Lunar Modeling and Database

Irradiance Model

Irradiance Data

For development of the lunar irradiance model analytic form and determination of the model coefficients, the ROLO observational dat are converted to disk-equivalent reflectance. The ROLO metadata table contains the computed sums of pixels on the lunar disk, including the unilluminated portion, in instrument units for each ROLO lunar image, These pixel sums I_Σ are converted to exoatmospheric irradiances I' by:

$$I' = \left(I_\Sigma \cdot C_L \cdot C_{ext}\right) \cdot \Omega_p$$

where C_L is the radiance calibration coefficient, C_{ext} is the extinction correction, and Ω_p is the solid angle of one pixel. For both model development and spacecraft observation comparisons, irradiance values are corrected to standard distances for Sun-Moon (1 AU) and Moon-observer (384,400 km). For a band k, the distance-corrected irradiance I_k is given by:

$$I_k = I'_k \cdot \left(\frac{D_{M-V}}{384{,}400}\right)^2 \cdot \left(D_{S-M}\right)^2$$

where D_{M-V} is the Moon-observer (viewer) distance in km and D_{S-M} is the Sun-Moon distance in AU. The conversion to reflectance A_k is:

$$I_k = \frac{A_k \cdot \Omega_M \cdot E_k}{\pi}$$

where Ω_M is the solid angle of the Moon (6.4236x10^-5 sr) and E_k is the solar irradiance at the effective wavelength of band k, both at standard distances. This conversion involves a solar spectral irradiance model, which may have significant uncertainties in some wavelength regions. However, the direct dependence on solar model cancels to first order as long as the same model is used in going from irradiance to reflectance and back.

The reflectances A_k, along with the corresponding observational geometry parameters, are the quantities that populate the lunar model.

Model Form and Development of Coefficients

The analytic expression for the lunar disk-equivalent reflectance was developed empirically, choosing a form that minimized correlations among the fit residuals. Fitting is done in the natural logarithm of disk-equivalent reflectance A_k:

$$\ln A_k = \sum_{i=0}^{3} a_i g^i + \sum_{j=1}^{3} b_j \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi + d_1 e^{-g/p_1} + d_2 e^{-g/p_2} + d_3 \cos\left(\frac{g-p_3}{p_4}\right)$$

where g is the absolute phase angle, θ and φ are the selenographic latitude and longitude of the observer, and Φ is the selenographic longitude of the Sun.

