Cross-calibration of Geostationary Satellite Visible-channel Imagers Using the Moon as a Common Reference

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Motivation

The archives of meteorological satellite imagery constitute a time series of Earth observations extending back to the 1970's.

- recognized as valuable resources for climate evaluation and detecting climate change

Assembling observational data from multiple instruments on different platforms into extended data records requires that the sensors be calibrated to a consistent scale, and stabilized over the instruments' lifetimes.

- visible-channel imagers on meteorological satellites typically do not have on-board calibration systems
- a stable external reference is needed
- the Moon can be used as radiometric calibration source
  - invariant reflectance, but continuously changing apparent brightness
  - requires special techniques for its use

NOAA−NCDC sponsored project to apply lunar calibration to satellite imagers

- to support development of Climate Data Records

The Moon as a Calibration Source

The Moon is an exceptionally stable “solar diffuser” — invariant to $<10^{-8}$ yr^{-1}

The lunar surface is non-uniform, the reflectance is non-Lambertian, and the state of illumination and appearance is constantly changing

To utilize the Moon for a calibration reference requires using an analytic model with a continuous predictive capability

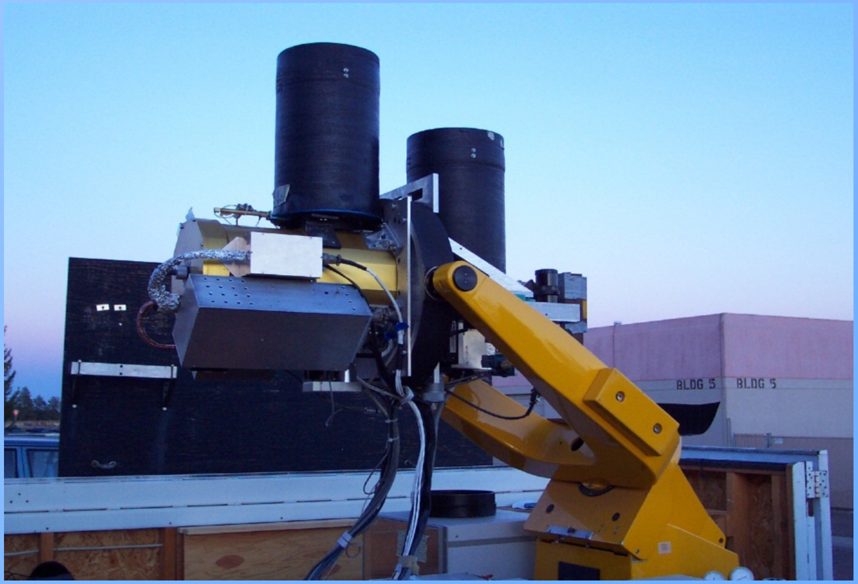
- to accommodate any view by a spacecraft sensor
- a model must be developed from several years of observational measurements, to capture the cyclic brightness behavior sufficiently for modeling
- the precision of a lunar model depends on the extensiveness of measurements

The lunar calibration system developed at USGS provides predictions of the lunar spectral irradiance at reflected solar wavelengths: 350–2500nm

- actively used for on-orbit calibration of NASA EOS instruments: MODIS, SeaWiFS, ALI, Hyperion, ...
- planned for use by next-generation operational satellite imagers: GOES-R, NPP−VIIRS, LDCM−OLI, Meteosat 3rd Gen FCI

Lunar radiometric reference — the USGS lunar irradiance model

- Empirical model developed from fitting an extensive dataset of ground-based lunar measurements
- Data acquired over 8+ years by the Robotic Lunar Observatory (ROLO)
  - twin 20 cm f/5 imaging telescopes
  - 23 VNIR bands 350−950 nm
    9 SWIR bands 950−2450 nm
  - nightly stellar extinction observations to derive atmospheric corrections
  - >85,000 individual Moon images
  - calibration tied to star Vega



USGS campus Flagstaff, AZ

- Analytic model form — a continuous function of the geometric variables of phase and lunar libration
- Mean fit residual ~1% — a measure of the model's predictive precision

