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SKIRT Space Shuttle Glow Experiment

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This paper describes a spectrometer/radiometer experiment to obtain infrared, visible, and ultraviolet measurements of Space Shuttle glow. The payload, Spacecraft Kinetic Infrared Test (SKIRT), is a cryogenic circular variable filter infrared spectrometer with a number of infrared, visible, and ultraviolet radiometers covering the spectral range of 0.2–5.4 μm and 9.9–10.3 μm. It will measure Shuttle glow as a function of mission elapsed time, Orbiter attitude, temperature, and Orbiter events such as thruster firings. The measured data should have sufficient spectral resolution and sensitivity to identify molecular species contributing to Shuttle glow emissions. SKIRT is manifested on STS-39.

Introduction

IT is known that spacecraft in low Earth orbit produce a "glow" above surfaces which are oriented into ram, i.e., pointed into the direction of motion.[1] This phenomenon was first reported in 1977 on the Atmosphere Explorer satellite program,[2,3] visibly photographed somewhat serendipitously in 1982 during the STS-3 Space Shuttle mission,[4] and confirmed on numerous other Shuttle and satellite missions.[5] The glow is caused by the interaction of low-Earth-orbit spacecraft, traveling at almost 8 km/s, with ambient atmosphere where, at nominal Shuttle altitudes of approximately 300 km, atomic oxygen (O) is the predominant species. This interaction of atomic oxygen and other trace atmospheric constituents with high velocity, i.e., high kinetic energy, spacecraft surfaces and various chemicals associated with the orbiting vehicles produce excited molecules, which then emit radiation that is seen as glow above spacecraft surfaces.

Even though glow has been detected on both satellites and Shuttles, the available orbital data is very sparse and not well integrated. In the visible, hand-held spectrophotometer observations from the aft flight deck of the Shuttle have provided the most extensive data base. The source of this glow is thought to be electronically excited nitrogen dioxide (NO_2^*) created by the impact of atmospheric oxygen with nitric oxide (NO) on Shuttle surfaces facing the velocity vector,[6] In the case of low-Earth-orbit satellites, filtered photometers onboard Atmosphere Explorers have also detected excess radiances under certain orbital conditions. Highly vibrationally excited hydroxyl molecules (OH), created by the reaction of spacecraft materials with atomic oxygen, have been proposed as the source of this glow. Also, an ultraviolet glow has been observed by a spectrometer on the S3/4 satellite that is consistent with electronically excited nitrogen (N_2) and its emission. In the infrared region, vibrationally excited OH and carbon monoxide (CO) were observed with poor signal to noise on a recent satellite program. Thus, it is likely that several different processes are occurring on-orbit and there is probably not a single glow reaction mechanism.

Figure 1 gives measured glow intensities vs wavelength for Shuttle as well as for other other sensors. Shuttle glow data in

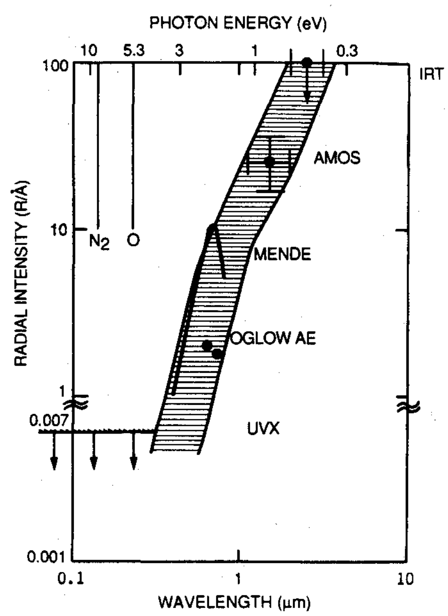

Fig. 1 Spectral distributions of satellite and shuttle glow observations as a function of intensity vs wavelength.

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this figure are limited to the visible portion of the electromagnetic spectrum by the optical transmission characteristics of the Orbiter aft flight deck windows.

