ROTATING SHADOWBAND SPECTRORADIOMETER
MODEL RSS-1024/UVRSS-1024

BULLETIN RSS/UVRSS-1024

General Description

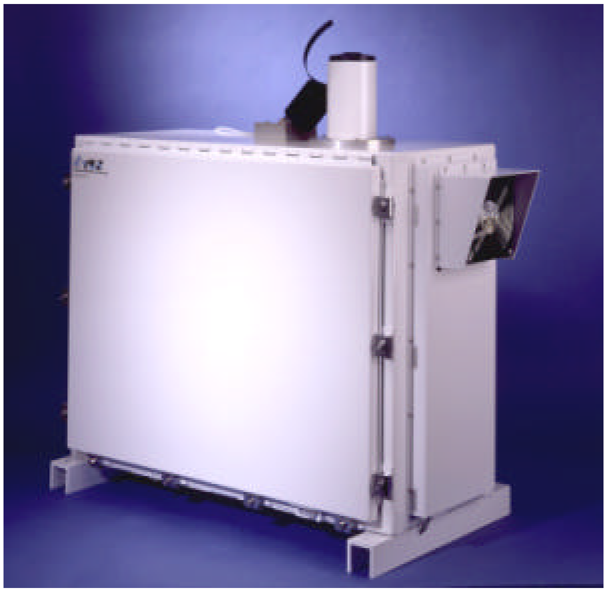
The Rotating Shadowband Spectroradiometer (RSS) combines a high-performance 1024-pixel Charge Coupled Device spectrograph with an external rotating shadowband. It provides automatic direct, diffuse, and total spectral irradiance measurements at high resolution. Two variants of the RSS are available:

- **RSS-1024.** Covers 360-1100 nm. Resolution of 0.3 nm FWHM at 360 nm increasing to 3 nm at 1100 nm. The far out-of-band (OOB) rejection ratio is better than 10^{-5}. Wavelength stability in operation is ±0.1 pixel (±0.02 nm at 360 nm to ±0.2 nm at 1100 nm).
- **UVRSS-1024.** Covers 290-360 nm. The standard model has resolution of 0.3 nm FWHM at 300 nm increasing only slightly through the spectral range, and far OOB rejection ratio between 2 and 5 x 10^{-7}. Wavelength stability during field operation is ±0.1 pixel (±0.01 nm at 290 nm to ±0.02 nm at 360 nm). The standard 0.3 nm slit width provides the highest OOB; an available slit width option produces effective bandwidths of 0.6 nm FWHM, but degrades OOB rejection.

The unique optical design and state-of-the-art astronomical-grade slow scan CCD array results in a very stable instrument, with no moving parts to control wavelength accuracy or throughput. This provides both high speed performance and long term stability superior to other spectroradiometers. The simple design approach helps the RSS maintain its calibration while in long-term operation in the field. Because the RSS samples all wavelengths *simultaneously*, spectra taken under varying sky conditions are an accurate time-average over the sampling period at all wavelengths.

Direct-normal solar irradiances allow calculations such as:

- Retrieval of atmospheric column quantities for species such as aerosols, NO_2, H_20, and 0_3
- Field calibration verification via Langley regression
- Determination of optical depths
- Spectral reflectance and BDRF



RSS-1024 Spectroradiometer

Principle of Operation

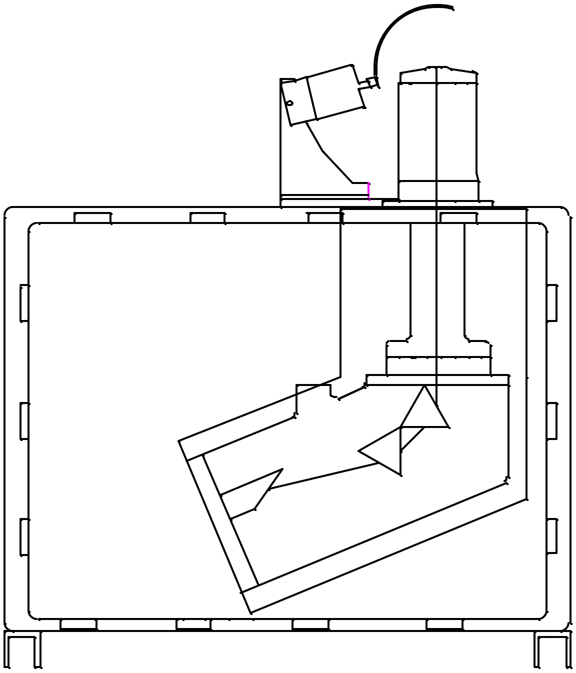
Light enters the RSS through an optimized cosine response-optimized diffuser fore optic. An external shadowband alternately shades and exposes the diffuser, making sub one second speed direct-normal, diffuse-horizontal, and total-horizontal spectral irradiance measurements. Sampling rates can be as fast as once every 30 seconds. The technique provides direct-diffuse and direct-total ratios that are fully independent of calibration.

