GSICS-RDURD

Global Satellite
Inter-Calibration System

USER REQUIREMENTS DOCUMENT

tional logo of the entity providing/ maintaining the document

Version 0.1

April 2015

RECORD OF DOCUMENT CHANGES

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Version** | **Date** | **Nature of change** | **Done by** | **Approved**  |
| 1.0 |  | Creation |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

Contents

[GSICS User Requirements Document 4](#_Toc416377246)

[1. Purpose of the document 4](#_Toc416377247)

[2. Requirement sources 4](#_Toc416377248)

[3. Synthesis of requirements 4](#_Toc416377249)

[3.1. Scientific requirements 4](#_Toc416377250)

[3.2. Service requirements 5](#_Toc416377251)

[Annexes 6](#_Toc416377252)

[Annex 1: Use of satellite data records in climate analysis Requirements of the Global Space-based Inter-calibration System (GSICS), 6](#_Toc416377253)

[Annex 2: Extract from Satellite instrument calibration for measuring global climate change, Ohring G., Wielecki B., Spencer R., Emery B., Datla R., Bulletin of the American Meteorological Society, September 2005, p.1307-1308 11](#_Toc416377254)

# GSICS User Requirements Document

## Purpose of the document

This document consolidates the status of user requirements for GSICS products and services from satellite data users, either for near real-time applications or for off-line or historical data reprocessing.

## Requirement sources

The following sources of requirements have been considered:

* Outcome of GSICS User Workshops
* Reports from GSICS beta-testers and other feedback collected by the GCC and GPRCs
* WMO Rolling Review of Requirements (<http://www.wmo-sat.info/oscar/requirements>)
* Use of satellite data records in climate analysis: Requirements of the Global Space-based Inter-calibration System (GSICS), Adrian Simmons, Chair, Steering Committee for the Global Climate Observing System (GCOS), 2013.
* [Satellite instrument calibration for measuring global climate change](http://map.nasa.gov/documents/CLARREO/BAMSOhringetalSept2005SatelliteClimateCalib%5B3%5D.pdf), Ohring G., Wielecki B., Spencer R., Emery B., Datla R., Bulletin of the American Meteorological Society, September 2005, p.1303-1313

## General statement of needs

GSICS Products are intended to support any application relying on accurate and globally consistent satellite data. This is the case of the generation of seamless composite satellite imagery products, or of stable quantitative Level 2 products such as cloud analysis, radiative flux, aerosol detection, or sea or land surface observations. It is necessary to provide Level 1 data with a stable and consistent calibration over time and across instruments, to enable Level 2 or Level 3 products to be more stable, less noisy, and to reduce the need for tuning of each product to each instrument, thus reducing the development and validation effort and improving the final product quality.

Tying the measurements to absolute references is also important for integrating surface and space observations.

For Numerical Weather Prediction users it is useful that the potential bias in satellite observations is understood and reduced in the ingested data, thus enabling the ultimate linear bias correction by the model to be more meaningful, and optimize the impact of the data; absolute calibration also helps to anchor the model.

A particular use of GSICS products is for climate change detection and monitoring. In this respect, GSICS aims to serve as a building block of the Architecture for Climate Monitoring from Space. Climate applications normally do not require near real-time products but has stringent uncertainty and stability requirements as it requires the detection of temperature changes as tiny as a few tenths of a degree per decade and e.g. ozone trends as small as 1% per decade. To create the stable long-term climate data records it is necessary to inter-calibrate sensors on similar and different satellites, and to inter-calibrate satellite observations with in-situ observations. While the requirement of intercalibrated data is confirmed for reanalysis projects, climate analysis studies also require various types of information, including low level instrument monitoring as explained in Annex 1: *“The strategy of GSICS as set out in the preamble places it in a unique position to help, as its monitoring of instrument performance, tying of measurements to absolute references and standards, and lessons learnt in developing inter-calibrations generates much of the information that is needed to use more basic forms of the data in reanalysis. In turn, experience gained in reanalysis may feed into improved inter-calibration by GSICS.*

*Inter-calibration is nevertheless needed for reanalysis as well as other climate applications. Reanalysis may use inter-calibrated records either directly for assimilation if forward modelling has not been developed for individual instruments of a particular type, or indirectly through assimilation of retrievals for some variables and instruments. A number of fields for the assimilating models used in reanalysis may be derived from a series of data records that benefit from inter-calibration. Requirements are likely to evolve, as research into improving the assimilation of satellite data continues to progress.”*

Satisfying the needs of the NWP, climate and environmental monitoring communities for historical and current satellite data with reduced calibration uncertainties therefore requires a combination of diverse approaches.