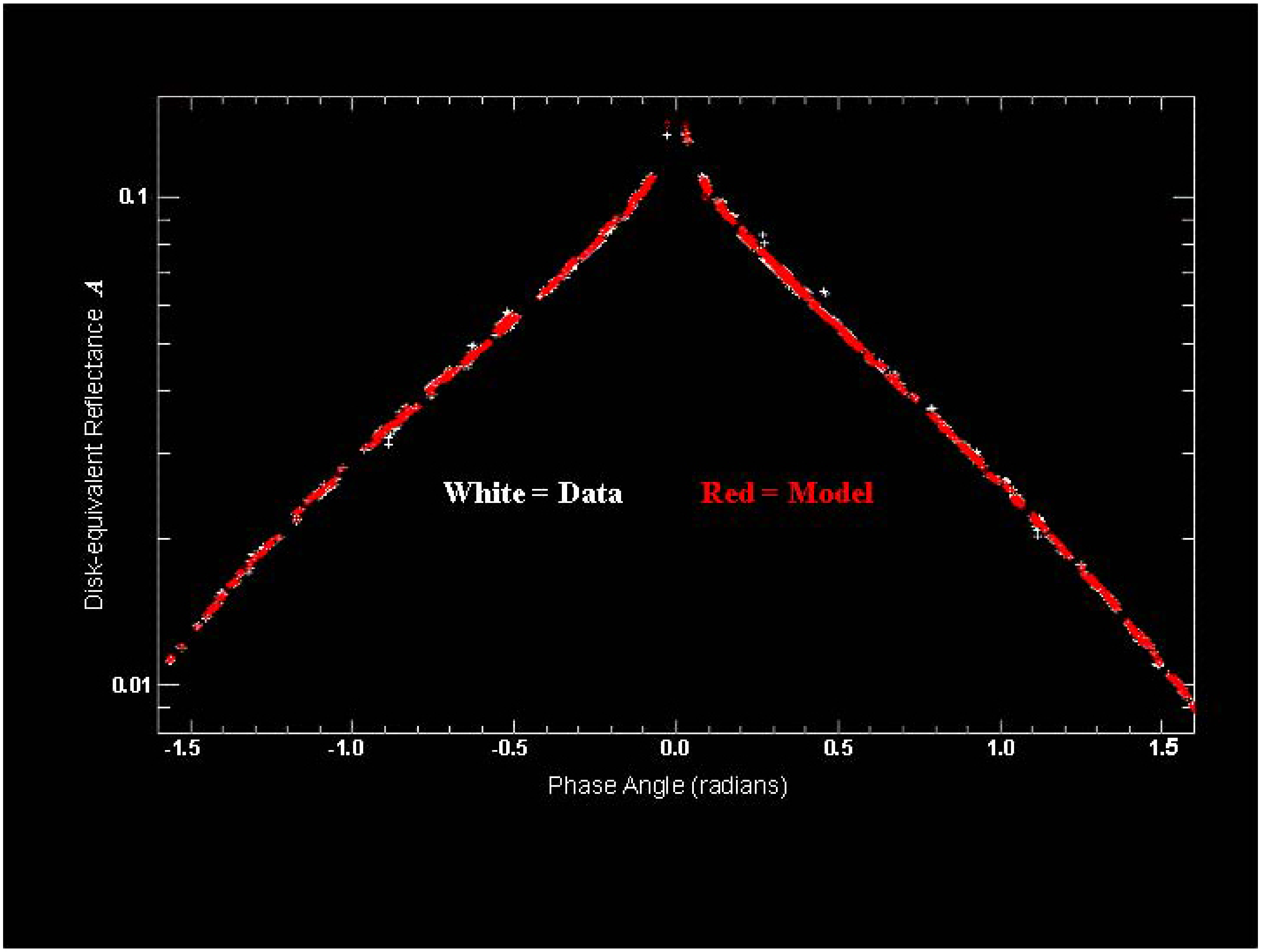
The first polynomial represents the basic photometric function dependence upon phase angle, neglecting any opposition effect. The second polynomial approximates the asymmetry of the surface of the Moon that is illuminated, primarily the distribution of maria and highlands. The c-coefficient terms account for the face of the Moon that is actually observed (topocentric libration), with a consideration of how that is illuminated. The form of the last three terms, all non-linear in g, is strictly empirical. The first two represent the opposition effect and the last one simply addresses a correlation seen in the residuals.

The ROLO data selected for fitting are constrained to $1.55° < g < 97°$, and the requirement that all images used be part of complete 32-filter sequences. Data were weighted based on nightly observing conditions. Two iterations of a least-squares fitting process were applied using the above form, but with all the non-linear terms set to zero. After the first fit, data with residuals greater than 3 standard deviations of the residual average were removed. After the second fit, any point with residual >0.25 was removed. This process leaves about 1200 observations for each band. Then a fitting process that handles both the linear and non-linear terms in multiple steps was applied, resulting in 8 coefficients that are constant over wavelength (4 for libration and the 4 opposition effect parameters) and 10 additional coefficients for each band.

