Prime Candidate Earth Targets for the Post-Launch Radiometric Calibration of Space-Based Optical Imaging Instruments

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ABSTRACT

This paper provides a comprehensive list of prime candidate terrestrial targets for consideration as benchmark sites for the post-launch radiometric calibration of space-based instruments. The key characteristics of suitable sites are outlined primarily with respect to selection criteria, spatial uniformity, and temporal stability. The establishment and utilization of such benchmark sites is considered an important element of the radiometric traceability of satellite image data products for use in the accurate monitoring of environmental change.

Keywords: Radiometric calibration, vicarious calibration, test sites, optical instruments, remote sensing, traceability.

1. INTRODUCTION

Earth surfaces with suitable characteristics have long served as benchmark or test sites to verify the post-launch radiometric calibration performance of satellite instruments. The associated methodologies are often referred to as vicarious or ground-look calibration. Table 1 lists some of the published work on the use of such methodologies [1-39]. Many of these approaches use surface and atmospheric measurements to estimate top-of-atmosphere radiance at the entrance aperture of a given satellite instrument. This provides a verification of, or an update of, the nominal instrument calibration and helps to monitor instrument performance over time. Historically, field measurement campaigns at calibration test sites typically targeted only one instrument per field sortie, but many of the more recent campaigns have concerned multiple instruments that passed over a given test site within a short time or on the same day. Nevertheless, efforts such as these remain resource intensive. Therefore, it has also been of considerable interest to develop less expensive complementary approaches that can provide more frequent calibration updates, even if they are less accurate. In particular, the use of terrestrial targets to provide updates of the radiometric calibration of a given satellite instrument without coincident surface measurements or to transfer radiometric calibration between satellite instruments (so-called cross-calibration) without coincident surface measurements has increased. The possibility of taking advantage of autonomous in-situ instruments in this context has been proposed [36].

2. SITE SELECTION CRITERIA

The following site selection criteria are recommended [10].

1. The site should have high spatial uniformity, relative to the pixel size, to minimize the effects of scaling radiometric data to the size of the entire test site. This is especially important for cross-calibration between instruments because it minimizes the effects of misregistration. The site should also be centred in an area large enough to accommodate the sampling of a large number of pixels and to minimize atmospheric adjacency effects due to light scattered from outside the target region.

Table 1. Earth target types that are often used for the post-launch vicarious or ground-look calibration of satellite instruments. Some of the published works on the use of these terrestrial target types are cited. (BRDF = bidirectional reflectance distribution function; VNIR = visible and near infrared.)

	Comments	**References**
Dry lake beds or playas	Best calibration targets, but may be subject to soil moisture effects and snow cover	[1-13]
Deserts	Potentially good calibration targets, but subject to BRDF effects if there are dunes	[14-19]
Ice or snow fields	May work well in the VNIR, but solar zenith angles tend to be large	[20-23]
Semi-arid rangeland	May work well if limited phenological activity and terrain flat	[24-25]
Grassland targets	Requires surface measurements to work well; subject to phenological and BRDF effects	[26-27]
Atmospheric scattering	Works well for specialists, but less practical to use operationally	[28-31]
Uniform cloud cover	Works well for specialists, but less practical to use operationally	[28-29, 32]
Ocean glint	Works well for specialists, but less practical to use operationally	[28, 32]
Multiple target types	Provide a range of intensities that help improve accuracies	[33-39]

