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The Investigation of Spacecraft Optical Environment (ISOE)

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INVESTIGATION OF SPACECRAFT OPTICAL ENVIRONMENT (ISOE)
Final Report

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The Auroral Photography Experiment (APE)

1. INTRODUCTION

In the framework of this program the Lockheed Palo Alto Research Laboratories is performing the Auroral Photography Experiment (APE), a joint experiment with AFGL to make observations of shuttle induced emission effects such as shuttle glow and thruster induced effects. In addition, observations will be made of natural background phenomena such as the aurora and airglow. At very high latitude where the shuttle transits the auroral regions we shall also attempt to observe the direct effects of precipitation and precipitation induced discharges. In this program the Air Force flew Lockheed instrumentation as secondary payload on the shuttle and the payload/mission specialists made observations through the orbiter windows with the equipment. For the first flight in late 1988 the APE configuration A was flown. The lighting conditions were unfavorable for the shuttle orbit flown for this mission. In November 1989 the APE experiment was flown on STS-33. The hardware is essentially a re-flight of the Auroral Photography Experiment (APE) which was flown on mission 41-G augmented with the spectrometer and Fabry-Perot. During STS-33 flight several performances of the APE experiment were performed. There were a number of difficulties with the experiment and it was found that the mechanical mounting of the instruments was not totally satisfactory. There were some problems with the way the film was loaded for some of the observing opportunities. Some faint spectrum of thruster firings and shuttle glow were obtained. As a result of the experiences gained on this flight we have made several improvements and modifications to the experiment. The experiment will be reflown again in the near future with the improved Configuration B which includes the spectrometer and the Fabry-Perot.

The Lockheed tasks associated with this program are the providing of the experiment hardware and assisting the Air Force in the definition of flight operational requirements, and helping with flight operations and data analysis. In addition there is an active parallel data analysis effort of the data taken on the prior APE experiments. The APE experiment was reflown in 1988 on a DoD mission in hardware configuration A which includes only the filter system. Unfortunately the daylight conditions were unfavorable for data taking and the instrument was not operated during this flight. The experiment was flown on STS-33 with hardware configuration B which included the spectrometer and the Fabry-Perot interferometer.

2. SCIENTIFIC OBJECTIVES

The APE experiments were envisaged to make auroral observation from the shuttle to investigate atmospheric natural background light emissions. In recent years some advances have been made towards understanding these artificially induced emissions. Spacecraft body-induced emissions in the visible spectral range were named "shuttle glow". Through a sequence of experiments we were able to characterize shuttle glow and gain some understanding of the physical processes generating the glow. However, there is still some work necessary to verify some aspects of the theory of glow production. Another source of strong background light is provided by the attitude-control jet thrusters. So far there are very few experimental data concerning the spectral character of these types of emissions. Over the years the priorities of the Auroral Photography Experiment (APE) have shifted from observation of the purely natural phenomena of auroral and airglow, the investigation of shuttle glow and thruster emissions.

2.1 Spacecraft Induced Glow

Glows associated with space experiments are not new. A rocket experiment flown into the mesosphere and lower thermosphere in 1956 (Heppner and Meredith, 1958) cited optical backgrounds in visible photometers near the 100-km altitude region. These early experiments noted background ratios in the background signal of photometer channels suggesting a continuum type emission. Nitrogen dioxide emission was reported as a likely explanation of the phenomena. It wasn't clear in these early rocket data whether gas-phase reactions were taking place with outgassing contaminants or whether there was a surface reaction involved.

The AE-C and -E satellites were equipped with a Visual Airglow Experiment (VAE) which observed atomic and molecular features in the earth's airglow layer. Backgrounds in the filter photometer channels of AE-C were found to have a variability with ram angle below 170 km according to Torr et al.,(1977). A thorough analysis of the data from AE-C and -E was reported by Yee and Abreu (1982, 1983) over the altitude range of 140 to 300 km. The data displayed a detectable level of luminosity in the near-UV channels of the instrument (3371 Angstroms), with increasing luminosity towards the red wavelengths (7320 Angstroms). The background in all filter channels, when plotted, described a bright ram source, increasing in brightness toward the red wavelengths. The analysis indicated that the glow extended well away from the spacecraft, suggesting the probability that the emitter is a metastable. The Yee and Abreu analysis reported a strong correlation between the ram emission intensity and altitude. The emission intensity closely followed the atomic oxygen scale height above 160 km altitude. This discovery of the glow relationship to the oxygen flux was an important key to establishing and understanding the physical process leading to the glow.

Glow observations have been reported by a number of investigators from shuttle missions STS 3, 4, 5, 8, 9, 41D, 41G, 51D and 61C (Refs: Banks et al., 1983; Mende et al., 1983; Mende, 1983; Mende, 1984; Mende et al., 1984 a, b, & c; Torr and Torr, 1984; Torr, 1985; Swenson et al., 1985 a & b; Mende and Swenson, 1985; Kendall et al., 1985 a & b; Mende et al., 1986; Swenson et al., 1986 a & b; Kendall et al., 1986; Tennyson et al., 1986). Banks et al. (1983) reported glow from orbiter television and still camera pictures around aft spacecraft surfaces while documenting glows associated with an electron accelerator experiment on STS 3. Observation of ram glows with STS 5, 8, and 9, using an intensified camera have been documented (Mende 1983, Mende et al. 1983, 1984a, 1984b) using an intensified camera. On the later missions (STS-8 and -9), objective grating imagery of spacecraft glow from the vertical stabilizer depicted a red structureless glow (Mende et al., 1984 b & c). The spectral resolution was on the order of 150 Angstroms. On the STS-8 mission it was observed that glows from surface samples including aluminum, kapton, and Z306 (a polyurethane black paint typically used in low-light-level detection instrument baffles) were not equally bright. The surface characteristic and/or the material makeup clearly was shown to effect the glow brightness.

High-spectral-resolution measurements of the ISOE spectrometer on STS-9 (Spacelab 1) show the presence of N_2 1PG bands (Torr and Torr, 1984 and Torr, 1985). There are also a number of other observed emission features which may be part of the natural auroral and airglow background environment and, therefore, may not be part of the shuttle glow.

UV glows were reported in the 2800- and 3371- Angstrom channels of AE spacecraft (Yee and Abreu; 1982, 1983). The UV glows were considerably weaker than those in the visible on that spacecraft. It has been postulated that the UV glows from NO might be likely on ram surfaces (Barrett and Kofsky, 1985; Green et al., 1985 a & b; Kofsky and Barrett, 1985; Swenson et al., 1985 b and 1986 b). Tennyson et al. (1986) reported no component of UV ram glow in their attempts on STS-61C. The 61C instrument was not looking at a surface and was a spectrometer with a small aperture. If UV glows are present from NO, they would be expected to be a very thin layer close to the surface. The Berkeley EUV experiments on STS-9 had fogged film and one of the contributing possibilities has been ram glow. Recombination of atomic Nitrogen on surfaces can lead to excited N_2 which emits Lyman-Birge-Hopfield (LBH) bands in the FUV. S3-4 satellite UV instrumentation (Huffman, 1980) have found N_2 LBH emission to originate near the spacecraft (Conway et al., 1987). Torr et al. (1985 b) have observed shuttle-induced emission in N_2 LBH also. Kofsky (1988) and Swenson and Meyerott (1988) have proposed recombination of N on the surface as being responsible. Swenson and Meyerott (1988) have found that a large source of N is likely in the plow cloud of low-altitude spacecraft due to atom exchange with the ramming atmosphere. This mechanism predicts a source flux and altitude distribution that supports the observations.

Chakrabarti and Sassen (1985) reported anomalies in the FUV from data acquired on STP78-1 satellite. Interpretation of Lyman-alpha (1215 A) intensity modulation with ram angle suggest several hundred Rayleighs of unexplained emission. Conclusive deduction of the source was not clear in the report. A ram modulation of 400 Raleighs in the LBH bands was also reported. These observations were made at 600-km altitude.

Ground-based measurements of the infrared shuttle glow have been reported by Witteborn, et al. (1985). Also, the Spacelab 2 IRT experiment reported backgrounds that were in great excess of what was expected from natural causes. How much, if any, of the IR glow is related to the process producing the visible glow is not clear. The IR glows are extended well away from the spacecraft and it is speculated that they result from gas-phase reactions of offgassing constituents including charge exchange with the ambient ionosphere.

In regard to the visible shuttle glow, a spectrum was reported from STS 41D with 34 Angstroms resolution by Mende et al. (1984 b) and Swenson et al. (1985 b). These data show the shuttle ram glow to be an emission continuum within the instrument resolution. This spectrum was convincing evidence to suggest that OH and N_2 1PG are not the emission species on STS.

The current evidence strongly suggests the visible glow associated with the ramming atmosphere is a result of NO_2 in recombination (Swenson et al., 1985 b). The natural atmosphere is reacting with the 8 km/sec vehicle to produce the phenomena. According to this picture NO is produced by the spacecraft sweeping out atmospheric N and O.

Some of the NO which forms, remains adsorbed by the surface. Wall catalytic formation of NO is well known to be efficient in laboratory experiments (Reeves et al., 1960). NO reacts very quickly in 3-body recombination with OI to form NO_2. The surface monolayer of NO. then. is exposed to atmospheric OI on ram spacecraft surfaces. Since NO_2 is formed by *ramming* OI, the 5 eV OI also contains enough energy to unbond the formed NO_2 from the surface. The complex quasi-continuous spectrum of NO_2 explains the lack of distinct spectral lines in the glow spectrum. Figure 1 is a schematic describing the postulated sequence of chemical events occurring, leading to the emission process. The bottom portion of the diagram shows the ramming OI interacting with surface-sticking NO to form excited NO_2. The excited NO_2 which exits the surface, gives the red glow.