Once inside the diffuser, light passes through an entrance slit, through an entrance lens into dual prisms which refract the light. Finally, a camera lens focuses the spectrum onto a Peltier-cooled, 1024x256 pixel element astronomy-grade slow scan CCD. Careful attention to anti reflection coatings and a large volume of space around the spectrograph itself helps give the system state-of-the-art out of bandwidth performance.

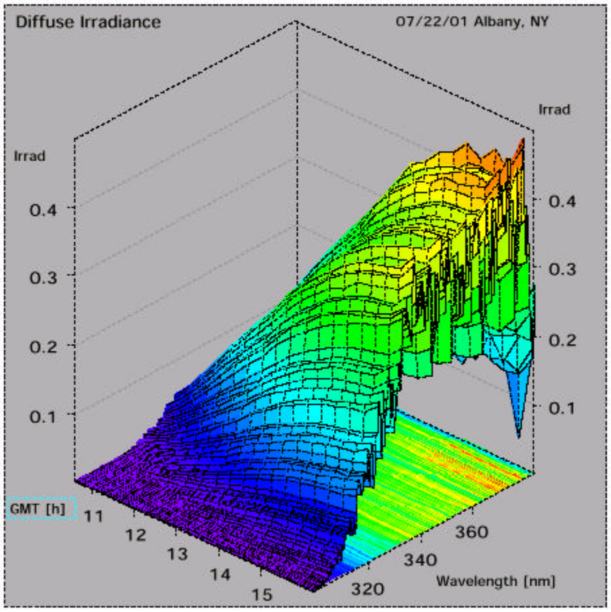
The CCD analog subsystem employs dual slope integration and column binning. CCD signals are acquired by a precision 16-bit analog-to-digital processing subsystem controlled by an embedded CPU. A second CPU manages the shadowband, and a third 32 bit CPU manages data calibration, database storage and the web server.

YANKEE ENVIRONMENTAL SYSTEMS, INC.

A precision multi-channel analog proportional-differential-derivative thermal management subsystem precisely maintains the temperature of five different thermal zones within the spectrograph.



Side cut-away view of UVRSS.

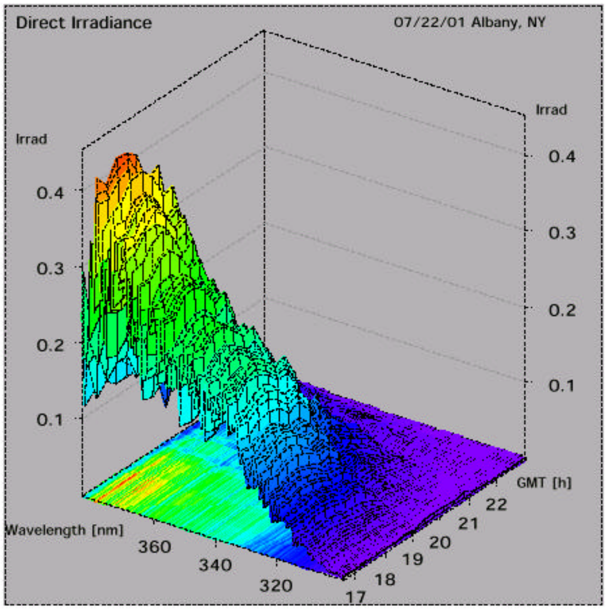


Its job is to keep the temperature of internal optics held stable and above ambient temperature fluctuations. Any environmentally-induced temperature fluctuations would serve to "tune" the wavelength response. In addition, this subsystem also controls the shutter and maintains the CCD's thermoelectric coolers at about 15°C on the RSS and near 0° on the UVRSS. For data presentation, the Data Visualization Engine and YESDAQ database permit data access via TCP/IP to any web browser.