2. The site should have a surface reflectance greater than 0.3 in order to provide higher signal-to-noise ratio (SNR) and reduce uncertainties due to the atmospheric path radiance.
3. The surface of the site should have flat spectral reflectance. This becomes important if the multiple instruments involved in cross-calibration have spectral bands with different response profiles.
4. The surface properties of the site (reflectance, BRDF, spectral) should be temporally invariant. Otherwise, adequate accuracy would be obtained only if these properties were measured for every calibration. This implies that the site should have little or no vegetation.
5. The surface of the site should be horizontal and have nearly Lambertian reflectance to minimize uncertainties due to differences in solar illumination and observation geometries. It should also be flat to minimize slope-aspect effects.
6. The site should be located at high altitude (to minimize aerosol loading and the uncertainties due to unknown vertical distribution of aerosols), far from the ocean (to minimize the influence of atmospheric water vapour), and far from urban and industrial areas (to minimize anthropogenic aerosols).
7. The site should be in an arid region to minimize the probability of cloudy weather and precipitation that could change the soil moisture and hence the surface reflectance. The low probability of cloud coverage also increases the probability of the satellite instruments imaging the test site at the time of overpass.

3. SPATIAL UNIFORMITY AND TEMPORAL STABILITY OF TEST SITES

Benchmark sites used for instrument calibration should be well understood in terms of their spatial uniformity and temporal stability [40, 41]. From the radiometric perspective, the spatial uniformities of the types of calibration test sites being considered are generally good, such that appropriate radiometric averaging over imagery of these sites will yield small errors due to spatial variations in surface reflectance. For example, Railroad Valley Playa's spatial variability is within 0.5 percent in the specific calibration test site area used by the University of Arizona and collaborators [11]. The La Crau test site in France is not as smooth at detailed scales as some of the other test sites, but it has spatial uniformities within 2 percent in the visible bands and within 4 percent in the near-infrared band [5]. The large sites of 100 km by 100 km in the Saharan and Arabian Deserts were selected on the basis of having less than 3 percent spatial variability [16]. However, these are large areas and it is likely that smaller regions with considerably smaller variability can be found. The spatial uniformity of test sites from the spectral perspective is also important for effective radiometric cross-calibration between multiple satellite instruments, which requires that the spectral dependencies of the instrument responses and the scene (illumination, atmosphere, and surface) be taken into account [42].

From the radiometric perspective, the temporal stabilities of the type of calibration test sites being considered are a bit more of a concern and there is less information in the literature in this regard. Attempts to calibrate multiple satellite instruments imaging a given ground target one or more days apart can yield mixed results [38]. Some playa surfaces are more susceptible than others to soil moisture and related surface roughness effects such that their surface reflectances will vary slightly over time. However, given the generally dry conditions at these calibration test sites, this variability should be more episodic in nature and strongly correlated to significant precipitation events. Experience in working with any given test site will help to mitigate this effect. Many of the large desert sand areas have dunes such that their reflectances are affected by variations in solar illumination angle (8-15 percent), but, once this systematic effect is removed, the remaining temporal variability is 1-2 percent [16]. For the La Crau test site, the temporal variability is within 0.4 percent and the significant BRDF sun angle effect (40 percent) is within 1 percent once corrected [5]. Hence, it is assumed that the temporal stability outside of unusual changes in soil moisture for playas and with adjustments for sun angle effects for desert sand sites is on the order of 2 percent. It is suggested that Shuttle Radar Topography Mission (SRTM) data be examined for each candidate test site in order to determine if topographic variations are problematic.

A key consideration is the assumed invariance of atmospheric conditions at calibration test sites. The points that follow are based on past sensitivity analyses results at green and near-infrared wavelengths [43].
For very clear atmospheric conditions, characterized by an aerosol optical depth of 0.06 at 0.55 micrometers:

- Atmospheric effects on surface-leaving radiances reaching a satellite instrument can be expected to be within 5 percent across all reflectances, except for dark targets with reflectances below 0.05, in which case the errors will be significantly higher percentage-wise.
- For surface reflectances typical of playas and desert sand imaged for calibration purposes, the atmospheric effect can be expected to be within 1 percent. This is because the various contributors to atmospheric effects tend to cancel out for surface reflectances near 0.2, sometimes called the critical reflectance.

