HARP Assessment of Uncertainty

The HIAPER Airborne Radiation Package (HARP) was designed to produce accurate measurements of actinic flux and irradiance. The Atmospheric Radiation Group (ARG) at the University of Colorado designed the irradiance measurements. The Atmospheric Radiation Investigation and Measurement group at NCAR designed the actinic flux measurements. Careful optical and detector design, multiple calibration techniques and model comparisons have been employed to minimize measurement uncertainties.

Measurement	Optical Design	Spectral Description	Wavelengths (nm)	Pixels	Sampling (nm)	FWHM (nm)
Actinic Flux	Concentric Domes	UV-VIS	280-680	512	0.8	1.7 @ 297 nm, 2.4 @ 400 nm
Irradiance Si	Integrating Sphere	VIS-NIR	260-1090	1024	0.8	3
Irradiance InGaAs	Integrating Sphere	NIR	903-2217	256	5	16

Optical development: The actinic flux optical collectors were manufactured by metcon inc with strict specifications for the angular response. The development of the irradiance optical light collectors was completed at NASA Ames, with testing and characterization conducted at the Atmospheric Physics Radiation Laboratory and the NASA Ames Airborne Sensor Facility. Additional angular response testing was conducted in the ARIM laboratory. Angular response uncertainties are summarized below in the discussion of measurement precision.

Detector design: The actinic flux system employs a Zeiss MCS (Multi Channel Spectrometer) monolithic monochromator equipped with a Hamamatsu S 7301-906 windowless back thinned blue enhanced 534 pixel cooled CCD detector. The combination of the monochromator, slit size and CCD provides a wavelength range of 280-680 nm with an effective 1.8 nm FWHM (Full Width at Half Maximum) resolution with a 20 micron entrance slit. The CCD temperature is controlled at 1.0° C by a piezoelectric cooler and control electronics. The system exhibits exceptional sensitivity from the UV into the visible which allows rapid full spectral acquisition times. Single monochromator systems traditionally have had difficulties measuring UV-B radiation due to stray light contamination of the UV-B signal. This monolithic monochromator/CCD combination minimizes the stray light by careful optical design and the use of a windowless CCD, eliminating a scattering source at the detector. Testing of the system in ambient solar radiation demonstrated spectral acquisition times of 100 ms which will allow for 5-10 Hz spectral data on the aircraft, making studies of cloud and aerosol radiation field perturbations and fast photochemistry possible. The system is contained in a sealed instrument box to prevent moisture condensation on the CCD elements.

The primary components of the spectral irradiance sensors for HIAPER are similar to those used on the IfTAlbedometer and the NASA Ames Solar Spectral Flux Radiometer (SSFR) (Pilewskie et al., 2003). The SSFR is sensitive in the spectral region between 300 nm and 2200 nm and is comprised of an identical pair of Zeiss Monolithic Miniature Spectrometer Modules (MMS 1 and MMS NIR) for simultaneous zenith and nadir viewing. The MMS-1 is equipped with a flat-field, 366 grooves/mm grating and a 256-element Hamamatsu Si linear diode array detector. The MMS-1 modules are temperature stabilized at 27°C ± 0.3°C. The MMS-NIR has a 179 1/mm flat-field grating with a 128-element InGaAs linear diode array that is thermoelectrically cooled to 0°C. Spectral resolution is 9 nm for the MMS-1 and 12 nm for the MMS-NIR. The spectral irradiance sensor for HARP has an expanded near-infrared spectral range to 2217 nm with a new 256-element Hamamatsu extended InGaAs array. For the shorter wavelength portion of the spectrum the Zeiss MCS UV-NIR 1024-pixel multi-channel spectrometer is uses, similar to that currently used in the IfT Albedometer. This improves the spectral resolution (full width at half maximum approximately 3 nm) and sampling resolution (0.8 nm). The Zeiss MCS is encased in a ceramic housing for thermal stability (temperature induced drifts less than 0.005 nm/K). During calibrations and flight, the irradiance dark current is monitored routinely by means of a triggered shutter, to ensure proper removal of the background signal. This is critical for the irradiance measurements as the sensors are particularly sensitive to temperature shifts.

