is done, operational use of remote sensing instruments for soil moisture estimation will not be realized.

The results of the snow pack experiments reported by Shi and Dozier (1995a,b,c; 1996, 1997; Matzler, et al., 1997) may have more immediate practical applications than do the soil moisture investigations. The ability to map snow cover and to estimate the equivalent water content of snow packs can be a great aid in the estimation of spring snow melt runoff from mountainous regions. Snow melt provides the essential runoff for replenishment of reservoir stocks in many parts of the world (e.g.,the western United States). The ability to accurately estimate the volume of this runoff in advance would be a great benefit to hydrologists, hydropower operators and water supply managers. The authors demonstrated the ability of multi-frequency, multi-polarization data to accurately discriminate between snow covered and non-snow covered regions in areas of high topographic relief (without the aid of topographic maps) and to estimate equivalent water content of snow cover (Shi and Dozier, 1995a, 1997). Ratio backscattering coefficients at the different frequencies could be adjusted to enhance the images and the estimated wetness values compared well with ground observations over the test site. Matzler, et al. (1997) demonstrated that different frequencies (35 GHz and 5.3 GHz) could be employed to discriminate between layers of snow pack based on temperatures and wetness.

Geology and Geomorphology

The geological and geomorphological investigations associated with the missions focused on observation of sand covered features in Arabian deserts (Dabbagh, *et. al.*, 1997; Schaber, *et al.*, 1997), mapping of volcanic lava fields and observations of associated deformations (Zebker, *et al.*, 1996; Rosen, *et al.*, 1996; Murino, *et. al.*, 1995) and mapping of alluvial flood plains (Hess, *et.al.*, 1995). The restricted range of wavelengths of the SIR-C/X-SAR instruments (3.1 cm - 23.5 cm) limits the penetration range of the beams and thus restricts the application of the system in subsurface investigations. Dabbagh, *et. al.* (1997) used L-band copolar (HH) data to penetrate up to 4 m of sand in the Arabian peninsula to reveal older geologic features such as drainage channels. The authors found that the X-band (VV) data could penetrate up to 3 m of sand. Schaber, *et. al.* (1997) employed the C and L-band data in a similar manner in an Egyptian desert overlain with a shallower sand layer (2 m). The authors found that C-band cross polar (HV), the L-band copolar, and the L-band cross polar data all produced enhanced images and were able to reveal deeper rock formations and fractures, while shallow quaternary drainage channels were visible at all channels. They also concluded that L-band copolar data at small incidence angles may be able to detect shallow groundwater deposits in arid regions- a potentially valuable contribution.

The volcanology investigations focused on analysis of lava fields and geologic structure and deformation of volcanoes in southern Italy (Murino, *et.al.*, 1995) and Kilauea Volcano, Hawaii (Zebker, *et. al.*, 1996; Rosen, *et al.*, 1996). Murino, et al. (1995) employed C and L-band copolar (HH) and cross polar (HV) data to reveal lava fields of different ages (5000 years and 10,000 years) and to separate lava fields from undisturbed areas. In the Lattari and Picentini mountains, three sets of geologic lithologies were identified and fault lines were clearly evident on the images. The Kilauea Volcano studies reported by Zebker, et al. (1996) and Rosen, et al. (1996) attempted to measure the deformation that occurred in the time span between the two missions, as well as short term (daily) deformation between successive passes on the same missions. A vertical deformation of up to 14 cm was observed over an area of several km^2 around the volcano in the time between the two flights. Comparisons with GPS field measurements showed that while the maximum deformation agreed to within 2 mm, estimates of the deformation did not correspond to the field measurements at any one point in the field, implying that the radar data can detect general deformation trends over large areas, but not exact geographical values. It was also found that the L-band data was superior to the C-band for vegetated areas for these analyses.

Hess, et al. (1995) employed C and L-band multi-polarization data to map areas of flooded forests in the Amazon rainforest and to discriminate between vegetation classes corresponding to water tolerance. This study was part of an ongoing investigation by the authors to quantify methane fluxes and production of Amazon rainforests (Kasischke, et al., 1997). Vegetation classes corresponding to different rates of methane production were successfully identified.