For average cloud-free atmospheric conditions, characterized by an aerosol optical depth of 0.33 at 0.55 micrometers:

- Atmospheric effects on surface-leaving radiances reaching a satellite instrument can be expected to be within 5 percent for surface reflectances typical of playas and desert sand.
- For brighter targets such as snow, atmospheric effects will be greater, primarily because high surface reflectances are more sensitive to variations in atmospheric particle size distribution.
- At near-infrared wavelengths outside atmospheric gas absorption features, the errors will be slightly less than for those at green wavelengths. Conversely, errors at blue wavelengths will be slightly greater.

4. PRIME CANDIDATE EARTH TARGETS

Table 2 lists 36 terrestrial sites used on a regular or occasional basis for the radiometric calibration of space-based optical imaging instruments used for Earth observation. The list was put together based on various sources that have been published or have been “floating around” in the calibration community. The incompleteness of available information on even these prime test sites is an indication that much more coordination and documentation are still needed to facilitate the wider use of calibration test sites in remote sensing [35, 36, 44]. Table 2 lists candidates for consideration as the best (“prime”) benchmark sites available and hence includes only playa (dry lakebed) and desert sand sites.

- Snow fields are excluded primarily because high surface reflectances are more sensitive to variations in atmospheric particle size distribution, as already noted, but also because they are usually located at latitudes characterized by high solar zenith angles.
- Vegetation targets are excluded because they are subject to phenological changes as well as reflectance anisotropy effects.
- Water targets are excluded because low surface reflectances are more sensitive to atmospheric path radiance as well as effects such as sun glint.
- Other target types are excluded because the associated calibration approaches require more specialized treatment, which is not in keeping with the spirit of wider, more systematic use of benchmark test sites.

Although the type of ground target is restricted to playas and desert sand areas, it should nevertheless be noted that it is advantageous to have multiple targets with a range of intensities to obtain calibration points that cover a significant portion of the dynamic range of the instrument.

The 36 sites in Table 2 are categorized as being among the best sites with (5 sites) or without (19 sites) routine surface measurements and other potentially good sites (12 sites). Most of the sites have spatial extents (at least 10 km x 10 km) good for instruments with large and small footprints, whereas nine of the sites are suitable only for small footprint instruments. Essentially all of the sites, once characterized, could be used without routine surface measurements.

Table 2. Terrestrial sites used on a regular or occasional basis for the radiometric calibration of space-based optical imaging instruments used for Earth observation. The category column is intended to indicate the acceptability of the site for radiometric calibration purposes. Although Google Earth imagery only provides mosaicked coverage at single times, it does allow a detailed visual inspection and thereby a conservative estimate of the qualities of each site. The assistance of Danielle Tornow for verification of site coordinates and Landsat WRS-2 centres, as well as the assessment of Google Earth imagery, is gratefully acknowledged.

ASL = above sea level
E-W = East-West; N-S = North-South
I = among best sites with routine surface measurements
II = among best sites without routine surface measurements
III = other potentially good sites
L = site good for instruments with large and small footprints (at least 10 km x 10 km)
S = site good only for small footprints
CNES = considered by CNES to be one of the best of the Cosnefroy (1996) sites, based on long term trending of North African and Arabian sites
*Terrain elevation obtained from Google Earth