Prism versus Grating Instruments

Traditionally, ruled optical diffraction gratings have been the wavelength selection mechanism of choice for narrowband spectral irradiance measurements at sub-nanometer slit widths. In the RSS, prisms were chosen as the primary dispersion mechanism for the following important design reasons:

- Prisms offer excellent far out-of-band (OOB) rejection. Especially in the UVRSS, OOB rejection is critical since low energy measurements in the UV-B are contaminated with intense sunlight light at longer visible wavelengths.
- Prisms can span a much wider spectral range while maintaining uniform throughput. In the visible/NIR RSS, a 92% throughput is possible over the region from 360 to 1100.
- Prism throughput is highly stable over time vs. gratings. The RSS prisms are made from amorphous fused silica (synthetic quartz)—an extremely tough and durable material that does not degrade or change with radiation or time. Gratings suffer from oxidation effects that degrade their diffraction efficiency over time.
- It is much easier to achieve and maintain wavelength stability with a prism. In gratings (like any mirror), the derivative of the deviation angle is two with respect to an angular shift of the grating: the spectrum is shifted by two times the amount of the angular deviation. In an equilateral prism, the same derivative of the deviation angle is zero at the minimum deviation criterion.



YANKEE ENVIRONMENTAL SYSTEMS, INC.

- Unlike *grating* spectrograph designs, *prism* spectrographs do not require additional diffraction order-sorting filters or optics. These filters can degrade over time.
- Gratings in scanning monochromators using photomultiplier detectors must be moved via complex and often fragile mechanisms and typically take several minutes to complete a scan, during which time the sky condition can change dramatically. The motor and mechanical translation stages increases the cost of the instrument substantially and introduces uncertainties related to the wavelength calibration as well as operational reliability.

Calibration Stability

The RSS was designed for long term scientific climatic research of the earth's atmosphere, which requires excellent long-term calibration stability in order to produce useful data. The locked-down internal optics are the key to the system's excellent long term stability. Extreme care was given to all aspects of the optical design to reduce the chance of mechanical dimensional changes that could adversely affect the instrument's spectral, angular, or absolute response. An extensive field-test program at the US Department of Energy's ARM site is ongoing to track and verify this stability.

Instrument Development

The initial concept for the RSS instrument was driven by a team of scientists at the Atmospheric Sciences Research Center at the State University of New York/Albany. YES worked closely with this team during the R&D of the commercial version. Because the RSS instrument is important to climate change research and is used by the US Department of Energy, it funded a portion of its development.

Communication Link Methods

Data can be viewed on any browser-equipped workstation for real-time display and analysis. For communications, the built in 10/100 BaseT Ethernet connections is preferred. For remote sites, a dial in PPP (V.90) modem is provided. for off-grid remote measurements. Both 10/100BaseT Ethernet and V.90 modem for PPP are provided. As with the Model TSI-880, acquired data scans are initially stored internally via YESDAQ. The Data Visualization Engine package is included with the system and permits viewing of YESDAQ data, permitting users to rapidly browse data using a web browser. Also, database connections via ODBC, or JDBC to 3rd party applications (e.g. MS-Excel, Matlab or Splus) are supported. The DVE package provides wavelength and absolute-calibrated spectral scans and produces fully calibrated spectral irradiance data.

Architectural Differences between the UVRSS and Visible RSS systems

Both the visible RSS and UVRSS versions of the instrument use identical electronic systems and firmware; however, the geometry of the optical elements and detector are carefully optimized for each domain.

UV Pre-filter

The UVRSS instrument is configured with a visible pre-filter installed; outdoor applications require this filter to block the strong visible solar signal, however some laboratory applications may not; the system can be supplied without it as an option.