The glow spectrum from 3-body gas phase recombination of laboratory experiments (Paulsen et al., 1970) is blue shifted from the shuttle observations but very similar in shape. The most critical aspect of the NO_2 theory is the lifetime considerations. Yee and Dalgarno (1983) analyzed shuttle data to deduce an average molecular travel of 20 cm (confirmed by Swenson et al., 1986 a). The 70 μsec lifetime of Schwartz and Johnston (1969) or 40 μsec of Bylicki et al., (1984) suggest the NO_2 must be exiting the surface with 2-4 ev translational energy to account for the observed thickness of the glow. There is sufficient energy in the ramming OI to account for the rebound energy. It is, however, unprecedented in laboratory experiments to have such an 'elastic' process in the surface recombination.

The best evidence for NO formation and sticking on orbiting surfaces is reported by the mass spectrometer investigations and what has been observed in the way of NI, NO, and NO_2. Engebretson and Mauersberger (1979) described in detail, the response of NO with respect to thermal and orbital parameters for their instrument on AE-C satellite. It has been known since mass spectrometers first flew, that most of the atmospheric NI entering the mass spectrometer orifice, converts to NO with wall collisions and in fact, a large percentage of the NI signal is deduced from the NO (mass 30) signal in the instruments (see Engebretson and Mauersberger, 1979 and the references cited therein). It has been well established in laboratory experiments that the NI and OI wall reaction form gas phase NO. Engebretson and Mauersberger (1979) then reported a most interesting phenomenon. They reported that NO was absorbed on the spectrometer walls (with efficiencies higher at low wall temperatures). The top part of the chemistry shown in Figure 1 reflects what has been observed in the mass spectrometer orifice. They observed the gas phase NO. and from temperature and altitude geometry, they deduced that a significant amount of NO was sticking to the wall. More recently, Engebretson (1986) and Engebretson and Hedin (1986) have presented detailed analyses of specific orbits of DE satellite showing that the mass spectrometer orifice exhibits pronounced wall temperature modulation. Von Zahn and Murad (1986) have found from mass spectrometer measurements from a shuttle mission (STS-41B) *that the exit flux of* NO_2 *is more than sufficient to account for the* observed glow intensities reported on earlier missions.

The analysis of intensity of shuttle glow has been performed on several missions. The measurements from STS-41G at low altitude added a confusing data point to the existing data base. The intensity on this mission was much less than it had been measured on previous missions (Kendall et al., 1986). After further investigation, it was found that the surface temperature for this particular observation was much warmer than earlier observations. A study of all the previous intensity measurements along with a thermal modeling study of the tile temperature for the associated glow measurements was undertaken. When the temperature history of the ram tile surface was modeled for three measurements of glow intensity from three different missions, it was found that the results of this study (Swenson et al., 1986 b) were consistent with the NO theory and in fact provided a measure of the surface bond energy the NO had with the surface (~.14 ev). The study further suggested that the lesser intense glow seen on the AE spacecraft (which had surface temperatures much warmer than the shuttle tile during observations) was also consistent with these findings.

In the earlier section, we discussed the results showing that the apparent glow intensity above surface samples varied in intensity over respective samples. A thermal model was performed for these material samples which were mounted on the insulating 'beta' cloth on the RMS. The predicted glow intensity associated with the temperature of each material sample was found to be in reasonable agreement with the measured intensity associated with each sample. The emissivity associated with each material was largely responsible for the different cooling rate associated with each sample. The early conjectures, that material traits such as cleanliness or a surface chemistry associated with one and not the other, we feel were incorrect and that 'temperature' can also explain what we saw.

In the near infrared we would expect to see some emission intensities due to the near IR portion of the NO_2 continuum. It was shown in laboratory experiments that the shape of the NO_2 continuum strongly depends upon the type of reaction which produces the NO_2. Since the shuttle glow production is some form of surface catalytic reaction it is not surprising that the shuttle glow continuum is somewhat red shifted from the spectrum of the laboratory produced gas phase reaction (Swenson et al., 1985 b).

Shimazaki and Mizushima (1985) predict a mechanism for shuttle glow production in which the NO molecules get vibrationally excited through collision with shuttle surfaces. Green et al. (1985) makes a case for NO vibrational overtone transitions having a substantial contribution in the visible region. If this were correct then the corresponding IR transitions at 2 and 3 microns would be several order of magnitude greater than the visible component. Green et al. suggest that the glow intensity might be comparable to earthshine in the infrared and therefore may be several Mega-Rayleighs of emission.

Torr (1987) has reported that at lower altitudes (250 km and below) a spacecraft will generate a dense layer of gas due to the "snow plow" effect. Accordingly, in the spacecraft frame of reference, the fast streaming ambient atmospheric molecules have a large probability of collision with the particles which are caught in this region.

Because the masses are generally similar there will be a very efficient re-distribution of the ram energy of the incoming molecules. This would result in a high kinetic temperature in this dense region. Although no particular mechanism was proposed, it was suggested (Torr, 1987) that this region would produce intense gas phase molecular emissions in the IR region.

2.2 Thruster Induced Glow

It is by now well documented that when the thrusters on the shuttle are fired, there is a large enhancement of the surface glow. This phenomena is distinct from the bright gas phase glow. The gas phase glow is quite transient and very bright, whereas the thruster induced surface glow persists for a time duration of 30 seconds before fading to the normal background glow level. The investigation of this gas phase glow has gained importance lately because it provides an opportunity to study the interaction of unburned rocket fuel with the ambient atomic oxygen atmosphere.

In addition to this spontaneous light emission it was observed that there is also a marked enhancement of the spacecraft ramglow after thruster firings. The time development of the thruster firings can be best studied by means of the orbiter closed circuit TV cameras. A thruster firing event documented by the orbiter TV cameras on video tape are included in Figure 2. To aid in the timing of the event a time counter which ran in seconds and one hundredth seconds was superimposed on the frames. The status of this time counter provided a unique identification of the TV frame. The first timed image is a background frame at :53:32. The second and third images show the thrusters while in operation. The subsequent frames show the decay of the glow on the engine pods which persisted well after the thrusters had been shut off. The TV sequence (Fig. 2) was taken on mission STS-8 at an altitude of 220-km.

Figure 3 shows the thruster induced glow intensity as a function of time. This was obtained by integrating the video signal from all pixels inside of a rectangular area which includes the glow on the port side engine pods This integrated signal was plotted by a chart recorder. Note that the video signal may include a number of relatively unknown parameters such as the signal non-linearities and the time response characteristics of the television system. Two observations were plotted on Figure 3. The top one is from the low altitude portion of STS-8 at 220-km altitude and the bottom is from STS-3 at 240-km altitude. The decay is considerably longer for the low altitude case.

To investigate the glow production efficiency of the various thrusters an experiment was performed on the STS-8 mission. In this experiment the camera was opened for 2 seconds. During the exposure a selected thruster was fired for a minimum single impulse by manual operation of a crew member. There are 6 vernier thrusters on the orbiter (Fig. 4). Some of them can be operated singly while others are usually operated in pairs. Four different combinations of thruster firings were performed and the results were photographed. A two second duration background exposure was also taken in between each thruster firing to assure us that all thruster effects disappeared prior to the next firing. The results are shown on Figure 5 in the form of a collage of the photographic images. The top left picture represents the background image. The camera was in the objective grating configuration and the orbiter attitude was such that the velocity vector is from the direction of the starboard wing. By comparing the images we note that only the downward firing tail thrusters only have a noticeable effect on the picture background. The following explanation can be provided. The downward tail thrusters are directed towards the wing. The gases emitted by the other thrusters leave the vicinity of the orbiter very quickly, however the downward tail thrusters throw their output on the wing where the gases thermalize and will take up the velocity of the spacecraft. This luminous cloud will travel with the spacecraft.

The thruster fuel is monomethylhydrazine which combines with nitrogen tetroxide. The principal neutral products in the atomic O environment, according to Murphy et al. (1983), are H_2O, N_2, CO_2, CO, and H_2, with minor amounts of NO_2 (or monomethylhydrazine, since they each have a molecular weight of 46) and O_2. The neutral densities are typically 7-8 orders of magnitude higher than the charged particle densities. It has also been claimed that there may be substantial amounts of unburned fuel at the beginning and end of a thruster firing.

In the framework of the APE experiment we could obtain a spectrum of the thruster induced glow and could determine whether the spectra is similar to the shuttle glow spectrum. We expect that the gas phase emission directly above the nozzles would be quite a different spectrum. It is known from color photos that this emission has a bluish color. One would probably see the O_2 Herzberg bands in the blue violet region.

2.3 Natural Background Measurements

Airglow. In addition to the spacecraft induced optical contamination there are a number of other intense background components in the visible and near IR such as airglow emission due to the molecular O_2 and OH. The flight experiment would provide an opportunity to obtain data about the intensity and altitude variations of these bands. Swenson et al. (1988) have used this technique and obtained better than 1 km altitude resolution of the airglow layers. In this work Swenson et al. (1988) used our Spacelab 1 (STS-9) instrument TV video data (Mende, et al., 1984d, 1985), (Sandie et al., 1983) of the visible and UV limb airglow layers. With appropriate star images in the field of view and accurate knowledge of the spacecraft position (position only, not attitude) we can measure the airglow layer altitude with an accuracy better than 1 km. Substantial variation in airglow layer attitudes have been found and there is a possible association with the local lower atmospheric generated gravity waves. Thus, a whole set of limb height measurement could be obtained by making observations in the limb view direction with our instrument complement.