Several ground-based laboratory experiments are also being conducted in an effort to duplicate on-orbit observations.[7] Figure 2 shows laboratory data contrasted with Shuttle glow observations. The laboratory luminescence data were generated by directing pulsed oxygen atoms traveling at orbital velocities toward surfaces doped with NO molecules. Heterogeneous recombination of O and NO results in NO_2^*. The excited nitrogen dioxide then leaves the surface and emits ultraviolet/visible (uv/vis) radiation. The sample surfaces in these experiments were coated with Z306 telescope baffle paint.

To understand glow emissions an on-orbit analytical investigation that provides infrared, visible, and ultraviolet spectral and temporal measurements is desirable. Our experiment, SKIRT, is designed to obtain the first dedicated on-orbit measurements of Shuttle glow from the Orbiter cargo bay at sufficient spectral resolution, sensitivity, and wavelength coverage to help identify the emitting species. Once they are identified and characterized as a function of the orbital environment, the results may be compared to ground-based laboratory experiments, reaction mechanisms postulated, and their effect on military and civilian electro-optical systems quantified.

SKIRT consists of two separate payloads, designated as SKIRT circular variable filter (CVF) and SKIRT gaseous luminosity/optical surfaces (GLOS), mounted on the Hitchhiker-M cross bay payload support structure (Fig. 3).

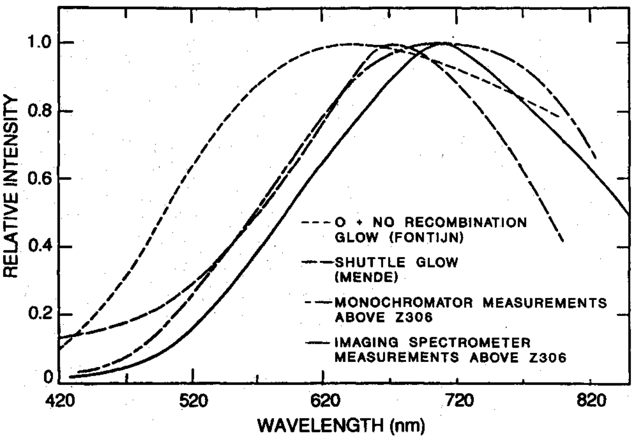

Fig. 2 Laboratory glow data contrasted with Shuttle observations in the visible wavelength region.

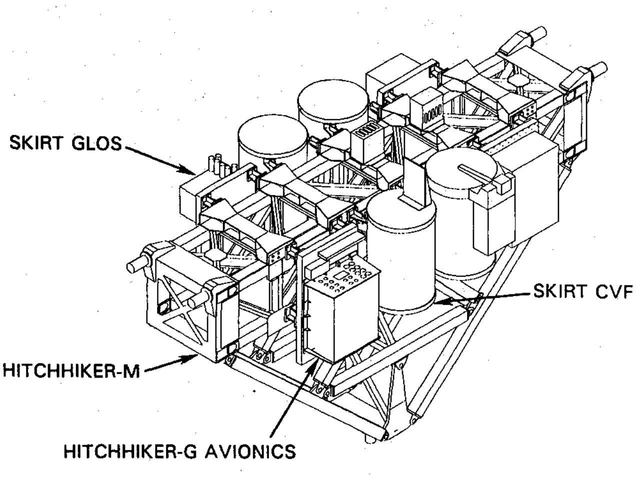

Fig. 3 STP-1 Hitchhiker payload configuration showing SKIRT CVF and SKIRT GLOS mechanically mounted on the Hitchhiker-M cross bay payload support structure with an electrical interface to the Hitchhiker-G avionics.