Lunar calibration process

- Measurements from images of the Moon, spatially integrated to irradiance:
  - pixel conversion to radiance — using constant calibration coefficients (e.g. pre-launch) reveals temporal trends
  - selection of pixels on the lunar disk

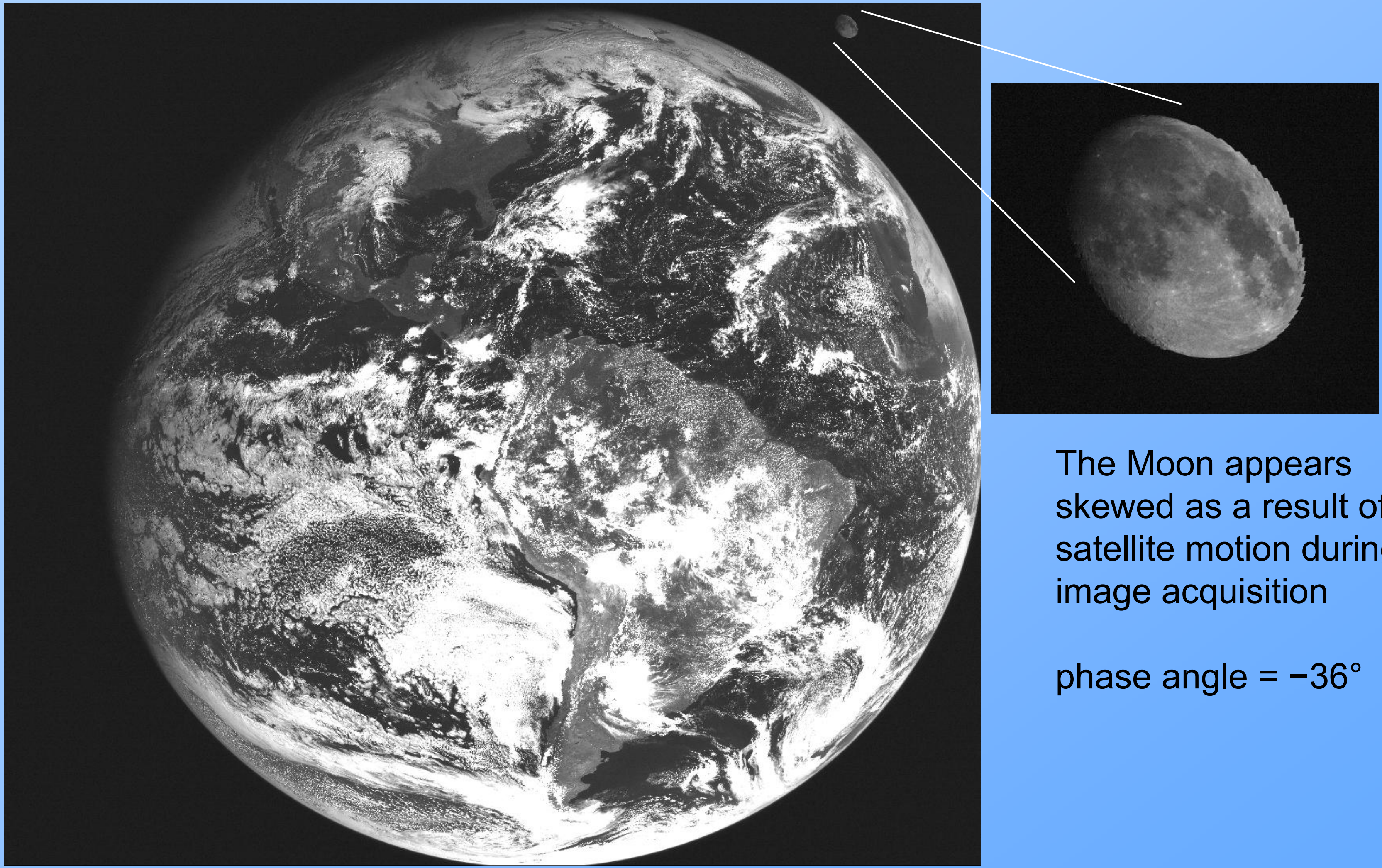
$$I = \Omega_{\mathrm{p}} \sum_{i=1}^{N_{\mathrm{p}}} L_i$$