Accuracy Determined from Instrument Calibration: Spectrally resolved flux measurements require accurate wavelength assignment and radiometric spectral calibrations. The Atmospheric Radiation Investigations and Measurements (ARIM) calibration facility in the Atmospheric Chemistry Division includes multiple line sources for wavelength calibrations from the UV to the NIR (Shetter and Müller, 1999). Additional irradiance assignment calibration is achieved by referencing to various sources such as HeNe lasers, temperature stabilized laser diodes, and several line sources from Hg, Xe, and Ar lamps. The actinic wavelength accuracy of <0.2 nm results in radiometric uncertainties of about 1.5% in the UV-B, 0.5% in the UV-A and 0.2% in the visible. The irradiance wavelength accuracy is as large as 1 nm in the NIR, however, the larger FWHM results in small irradiance uncertainties (<<1%).

An enclosed optical bench was used for precise distance measurements of irradiance calibrations using multiple 1000 watt NIST traceable QTH irradiance standards from 250-2400 nm. For the absolute calibration of the fluxes, the largest uncertainty arises from the calibration lamp certification (4.0% in the UV-B range and 3.0% in the UV-A range, 2% in the visible range and 4-5% in the NIR). Regular intercomparisons have been performed to assess the quality and consistency of the standards and remove outliers. The accuracy of the current output of the power supply is given by the manufacturer to be +/-0.1%, which results in a maximum uncertainty in the UV-B intensity of 0.9%. The uncertainty from how well the geometrical conditions of the original calibration were reproduced in our calibration stand is estimated to 1.5%. The determinations of the distance from the lamp filament to the effective plane of the collection head can be carried out with an overall uncertainty of 4 mm which translates into an uncertainty of 1.0% at the 50 cm calibration distance.

The laboratory calibrations of the spectrometer systems using the NIST standards provide accurate primary calibrations pre- and post-deployment. Laboratory calibrations are also done with a field calibration unit to link the primary standard to a secondary 250 watt QTH reference lamp. The field calibration unit can then be used to track any changes in the spectrometers sensitivities during deployments. This unit contains a short fixed optical bench, line source wavelength calibration lamps, and a radiometric power supply. For the transfer to the field calibration stand, we estimate an uncertainty of 2.0%.

The uncertainty of actinic flux measurements in the UV-B can be dominated by stray light in the spectrometer without careful signal correction. The uncertainty of this correction is difficult to quantify and increases near the detection limits of the spectrometer. This is an area of research in the actinic flux community.

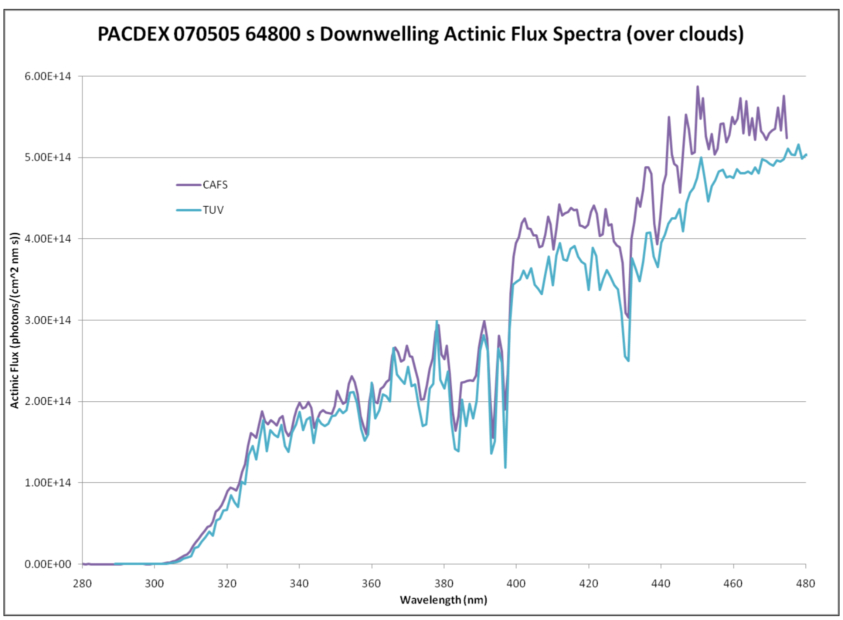
The accuracy assessment of the calibration is summarized in the table below:

Absolute Calibration Uncertainty Summary

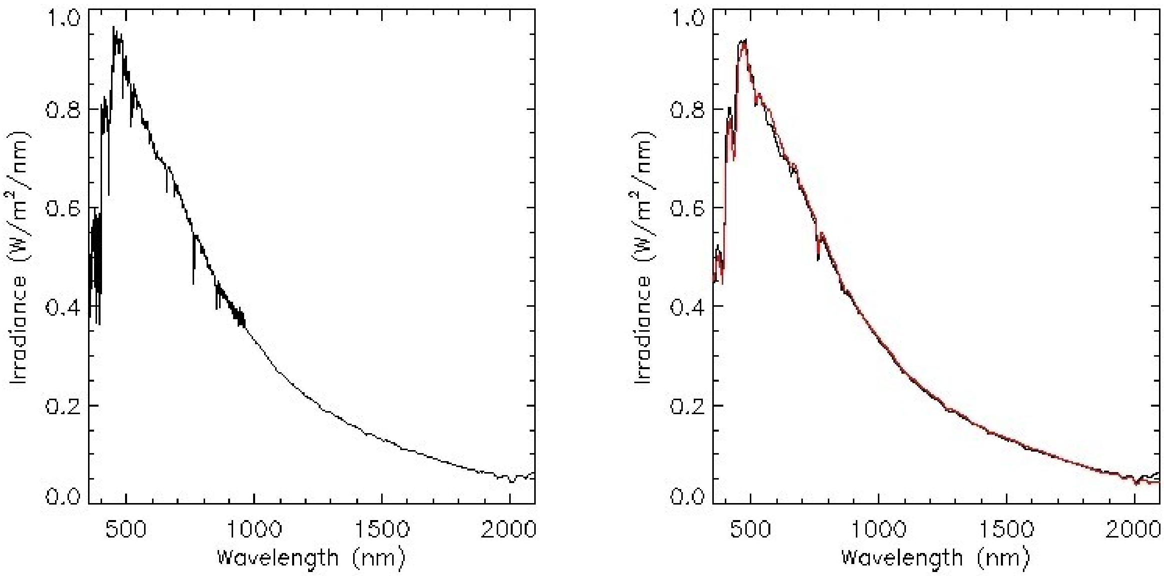
	UV-B (%)	**UV-A (%)**	**Visible(%)**	**NIR (%)**
Lamp Certification	4	3	2	5
Cal Geometry	1.5	1.5	1.5	1.5
Radiometric PS	0.9	0.6	0.4	0.2
Cal Distance	1	1	1	1
Transfer	2	2	2	2
Wavelength (<0.2nm)	1.5	0.5	0.2	<<1
MAX SUM TOTAL	**10.9**	**8.6**	**7.1**	**9.7**

Accuracy demonstrations by comparison with radiative transfer models:
Radiative transfer calculations in clear sky are generally well understood. Thus, comparison of measured clear sky data with a radiative transfer model is one demonstration of instrument accuracy.

The figure below shows the CAFS and TUV actinic flux spectra over the ocean, but with clouds in the vicinity (as seen in the forward camera view, a few minutes prior to the spectra). When measuring actinic flux, clear sky periods are often difficult to isolate, because even clouds on the horizon influence the actinic flux. The modeled clear sky flux does not take these clouds into account and is thus 10-15% lower than the measured actinic flux throughout the spectra. The plot indicates peak alignment and spectral consistency.