Optimal Slit Size

A precision laser machined slit is supplied, and is externally located to permit exchanges by the user. The supplied slit is optimized for outdoor atmospheric work, and may be exchanged if more or less signal is available. The general engineering tradeoff is spectral resolution vs. light gathering (for SNR). However, because the aberration limit for the UVRSS is approximately 0.2 nm FWHM, attempts to drop below approximately 0.3 nm FWHM by decreasing the slit size only results in a loss of light and subsequent loss of system SNR. As the slit size is made larger to gain throughput the expense is a corresponding loss in resolution.

Optical components within the system operate in a dry nitrogen purged environment to eliminate potential condensation on the surface of the cooled internal CCD that would blur the refracted light and ultimately contaminate it. Internal humidity and pressure are continuously monitored to ensure the integrity of the seal over its lifetime.

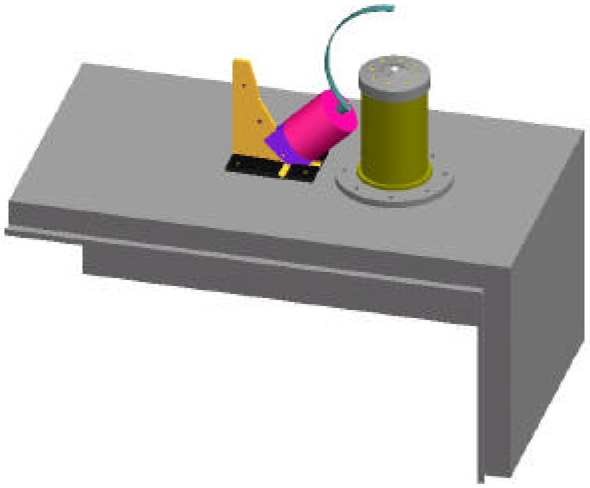
Laboratory Use

This section discusses using the instrument as a spectrograph/CCD detector for laboratory radiance and irradiance measurements. As every optical measurement setup tends to be application-specific, the following discussion is intended to cover some of the design tradeoffs involved in attaining adequate SNR and sampling performance.

YANKEE ENVIRONMENTAL SYSTEMS, INC.

Radiance Measurements

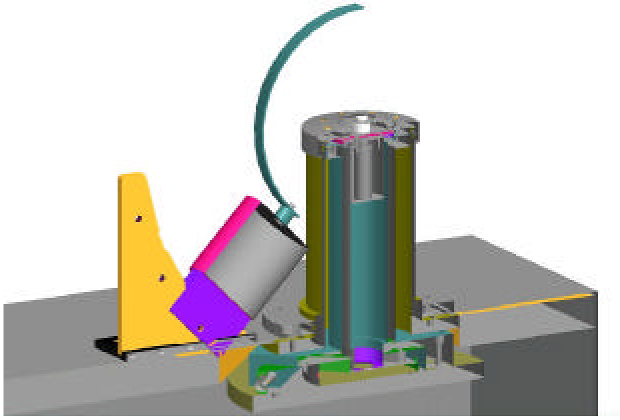
The spectrograph normally ships in an irradiance configuration with an optimized Teflon™ Lambertian fore optic, setup for measuring *spectral irradiance*, (180° field-of-view) directly. The RSS and UVRSS ship with an exterior shadowband attachment; indoor models are simply outdoor variants without shadowband but with a radiance attachment.



3-D view of RSS fore optic

With the diffuser removed for radiance measurements, a light source is typically used to illuminate a target, and reflected light is gathered onto the exterior slit via the radiance accessory. By definition "perfectly collimated" light has infinite radiance and is impossible to create physically. In a laboratory application you typically do not want to be focused at infinity, but rather at a target a finite distance away. So the real question is, how large do you want the "image of the entrance slit" to be? Because it has infinitesimally small solid angle. radiance is really a mathematical abstraction where the solid angle of the source theoretically goes to zero. As the solid angle goes to zero, radiance goes to infinity. There is no physical source that can generate light like this (our sun has a solid angle of about 0.5°).

Irradiance (represented as I or E depending on the discipline) is the double integral over π steradians of radiance and is as a function of the optical signal times the cosine angle of the incident angle vs. the receiving surface normal. In theory, you always measure irradiance over a given area, as it is impossible to *directly* measure radiance. We can only build instruments with finite solid angle.