In addition to measuring the intensity profile along the limb there is another important atmospheric parameter which is accessible to remote sensing measurement. This parameter is the temperature of the atmosphere. This can be measured by remote sensing techniques using the rotational lines of the airglow emission. Using the STS-41G data Mende et al. (1988) obtained the airglow rotational temperatures of the O_2 (0,0) and the OH bands. The STS 41-G data provided only a very few usable exposures. It is proposed that on the upcoming APE missions we should take a series of temperature measurements to validate the method and to obtain temperature vs. altitude profiles. The rotational line temperature measurement is performed by using the camera in the Fabry Perot configuration.

Aurora. At higher latitudes we can make limb measurements of the auroras. On the limb it is possible to make altitude profile measurements. On 41-G such measurements were performed using the spectrometer. The spectrometer slit was aligned in the vertical direction and limb spectra was obtained. In this manner the auroral lines in the image are an actual height profile of the emission feature. Both the particle energy deposited and the atmospheric composition varies with altitude. The different emissions profiles will provide a number of relationships between the spectrum of the energetic particles causing the aurora and the atmospheric composition. This data should help with resolving the many discrepancies which still exist in the understanding of the mechanisms of auroral emission.

2.4 Shuttle Electron Discharges

During auroral displays the shuttle in high latitude orbits directly encounters the auroral bombardment. Auroral electrons are several keV in energy. Insulators on the shuttle during these bombardment are expected to charge up and perhaps generate electrical discharges. Although evidence for those kind of discharges have been found from shuttle flights after return from orbit there has not been any direct photographic recording of the discharges. It is suggested that during a high latitude APE mission we should search for those discharges.

3. THE APE EXPERIMENTS

During the first APE mission in 1985 only a limited set of the APE hardware was flown. As it happened other hardware component parts were included in the flight as part of another experiment called the OGLOW experiment. The limited set of APE hardware was named APE configuration A and the hardware including the OGLOW hardware was named APE configuration B. Configuration A is an 'imaging' configuration and is shown at the top of Figure 6. Configuration B includes an imaging as well as a Fabry Perot and spectrometer configuration which are described in the middle and bottom panels of Figure 6. This complete hardware was flown on STS-33.

The APE configuration A consisted of the:

1. Image Intensifier
2. 8 filters
3. Filter changer
4. Filter pouch
5. Filter Carrier

The APE configuration B hardware includes all of the above plus:

1. Spectrometer
2. 135 mm focal length spectrometer lens.
3. Fabry-Perot etalon interferometer.

The APE 2 hardware was completed in December 1987 and was delivered to Johnson Space Center. The instruments were calibrated for intensity and spectral response. This was accomplished with the various filters in imaging mode and also in spectrometer mode. In the spectrometer mode we have also obtained the function of spectral dispersion with linear distance on the image plane. For the absolute intensity calibrations we have used a C14 secondary standard.

The first flight of the APE experiment took place in 1985 on STS 41-G. The experiment was reflown in 1988 on a DoD mission with hardware configuration A which includes only the filter system. Unfortunately the daylight conditions were unfavorable for data taking and the instrument was not operated during this flight. The first useful flight of the APE experiment in the framework of this contract was on STS-33 in November. 1989. For this flight the APE hardware configuration B was used which included the spectrometer and the Fabry-Perot interferometer.

During the STS-33 mission all APE experiment objectives, except the Aurora objective, were performed. During the flight of STS-33 the mission specialist reported that she obtained some excellent exposures of the shuttle glow. She also performed the experiments in which we attempted to obtain the spectra of the shuttle glow. There was some indication that the mission specialist had a few minor difficulties in performing these experiments. She said, for example, that in some of the set ups there was some light leakage into the camera shroud from the orbiter cabin. Additionally, she reported some difficulties in the operation of the spectrometer. A few weeks after the completion of the mission the experiment data was received. Initially it appeared that data from the black and white film did not come out very well. On the other hand, the images taken on the color film were of very high quality. Examination of the negatives both black and white and color revealed that the problem was in the processing and it appears that in some instances good quality data was obtained on the black and white film. The interpretation of the spectral data requires the microdensitometering of the results. It appears from the data that a satisfactory spectrum of the thruster emissions was obtained during the mission.

The mission specialist also complained about the APE flight hardware mounting arrangement. The mounting using the BOGEN or multiuse arm supplied by NASA was not rigid enough to carry the bulky spectrometer. Problems were experienced especially when adjustments had to be made on the spectrometer such as changing slit or grating.

From the STS-33 experiment it was learned that the sensitivity of the spectrometer was marginal for the detection of the faint shuttle glow or the weaker thruster plumes. In order to increase the instrument's sensitivity we purchased a grating with higher rulings which will increase the spectral dispersion. This will allow using shorter focal length lenses and retain the same resolution: Shorter focal length lenses at the same aperture would result in a faster spectrometer with higher light gathering efficiency.

A new type of instrument was designed and built using 600 line pair per mm grating and a 55 mm focal length lens for the spectrometer camera lens. This allowed the decrease of the F ratio of the camera from F/3.5 to F/1.2, or improve the light level gain almost to a factor of 9.

At the time of writing this report the hardware is at the custody of the Air Force in Houston and is essentially ready for another flight.

4. CONCLUSIONS

During the framework of this program the APE experiment was flown on the shuttle twice. During the first flight, in late 1988, the lighting conditions in the shuttle orbit were inadequate to take any data. The APE experiment therefore was not operated on this mission. On this mission, only the APE hardware configuration A was flown which would have only allowed filtered photography. Over the years the main goals of the APE experiment have been redefined and there is considerably greater interest in the performance of the spectrometer investigations. One of the main goals of the APE experiment was to obtain higher resolution spectral data of the shuttle glow and resolve whether the shuttle glow is truly a continuum. The previous shuttle glow measurements were done with a spectrometer which had a resolution of 30 Angstroms. The APE spectrometer resolution was increased by a factor of 3 from the previously flown version. The other primary goal was to measure the spectra of shuttle thruster plumes. Therefore an excellent opportunity manifested itself during the second flight when the APE experiment was scheduled to be reflown on STS-33.

The APE experiment in its full hardware configuration including the spectrometer was flown in November 1989. This configuration is shown on Figure 6. The system configurations for the APE-B hardware complement is illustrated on Figure 6. In all three configurations the "hand held" image intensifier is used. This intensifier has a blue light gain of about 50,000. The photo-cathode is usually an S-20 type with a fiber optic window substrate. The output of the tube is a phosphor screen on a fiberoptic substrate. The output is lens coupled and the bright image of the phosphor is projected on the film by means of a relay lens. This relay lens magnifies the image so that the 25 mm phosphor of the image tube is enlarged to fill the entire 35 mm film frame. The three illustrations shown on Figure 6 show the 3 different optical configurations.

The top of figure 6 is the filtered imaging mode. In this mode the image intensifier is preceded by the filter slider. The astronaut places manually a filter into the slide carrier. Then he can move the filter into the optical path by sliding the slide carrier. The filters are 2 inch diameter interference filters with a pass band which is usually greater than 30 Angstroms.

In the center illustration we show the inclusion of the Fabry-Perot etalon between the filter slider and the camera lens. The Fabry Perot used in the APE experiment is a 2 inch clear aperture air spaced Fabry Perot. The free spectral range is about 30 Angstroms and the finesse is about 14 or 15. Therefore, the spectral resolution is about 2 Angstroms with this instrument.

At the bottom we show the spectrometer configuration. In this we attach the spectrometer in front of the lens of the instrument. The spectrometer has two sliders to move optical elements in and out of the optical train. From the front of the instrument the first slider carries 2 slits and a clear field aperture. In the spectroscopic mode we use either of the two slits. The coarse slit is to be used for very faint objects where the use of the narrow slit would seriously inhibit the recording of the spectrum. Whenever possible the fine slit is to be used. The third position of this slider shows a clear field image with a fiducial cross hair in the position of the slits. The observation of the fiducial superimposed on the image can be used to observe the spatial location of the slit in the image of the object. The second slide carries the grism, i.e. the grating, which is deposited on a prism. The prism is used to counteract the deflection of the rays by the grating. Because of this arrangement the spectrometer produces an image or a spectrum close to the optic axis of the system without bending the principal rays.

The APE experiment provided valuable data on spacecraft glow and thruster emission spectra both. Apparently, both spectra appeared very weak. The glow spectrum confirmed the validity of previously obtained spectrum and showed no new structure. The thruster emission spectrum is currently being analysed and there appears to be some interesting features in the spectrum.

Perhaps one of the most significant accomplishments of the STS-33 flight is the lesson learned about how to improve low light level spectral measurements from the shuttle.

On all missions we have used the BOGEN bracket extensively. This is a multiuse mounting bracket which is not overly rigid to properly hold the instruments in position in the ground based 1g environment. However in the past it was always assumed that such mounting arrangement would be quite satisfactory in space where there is no apparent gravity to contend with. Unfortunately the spectrometer requires crew interaction to operate it and from the information the crew provided it was clear that the mounting was unsatisfactory for keeping the instrument rigid while the crew made hand adjustments. As a result of the STS-33 flight a new type of instrument mount was designed an built by the Aerospace Corporation. This mount was attached to the upper window cover clamps at four places and provided a solid mount for the APE observing instruments for look angles through the aft flight deck windows.

We also learned that the APE spectrometer in the high spectral resolution mode was not sensitive enough for the spacecraft glow measurements. On previous missions the spectrometer used a 300 lines per mm grating with a 50 mm F/1.2 lens for each collimator and camera. Using a slit which was 50 micron in width the spectral resolution was.

$$d\lambda = \frac{1}{3000} \cos\alpha \times \frac{.050}{50} = 3.3 \times 10^{-7} = 33\text{Å}$$

In order to increase the spectral resolution the for the STS-33 mission we used a narrower slit (17 micron) and increased the camera focal length to 135 mm. Thus the predicted spectral resolution became:

$$1d\lambda = \frac{1}{3000} \times \frac{.17}{50} \quad 10\text{Å}$$

Unfortunately both of these modifications resulted in a significant loss of light throughput and it was found that the STS-33 results were marginal in terms of signal-to-noise r tio. Following the STS-33 flight we made a more substantial re-design on the spectrometer.