Precipitation and Climate

Precipitation and climate studies focused on the use of multifrequency, multipolarization radar data to estimate rainfall rates and classify precipitation types (Jameson, et. al., 1997) and to observe glacier dynamics (Rignot, et al., 1996; Matzler, et al., 1997; Rott, et al., 1998). The shuttle missions afforded the unique opportunity to observe storm dynamics associated with Cyclone Odille (April, 1994) and Typhoon Seth (October, 1994) using a variety of radar frequency/polarization configurations. Quantification of rainfall rates was approached as an inversion problem, *i.e.*, to estimate the radar parameters most likely to have produced the observed scattering profile. As such, the collected data provided an opportunity to develop and test inversion algorithms to be employed with the Tropical Rainfall Measuring Mission (TRMM) satellite that was launched in 1997. Rainfall profiles were obtained from the C-copolar (VV) and X copolar (VV) scatterometer data. The inversion algorithm demonstrated that rain rates could be estimated within small error bounds at higher altitudes (> 7 km), but that error increased greatly at lower altitudes and was greatest at heights less than 5 km. Rainfall mechanisms could also be accurately discriminated, as convective rainfall was separated from strafiform dynamics. Another similar study approached the problem through the conventional method of development of reflectivity- rainfall rate relationships, known in the radar field as Z-R relationships (Moore, et al., 1997). Again, good results were obtained; however, the authors point out that, as in the previous case, actual field verification of the results are not possible.

The radar-based glacier studies of Rignot, et al. (1996), Matzler, et al. (1997) and Rott, et al. (1998) are included in this section because of the relationship between glacier dynamics and long term climate change. Northern latitude glaciers in Austria were studied (Matzler, *et al.*, 1997; Rott, *et al.*, 1998) as well as southern glaciers in Chile (Rignot, et al., 1996). The focus of the studies was to map the extent of the glaciers, estimate ice velocities, observe glacial calving (separation), and attempt to identify areas within the glacier field of accumulation or ablation. In some cases, equivalent water content of glacial snowpack was also estimated (Matzler, et al., 1997). Glacier dynamics are studied by radar interferometry, *i.e.*, calculation of the phase difference of two images acquired at different passes at the same incidence angle (Rott, et al., 1998; Rignot, et al., 1996). The phase differences are related to the surface displacement of the glacier. In this case, the L-band and C-band data were acquired on each pass at a spatial resolution of about 30 m, and the interferograms were computed for each band. Image analysis can be employed to determine the direction and rate of ice flow and to identify areas where ice is accumulating or abating. Rott, et al. (1998) determined that the Moreno Glacier in the southern Patagonia icefield showed a displacement of about 17 cm/d over the period of the October mission to an accuracy of 2 cm/d, and that the glacier shows a net annual accumulation of 5540 mm of equivalent water to an accuracy of +/- 500 mm.

Surface Mapping and Topography

The surface mapping investigations associated with the April and October 1994 shuttle missions were focused on the development of relationships between measured backscatter from the SIR-C/X-SAR radars and surface roughness and topographic characteristics. One major research team focused on this effort (Weeks, et al., 1997), while others also addressed it as a secondary issue associated with hydrologic investigations (Souyris, et al., 1995, 1996; Zribi, et al.,1996, 1997). Zribi, et al. (1996, 1997) and Rakotoarivany, et al. (1996) sought to assess the sensitivity of radar backscatter data to soil roughness over bare soils in Orgeval, France during wet seasons. In addition, simulated backscatter data from two numerical models were compared to observed SAR data taken over surfaces with varying roughness. The authors found that differences in backscatter response was high over areas with moderate periodicity and height root mean square. It was also found that one well known backscatter model (IEM) performed well for smooth surfaces while a different one performed better for rough surfaces.

Weeks, et al. (1997) tested the applicability of several inversion algorithms to relate SAR backscatter to surface characteristics in Death Valley, CA. The authors found that a foreground/background inversion scheme was able to separate surface roughness signal from background noise through filtering of the different radar frequencies. However, the signal to noise relationship was a significant function of roughness scale and frequency. Large scale features could be accurately identified as could small scale features to some degree. Intermediate scale features were more difficult to identify. The authors were able to identify four levels of surface features from the data and conclude that a stable algorithm must sacrifice roughness resolution.

Summary and Conclusions

Due to the nature of earth science investigations, it is not to be expected that some fundamental breakthrough in understanding of the physical or biological processes under observation could be realized from one or more short term remote sensing missions. The measurements obtained during these missions represent mere snapshots of the processes under the particular set of environmental conditions which prevail at the time of the missions. Thus, fundamental knowledge of the processes must be gained from repeated observations under the full range of conditions which can occur at the test sites, and enough sites must be tested in order to gain sufficient information to make informed inferences. This is necessarily a slow and tedious process. However, progress can be made from discrete missions such as the two SIR-C/X-SAR flights in three categories: Clear demonstrations of the capability of active microwave instruments to measure some processes that have important scientific or practical value, and thus provide impetus for further mission or satellite development; Development and testing of algorithms that can be employed with current satellites or other instruments to enhance their productivity or usefulness; and, Advance basic algorithm development to use microwave backscatter measurements to observe and understand important physical or biological processes with scientific or practical implications.