L_i = pixel radiance
Ω_{p} = pixel solid angle
N_{p} = # of pixels on Moon

- Model-generated irradiances
  - inputs: observation time, instrument (satellite) location at observation time; sensor spectral response
  - photometric geometry (phase and libration) computed from ephemeris
  - model outputs: interpolated to instrument spectral bands; corrected for image acquisition effects (e.g. oversampling), Sun−Moon and Moon−observer distances

- Measurement/model comparisons
  - normalizes lunar brightness variations (primarily with phase)
  - time-series of comparisons reveal sensor response changes
  - these temporal changes are quantified to develop calibration corrections and inter-satellite bias evaluations
  - corrections stabilize the sensor response, and can be applied directly to radiance data products

The Moon captured in GEO visible-channel images



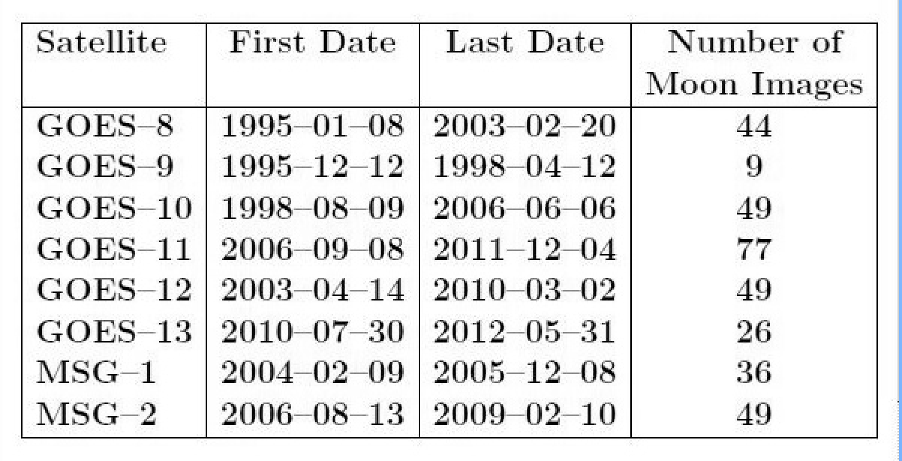
The Moon appears skewed as a result of satellite motion during image acquisition

phase angle = −36°

GOES-12 vis channel 2008-11-10 14:45

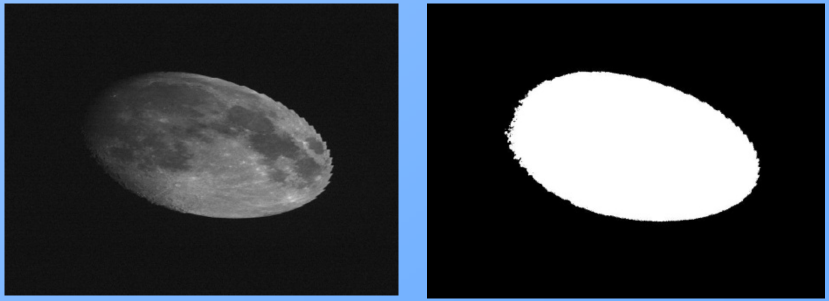
Lunar calibration applied to geostationary satellites

- Step 1: finding images of the Moon in archives
  - captured by chance: coincidence of Moon position with routine imaging schedule; appearances are predictable from satellite orbit and lunar ephemeris
  - dedicated observations by GOES East and West, begun in 2005 (GOES−10)



Satellite	First Date	Last Date	Number of Moon Images
GOES–8	1995–01–08	2003–02–20	44
GOES–9	1995–12–12	1998–04–12	9
GOES–10	1998–08–09	2006–06–06	49
GOES–11	2006–09–08	2011–12–04	77
GOES–12	2003–04–14	2010–03–02	49
GOES–13	2010–07–30	2012–05–31	26
MSG–1	2004–02–09	2005–12–08	36
MSG–2	2006–08–13	2009–02–10	49

- Step 2: image subsampling, selection of on-Moon pixels, lunar irradiance measurements