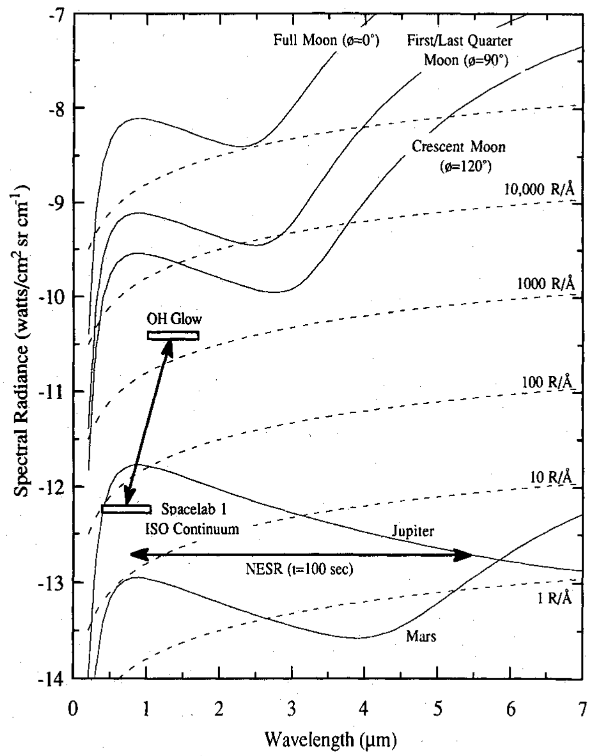

Fig. 4 SKIRT CVF sensitivity limits, as compared with possible glow intensities and calibration sources.

Together with other experiments and avionics, it is designated as STP-1 and is manifested on STS-39 for a 1991 launch into a 260-km altitude circular orbit. SKIRT is a joint U.S. Air Force and NASA experiment managed by the Optical Environment Division, Geophysics Directorate, Phillips Laboratory, U.S. Air Force Systems Command. Integration and flight operations support are provided by the Hitchhiker Program Office of NASA Goddard Space Flight Center.

This paper describes SKIRT mission objectives, hardware design, and flight operations.

Mission Objectives

SKIRT's primary mission objective is to obtain simultaneous spectral and radiometric measurements of Space Shuttle glow. Since this effect occurs when spacecraft surfaces are exposed to ram, SKIRT is designed to operate during ram and nonram attitudes to obtain glow and nonglow measurements. An aluminum plate mounted near the SKIRT CVF field-of-view provides a surface glow source when oriented into the velocity vector. We expect to see glow emissions not only from this plate, but also from surrounding payload and Orbiter surfaces. During nonram attitudes space background and ambient Orbiter environment will be measured. Subtracting spectrometer and radiometer nonram background signals from ram attitude signals should provide surface glow signatures. Based on these data, we hope to identify the chemical species associated with Shuttle glow and quantify emission intensities as a function of mission elapsed time, surface temperature, Orbiter attitude, Orbiter environment, Orbiter activities, and atmospheric composition.

A secondary objective is to provide data on the general Orbiter environment in support of the CIRRIS-1A cryogenic infrared Earthlimb sensor which is a primary payload onboard STS-39.[8]

Figure 4 shows the SKIRT CVF sensitivity limit as compared with possible glow intensities and calibration sources. The noise equivalent spectral radiance (NESR) after 20 co-added scans is indicated. Dashed curves are constant levels in Rayleighs/Angstrom. Radiances are given for various lunar