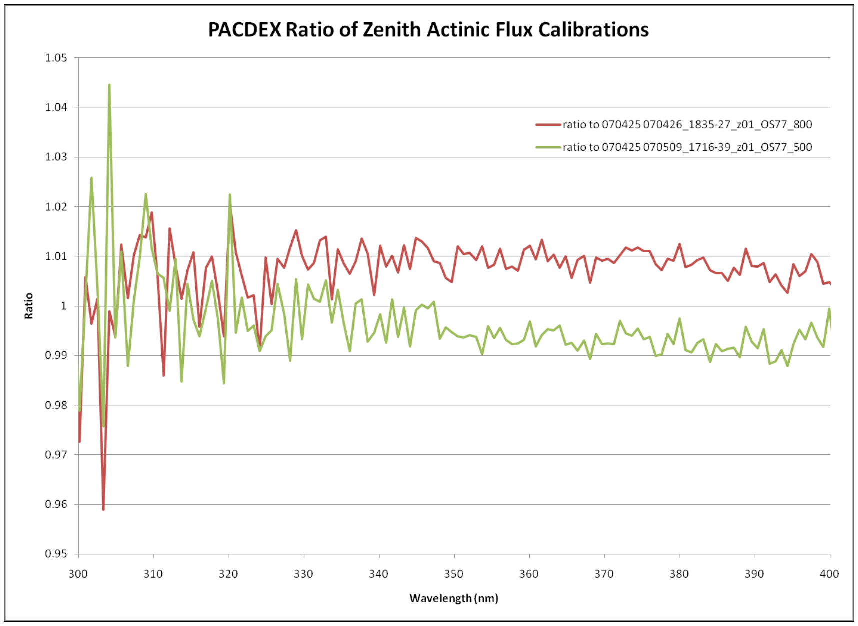
The left figure below shows the measured HARP irradiance data (black line) under clear sky conditions. The downwelling irradiance spectrum was recorded when the aircraft was at approximately 40,000 ft, thus the modeling is simplified with little water vapor and no clouds. On the right is the same spectrum plotted in black, smoothed to the resolution of the radiative transfer model. The red spectrum is the result of the radiative transfer model.



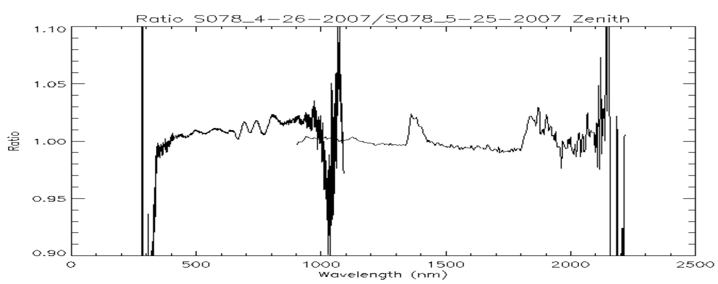
The absolute accuracy depends largely on the accuracy of the calibration standard. The NIST standards are rated at 2% in the visible and 5-6% in the NIR (2000 nm).

Precision. A number of parameters affect the reproducibility (precision) of the actinic flux and irradiance values. Because of their statistical behavior, these uncertainties will be given as 2 sigma values. From the day-to-day variability of the calibration functions during the mission as well as from experiences from the laboratory calibrations, we estimate the reproducibility of the radiometric spectral calibration measurements to be 1.0%. Regular calibrations with multiple lamps allow for removal of outlier calibrations. Such calibrations can occur under conditions of extreme cabin or external aircraft temperatures, or with misalignment of the calibration jig components.

The figure below shows the ratio of PACDEX actinic flux calibrations showing the absolute differences to be <2% through most of the spectrum. High noise is seen in the UV-B where the calibration lamp signal is lowest.



The figure below shows the ratio of two irradiance calibrations performed near the beginning and end of PACDEX with the absolute differences <2% through most of the spectrum. High noise is seen where the instrumentation sensitivities and/or lamp output are lowest. The high values around 1400 and 1900 nm are the results of changes in water vapor in the calibration air surrounding the calibration stand.