Site Location	**Centre Latitude, Longitude (Degrees), Altitude ASL (m)**	**Size of Usable Area (E-W km x N-S km)**	**Description**	**Landsat WRS-2 Path/Row Descending Node**	**Category**
Algeria 3	+30.32, +7.66, 245*	75 x 75	Eastern part of Landsat WRS-2 192/39, just outside of west edge of 191/39. Used by CNES (100 x 100 km) – smaller area would be better. Google Earth: Ranges from a dune wave pattern towards the northwest, to a criss-crossing dune pattern in general, to a pock-marked appearance towards the south-east. Reasonably spatially homogeneous in its heterogeneity when averaging over areas of 75 km x 75 km. A darker than average site.	192/39	II L CNES
Algeria 5	+31.02, +2.23, 530*	75 x 75	Southern edge towards western corner of Landsat WRS-2 195/38. Google Earth: Complex dune patterns at multiple scales. Otherwise, uniform in colour and intensity with only slight variations across a large area of 75 km x 75 km.	195/39	II L
Amburla, Tanami Desert, Northern Territory, Australia	-23.385, +133.119, 626	1 x 2	An arid desert site located on a long flat plain characterised by a red soil with a sparse cover of Mitchell grass. Located 100 km northwest of Alice Springs. Used for cattle and camel grazing. Ephemeral vegetative growth following heavy tropical thunderstorm activity or slow-moving rain-band activity (may be significant but is uncommon). The site has moderate column amounts of water vapour (typically 5 to 40 kg m-1) and aerosol optical depth (typically 0.03 at 0.5 micron). The site is instrumented to monitor continuously at several points the surface radiation budget and meteorological parameters. (Source: AATSR Validation Implementation Plan PO-PL-GAD-AT-005 (3), http://www.leos.le.ac.uk/AATSR/Downloads/AATSR_VIP_Version3.pdf.) Google Earth: Various drainage patterns, small ranges of colours and intensities. The most useable part is limited to a small area approximately 1 km (E-W) by 2 KM (N-S).	102/76	III L

Arabia 1	+18.88, +46.76, 659*	50 x 50	In eastern part of Landsat WRS-2 165/47. Google Earth: Dunes at several scales across whole area, but reasonably spatially homogeneous in its heterogeneity when averaging over 50 km x 50 km areas, especially north and north-west of centre coordinates. Overall very uniform in intensity and saturation, although the surface appears lighter in intensity towards the east.	165/47	III L
Arabia 2	+20.13, +50.96, 217*	100 x 100	Close to centre of Landsat WRS-2 162/46. Large desert area Rub' al Khali, the Empty Quarter of the Arabian Peninsula. Google Earth: Dunes at multiple scales, less pronounced towards the north. Reasonably spatially uniform over large area of at least 100 km x 100 km located just north of the coordinates provided.	162/46	II L
Barreal Blanco, San Juan, Argentina	-31.86 -69.45, 1872*	0.5 x 0.5	Located in northwest Argentina in Provincia de San Juan. Used on a joint campaign with Argentina's CONAE to calibrate the satellite instruments EO-1 ALI and Hyperion as well as Landsat-7's ETM+ and Terra's ASTER. The EO-1 and ASTER site measured 16x4 20-m pixels on a 100-280 axis. ETM+ consisted of a 16x4 30-m pixel site on a 010-190 axis. The site was chosen because there was a need to calibrate the instruments on-board EO-1 immediately after the January launch and weather conditions are favourable in the Southern Hemisphere in January. Google Earth: Small homogeneous bright site. May be prone to saturation at high sun. Uniform areas are limited to 0.5 km x 0.5 km or less, but there are several such areas.	232/82	II S
Bonneville Salt Flats, Utah, USA	+41.00, -113.57, 1284*	10 x 10	Can be underwater at times. Areas with human activity. Google Earth: Saturated across the northern half and so cannot assess that area. Google Maps satellite imagery in the southern half shows more detail than Google Earth when zoomed in and the surface there looks very uniform in colour and very bright.	39/32	III L
Dunhuang, China	+40.13, +94.34, 1220	25 x 25	Located in the Gobi desert in north-west China, about 35 km west of the city of Dunhuang (Gansu Province). The calibration area is situated on a stabilised alluvial fan. The area used for vicarious calibration measurements is approximately 400 m x 400 m in the centre of the fan and the surface comprises cemented gravels, with no vegetation. Sources of meteorological data for the site include the Dunhuang-PAM automated weather station, which is part of the Asian Automatic Weather Station Network. Atmospheric aerosols over the site are typical of a rural continental location, although some larger particles were observed, possibly influx from the sand dunes to the north-west. Sandstorms affect the site on around 8 days per annum and atmospheric dust is a significant factor on around 60 days per annum. (Source: Network for Calibration and Validation of Earth Observation (NCAVEO) web site, http://www.ncaveo.ac.uk/calibration/radiometry/in-flight/#dunhuang.) AERONET site. Google Earth: Looks very uniform in intensity and colour, especially in Google Maps satellite imagery, which shows more detail.	137/32	I L
Dunrobin, Queensland, Australia	-22.67, +146.13, 336	0.15 x 0.15	Clay pan. Located on the Dunrobin property, north of Jericho. Google Earth: General area too spatially heterogeneous to use, but site of interest is a small area with a bright whitish surface. Imagery too coarse to see detail. Could be good for small footprint instruments.	94/76	II S