In order to improve the grating dispersion while maximizing the light collection. Thus we purchased a 600 line pair per mm grating which doubled the dispersion. Secondly, we made a new slit mount which carried two slits: a fine slit for high spectral resolution when the intensity permitted it: and a wide slit for coarse spectral resolution for making very low light level spectral measurements.

The spectrometers we use have an imaging mode and a spectral mode. It is highly desirable that the instruments in both modes should produce the image on the optic axis of the instrument or near the center of the field. In order to accomplish this we use grisms or gratings mounted on prisms so that the first order or spectrally dispersed image should appear near the center of the field. In going to 600 lines per mm from 300 we needed to double the power of the substrate prism. To accomplish this we had to use a very high index material which permitted the use of a reasonably thin prism.

The spectrometer is illustrated on Figure 7. In the top illustration the spectrometer is in the imaging mode. A real image of the object is produced in the plane of the clear aperture and the fiducial. This image is relayed into the intensifier by the lens pair formed by the collimating and camera objective lenses. In this mode the grating is pulled out of the optical train.

In the second illustration we show one of the slits and the grating both in the optical path. Light rays from the slit entering the collimating lens will be made parallel. The parallel rays go through the grating where they get deflected different angles according to their wavelength. The substrate prism deflection is such that it counteracts the deflection of the green light rays passing though the grating. Thus, the green spectral region will appear in the center of the image. The Camera Objective focuses the parallel rays into a single point corresponding to each wavelength. Thus a spectrum is produced on the photocathode of the image intensifier.

The spectrometer slit slider was also modified and a 3 position slider was devised with detents. This way the crew member could select the direct imaging mode with a crosshair marking the position of the slit, a coarse resolution high throughput slit mode and a fine high spectral resolution slit mode.

This modification retained the spectrometer's high throughput since we were using F/1.2 optics throughout and increased the spectral resolution to about 15 Angstroms. The instrument performance can be easily verified by observing the mercury spectrum and verifying that the mercury doublet is resolvable in the fine slit mode.

As a result of the work under this program the instrumentation and the flight procedures have a reached a mature stage and the experiment is ready for a flight which has a very high probability to provide definitive results.

5. APPENDIX: Summary of Ape Flight Operations Planning

At a flight planning meeting at Johnson Space Center on the 22nd of March 1989. Drs. C. Pike and Edmond Murad from the AFGL and Dr. S. B. Mende from Lockheed defined 4 functional objectives for the APE experiment:

1. Auroral and Airglow Photography
2. Auroral Effects on the Orbiter
3. Shuttle Glow
4. Thruster induced Effects

5.1 Objective 1: SHUTTLE GLOW

5.1.1. Glow Spectra.

Scientific/Technical Objectives

The main objective is to obtain a good spectrum of the shuttle glow. The only definitive measurement of the shuttle glow in the visible was performed on the 41-D mission in September 1985. The glow spectrometer used on that occasion had a wavelength resolution of about 30-40 Å. There are only two successful spectral exposures on record. It would be extremely important to repeat the spectral exposures of shuttle glow and take advantage of the improved spectrometer.

Configuration: Spectrograph

Attitude: + or - ZLV and V in + or - Y.

Procedures: The sequence of procedures used to carry out this experiment is: APE-4, APE-15 and APE-5

View angles: View angles are illustrated on Figure 8a.

Thrusters should be inhibited for one minute prior to exposure.

5.1.2. Glow Effect on Window.

Scientific/Technical Objective

The objective is to determine the extent to which low light level photography is affected by ram glow. In this experiment we will take an image intensified image of the earth limb and stars in two cases. In one case the window is in the ram and in the other case the window is in the wake.

Configuration: Imaging Mode (White light)

Attitude: No specific attitude is requested. Whichever window is used should be in the wake in one case and in the ram in the other case.

Procedures: APE-2, APE-16, APE-5.

View Angle: View angle is shown on Figure 8b.

Thrusters should be inhibited for 1 minute prior to exposure.

5.1.3. Glow Time/Temperature Dependence

Scientific/Technical Objective

In this objective we intend to determine whether glow intensity is changing significantly during the night half orbit. As we enter the nightside on orbit the shuttle surface temperature drops significantly. According to the Swenson et al. (1985) theory the shuttle glow should become brighter.

Configuration: Imaging Mode Filters.

Attitude: + or - ZLV and v is +Y or -Y.

Procedures: APE-2, APE-9, APE-5.

View Angle: View angle is shown on Figure 8c.

Thrusters should be inhibited for 1 minute prior to exposure.

5.2 Objective 2: OMS/PRCS/VRCS PHOTOGRAPHY

Scientific/Technical Objective

The spectra of the thruster emissions were never measured during previous missions. There is one early photograph of relatively low spectral resolution which was taken in an objective grating configuration. From this photograph it appears that the thruster emission is also a continuum in the visible and somewhat similar to shuttle glow. The thruster emissions are quite bright and it should be reasonably simple to get a good high resolution spectra from the measurements.

Configuration: Spectrometer. Set the front aperture to F/1.2 Exposure 4 sec.

Attitude: It would be highly desirable to fire in one case into the ram and in the other case into the wake.

Procedures: APE-4, APE-11, APE-5. Jet firing should be synchronized with the exposure. Two crew members are required. One crew member is needed to count down and start exposure sequence while the other operates the thrusters. Upon firing of the thruster, take a series of 3 exposures of the exhaust plume. Repeat the series of 3 exposures for each thruster firing planned during this period of Orbiter darkness.

View Angle: Spectrograph slit to be aligned with centerline of thruster so that spectra is taken of the center of plume from nozzle outward (Figure 8d).

5.3 Objective 3: AURORAL AND AIRGLOW PHOTOGRAPHY

5.3.1. High Latitude Auroral Photography. (Observations at 50 magnetic or higher)

Scientific or Technical Objective

From orbit it is possible to obtain limb altitude profiles. In this experiment we will obtain auroral limb altitude spectral profiles. Such experiments were attempted on 41-G but the improved resolution of the spectrometer should provide a better data set.

Configuration: Spectrometer.

Attitude: The high latitude limb should be in the field of view.

Procedures: APE-4, X, APE-5

View Angle: Set the spectral slit on the limb containing auroras. Slit should be parallel with magnetic field (Close to local vertical in auroral regions). (Figure 8e)

5.3.2 Airglow observations magnetic latitude <50 degrees

Scientific/Technical Objective

Airglow limb observations can provide the altitude temperature profiles of the OH and O_2 bands. The dynamics of the atmosphere at 80-100 km is not very well understood. The knowledge of the temperature variations at these altitudes would be of great importance in understanding the dynamics especially gravity waves in the upper atmosphere.

Configuration: Imaging mode including the Fabry-Perot.

Attitude: Image detector must observe the limb (+ or - ZLV O.K.).

Procedures: APE-1, APE-6, APE-5.

View Angle: Take image of the limb with camera centered slightly lower than limb (Figure 8f).

5.3.3 Airglow Photography Equatorial Magnetic Latitude <15 Degrees

Scientific or Technical Objective

Study of airglow enhancements near the magnetic equator. Near the equator there are some special ionospheric turbulence phenomena taking place. 6300 and 7774 airglow shows these effects because their intensity is proportional to the local ion density.

Configuration: Imaging mode with Fabry Perot.

Attitude: Image detector must observe the limb (+ or - ZLV O.K.).

Procedures: APE-1, APE-7, APE-5.

View Angle: Take image of equatorial limb. Camera should be centered higher than the limb. Need to look at high altitude regions. (Figure 8g)

5.4 Objective 4: AURORAL EFFECTS PHOTOGRAPHY

Scientific/Technical Objective

When the orbiter is flying through some local auroral precipitation, the orbiter is bombarded by auroral particles. The purpose of this experiment is to observe if there are any optical emissions caused by the discharges which might occur under auroral bombardment.

Configuration: White light imaging mode.

Attitude: (-ZLV payload bay up)

Procedures: APE-1, APE-Y, APE-5.

View Angle: Take images of the payload bay.

Monitor Thruster History.

6. CONTRIBUTIONS

Scientists who contributed to the research in this document are:

S. B. Mende, G. R. Swenson and R. E. Meyerott

Publications and Reports

Two manuscripts which were partially sponsored by the contract were submitted for publication. These are:

Mende, S. B., G. R. Swenson, E. J. Llewellyn, W. F. Denig, D. J. W. Kendall, and T. G. Slanger, Measurements of Rotational Temperature in the Airglow with a Photometric Imaging Etalon Spectrometer. Journal of Geophys. Res., 93, 12861-12870, 1988.

Swenson, G. R. and R. E. Meyerott, Spacecraft Ram Cloud Atom Exchange and N_2 LBH Glow. Geophys. Res. Letters 15, 245-248, 1988.

7. REFERENCES

Banks, P. M., P. R. Williamson and W. J. Raitt, Space shuttle glow observations, Geophys. Res. Lett., 10, 118, 1983.

Barrett, J. L. and I. L. Kofsky, The NO-NO_2 System at laboratory- surfaces, Second workshop on spacecraft glow, NASA Conf. Pub. #2391, 165, 1985.

Bylicki, F., H. G. Weber, H. Zscheeg, and M. Arnold, On NO_2 excited state lifetimes and G factors in the 593 nm band, J. Chem. Phys., 80, 1791, 1984.