Cross-section view of fore optic

F-number is calculated from the distance of the lens from slit divided by the diameter of the lens. The F-number of a RSS is not the same as that for a UVRSS; in the RSS it is optimized for resolution and not throughput whereas in the UVRSS we open up to get more light throughput. The absolute spectral responsivity of the spectrograph (in photons or watts/unit area), is given in photon flux units. The throughput of the spectrograph is almost flat vs. wavelength in the UVRSS, except for fluctuations of the CCD (this is provided with the instrument).

When setup as a spectrometer a variety of measurements can be made. For radiance measurements, an optional radiance lens optic must be installed in front of the system's entrance slit. For typical measurements of far-field radiance (e.g. sky radiance) the entrance lens focused at infinity; the distance of the lens to the slit is equal to the lens' focal length. The lens diameter is made slightly larger (thus the F-number slightly smaller) than the F-number of the spectrograph. The only free parameter is the focal length. Keeping in mind that the entrance slit geometric area is finite, this controls the angular measurement in the far field. Therefore the farther away the lens (and larger) the narrower the actual field of view is out at infinity. The angular field of view specified in radians is nothing more than the length of slit divided by the focal length of the lens. The slit can be changed easily. Given a slit height of 2.5 mm, if we wanted to collect light 1/2 degree along the slit height axis you'd need a lens that is 100•2.5 mm or 25 cm away from the slit. And because it has to be F=7; the lens diameter must be 25 / 7 (cm) or 3.5 cm in diameter. This would yield a 1/2° F.O.V. in the slit height (*transverse*) direction of the slit. This finite F.O.V. must be considered in your application. Also, the issue of chromatic aberration and UV transmission must be considered in all optical components in your system, e.g. windows.

After absolute power and wavelength accuracy, the next most important factors in any spectral measurement are noise and dynamic range. The dynamic range in any individual measurement of the CCD system used is close to 16 bits, or a part in 64K. However, for shorter exposures, the dark count statistics do not enter the calculation. So more accurately, in this case the *range* is 16 bits, but the SNR is controlled by Poisson statistics of the charge wells in the detector, which in turn are governed by the quantum limit of the CCD device itself. In the RSS the real noise that matters is not an additive noise term, thus it is not adequately expressed as noise equivalent power. Since we are counting photons, the more light we have to work with, the more uncertainty; however, the fractional area (noise) goes up as the square root of the signal. The "noise-equivalent radiance" (NER) or "noise equivalent power" (NEP) depends on the signal being measured. *Etendue* (the product of radiant flux density and the area of a radiating or receiving surface) is typically used in the context of Fabry-Perot interferometers.

If one thinks of light as simply as an analog quantity with an infinite number of photons, the NER can be calculated based on the readout noise and given the range of the UVRSS the NER looks fantastic. However, the real noise in the measurement is due to the Poisson statistics and *is not an additive noise term*. It is the uncertainty in this noise term that matters when using the data. Its variance is proportional to the square root of measured signal, counted in electrons:

SQRT(N) / N = $N^{-1/2}$

… which is the fractional uncertainty in the measurement itself. If you set the integration time such that you completely fill charge well on a CCD pixel you have about 130,000 electrons. However, the UVRSS performs a vertical column (binning) on the 256 pixels in each column (the CCD is a two dimensional array of 1024 x 256 pixels), so this must be considered as well. Only with precise knowledge of the expected optical signal can the signal-to-noise ratio be accurately calculated.