Egypt 1	+27.12, +26.10, 226*	100 x 100	South-west quadrant of Landsat WRS-2 179/41. Used by CNES (100 x 100 km). Google Earth: Dunes at multiple scales, but spatially homogeneous in intensity overall, confirmed by Google Maps, which shows better imagery (although may be same imagery cosmetically improved).	179/41	II L CNES
Egypt 2	+22.94, +28.79, 248	10 x 10	Areas with human activity (roads; oil wells?). Google Earth: Patchy (in colour and intensity) across larger area. Reasonably uniform areas of 7 km x 7 km, possibly 10 km x 10 km.	177/44	III L
Ivanpah Playa, Nevada/ California, USA	+35.5692, -115.3976, 813	1 x 1	Dry-lake playa, located right on the border of California and Nevada along I-15. It is smaller than Railroad Valley, and at lower elevation, but is by far more convenient to use and is more spatially uniform as well. Google Earth: Looks very smooth and homogeneous in intensity and colour.	39/35	I S
La Crau, France	+43.47, +4.97, 28	1 x 2	The area has a thin pebbly soil with very sparse vegetation cover. About 50 km north-west of Marseille, not far from the Mediterranean, so possibility of atmospheric water vapour and aerosol problems. (Source: Network for Calibration and Validation of Earth Observation (NCAVEO) web site, http://www.ncaveo.ac.uk/calibration/radiometry/in-flight/#lacrau). AERONET site. Google Earth: Looks homogeneous in intensity and colour across the site. Surface slopes upward significantly from north (approximately 10 m ASL) to south (approximately 30 m ASL).	196/30	I S
Lake Frome, South Australia, Australia	-30.85, +139.67, 3	10 x 10	Lake Frome is a dry salt lake consisting of a flat surface, an extremely bright salt crust, less bright crust variants, and the dark clay soils of the islands. Spatially homogeneous areas range from 2 km x 2 km to 10 km x 10 km in size. The specified coordinates are centred on the area (roughly 2 km x 2 km) used for Hyperion calibration, whereas the 10 km x 10 km area is to the north. May be prone to saturation at high sun. Google Earth: Looks very homogeneous across the site, but the imagery may be saturated such that details cannot be discerned.	97/81	II L
Libya 1	+24.42, +13.35, 648*	50 x 50	Close to centre of Landsat WRS-2 187/43. Used by CNES (100 x 100 km) – smaller area(s) would be better. Google Earth: Dunes at multiple scales, but spatially homogeneous overall for several areas of 50 km x 50 km. Dunes become less pronounced towards the south-east. Surface colour also varies from north-west to south-east.	187/43	II L CNES
Libya 2	+25.05, +20.48, 329*	100 x 100	Outside south-west corner of Landsat WRS-2 182/42. Google Earth: Strong dune and rivulet patterns at multiple scales. Otherwise, large spatially homogeneous area of 100 km x 100 km available. Some smoother areas of 25 km x 25 km approximately 200 km north-east of centre coordinates. There appear to be slight variations in intensity and colour across the area but these may arise from different images.	182/43	II L