It is clear that the SIR-C/X-SAR missions made significant contributions in all three of these areas. Clearly, the most important of these is the very significant results in the first category. In the areas of forest mapping and biomass estimation, ocean wave observations, rainfall quantification, snow cover mapping and estimation of water content, glacier observations, and crustal deformation associated with volcanoes and earthquakes the SIR-C/X-SAR results provided convincing evidence of the ability of the instruments to provide accurate measures of quantities associated with these important processes. The results of these missions contributed significantly to the utility of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 to observe and quantify tropical rainfall and to the decision by NASA to design and launch an active microwave satellite (Lightsar) within the next two years. The operation of these satellites has the potential to make tremendous contributions to basic science and may have great practical impact on the lives of the people of the Unites States and elsewhere. A few of these developments are:

Forest mapping and biomass estimation: improved ability to close the global carbon cycle should significantly enhance analyses of global warming trends and impacts. Also, improved and timely forest mapping should impact the efficiency of forest management practices and influence the market for wood products such as paper and furniture. Prices to the consumer should reflect this increased efficiency.

Ocean wave observations: improved ability to forecast ocean waves using an integrated numerical model updated with satellite observations will impact the lives of people living in coastal environments subject to hurricane activity. Improved storm surge estimates will guide managers in making more informed decisions with regard to construction standards and evacuation warnings and planning.

Glacier observations: accurate, routine and timely measurements of glacier movement, deformation, accumulation/ablation, and water content will significantly improve estimates of global warming due to the relationship between glacier dynamics and global temperatures. Melting glaciers are responsible for the majority of observed sea level rise over the past century, so again, improved estimates of these quantities will have significant impact on people living in coastal communities.

Observations of crustal deformation: the SIR-C/X-SAR missions showed that crustal deformations could be measured over large spatial areas to an accuracy of 2 mm. Accurate and consistent measurements of crustal deformation in the vicinity of volcanoes and fault lines will lead to better understanding of the processes of volcanic eruptions and earthquakes. This better understanding should lead to improved prediction capability for these natural disasters.

Snow cover mapping and estimation of water content: the success of the investigations in this area may have the most immediate benefit to the general public. Convincing evidence was provided of the ability of active microwave radars to accurately map areas of snow cover, estimate the depths of the snow layers and quantify the equivalent water content of the snow. As snow pack provides most of the water for replenishment of reservoirs in the western United States, the use of the measurements to be provided by Lightsar will give water managers in this region invaluable information about future water supplies. This will make for a greatly improved efficiency of water use. This improved efficiency should be reflected in the cost of water and electricity to the consumer.

Rainfall observation and quantification: the launch of the Lightsar satellite will make possible the consistent observation of precipitation processes over much of the earth. Lightsar will complement the existing TRMM mission, which was itself greatly impacted by the knowledge in radar reflectivity/rain rate relationships gained from the SIR-C/X-SAR results. Accurate radar estimates of storm dynamics and precipitation rates will greatly improve weather forecasting and flood forecasts with obvious benefits to the general public.

Attempts to develop algorithms to work with existing satellites such as ERS-1,2 or JERS-1 generally failed to produce convincing results. The results in oceanography and forest mapping demonstrated that current satellite instruments lack either the spatial resolution or radar frequency-polarization characteristics to adequately observe the processes associated with these fields. In the cases of hydrology (vegetation correction) and wetland flooding cycles the investigators conclude that the existing ERS-1,2 and/or Canadian Radarsat might be employed with correction algorithms to adequately observe the important processes. Of course, the anticipated launch of the new Lightsar will complement and extend the capability of the existing satellite systems and will allow for the development of algorithms to correct the radar backscatter signal for surface roughness and vegetation effects in soil moisture estimation.

Progress was also made in the area of algorithm development. This was particularly apparent in the fields of surface roughness and topographical mapping and precipitation quantification. It appears that significant progress was made in the development and/or testing of inversion algorithms to determine parameters associated with the observed backscatter signal in these cases. In some cases, including surface roughness and soil moisture estimation, it was determined that significant problems occur with the use of existing algorithms. It appears that the use of active microwave instruments is still in its infancy in the field of hydrology, and considerable basic work on algorithm development needs to be done before it can become an operational reality.

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Beginning with OSTA-1 in November 1981, and ending with Neurolab in March 1998, thirty-six shuttle missions are considered Spacelab missions because they carried various Spacelab components such as the Spacelab module, the pallet, the Instrument Pointing System (IPS), or the MPESS. The experiments carried out during these flights included astrophysics, solar physics, plasma physics, atmospheric science, Earth observations, and a wide range of microgravity experiments in life sciences, biotechnology, materials science, and fluid physics which includes combustion and critical point phenomena. In all, some 764 experiments were conducted by investigators from the United States, Europe, and Japan. These experiments resulted in several thousand papers published in refereed journals, and thousands more in conference proceedings, chapters in books, and other publications. The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis of the more significant experiments and an extensive list of the publications that were produced. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied.

14. SUBJECT TERMS
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