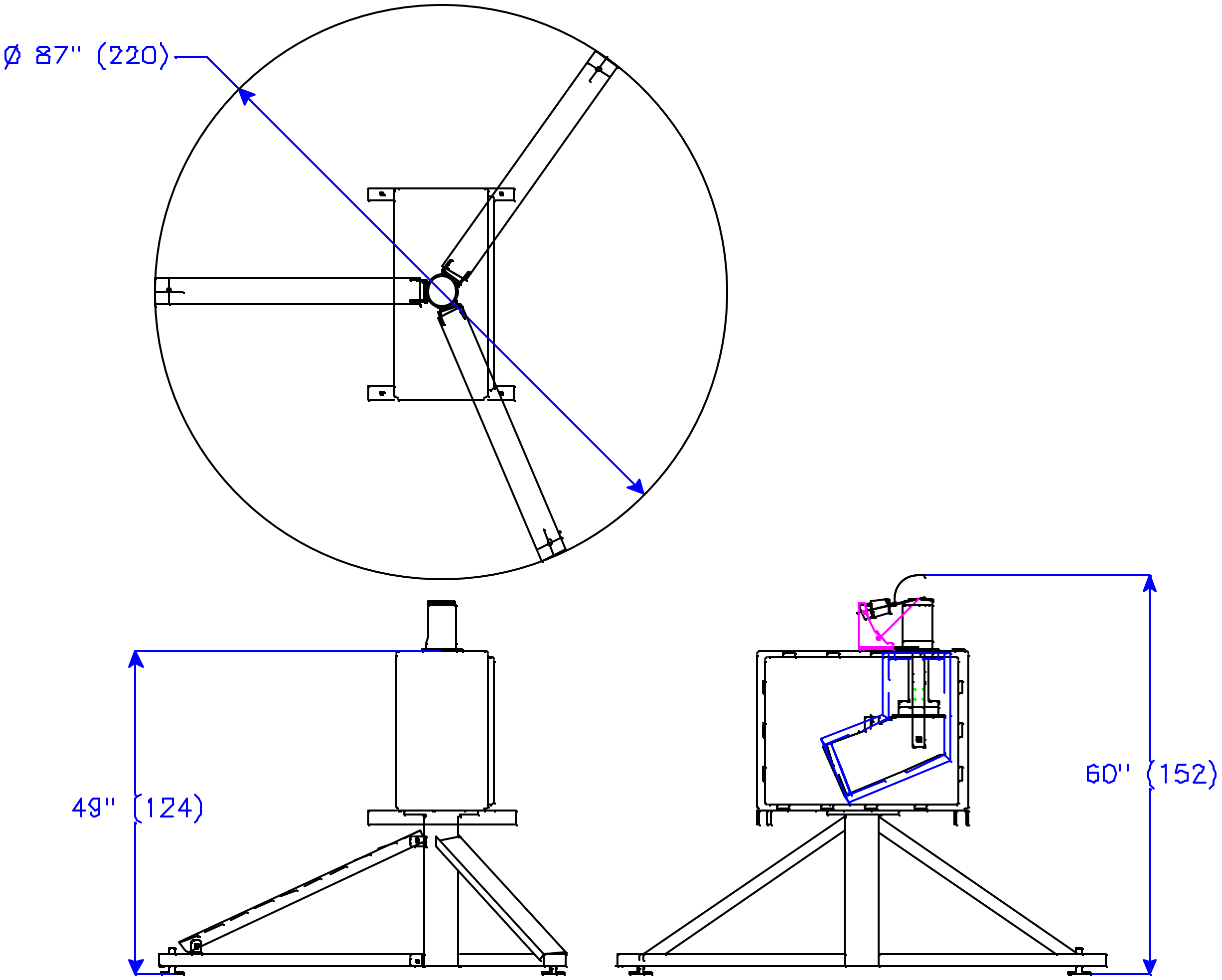
Raman Spectroscopy

In Raman spectroscopy where a laser is used as the sample illuminator, the instrument can be used as a spectral detector, assuming a holographic filter is inserted to block the laser energy. Given a reasonable surface reflectance of a given sample material, if the chemical of interest has a fairly large Raman spectral cross section, there should be plenty of SNR. However, as there is always a practical limit to the amount of laser power with which you can safely illuminate a sample, this governs the integration time required. If the sample is moving relative to the instrument, the integration time must not be too great.

In this configuration, consider that the lens (from geometric optics) says we would have an image of the spectrograph's slit on the target, assuming a fictitious lamp inside the spectrograph at the CCD. This means that if one alters the focal length of the lens, so that the target can be moved closer or farther away. At the target, the lens would "image" the entrance slit on target, the laser will illuminate the area on the target. As the focal length is increased, the effective area of the slit image on the target increases (simple magnification). Suppose that we focus on the surface of a uniformly radiating target, illuminated by a laser. Then the amount of light received by the instrument is invariant to the distance to the sample target, since the area increases in exact proportion to the $1/r^2$ loss due to distance.