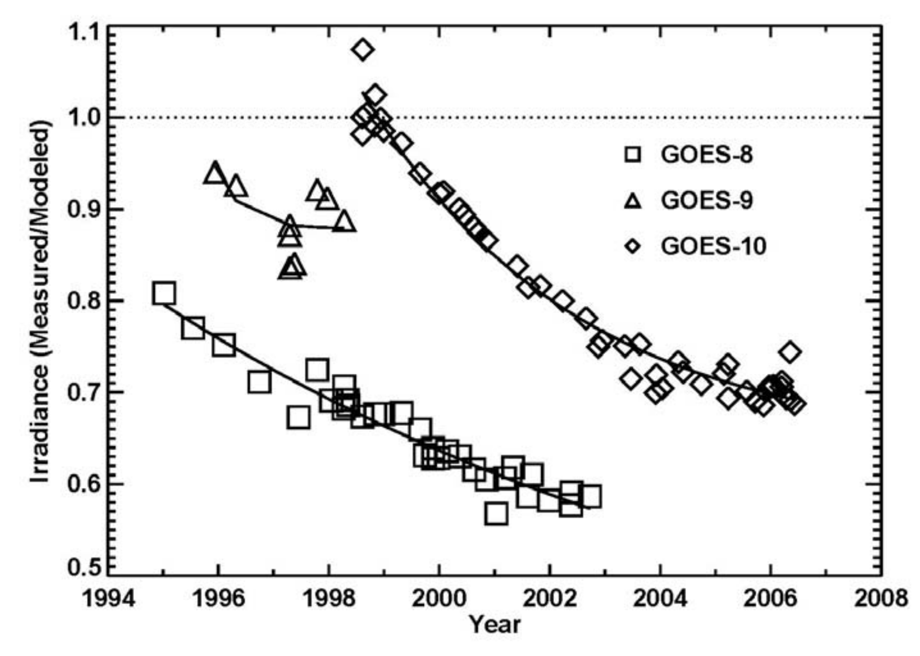


$$I = \Omega_\mathrm{p} \sum_{i=1}^{N_\mathrm{p}} L_i$$

L_i = pixel radiance
Ω_p = pixel solid angle
N_p = # of pixels on Moon

Lunar calibration applied to geostationary satellites

- Step 3: generate model lunar irradiances
  - lunar model outputs are spectrally interpolated to sensor bands, and corrected for the particular conditions of the observations (e.g. distances)
  - results are directly comparable to the measurements from images
- Step 4: collect into time series for each imager; fit temporal response trend
  - degradation modeled with decreasing exponential form: $a_0 + a_1[1 - \exp(-a_2\, t)]$



- measured/model ratio
  - normalizes variation in lunar brightness with phase, etc.
- comparisons against the lunar reference
  - offsets show calibration biases (pre-launch)
  - magnitudes of degradation validated