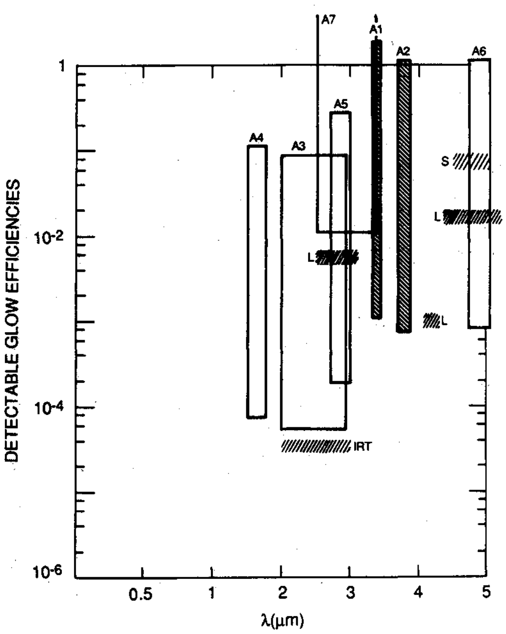

Fig. 5 Detectable glow limits with SKIRT GLOS radiometers showing the dynamic ranges for several of the detectors.

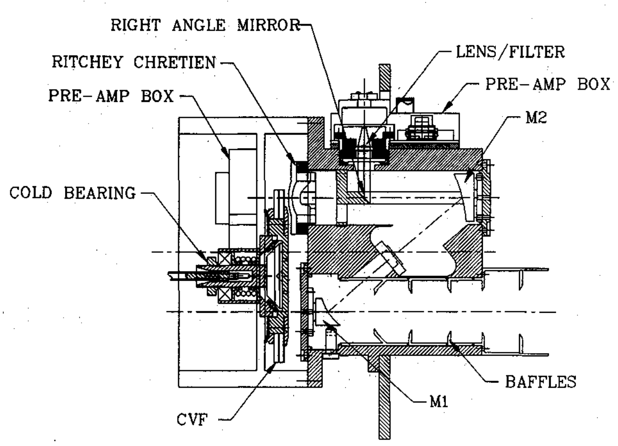

Fig. 6 SKIRT CVF optical head assembly.

phases and for Mars. The expected OH Meinel band emission is shown, as estimated from Imaging Spectrometric Observatory measurements on Spacelab 1.[9] Figure 5 shows the detectable glow efficiencies and dynamic ranges vs wavelength for several of the SKIRT GLOS radiometer channels.

Payload Design

SKIRT CVF

SKIRT CVF is a solid-nitrogen-cooled infrared circular variable filter spectrometer with a long wavelength infrared (LWIR) radiometer that shares the same collection optics. The spectrometer uses an In:Sb detector and covers the wavelength region of 0.7–5.4 μm at 2–3% spectral resolution (the use of a CVF spectrometer for measuring shuttle glow in the infrared was proposed by Mumma and Jennings in 1985[10]). The radiometer has a Hg:Cd:Te detector and covers a single broad channel from 9.9–10.3 μm. This spectral region is in between the strong vibrational rotational band emissions of atmospheric ozone and carbon dioxide at 9.6 μm and 15 μm, respectively. It is a region of high optical transmission and is considered an "atmospheric window" for infrared systems which must have a clear optical path looking through the atmosphere. It is included in this experiment to determine if there is any filling in of this bandpass by glow emissions. The detectors and optical components are cooled to 60 K. Specifications are shown in Table 1.

Table 1 SKIRT CVF/radiometer specifications

Spectrometer	
Wavelength range	0.7–5.4 μm
Spectral resolution	2% nominal
Detector	In:Sb
NESR (60 K, 5 μm, 17 Hz)	6×10^{-12} W/cm^2 sr cm^{-1}
Scan time	5 s
Field of view	2×2 deg (full)
Aperture size	1.52 cm (diameter)
Optical transmission	>0.4
Operating temperature	<60 K
Instrument power	30 W
Heater power	30 W
Radiometer	
Spectral bandwidth	9.9–10.3
Detector	Hg:Cd:Te
NER (60 K, 11 μm, 17 Hz)	9×10^{-9} W/cm^2 sr
Field of view	2×2 deg (full)
Aperture size	1.52 cm (diameter)
Optical transmission	>0.4
Operating temperature	<60 K
Instrument power	30 W
Heater power	30 W
Dewar	
Cryogen	N_2 solid
Pumping method	Vent to ambient
Hold time	5 days preflight 60 days on-orbit (closed cover)