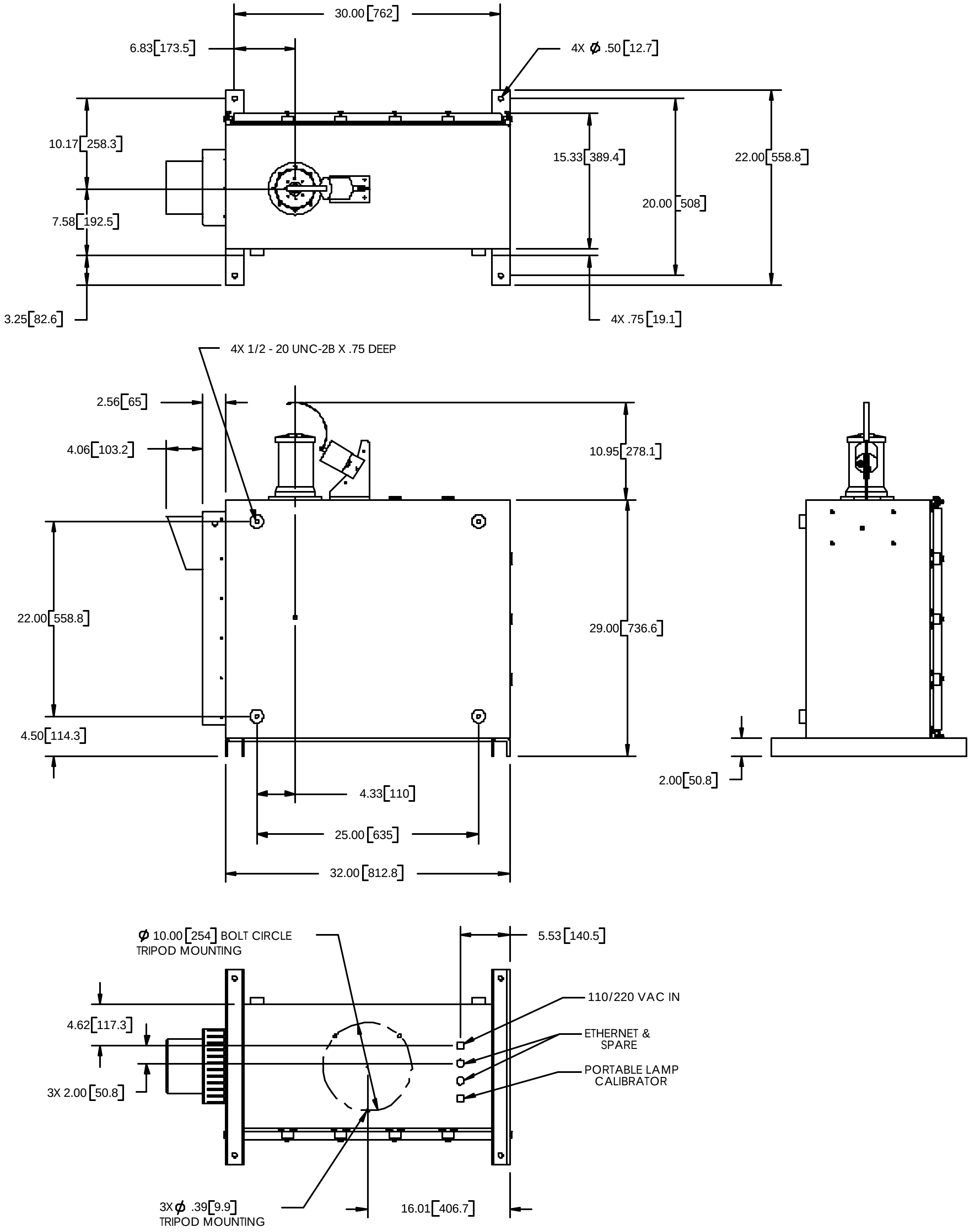
Lab applications typically involve radiance and not irradiance-hence no diffuser. The salient issues are then simply the size of the entrance slit, the f-ratio of the optics (about 7) and the efficiency product of the optics throughput and the detector responsivity. Since the entrance slit is fairly small - the area of the target is often quite a bit larger making measurement setup simple. To optimize the system throughput, you will need to know the illumination area, working distance and allowable power on your target. Assuming there is some energy density limit on the sample, one can back off the illumination and expose the target with a larger area. We'd prefer the image of the slit to be larger permitting you to drop the flux density on the target. this means you don't have to get real close to work. Assuming you can over illuminate the target the working light is therefore limited by the size of the slit (which is controlled by the area of the CCD) and the F-number of the spectrograph. Wider slits are possible on special order, however, you should consider the optical resolution that is truly required for sufficient analysis. If your lab setup is "light throughput limited" and you do not need high resolution then a larger slit makes sense.