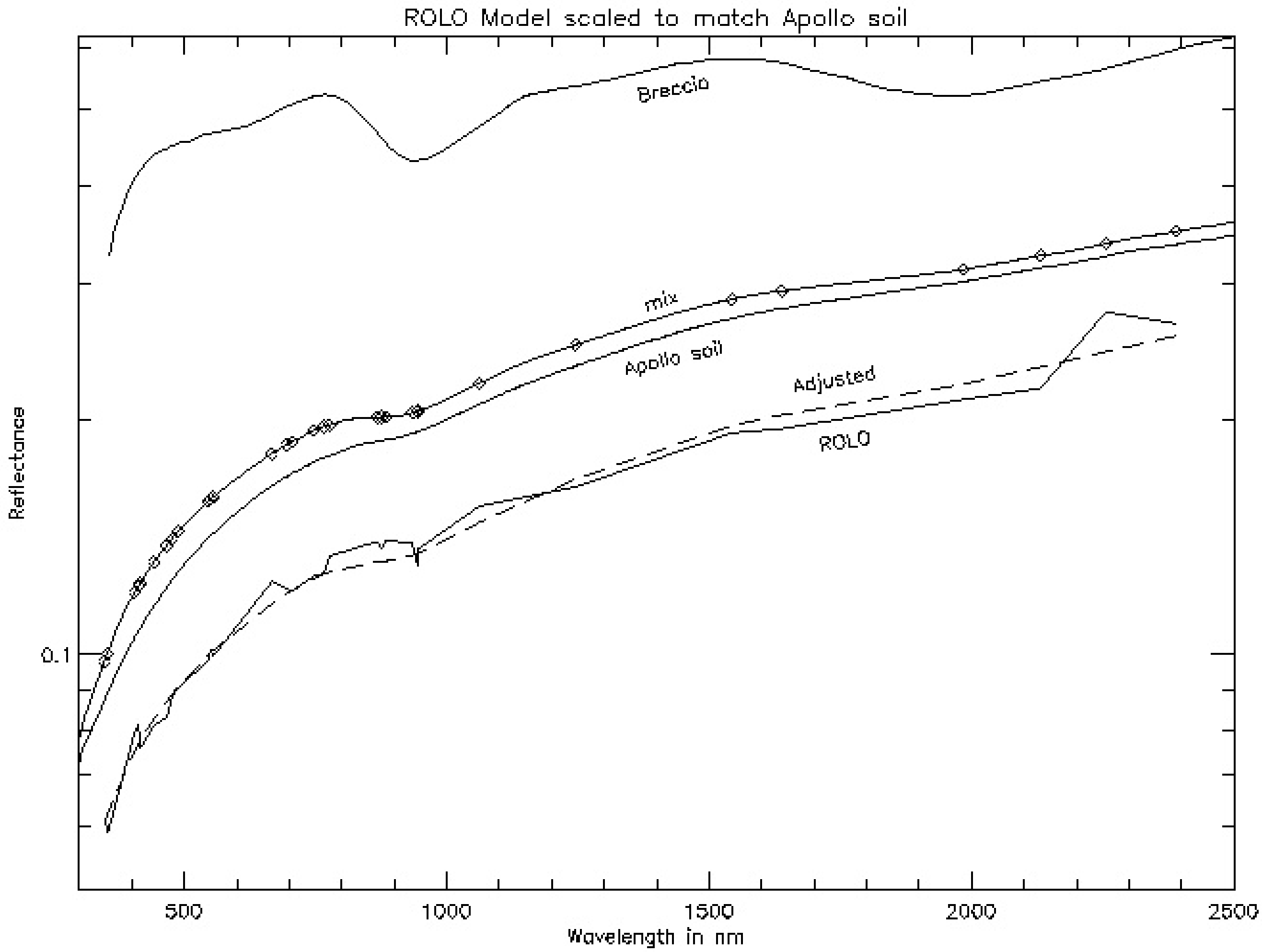
The coefficients for model version 311g (2004 April) have been published[1]. The 320 wavelength-dependent coefficients are available in ASCII text format for personal use by interested scientific personnel; contact the Project Scientist, Tom Stone.

Model Performance

The mean absolute fit residual over all bands is 0.0096 in ln A, or about 1%. This is a measure of the model's capability for predicting the variation in irradiance due the geometric effects of phase and libration. Although the processed ROLO data span about 1/4 of the 19.6-year libration repeat cycle, libration coverage is sufficient for a satisfactory fit and predictive capability. The phase plot below shows the lunar model results (in red) and the observational data (in white) for 1234 data points in the ROLO 555nm band. The phase range is 90 degrees before Full Moon to 90 degrees after. The model deviations from a smooth phase curve show the effects of libration. Model studies have determined that libration effects are responsible for up to 7% of the total irradiance signal over the full range of libration angles.



The lunar model version 311g produces reflectance spectra that exhibit band-to-band deviations not characteristic of the lunar reflectance, which is generally smooth. A correction was developed to adjust the model outputs to a form representing a mis of Apollo-16 sample laboratory spectra. These are shown in the plot below. The sample "mix" spectrum (95% soil, 5% breccia) is scaled to the model outputs ("ROLO") and fitted with a linear function of wavelength.



ROLO Database

In 6+ years of regular operations, ROLO has acquired over 85,000 images of the Moon and several hundred thousand star images. Archived images are formatted in cube pairs of the 23 VNIR and 9 SWIR bands. The archive format is compatible with the USGS ISIS system.