The optical assembly (Fig. 6) includes collecting and reimaging optics, a vibrating reed chopper, a rotating filter, and detector/preamplifier assemblies. Incoming radiation enters from the right through a baffled tube onto mirror M1. The collected energy is then chopped by the vibrating reed chopper located immediately behind the first field stop and sent to M2. For the CVF, relay optics reimage the field stop at the first surface of the rotating filter. The CVF consists of four segments. Each segment is a wedge-coated interference filter and has spectral optical transmission characteristics linearly dependent on radial position. Only energy that passes through a particular section of the filter segments is reimaged onto the detector. In the case of the radiometer, a right-angle mirror diverts a portion of the beam through the narrow bandpass filter and a germanium lens focuses the energy onto the detector.

The SKIRT CVF also has a dewar/cryogen system, aperture cover assembly, glow plate, and avionics. Figure 7 is a drawing of the payload. This assembly is mounted into a Get Away Special can that has been adapted for a Hitchhiker mechanical and electrical interface.

The SKIRT CVF dewar uses solid nitrogen as the working cryogen for cooling the optical instruments. The thermal design provides the following:

1) Maintains the nitrogen in a solid phase after final freezing for approximately 5 days prior to launch.

2) Provides sufficient cryogen capacity for an 8-day mission.

3) Ensures the cryogen will safely vent in the event of loss of dewar jacket vacuum. Space Shuttle safety requirements are a primary design consideration.

The dewar encloses a 38.6-l cryogen tank filled with 94% void fraction aluminum foam (to ensure good thermal paths between the cryogen and tank wall). The effective cryogen volume is approximately 36 l. Surrounding the tank is a single vapor-cooled radiation shield (VCS) with multilayer insulation.

Prior to launch, the system is filled with liquid nitrogen and then frozen to approximately 30 K by flowing liquid helium through heat exchanger coils. The pressure of the nitrogen after freezing is below atmospheric. Since ground vacuum venting is not provided, there is no venting of nitrogen vapor during launch pad hold time and the VCS will not be operational. The parasitic heat load into the cryogen on the ground in a launch configuration is approximately 1.8 W. Because of this, the solid nitrogen is subcooled sufficiently to prevent it from melting at 63 K (94 Torr) prior to launch. Hold time on the pad is helped by two phase changes of the nitrogen — solid/solid at 35 K and solid/liquid at 63 K.

Following launch, the system will begin venting through a mechanical check valve set for 15 Torr, which corresponds to a solid-vapor state at 55 K. Once in orbit with the VCS active, the parasitic heat load will be 1.3 W with the aperture closed and 2.1 W when the aperture is open and the experiment operational. On-orbit cryogen lifetime is estimated at approximately 60 days, which should ensure uniform cryogenic operation during the planned 8-day mission.

The top plate is provided by the SKIRT CVF payload since it contains the aperture cover assembly and glow plate. The aperture cover is commanded open by the ground via S-band telemetry for on-orbit operations. Otherwise, it remains closed to prevent contamination of the cryogenic optics from Orbiter activities such as thruster firings, water dumps, and other events that produce condensible gaseous products around the vehicle. The glow plate is aluminum painted with a standard