Mechanical Interface



DIMENSIONS IN INCHES, shown mounted on optional tripod

YANKEE ENVIRONMENTAL SYSTEMS, INC.



YANKEE ENVIRONMENTAL SYSTEMS, INC.

Specifications

Parameter	RSS	UVRSS
Spectroradiometric Method	Dual Prism w/1024 Si CCD detector, cooled to 5°C	Dual Prism w/1024 Si CCD detector, cooled to 5°C
Spectral Accuracy	0.1 pixel (±0.2nm)	0.1 pixel (±0.06nm)
Spectral Repeatability	Too small to be measured, all temps	0.005 nm RMS
Sampling Interval	0.75 nm	0.07 nm (0.3nm effective slit width)
Spectral Range	360-1100nm continuous	288-365 nm continuous*
Out-of-Band rejection	10^{-6}	10^{-6}
Absolute calibration over entire λ range?	5% (over full temperature range)	5% (over full temperature range)
Cosine corrected?	YES	YES
Multiple Averaging?	YES	YES
Scanning time	1 second	1 second.
Internal moving parts that control the wavelength selection	NO	NO
Has shadowband for automated direct/diffuse measurements?	YES	YES**
Can be calibrated with standard FEL lamps?	YES	YES
Can be calibrated on its side for base-down FEL?	YES	YES
Thermally stabilized?	YES, @ 50°C	YES, @ 50°C
Temperature Range	-50°C to +50°C	-50°C to +50°C
Waterproof?	YES, NEMA-4X	YES, NEMA-4X
Software support	MS-Windows 95/NT, Mac, & Unix	MS-Windows 95/NT, Mac, & Unix

RSS-1024: Other Specifications		**UVRSS-1024: Other Specifications**	
Effective Slit Bandwidth	0.6 nm @ 360 nm up to 4nm @1100nm, 2.25 pixels FWHM	Dispersion Optic	Transmission, fused-silica prism spectrograph
ADC @ CCD detector (bits)	16	Spectral Resolution	0.3 nm FWHM @300 nm; optional 0.6 nm slit width available but not recommended for most applications.
Raw Angular Response	<8% over +/- 70°	Wavelength Calibration	Hg lamp
Dark Count subtract?	YES	Dynamic range.	65,000 counts
Visible Resolution (pix)	1024	Fore-optic raw angular response error ration from ideal cos(z)	<5% over +/- 70°, correctable to 0.2%
Internal 2nd order sorting filter required?	NO		

* The upper wavelength limit is not 'hard,' but instead a consequence of intentionally declining responsivity to longer wavelengths achieved by band-blocking elements and dynamic range compression done in the fore-optic, all to minimize stray light contribution at the shortest wavelengths. The UVRSS lower limit is set to capture the 289 nm Hg emission line for wavelength calibrations.

** The UVRSS makes measurements of the direct-normal, diffuse-horizontal, and total-horizontal spectral irradiances routinely and synchronously via the automated shadowband method similar to the RSS. This is

Copyright © 2003 Yankee Environmental Systems, Inc. All Rights Reserved. Specifications subject to change without notice.

possible only because of the simultaneous acquisition of the spectrum at all wavelengths. These irradiance components automatically share the same calibration coefficients.

Copyright © 2003 Yankee Environmental Systems, Inc. All Rights Reserved. Specifications subject to change without notice.