Libya 4	+28.55, +23.39, 118	75 x 75	South-west quadrant of Landsat WRS-2 181/40. Used by CNES (100 x 100 km) – smaller area would be better. Google Earth: Dunes at multiple scales, but large usable areas of 75 km x 75 km or more, especially north-west of centre coordinates. The surface varies slightly in intensity and colour across the area.	181/40	II L CNES
Lunar Lake Playa, Nevada, USA	+38.40, -115.99, 1750	1.5 x 2.5	Dry-lake playa, relatively flat with high reflectance beyond 0.7 micrometers; very spatially uniform, with portions varying by < 0.5 percent in reflectance. Surrounded by mountains. AERONET site. Google Earth: Looks very smooth and spatially homogeneous in intensity and colour.	40/33	II S
Mali 1	+19.12, -4.85, 305*	25 x 25	North central part of Landsat WRS-2 198/47. Google Earth: Some dune patterns at detailed scale and more pronounced at larger scales towards north. Patchy (in colour and intensity) across larger area, otherwise fairly spatially homogeneous for several areas of 10 km x 10 km to 25 km x 25 km.	198/47	III L
Mauritania 1	+19.4, -9.3, 392*	50 x 50	Northern edge of Landsat WRS-2 201/47. Used by CNES (100 x 100 km) – smaller area would be better. Google Earth: Dunes at detailed scales. Reasonably spatially homogeneous across 50 km x 50 km, although patchy (in colour and intensity) across larger area on western side. Large dune patterns across northern half of 201/46, so avoid there.	201/47	II L CNES
Namib Desert, Namibia 1	-24.98, +15.27, 691	15 x 15	Google Earth: Swirl dune patterns separated by homogeneous areas. May be worth looking at. Overall suitable area of 25 km x 25 km although there is a colour gradient across east-west. A 10 km x 10 km or 15 km x 15 km area would be safer. Swirl dune pattern disappears towards coast (west).	179/77	III L
Namib Desert, Namibia 2	-17.33, +12.05, 475	7 x 7	Google Earth: Pock marks and some dunes at detailed scales, more pronounced towards the north-west. Possibilities for small spatially homogeneous patches of 7 km x 7 km.	182/72	III S
Niger 1	+19.67, +9.81, 582*	50 x 50	At south-west corner of Landsat WRS-2 188/46. Google Earth: Dunes at detailed scales but not very pronounced. Large spatially homogeneous (in intensity and colour) areas: approximately 25 km x 25 km to east of specified coordinates and approximately 50 km x 50 km about 50 km to north of specified coordinates. A 100 km x 100 km window may also be workable.	189/46	II L
Niger 2	+21.37, +10.59, 517*	25 x 25	Just outside south-west quadrant of Landsat WRS-2 188/45. Google Earth: Dunes at detailed scales and some striations at coarser scale. Several large spatially homogeneous areas of approximately 25 km x 25 km. Darker colours than most of the other desert sites and patchy (in colour and intensity) across the area.	188/45	III L