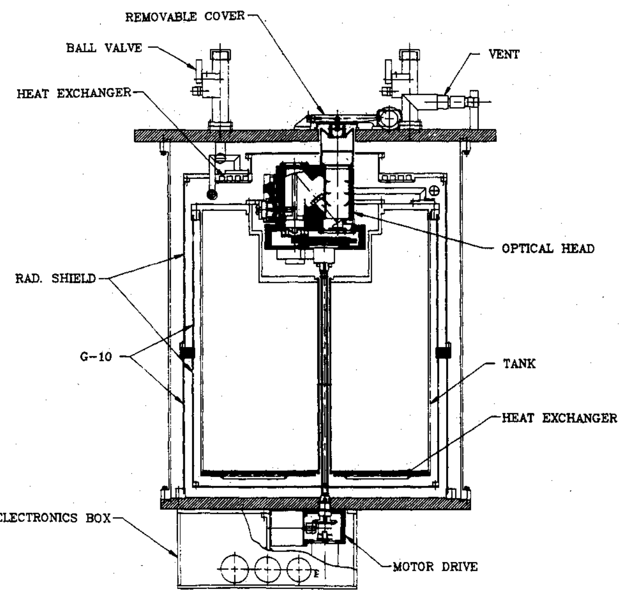

Fig. 7 SKIRT CVF drawing showing major components. This assembly mounts into the NASA Get Away Special can.

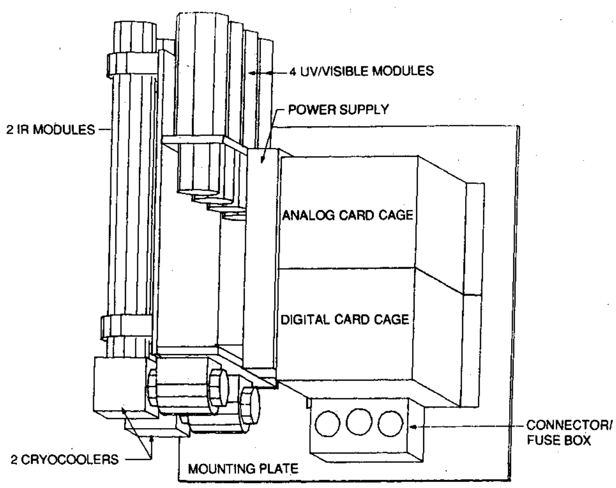

Fig. 8 SKIRT GLOS drawing with payload and containment covers removed showing the two IR modules and four UV/VIS modules.

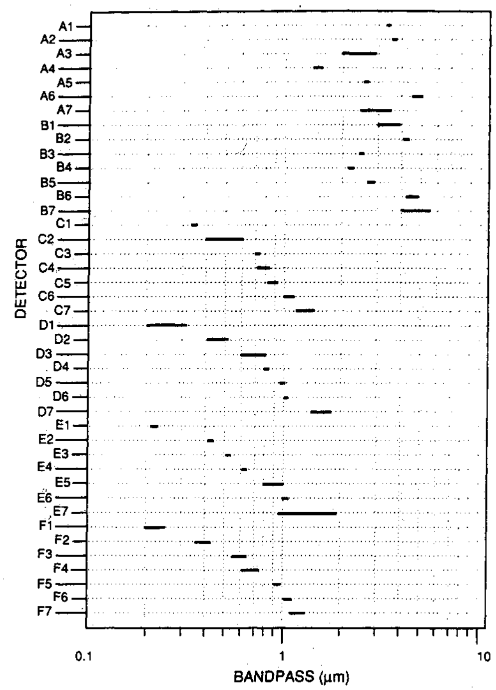

Fig. 9 SKIRT GLOS detector channels configuration covering the infrared, visible, and ultraviolet wavelengths.

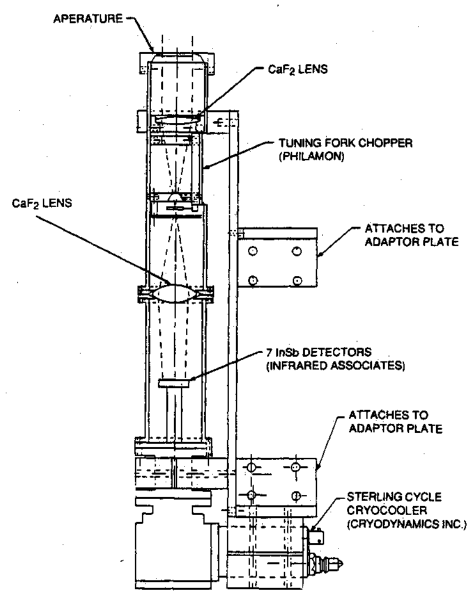

Fig. 10 SKIRT GLOS infrared module.