ALEX Images

Processed radiance images are mapped onto a common 576x576-pixel grid fixed to the selenographic coordinate system that covers all points on the Moon visible from Earth. This process uses a modified Lambert Azimuthal Equal-Area projection, locally termed the “ALEX” projection:

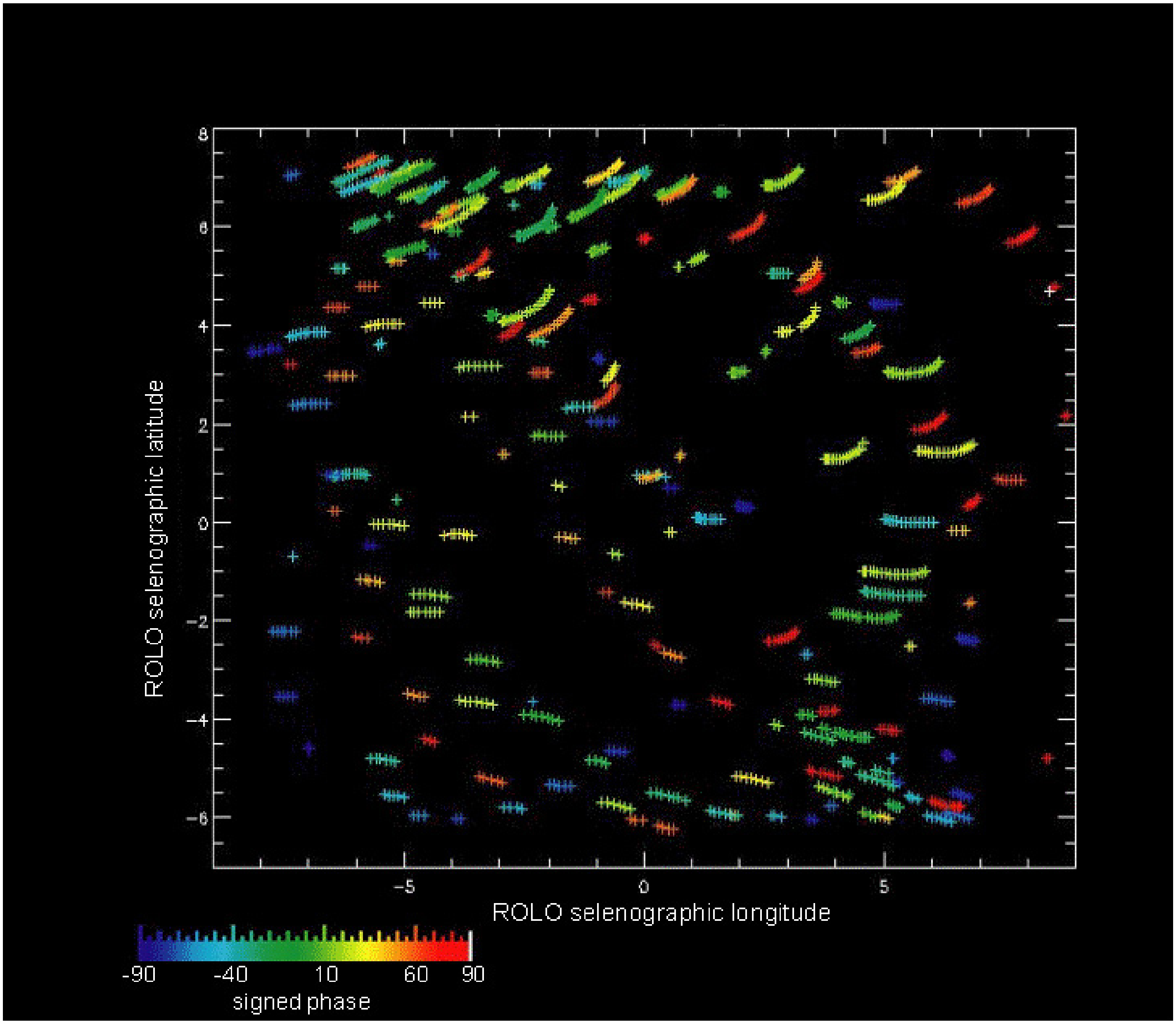
$$\alpha = P_2 \sin\left(\frac{\theta}{P_1}\right)$$

where α is the radial distance of the projected point from [0,0] in the selenographic coordinate system, and θ is the great-circle distance of a point from [0,0]; parameters P1 and P2 are chosen to give the desired coverage and spatial resolution, respectively. In the sample ALEX image shown below, the white band around the lunar disk is the accommodation for the range of libration angles viewable from Flagstaff. The ROLO ALEX grid extends ±11 degrees beyond the limb in selenographic longitude and latitude.

ROLO image in ALEX projection. This image was acquired on December 30 1998 03:45:06 UTC in the ROLO 550nm band. Phase angle is 40.6°; libration is -0.145° in selenographic longitude, +1.120° in selenographic latitude.