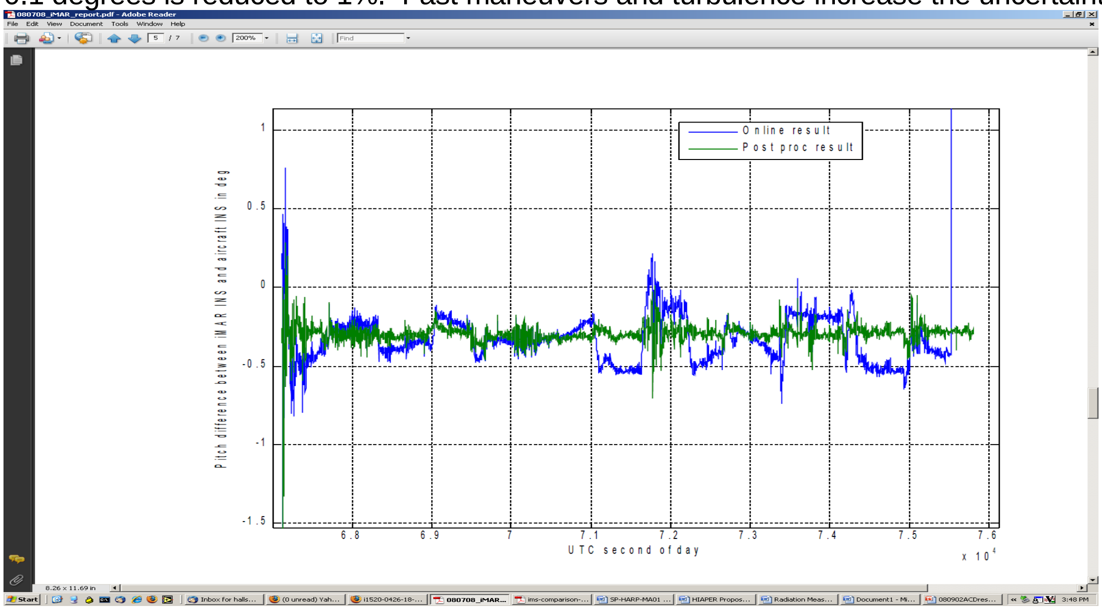
The wavelength calibration reproducibility of <0.02 nm translates into an uncertainty of 1.0% in the UV-B and 0.5% in the UV-A and visible for the actinic flux and negligible error for the irradiance.

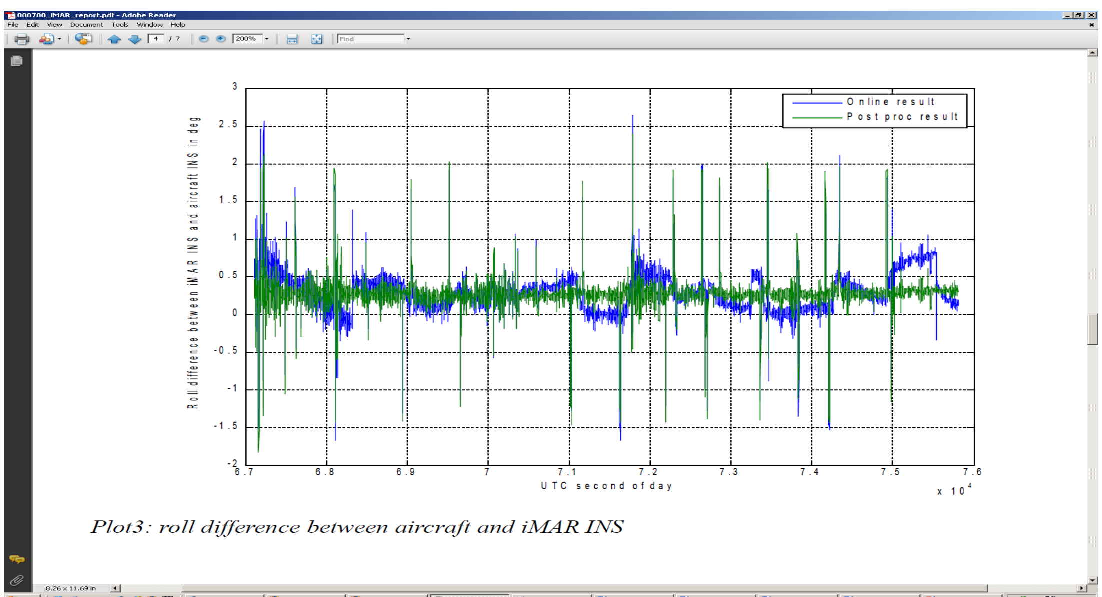
A rotating testing facility for determining the angular response as a function of wavelength of optical collectors is used to determine the attack angle and azimuthal response of the optical collectors. The resulting overall uncertainty due to residual anisotropy of the actinic flux optics is estimated to be 2.0% for the actinic flux, although this increases when the solar direct beam approaches the optical horizon (e.g. SZA ~ 90 degrees during level flight) along the optical horizons. For the irradiance, the variation from cosine response is generally small, however, a hotspot between 20-25 degrees results in a 10-15% deviation at these angles. The ARG laboratory corrects for the variation by correcting the direct solar beam and applying a diffuse correction. Improving the cosine response through modifications in the optical collector is an active area of irradiance research.