Chakrabarti S. and T. Sasseen, Investigation of vehicle glow in the far ultraviolet, Second workshop on spacecraft glow, NASA Conf., Pub. #2391, 108, May, 1985.

Conway, R. R., R. R. Meier, D. F. Strobel, and R. E. Huffman, The far ultraviolet vehicle glow of the S3-4 satellite, Geophys. Res. Lett., 14, 628, 1987.

Engebretson, M. J. and K. Mauersberger, The impact of gas-surface interactions on mass spectrometric measurements of atomic nitrogen, J. Geophys. Res., 84, 839, 1979.

Engebretson, M. and A. Hedin, *DE-2 mass spectrometer observations relevant to the shuttle* glow, Geophys. Res. Lett., 13, 109, 1986.

Green, B. D., G. E. Caledonia and T.D. Wilkerson, J. Spacecraft Rockets, 22, 500. 1985.

Heppner, J. P. and L. H. Meredith, Nightglow emission altitudes from rocket measurements, J. Geophys. Res., 63, 51, 1958.

Huffman, R. E., F. J. Leblanc, J. C. Larrabee, and D. E. Paulsen, Satellite vacuum ultraviolet airglow and auroral observations, J. Geophys. Res., 85, 2201, 1980.

Kendall, D. J. W., R. L. Gattinger, R. Wlochowicz, M. Garneau, G. J. Buttner, S. B. Mende, G. R. Swenson, E. J. Llewellyn, W. A Gault, G. G. Shepherd, B. H. Solheim and L. L. Cogger, OGLOW - An experiment to measure orbiter earth opt[illegible]l emissions, Canadian Aeronautics and Space Journal, 31, 227, 1985a.

Kendall,D. J. W., S. B. Mende, E. J. Llewellyn, W. A. Gault, and R. L. Gattinger, OGLOW- An experiment to measure orbiter glow and atmospheric emissions from the shuttle,Trans. Amer. Geophys. Union, 66, April 30, 1985b.

Kendall, D. J. W., R. L. Gattinger, E. J. Llewellyn, I. C. McDade, S. B. Mende and G. R. Swenson, Observations of glow from shuttle surfaces during mission STS-41G, Planet. Space Sci., November, 1986.

Kofsky, I. L. and J. L. Barrett, Surface-catalyzed recombination into excited electronic, vibrational, rotational, and kinetic energy states:a review, Second workshop on spacecraft glow, NASA Conf. Pub. #2391, 149, May, 1985.

Kofsky, I. L., Excitation of N_2 LBH bands emission by low earth orbiting vehicles, Geophys. Res. Lett., 15, 241, 1988.

Mende, S. B., Measurement of vehicle glow on the space shuttle, AIAA-83-CP838, AIAA Shuttle Environment and Operations Meeting, 79, 1983.

Mende, S. B., O. K. Garriott and P. M. Banks, Observations of optical emissions on STS-4. Geophys. Res. Lett. 10, 122, 1983.

Mende, S. B.,"Experimental Measurement of Shuttle Glow," AIAA-84-0550, presented at AIAA 2nd Aerospace Sciences Meeting, Reno, January 1984.

Mende, S. B., G. R. Swenson, and K. S. Clifton, Preliminary results of the Atmospheric Emissions Photometric Imaging Experiment (AEPI) on Spacelab 1, Science, 225, 191, July 13, 1984a.

Mende, S. B., G. R. Swenson, K. S. Clifton, R. Gause, L. Leger, and O. K. Garriott, Space vehicle glow measurements on STS 41D, Submitted to Journal of Rockets and Spacecraft, 1984b.

Mende, S. B., R. Nobles, P. M. Banks, O. K. Garriott and J. Hoffman, Measurements of vehicle glow on the space shuttle, J. Spacecraft and Rockets, 21, 374, 1984c.

Mende, S. B., G. R. Swenson and K. S. Clifton, Preliminary results of the Atmospheric Emissions Photometric Imaging Experiment (AEPI) on Spacelab 1, Science, 225, 191, July 13, 1984d.

Mende, S. B., G. R. Swenson, and K. L. Miller, Observations of E and F region Mg^+ from Spacelab 1, J. Geophys. Res.,90, 6667-6673,1985

Mende, S. B and G. R. Swenson, Vehicle glow measurements on the space shuttle, Second workshop on spacecraft glow, NASA Conf. Pub. #2391, 1, May, 1985.

Mende, S. B., G. R. Swenson, K. S. Clifton, R. Gause, L. Leger and O. K. Garriott, Space Vehicle Glow Measurements on STS 41-D, J. Spacecraft, 23, 189, 1986

Mende, S. B., G. R. Swenson, E. J. Llewellyn, W. F. Denig, D. J. W. Kendall, and T. G. Slanger, Measurements of Rotational Temperature in the Airglow with a Photometric Imaging Etalon Spectrometer. Journal of Geophys. Res.,93, 12861-12870, 1988.

Paulsen, D. E., W. F. Sheridan, and R. E. Huffman, Thermal and recombination emission of NO_2, J. Chem. Phys., 53, 647, 1970.

Reeves, R. R., G. Manella, and P. Harteck, Formation of excited NO and N2 by wall catalysis, J. Chem. Phys., 32, 946, 1960.

Sandie, W. G.,S. B. Mende,G. R. Swenson, and M. E. Polites, Atmospheric Emissions photometric imaging experiment for Spacelab 1, Opt. Eng., 22, 756, 1983.

Schwartz, S. E., and H. S. Johnston, Kinetics of nitrogen dioxide fluorescence, J. Chem. Phys., 51, 1286, 1969.

Shimazaki T., M. Mizushima, Shuttle Glow Emissions due to Radiative Relaxation of Highly Vibrationally excited NO molecules produced by surface reflection AIAA Rent # CP859, 79-87 (1985).

Swenson, G. R., S. B. Mende and K. S. Clifton, Space Shuttle ram glow: Implication of NO_2 recombination continuum, Second workshop on spacecraft glow, NASA Conf. Pub. #2391, 35, May, 1985a.

Swenson, G. R., S. B. Mende and K. S. Clifton, Ram vehicle glow spectrum: implication of NO_2 recombination continuum, Geophys. Res. Lett., 12, 97, 1985b.

Swenson, G. R., S. B. Mende and K. S. Clifton, STS-9 Shuttle glow: ram angle effect and absolute intensities, Geophys. Res. Lett., 13, 509, 1986a.

Swenson, G. R., S. B. Mende and E. J. Llewellyn, The effect of temperature on shuttle glow, Nature, 323, 529, 1986b.

Swenson, G. R., and R. E. Meyerott, Spacecraft ram cloud atom exchange and N_2 LBH glow, Geophys. Res. Lett., 15, 245, 1988.

Swenson, G. R., E. J. Llewellyn and S.B. Mende, Imaging observation of lower thermospheric $O(^1S)$ and O_2 airglow emissions from STS-9:Implications of height variations, J. Geophys. Res., in press, 1988.

Tennyson, P. D., P. D. Feldman, R. C. Henry and J. N. Murthy, Search for ultraviolet shuttle glow on STS-61C, EOS, 67, 322, April, 1986.

Torr, M. R., P. B. Hays, B. C. Kennedy and J. C. G. Walker, Intercalibration of airglow observations with the Atmospheric Explorer Satellites, Planet. Space Sci., 25, 173, 1977.

Torr, M. R. and D. G. Torr, Atmospheric spectral imaging, Science, 225, 169, July 13, 1984.

Torr, M. R., The UV-VIS optical environment of the shuttle, Second workshop on spacecraft glow, NASA Conf. Pub. #2391, 98, May, 1985.

Torr, M. R., D. G. Torr, and J. W. Eun, A spectral search for the Lyman-Birge-Hopfield band nightglow from Spacelab I, J. Geophys. Res., 90, 4427, 1985b.

Torr, M. R., Space Station Plasma Environment meeting, May 1987.

von Zahn, U. and E. Murad, Nitrogen dioxide emitted from space shuttle surfaces and shuttle glow, Nature, 321, 147, 1986.

Witteborn, F.C., K. O'Brien and L. Caroff, NASA Tech. Memo. 85972, 1985.

Wulf, E. and U. von Zahn, The shuttle environment effects of thruster firings on gas density and composition in the payload bay, J. Geophys. Res., 91, 3270, 1986.

Yee, J.-H., and V. J. Abreu, Optical contamination on the Atmospheric Explorer-E satellite, Proceedings of SPIE Technical Symposium, 338, 120, 1982.

Yee, J.-H., and A. Dalgarno, Radiative lifetime analysis of the spacecraft optical glows, AIAA-83-2660, AIAA Shuttle Environment and Operations Meeting, 191, 1983.

Yee, J.-H., and V. J. Abreu, Visible glow induced by spacecraft-environment interaction, Geophys. Res. Lett., 10, 126, 1983.