Phase and Libration Coverage

This plot shows the libration coverage of the processed ROLO dataset, with the phase indicated by color. Although these data represent 4.6 years of the full ROLO archive, not quite 1/4 of the 18.6 year libration repeat cycle, the libration space is substantially filled. However , if phase angle is restricted the a narrow range then libration coverage is sparse.



For and animation of the lunation cycle showing the optical librations though the phases, check out the Astronomy Picture of the day for November 8, 1999 (http://apod.nasa.gov/apod/ap991108.html).

ROLO Data Reduction Procedures

ROLO procedures for removing detector artifacts are straightforward. For the VNIR CCD, the bias level is measured from extra pixels in the CCD readout row. Dark current is determined as a function of exposure time from fitting unilluminated images acquired at the start and end of each observing night. For the SWIF camera, the detector is clocked out continuously, and the last frame before exposure is saved, to be used for detector readout characterization. Additionally, a dark frame image is acquired as part of each SWIR 9-filter sequence, to augment the twice nightly dark exposure time series. Linearity corrections for both detectors have been developed form special sets of observations. Flatfield images are acquired 2-3 times each lunation by viewing a spectralon plaque illuminated by a 100 Watt FEL lamp. These lamp images are processed to remove detector artifacts, then normalized the generate flatfield corrections images.

Atmospheric Extinctions Correction

Correction of ROLO lunar radiance measurements to exoatmospheric values is based on the extinction observed in the star images acquired through each observing night. The observed stellar irradiances are fitted to an extinction model that is formed from MODTRAN atmospheric transmission spectra, and thus is coupled across all ROLO bands. The fitting algorithm produces a set of parameters that scale the individual transmissions as a function of time and zenith angle through the night. These parameters are used in turn to generate extinction correction values for the Moon images. Atmospheric correction is one of the most important aspects of ROLO data reduction, and the processing algorithm is undergoing continued refinement.

The stellar extinction fitting procedure handles all the star observations acquired in a night as an ensemble, typically ~12 stars imaged 10-15 times in all 32 bands. Atmospheric transmission spectra for 6 separate constituents: “normal gases” (N2, O2, CO2 and trace gases, plus Rayleigh scattering), water vapor, ozone, and three aerosols, are convolved with the ROLO spectral response functions to develop extinction coefficients for each constituent on each band. These are scaled by a “relative abundance” factor and summed to give an effective optical depth for a given slant path length (airmass). The relative abundances are the free parameters of the fit; they are allowed to vary independently among the constituents, but are coupled across all the bands. The abundances are time-dependent, modeled by a 2nd-order Chebyshev polynomial, thus there are 3 free parameters for each of the 6 constituents. In practice, additional parameters are included to model time dependent instrument gain effects as well. For each lunar image, an extinction correction factor is constructed from the fitted parameters and the time and zenith angle of the image.

Calibration

Currently, the absolute scale of ROLO radiance data is tied to astronomical photometry of the star Vega. Published absolute energy density measurements were used to scale a synthetic spectrum for Vega, which was then convolved with the ROLO instrument spectral response functions to give the photon flux in each band. A dedicated reprocessing of all ROLO images of Vega produced exoatmospheric instrument response values, which were ratioed to the absolute fluxes to form the calibration.

In an effort to reduce uncertainties in the ROLO absolute calibration, an alternate method is being developed with involvement of the radiometry group at NIST. A large, on-axis collimated source that overfills the ROLO telescopes' field of view was designed and built at USGS. At the collimator focus is a uniform source that has been calibrated at the NIST FASCAL facility. This source is monitored via transfer to a NIST sphere source during field calibration work at ROLO. This is current work in progress.

ROLO Metadata Table

The final step in ROLO data processing is construction of a table of parameters for each lunar image, extracted from the image cube header information. This includes all observation geometry and ephemeris information, the extinction correction and calibration factors, the disk-integrated irradiance and sky background level (in instrument units), and error values for all derived quantities. The table is ordered chronologically by the acquisition time of each band. This table forms the basis for inputs to the lunar irradiance model.

Bricks

The input data for spatially resolved lunar radiance modeling are the processed, calibrated, and ALEX-projected (see Overview) lunar radiance images. Since each image contains roughly 250,000 pixels on the lunar disk, and there are over 65,000 processed images, the processed archive was re-sampled for handling within typical computer memory capacity. The images were separated into wavelength bands and subsampled, 3 lines by the full 576-pixel image width. Cubes were built up of the subsamples, with each new band corresponding to a processed image. These transposed radiance data are called ROLO “bricks”.

[1] Astronomical Journal 129, 2887-2901 (2005)