Railroad Valley Playa, Central Nevada, USA	+38.50, -115.69, 1435	10 x 10	Dry-lake playa, spatially homogeneous, consisting of compacted clay-rich lacustrine deposits forming a relatively smooth surface compared to most land covers, although it has a lower spatial uniformity compared to the Ivanpah and Lunar Lake sites. The surface composition is comparable to those of Ivanpah and Lunar Lake; however, all three sites suffer from the presence of iron absorption (Fe3+) in the visible part of the spectrum, characteristic of playas in this region of the US. AERONET site. Google Earth: Slightly patchy (in colour and intensity) across the playa.	40/33	I L
Rogers Dry Lake, Edwards Air Force Base, California, USA	+34.96, -117.86, 694	1 x 2	Dry-lake playa. Smooth surface with some cracks. Can be busy with air traffic and nearby vehicular traffic. Very restricted ground access. Within 100 km of Los Angeles. AERONET site. Google Earth: Slightly patchy (in intensity) across the playa.	41/36	II S
Sechura Desert, Peru	-5.90 , -80.43, 51	10 x 10	Arid, flat, no vegetation. Not far from ocean, so possibility of atmospheric water vapour and aerosol problems. Forego use or use cautiously in the absence of further information. Google Earth: Imagery is very cut up and so little can be gleaned from it.	10/64	III L
Sonoran Desert, Mexico AKA Yuma	+32.35, -114.65, 37	15 x 15	Arid, flat, no vegetation. Near US border and Yuma, Arizona. Best area centred south-west of specified coordinates. Surface slopes from south-west (~30 m ASL) to north-east (~60 m ASL). Google Earth: Nice site. Appears very spatially homogeneous in intensity and colour, despite small pock marks at detailed scale.	38/38	II L
Sudan 1	+21.74, +28.22, 325*	10 x 10	Close to centre of Landsat WRS-2 177/45. Used by CNES (100 x 100 km). Google Earth: Dunes at detailed scale, but choppier and less linear than other North African desert sites. Somewhat patchy (in colour and intensity) overall, but there are a few uniform patches of 10 km x 10 km.	177/45	III L CNES
Taklamakan Desert, China	+39.83, +80.17, 1079*	25 x 25	Nice area centred on indicated coordinates, near northern edge in the western part of the desert. Also a few other areas further east still in the northern part of the desert. Google Earth: Omni-directional dune pattern in detail, but spatially homogeneous at scales of interest. Little variation in colour and intensity across the main area noted above.	146/32	II L
Tinga Tingana, Strzelecki Desert, South Australia, Australia	-29.00, +139.83, 38	15 x 15	Airborne and ground based data have been taken to estimate the site's BRDF. Used for a variety of calibration and cross-calibration studies. Background aeolian dune system at a scale resolved by Hyperion allowing geometric studies as well as spectral calibration studies. Not easy to access on the ground. AERONET site. (Source: CSIRO Earth Observation Centre web site, http://www.eoc.csiro.au/hswww/Hyperion.htm#Calibration%20&%20Validation.) Google Earth: Not spatially homogeneous in intensity and colour at detailed and intermediate scales, but reasonably spatially homogeneous in its heterogeneity when averaging over 15 km x 15 km.	97/80	III L

Uyuni Salt Flats, Bolivia	-20.38, -66.95, 3650	25 x 25 perhaps 40 x 40 or more	Indicated coordinates appear to be near eastern edge. Coordinates more central to the salt flats would be -20.2, -67.6. Ground photos from tourism web sites indicate a very flat surface. Possibility of saturation in some spectral bands with high sun. Google Earth: Imagery saturated so hard to see details.	233/74	II L
Warrabin, Queensland, Australia	-26.28, +143.65, 162	0.2 x 0.2	Clay pan surrounded by grassland and ironstone. Located between Quilpie and Windorah. Google Earth: General area too spatially heterogeneous to use, but site of interest is a small area with a bright whitish surface located west of the specified coordinates. Imagery too coarse to see detail. Could be good for small footprint instruments.	95/78	II S
White Sands, New Mexico, USA	+32.92, -106.35 1196	10 x 15 perhaps 15 x 20	Alkali flats area of White Sands. A flat, extended area of gypsum sand. High, uniform, nearly Lambertian reflectance in the visible and near infrared. Altitude 1200 m, hence low atmospheric aerosol loading. High probability of clear weather. Very restricted ground access. Areas with human activity. Possibility of saturation in some spectral bands with high sun. Subject to soil moisture variations, high water table (can have standing water). AERONET site. White Sands National Monument (WSNM) has a long history of use as a calibration target for Earth observing instruments. The site is located in a mountain basin in south-central New Mexico. Although the area has very suitable weather conditions, with many clear days, the calibration site is not ideal because its reflectance is greatly affected by changes in soil moisture. The surface also deviates considerably from a Lambertian response at high solar and viewing zenith angles. However, the University of Arizona group uses a 500 m x 500 m area at the specified coordinates known as Chuck Site, which has a near-Lambertian response. (Source: Network for Calibration and Validation of Earth Observation (NCAVEO) web site, http://www.ncaveo.ac.uk/calibration/radiometry/in-flight/#whitesands) Google Earth: Some pock marks at detailed scales. Generally spatially homogeneous across an area of approximately 10 km (E-W) by 15 km (N-S).	33/37	I L
Winton, Queensland, Australia	-22.52, +142.94, 209	0.2 x 0.2	Clay pan surrounded by shrubs and grassland. Just outside the north-west edge of Bladensburg National Park. Google Earth: General area too spatially heterogeneous to use, but site of interest is a small area with a bright whitish surface. Imagery too coarse to see detail but may not be quite as spatially homogeneous as Dunrobin and Warrabin sites. Could be good for small footprint instruments.	96/76	III S
Yemen Desert 1	+16.87, +47.55, 949	15 x 15	Google Earth: Several possible areas of 10 km x 10 km, possibly a few at 15 km x 15 km. Nevertheless, significant patchiness in colour and intensity across the area.	164/48	III L