telescope baffle paint, Chemglaze Z306, which from previous experiments[11] is known to provide an intense visible glow when exposed to ram. The plate is mounted just outside the sensor's 2 × 2-deg field of view in order to provide a known surface glow source for the experiment and has sensors to monitor the plate temperature. The bottom cover is provided by NASA and provides connections from the SKIRT avionics box to the Hitchhiker avionics for power as well as real-time commanding and telemetry data downlink. All SKIRT CVF data are sent via Ku-band telemetry to the NASA Goddard Space Flight Center for real-time processing and display.

SKIRT GLOS

SKIRT GLOS (Fig. 8) is designed for radiometric measurements in the infrared, visible, and ultraviolet wavelength regions. There are 42 filtered channels covering the spectral region from 2000 Å to 5.4 μm. The bandpasses, displayed graphically in Fig. 9, were selected to isolate emissions from specific radiators. SKIRT GLOS is mounted on the Hitchhiker-M (Fig 3) such that its parallel fields of view are along the orbiter's Z axis looking vertically out of the cargo bay. In this orientation, it measures near-field emissions from orbiter and payload surfaces as well as Shuttle-associated gases and particles. The radiometers are functionally grouped into two categories, infrared and uv/vis.

To obtain sensitivity adequate to measure infrared emissions there are two infrared radiometer modules, which have 14 indium antimonide detectors mounted on the cold heads of two closed-cycle cryocoolers (Fig. 10). These detectors and filters are held near 80 K and cover from 1.5–5.4 μm. The emissions in the optical path above the payload are collected using telescoped optics with tuning fork choppers. Glow efficiencies of 10^{-4} photons per incident atomic oxygen are detectable from the phase-sensitive amplification network. The cryo-coolers are Cryodynamics, Inc. Model M15-R Stirling cycle cryogenic refrigerators using helium as the working gas. Because of the inability to efficiently dissipate thermal energy from the refrigerators while in the Orbiter cargo bay, the infrared modules will not operate continuously, but will be commanded on/off as upper temperature limits on the hardware permit.

Table 2 SKIRT GLOS detector filter bandpasses

Detector element	Bandpass, μm
A1	3.374–3.478
A2	3.699–3.874
A3	1.999–2.930
A4	1.519–1.784
A5	2.719–2.769
A6	4.734–5.038
A7	2.528–3.427
B1	3.067–3.984
B2	4.161–4.355
B3	2.582–2.634
B4	2.283–2.391
B5	2.817–2.943
B6	4.324–4.916
B7	4.075–5.500
C1	0.325–0.375
C2	0.400–0.600
C3	0.725–0.775
C4	0.775–0.825
C5	0.875–0.925
C6	1.020–1.120
C7	1.326–1.526
D1	0.275–0.325
D2	0.475–0.525
D3	0.600–0.800
D4	0.825–0.875
D5	0.975–1.025
D6	1.020–1.120
D7	1.530–1.800
E1	0.225–0.275
E2	0.425–0.475
E3	0.525–0.575
E4	0.625–0.675
E5	0.800–1.000
E6	1.075–1.125
E7	0.950–1.950
F1	0.200–0.250
F2	0.375–0.425
F3	0.575–0.625
F4	0.675–0.725
F5	0.925–0.975
F6	1.025–1.075
F7	1.120–1.320

There are four uv/vis modules using silicon and germanium detectors covering the wavelength range of 0.2–2.0 μm. Table 2 shows specific bandpasses for each of the 28 detector elements. To study transient events, such as thruster firings, eight of the radiometer channels will be sampled every 0.1 s. This time scale is comparable to thruster duration and near-field residence times. The data from all 42 radiometers are acquired simultaneously and an onboard microprocessor is used to sequence, format, and configure the data for real-time telemetry downlink.