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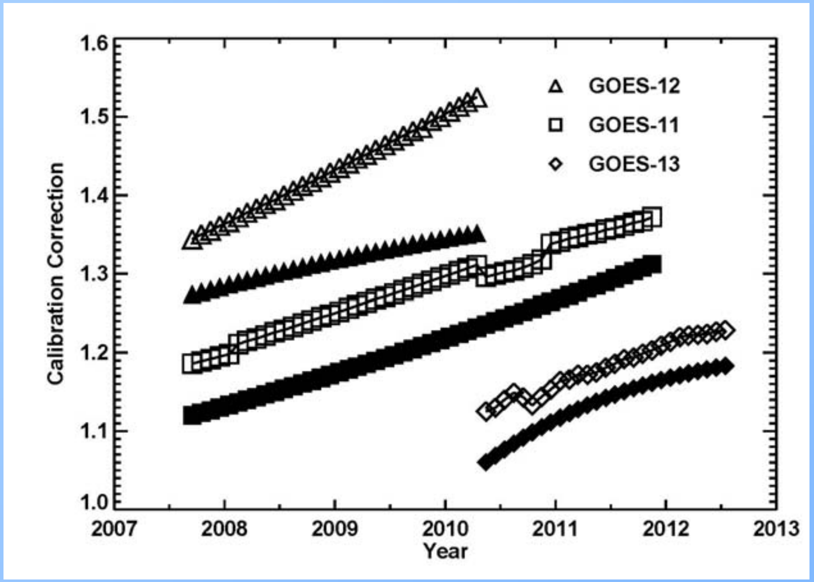
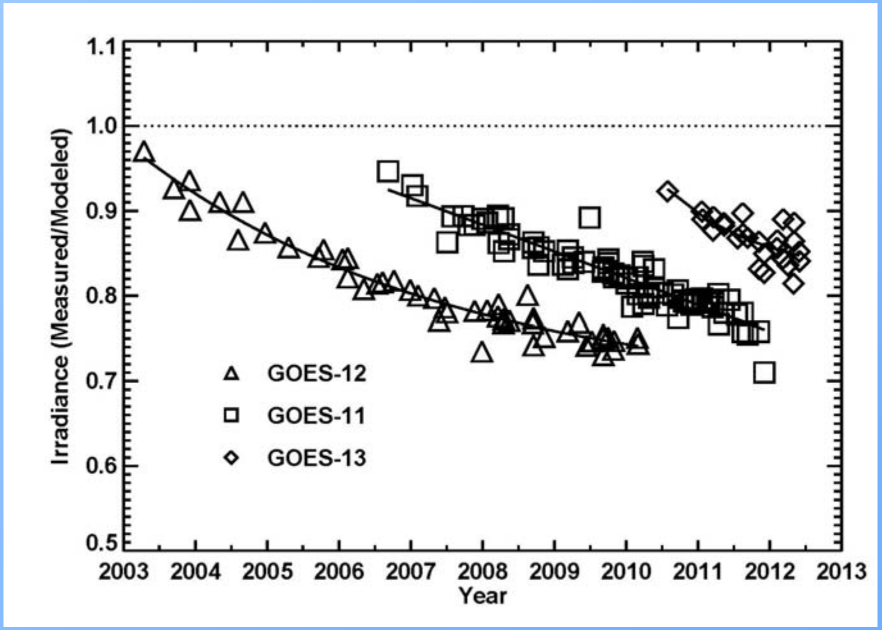
- Step 5: develop calibration corrections from temporal trends
  - trend evaluations give a quantitative measure of inter-sensor biases

correction





- open symbols: GOES operational post-launch calibration

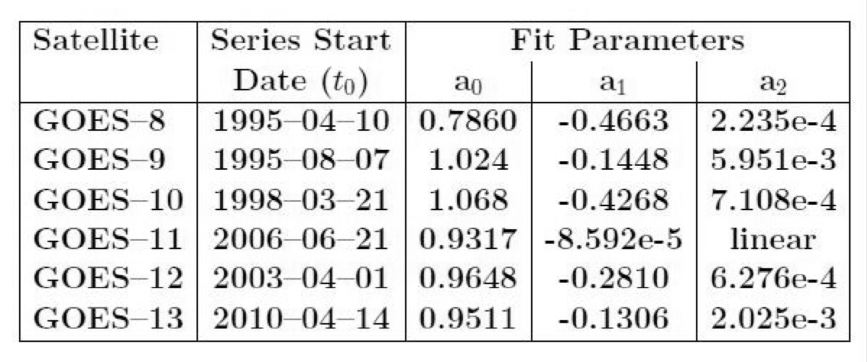
`www.star.nesdis.noaa.gov/smcd/spb/fwu/homepage/GOES_Imager_Vis_OpCal.php`