A number of agencies maintain a list of reference sites that they utilize for calibration purposes. The international Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) sub-group on Infrared-Visible Optical Systems (IVOS) has carried out some preliminary studies to collate this information, but it acknowledges that the exercise needs to be refined with the prospect of establishing some form of internationally accepted "CEOS Certification" for an appropriate sub-set of sites. It is expected that certification and the promotion of the use of certified sites as part of 'best practice' methodologies will lead to improved consistency between satellite instruments, reduced costs overall, and an ability to ensure the usefulness of the benchmark sites into the future [35, 36, 38, 43]. Clearly, the tabulation of prime candidate test sites presented in this paper is only an early step, but one that can provide a foundation for the establishment and utilization of benchmark sites to help underpin the accurate monitoring of environmental change.

CEOS/WGCV/IVOS notes that the key characteristics necessary to classify a site need to be specified in detail and proposes the following list as a starting point.

- Core Test Site (name, location, coordinates, size, shape, and orientation)
- Description of the Site
- Images (ground photos, digital topography, satellite screenshots, Google imagery)
- Current Status of the Site (instrumented, maintained, funding, visited, access)
- Surface Measurements (historical, meteorological, clear-sky data, seasonal variations)
- Surface Characteristics (sampling strategy, reflectance, BRDF, traceability, uniformity, topography, radar backscatter and thermal infrared signatures, surface and atmospheric stability, surveyed points)
- Site Usage (record of data and comparisons (ground, aircraft and satellite))
- Auxiliary Data (e.g., Landsat WRS2 Path/Row)

As a concrete step in this direction, the US Geologic Survey is working with partners around the world to establish a pilot web site that provides the start of a "Catalogue of World-wide Test Sites for Sensor Characterization". The on-line catalogue will provide easy public web site access to this vital information for the global community.

Other bold steps that involve test sites as a key element have been proposed. In particular, satellite missions dedicated to calibration and the concomitant data centres would establish the coordination needed to help make the Global Earth Observation System of Systems (GEOSS) a success and to provide the accuracies needed to monitor environmental change properly [45-46].

5. CONCLUDING REMARKS

The growing use of terrestrial targets for understanding satellite instrument performance has made them a key component of current and future post-launch calibration strategies. This paper summarizes the key considerations for site selection and provides a comprehensive list of prime targets for consideration as benchmark sites for the radiometric calibration of space-based instruments. The next step is to work with international agencies and organizations to refine the list further and to provide additional key information needed to characterize each site.

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