Spectrometer noise (read noise plus count variability) during calibrations is a very small fraction of the total signal for all detectors at all wavelengths.

The irradiance measurement precision in flight is highly dependent on the horizontal stability of the optical platform. A deviation of only 0.2° of the radiation sensor from the horizontal reference plane causes an uncertainty of the measured downwelling irradiance of about 1% at a solar zenith angle of 60°, which translates into a 4% deviation of the absorbed irradiance (*Wendisch et al.,* 2001). If a more realistic 1° horizontal misalignment is assumed, the irradiances deviate by 3% and the absorbed irradiances by 22% at a solar zenith angle of 60°.

The HARP stabilized platform has been developed to maintain a level platform within +/- 5 degree pitch and roll maneuvers, and to provide an accuracy response to less than 0.1 degree. The results of reprocessing of the HEFT-08 test flight by IMAR demonstrate the capability to track the pitch and roll in the figures below. The accuracy of the optical leveling alignment is estimated to be 0.1 degrees. The resulting irradiance uncertainty due to optical attitude misalignment of less than 0.1 degrees is reduced to 1%. Fast maneuvers and turbulence increase the uncertainty.





Plot3: roll difference between aircraft and iMAR INS

The precision assessment of the instrumentation is summarized in the table below:

Precision Summary

	UV-B (%)	UV-A (%)	Visible(%)	NIR (%)
Radiometric Cal Reproducibility	1	1	1	1
Wavelength Cal Reproducibility	1	0.5	<<1	<<1
Optical Anisotropy	2	2	<<1 (after correction)	<<1 (after correction)
Spectrometer Noise	2	<<1	<<1	<<1
Horizontal Misalignment	N/A	N/A	1	1
TOTAL	**3.6**	**2.9**	**2.2**	**2.2**

Uncertainty in Derived Quantities

Quantification of additional uncertainties in derived quantities of the actinic flux and irradiance are not quantified here. The ARIM laboratory provides calculations of photolysis frequencies using the latest JPL and IUPAC cross section and quantum yield data and can provide additional molecular calculations upon request. The uncertainties in the available molecular data vary considerably from reaction to reaction. Below 230 K, additional uncertainty could occur because the temperature dependencies of the molecular data for many reactions are unknown. Ozone column data may also be obtained under high altitude clear sky conditions.

From the measurement of solar spectral irradiance, the CU/ARG group derives cloud and aerosol optical properties including: cloud optical thickness and effective radius, cloud phase, flux divergence or layer absorption for either clouds or aerosols, net irradiance, radiative forcing, cloud and surface spectral albedo, and with the inclusion of actinic flux, single scattering albedo of clouds or aerosols. For these calculations, additional uncertainties include difference the multiplying effects of the stabilized platform alignment, assessment of atmospheric layer geometry and modeling uncertainties (when applicable).

References

Pilewskie, P., J. Pommier, R. Bergstrom, W. Gore, S. Howard, M. Rabbette, B. Schmid, P. V. Hobbs, and S. C. Tsay (2003), Solar spectral radiative forcing during the Southern African Regional Science Initiative, *J. Geophys. Res.*, 108(D13), 8486, doi:10.1029/2002JD002411.

Shetter, R. E., and M. Müller (1999), Photolysis frequency measurements using actinic flux spectroradiometry during the PEM-Tropics mission: Instrumentation description and some results, *J. Geophys. Res.*, 104(D5), 5647–5661.

Wendisch, M., D. Müller, D. Schell, and J. Heintzenberg, An airborne spectral albedometer with active horizontal stabilization. *J. Atmos. Oceanic Technol.,* **18**, 1856-1866, 2001.