− based on cross-calibration with MODIS

- filled symbols: developed from lunar calibration

GOES imager calibration corrections derived from lunar analysis

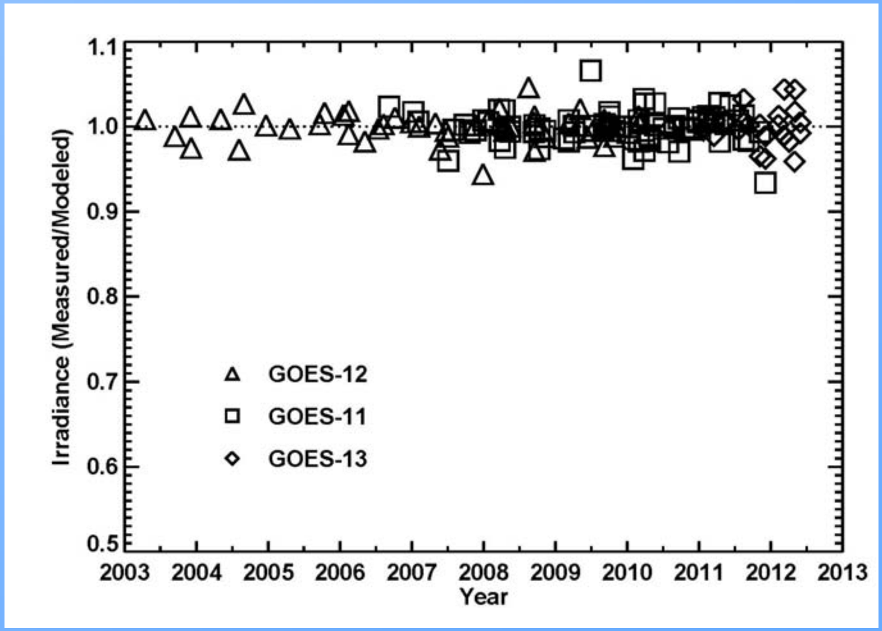
- Correction is the inverse of the trend fit: $\{a_0 + a_1[1 - \exp(-a_2\,(t-t_0))]\}^{-1}$



Satellite	Series Start Date (t_0)	Fit Parameters		
		a_0	a_1	a_2
GOES–8	1995–04–10	0.7860	-0.4663	2.235e-4
GOES–9	1995–08–07	1.024	-0.1448	5.951e-3
GOES–10	1998–03–21	1.068	-0.4268	7.108e-4
GOES–11	2006–06–21	0.9317	-8.592e-5	linear
GOES–12	2003–04–01	0.9648	-0.2810	6.276e-4
GOES–13	2010–04–14	0.9511	-0.1306	2.025e-3

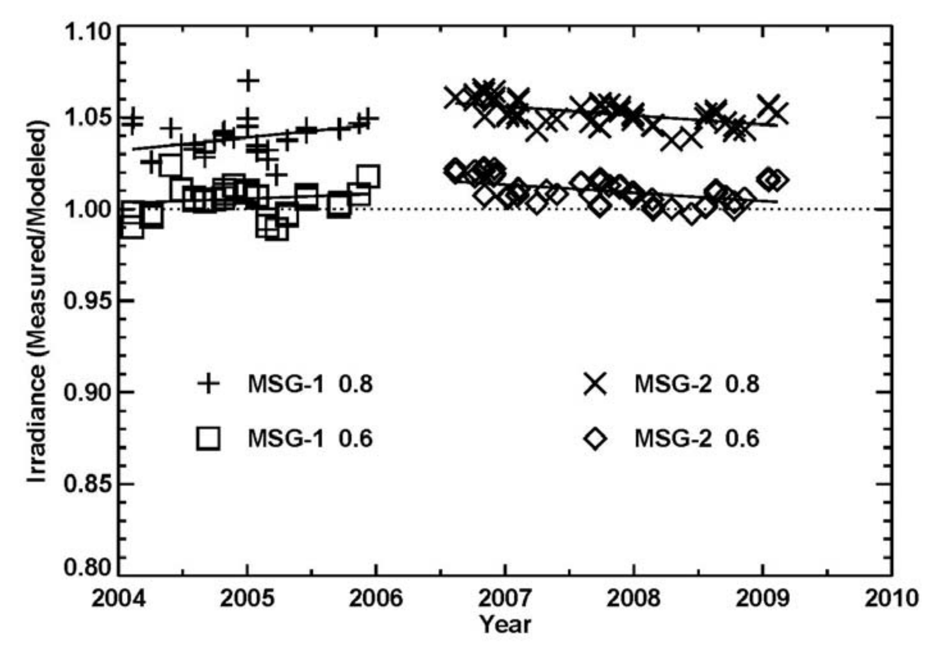
- time units = days

- choice of start date t_0 determines offset, assures consistent calibration over all imagers
- corrected time series represent a distribution of calibration measurements, used for statistical uncertainty analysis



Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat−8 and 9

- three reflective solar bands: 0.6, 0.8, 1.6 µm
- Full-Disk imaging on 15-minute repeat cycle
- Moon images found only in level−1.0 data (level−1.5 has space pixels nulled)



- small degradation trends
- annual variations seen, skews straight-line fits

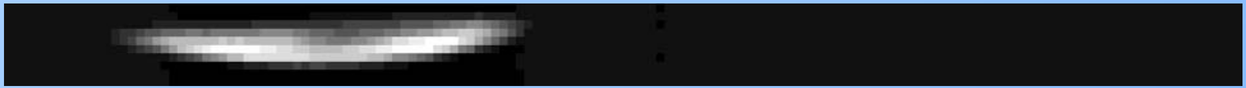
Summary

- Development of long-term, multiple-satellite data records (e.g. CDRs) demands consistent cross-platform calibration of sensors
- The Moon provides an external reference source for radiometric calibration
    - techniques and system have been developed for its use in reflected solar range
- Lunar calibration has been applied to geostationary visible-channel imagers
    - a study sponsored by NOAA−NCDC, to produce a calibration assessment in support of CDR development
    - images of the Moon found in online archives, e.g. NOAA CLASS
    - currently going back to GOES−8; earlier satellites limited by data availability
- Using constant (pre-launch) calibration coefficients, sensor response trends have been evaluated, leading to development of calibration corrections
    - corrections applicable to radiance data products acquired at any time
    - revised calibration of all imager instruments here to a common reference
    - uncertainty evaluations are work in progress
- Future operational imaging missions plan to utilize lunar calibration
    - LDCM OLI, GOES−R ABI, Meteosat Third Gen. FCI

AVHRR images of the Moon

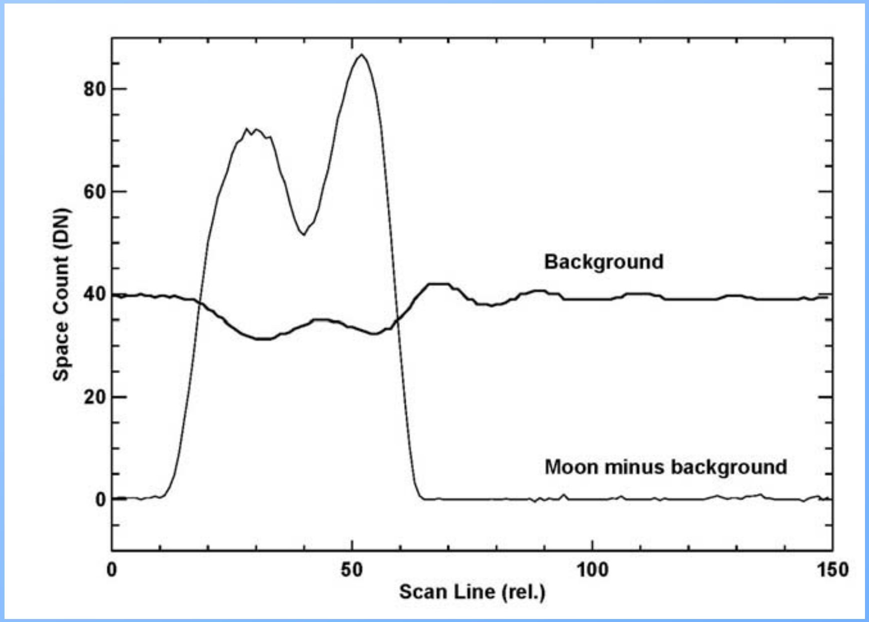
AVHRR instruments periodically image the Moon in space-view, 10 pixels/scan

NOAA−16 AVHRR 2002-12-12 16:37 Ch.2 space-view



- AVHRR space-view is used to set zero-radiance response, or “space clamp”; intrusion of the Moon produces anomalous effects on the background level

stretched to show background level



presence of the Moon drives the level low; clamp response exhibits oscillating ring-down after the Moon passes