Flight Operations

Since SKIRT is a Hitchhiker experiment, it is designated by NASA as a secondary payload and must therefore be scheduled in the timeline on a noninterference basis with the primary payloads. Fortunately, SKIRT was designed as a complementary experiment to the primary CIRRIS-1A infrared payload and piggybacks on many of its operations. In addition, once the CIRRIS-1A cryogen is exhausted on mission elapsed time (MET) day 5, on-orbit time becomes available and several dedicated blocks in the timeline have been set aside for specific SKIRT measurements.

Once the cargo bay doors are opened at MET 3 h SKIRT GLOS will be commanded on. Because of contamination concerns SKIRT CVF will be not be turned on until MET 21 h. This will allow the initial gaseous contamination inherent with the Orbiter to disperse down to lower concentrations, thus preventing gross contamination of the SKIRT CVF cryogenic surfaces. At MET 21 h, the Orbiter will be oriented such that it is flying starboard wing into the velocity vector and the cargo bay pointed to space. In this attitude, the SKIRT CVF glow plate will be exposed to ram. The instrument aperture will be commanded open and infrared spectra of Shuttle glow will be measured and the data telemetry down-linked to the ground. During this time, a mass spectrometer flying with the CIRRIS-1A will also be taking data to provide complementary data on Shuttle environment and atmospheric composition. SKIRT CVF and GLOS will operate under command and monitoring by ground personnel. Normally, SKIRT CVF will conduct a spectral scan every 5 s, but it also has the capability to stay at a specific wavelength if ground experimenters wish to monitor a spectral feature of interest. The Hitchhiker system offers the experimenter real-time data (S-band and Ku-band) and real-time commanding (S-band), thus making it a very powerful way of conducting space experiment operations independent of the Shuttle crew and NASA JSC controllers. At MET day 7 when the Shuttle contamination should be at its lowest levels, the Orbiter will conduct a flat spin maneuver to rotate the glow plate in and out of ram. This will measure effects of ram angle on glow. Calibrations and other measurements are planned at various times throughout the mission.

Summary

SKIRT CVF and SKIRT GLOS are designed to obtain spectral and radiometric measurements of Shuttle glow with sufficient spectral coverage and sensitivity to identify radiating species as a function of mission elapsed time, ram angle, temperature, and Orbiter environment. The results of this experiment are expected to help us understand the qualitative and quantitative nature of Shuttle glow and to extrapolate that chemistry to military and civilian electro-optical systems operating in low Earth orbits.

Acknowledgments

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NASA Goddard Space Flight Center Hitchhiker Office with funding provided by HQ Space Systems Division (AFSC). SKIRT CVF was designed and fabricated by Space Systems Engineering and SKIRT GLOS was designed and fabricated by Physical Sciences Incorporated. Specific acknowledgments are given to R. Olsen, G. Frodsham, and J. Frodsham of Space Systems Engineering; J. Griffin and R. Steeves of the Aerospace Engineering Division; S. Price, E. R. Good, F. Robert, D. Jacavanco, and G. Zdyb of the Optical/Infrared Technology Division, Geophysics Directorate, Phillips Laboratory (AFSC); J. Ulwick and A. Steed of Utah State University; D. Tremblay and G. Sacco of Physical Sciences Inc.; F. Espenak, T. Goldsmith, C. Chidekel, G. Durback, and D. Knapp of NASA GSFC; R. Agardy of The Aerospace Corp., V. Gehr of Omitron; S. Sheffield of Rockwell International; and C. W. Brown of the Department of Chemistry at the University of Rhode Island. Special acknowledgment is given to Carl J. Rice of The Aerospace Corporation, who is one of the SKIRT co-principal investigators. This work is part of the Ph.D. Dissertation for Mark Ahmadjian in the Department of Chemistry at the University of Rhode Island.

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