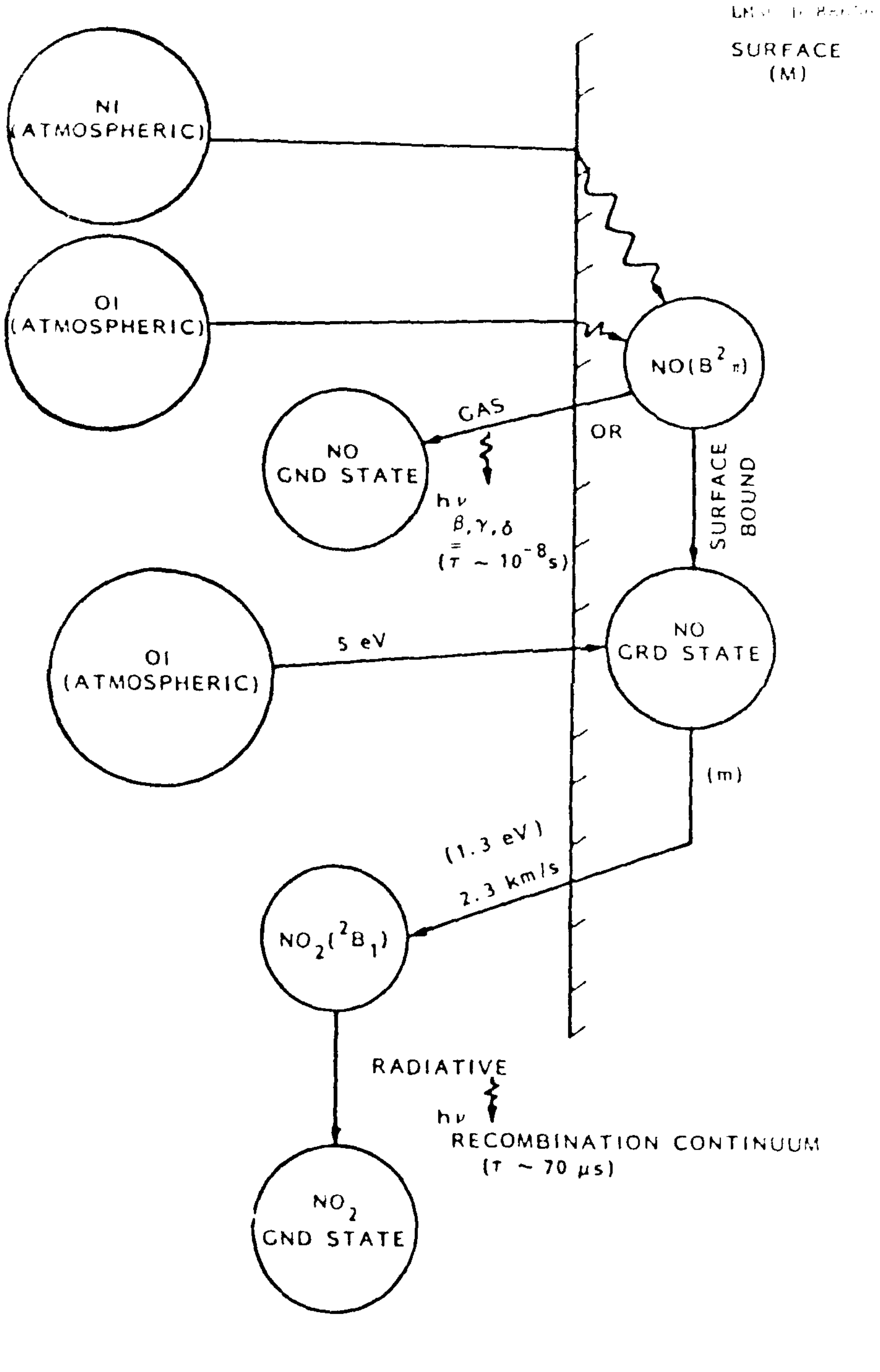


Figure 1. Schematic representation of the atomic N and O chemistry leading to the formation of NO_2 in an excited state.

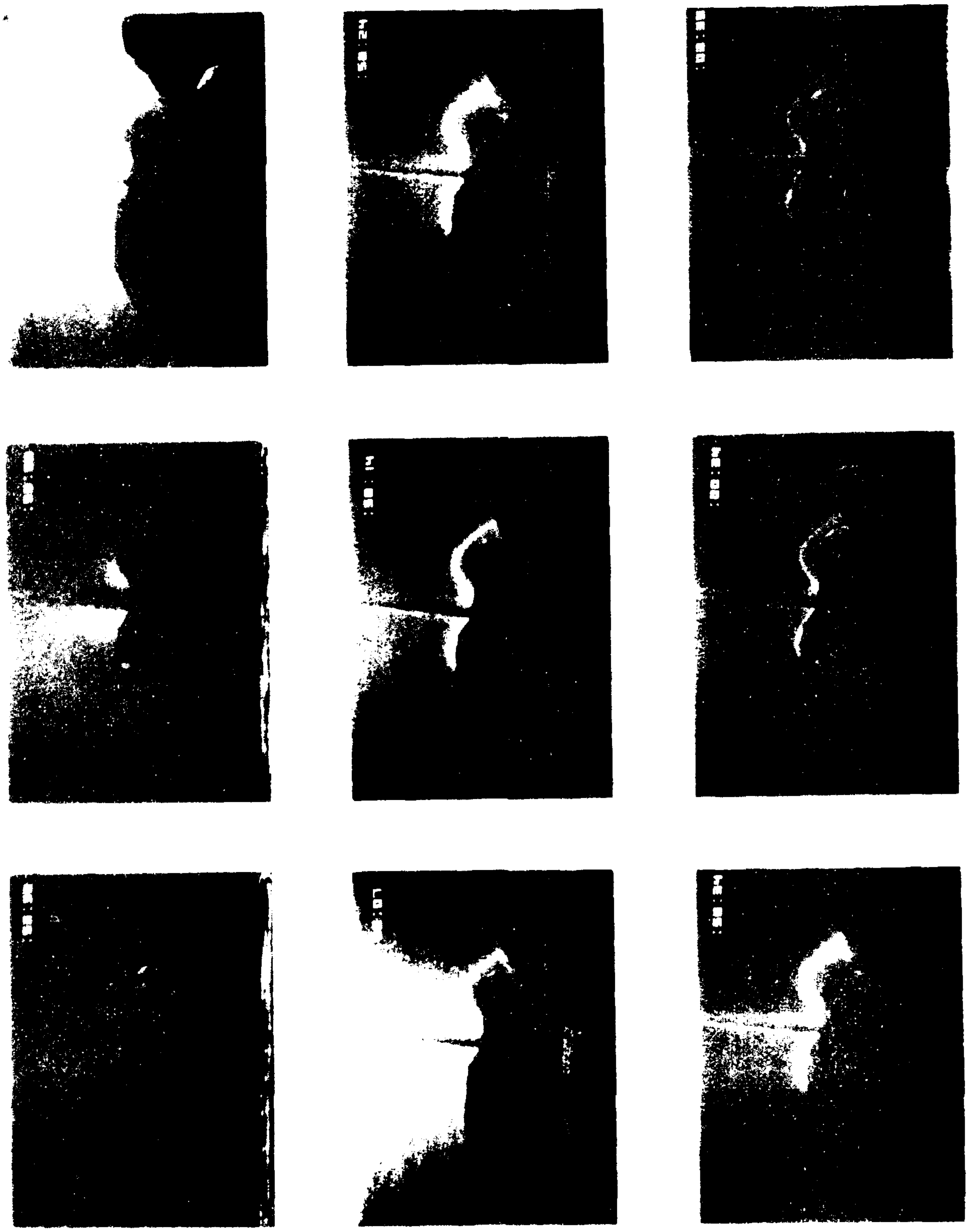


Figure 2. Collage of television monitor photographs of the thruster firing as recorded by the orbiter bulkhead closed circuit television cameras. Time counter in seconds and hundredth of seconds. Note that glow on engine pods is enhanced after jet firing.

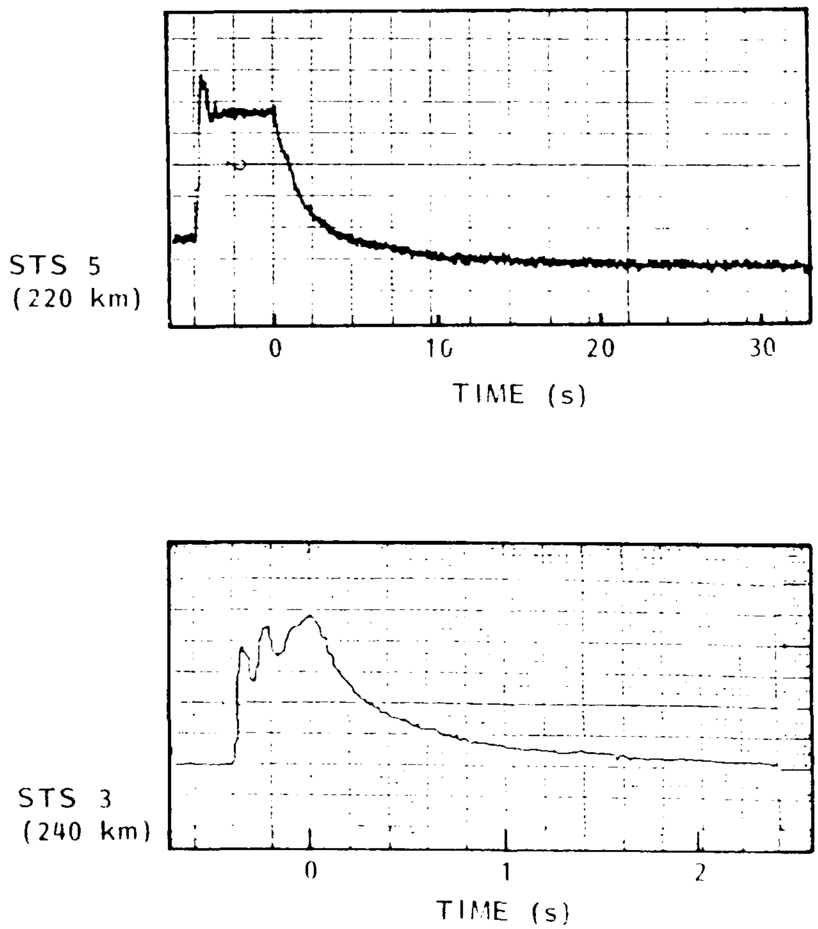


Figure 3. The function of the thruster glow intensity on the engine pods as a function of time after a thruster firing. The data was taken with the orbiter bulkhead video cameras. Intensity is in arbitrary units.

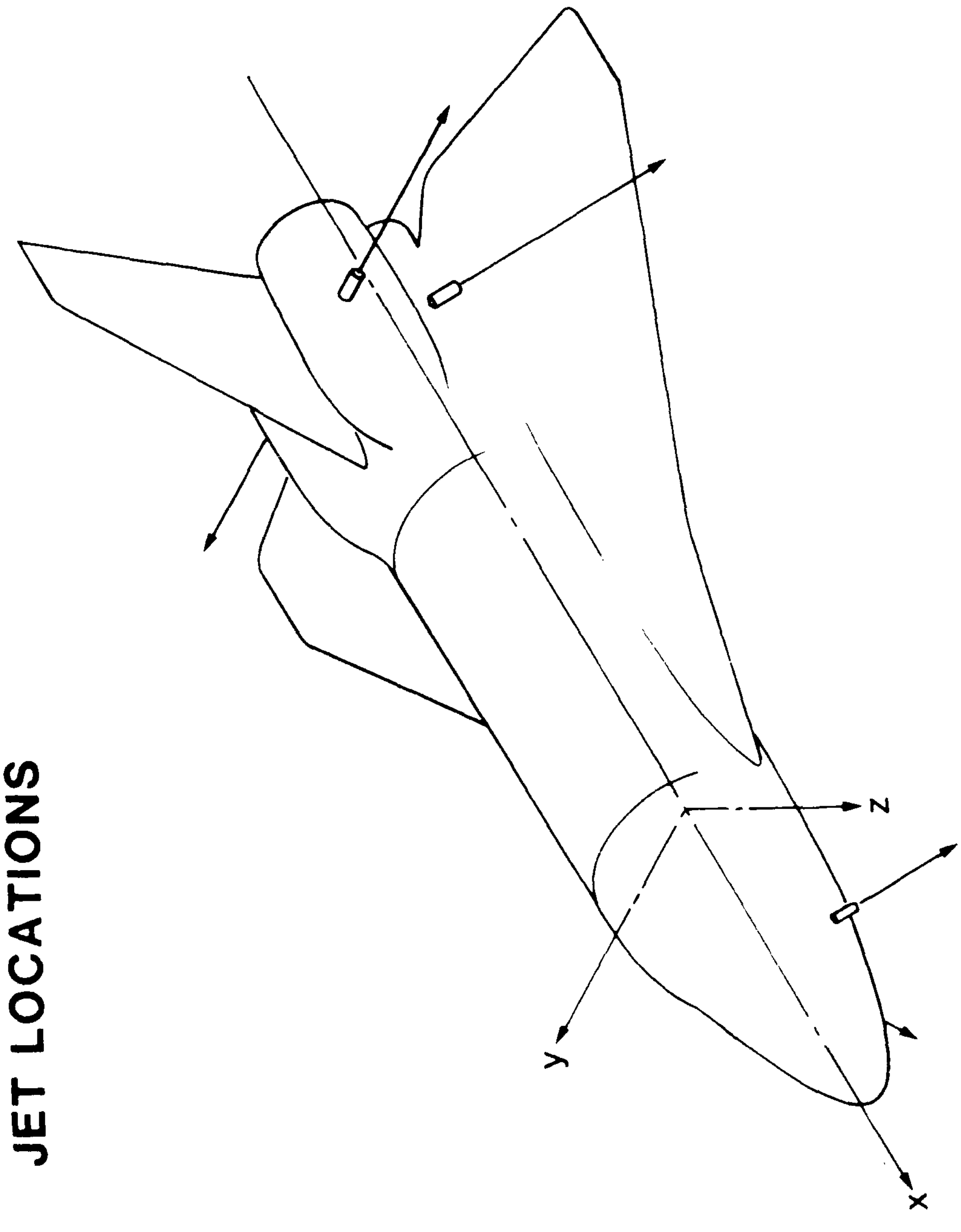
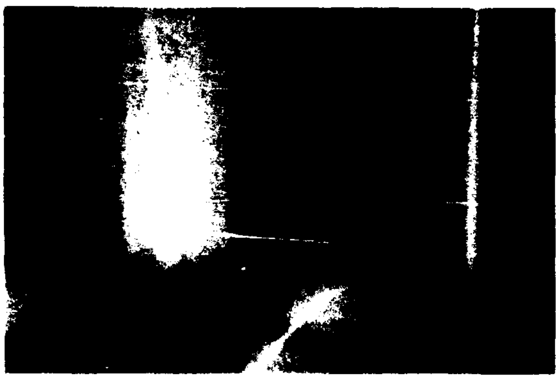
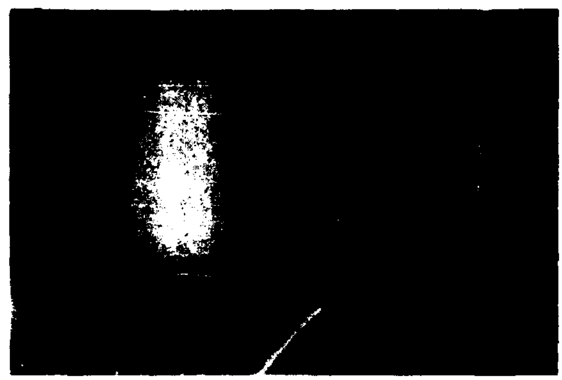


Figure 4. The position of the vernier thrusters on the shuttle orbiter.

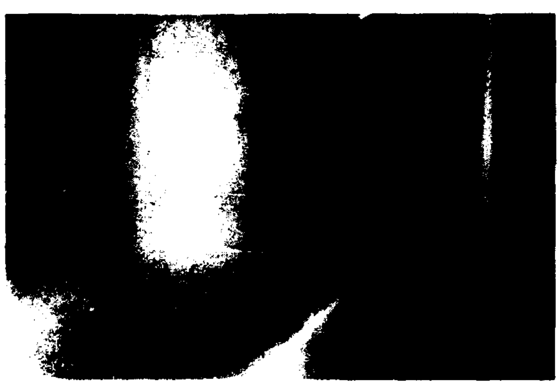
THRUSTER FIRINGS



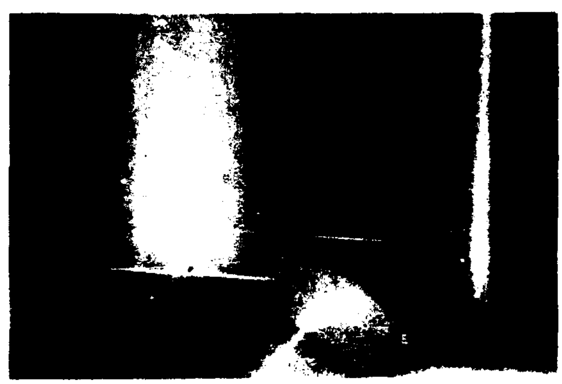
BACKGROUND



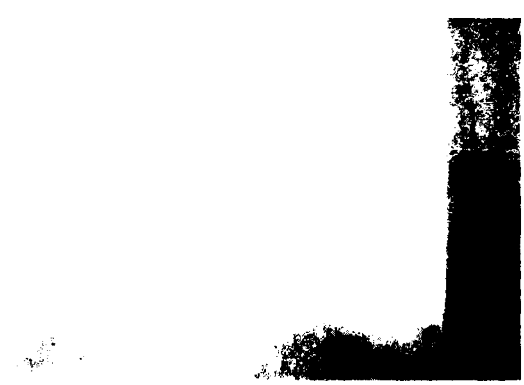
FORWARD JETS



TAIL YAW JET 1

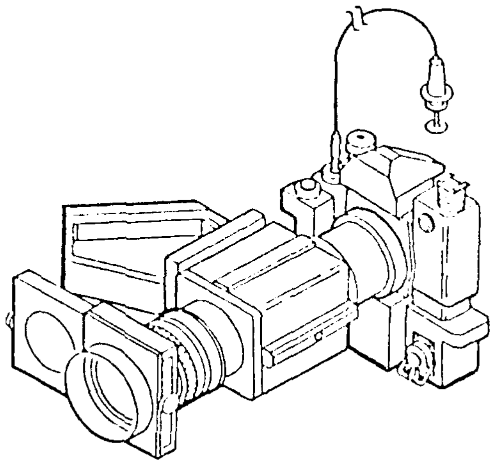


TAIL YAW JET 2

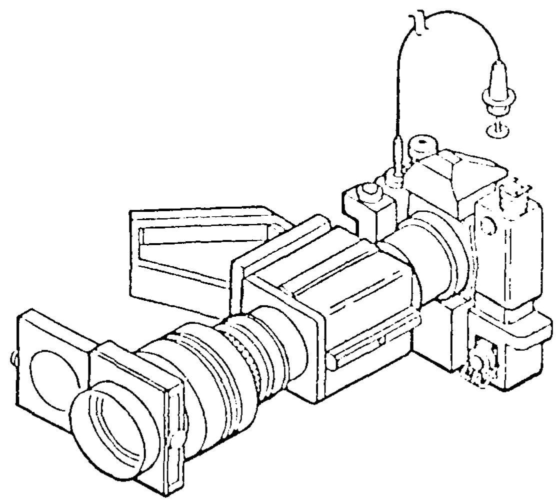


TAIL DOWNWARD JETS

Figure 5. The effect of firing thrusters during the exposures. Top left no thrusters fired.



FILTER ASSEMBLY



FABRY PEROT ASSEMBLY

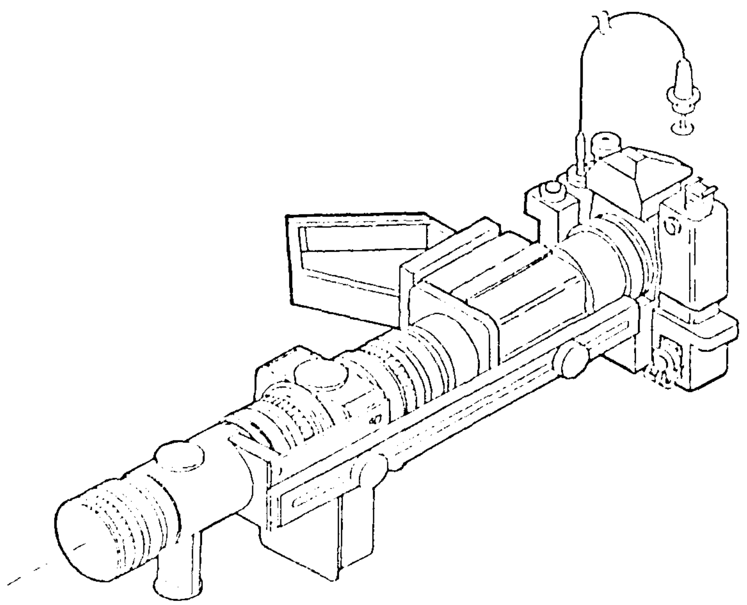


Figure 6. The ape hardware configurations.

SPECTROGRAPH ASSEMBLY

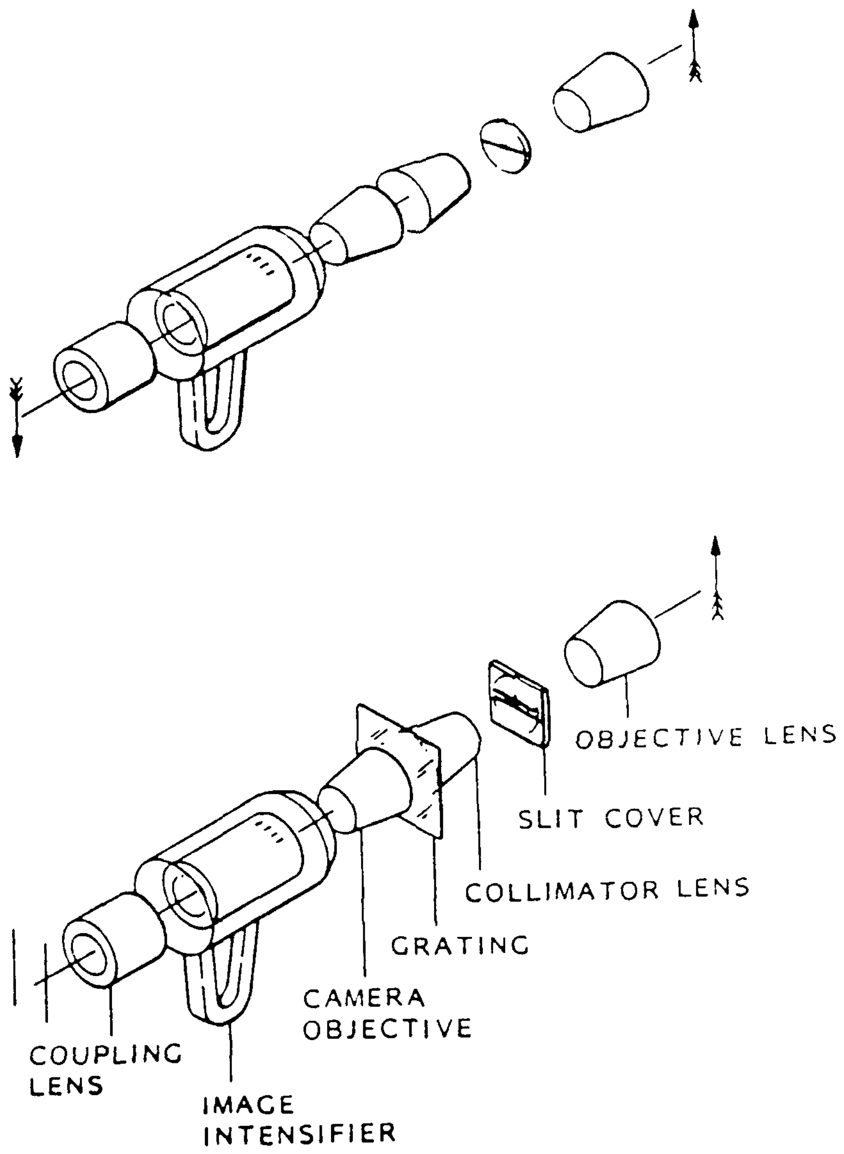


Figure 7. Image intensified slit spectrograph for shuttle glow observations.

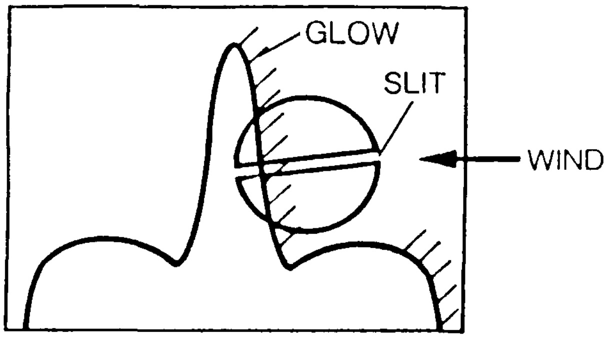


Figure 8.a. Glow spectra

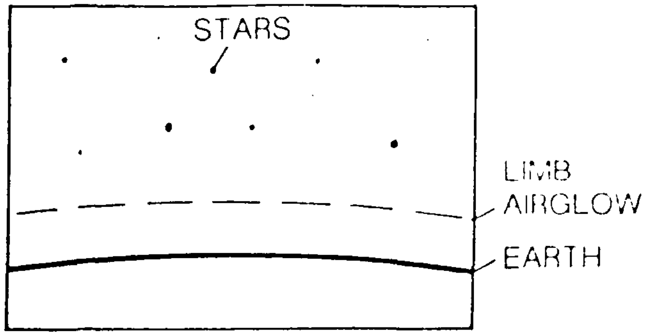


Figure 8.b. Window glow

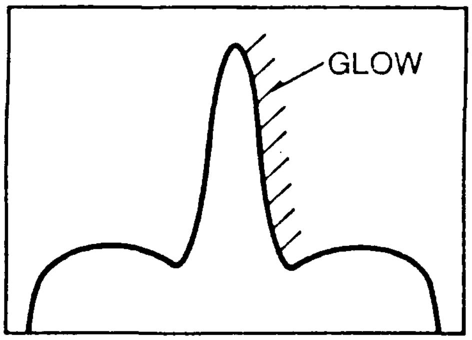


Figure 8.c. Glow image

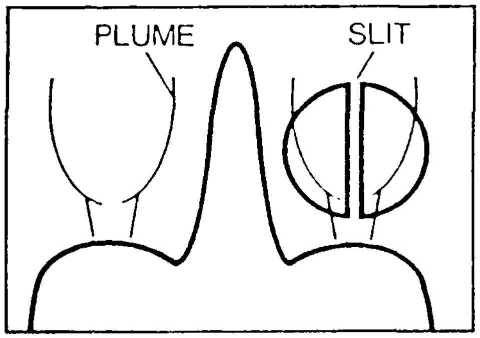


Figure 8.d. Plume spectrum

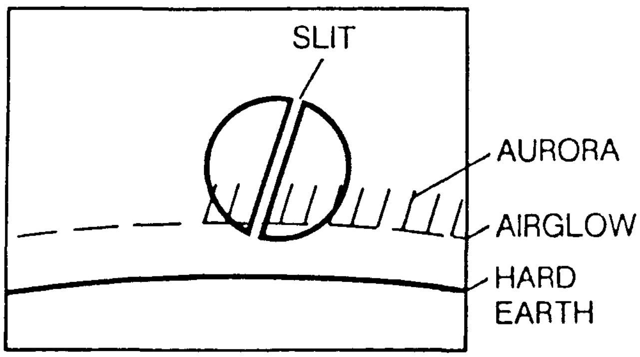


Figure 8.e. Auroral view

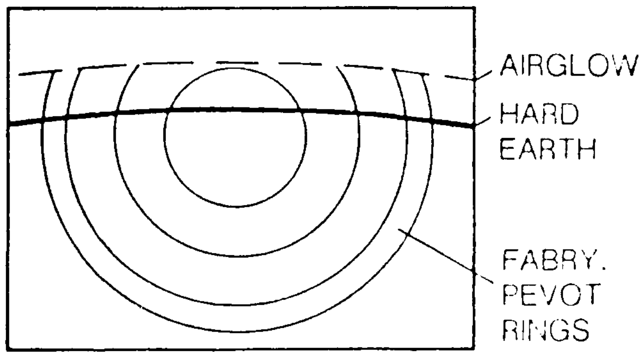


Figure 8.f. Airglow View

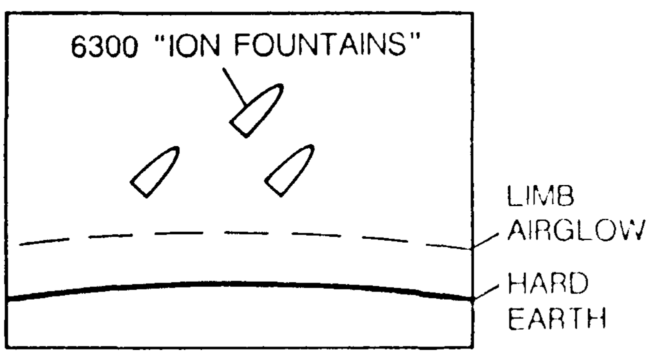


Figure 8.g. Equatorial Airglow photo

Figure 8. APE fields of views for the different observations.