## Expected benefits

Intercalibration performed by GSICS enhances the consistency of space-based radiometer calibration and, using a reference measurement network traceable to SI standards, ultimately leads towards absolute calibration.

The following benefits are expected for satellite data users:

* Enhanced quality of near-real time satellite products;
* Improved detection of climate variability and trends and ensuring that any drift of the entire inter-calibrated system measurements truly reflects changes of the Earth System;
* Better support to NWP reanalysis projects;
* Improved utility (ease of use) of satellite radiances in NWP;
* Better understanding of physical processes in atmospheric models;

The following additional benefits are expected for satellite operators:

* Reduced cost-benefit ratio from an optimized global system of satellites;
* Improved characterization of space-based radiometers allowing their extended use in spite of possible drift in sensitivity;
* Assessment of sensor performance to validate that satellite system meets the specified performance standards;
* Improved capability to detect, analyze and explain instrument anomalies, and to improve the development of future sensors.

## Synthesis of requirements

### Calibration requirements (passive radiometric measurements)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Spectral domains | IR | Solar/VIS | Solar/UV | MW |
| Instruments | All operational GEO and LEO. MODIS, AIRS, AMSR2……….. |
| Time period | Current and historical data |
| Spatial coverage | Global – Not only the high latitudes best covered by SNO |
| Radiometric calibration |  |  |  |  |
| * Accuracy
 |  |  |  |  |
| * Maximum bias over a decade
 |  |  |  |  |
| * Stability over a decade
 |  |  |  |  |
| * Absolute traceability
 |  |  |  |  |
| * Time averaging
 |  |  |  |  |
| * Timeliness
 |  |  |  |  |
| Spectral calibration | SRF correction |  |  |  |
| Navigation |  |  |  |  |
| Other parameters | Instrument event log |  |  |  |
|  |  |  |  |  |

### Service requirements

|  |  |
| --- | --- |
| Product presentation |  |
| Accessibility |  |
| Delivery mechanisms |  |
| Archiving |  |
| Documentation |  |
| User support |  |
| … |  |
| … |  |

## User feedback

Feedback was systematically requested from GSICS beta testers at the GSICS Users Workshop during the development phase of the first GSICS products, including in Cordoba (2010), in Oslo (2011), and Sopot (2012).

TABLE xx: General feedback

|  |  |
| --- | --- |
| ATBD  | Clear, useful, easy to reproduce |
| Data download | Good accessibility and availability |
| Product quality | Suitable and reliable |
| Particular request | Detailed uncertainty estimation |
|  |  |
|  |  |

TABLE xx: Product specific impact

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Organization | Report | GSICS Products | Application | Impact |
| JMA | 2010 | MTSAT (WV) | CSR | Significant |
| JMA | 2011 | MTSAT (IR) | SST | Significant |
| NOAA | 2010 | GOES | CTH |  |
| CM-SAF | 2011 | Meteosat/SEVIRI | Cloud cover | Apparent |
| EUMETSAT | 2010 | Meteosat/SEVIRI | TPW | Apparent |
| EUMETSAT | 2011 | Meteosat/SEVIRI | CTH | Apparent |
| NOAA | 2011 | GOES | CTP | Reduction of noise |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

## Remarks

..

…

…

## Annexes

### Annex 1: Use of satellite data records in climate analysis:Requirements of the Global Space-based Inter-calibration System (GSICS),

Adrian Simmons

Chair, Steering Committee for the Global Climate Observing System (GCOS)

Consultant, European Centre for Medium-Range Weather Forecasts (ECMWF)

1. **Preamble**

This note was prepared at the request of the Executive Panel of GSICS, following a presentation of its main contents to the 14th Session of the Panel on 15 July 2013. Comments made on a draft version by some of the colleagues whose work is referenced in section 4 have been incorporated. The note does not represent a formally approved GCOS document, but rather is a paper for discussion based primarily on consideration of the use of satellite data in reanalysis. Outcomes of the discussion may be included in the review of progress, adequacy and requirements that the GCOS programme has recently begun.

By way of introduction, it is noted that the home page of the GSICS website states that GSICS achieves its aims “through a comprehensive calibration strategy which involves:

- monitoring instrument performances,

- operational inter-calibration of satellite instruments,

- tying the measurements to absolute references and standards, and

- recalibration of archived data.”

and that “GSICS delivers calibration corrections needed for accurately integrating data from multiple observing systems into products, applications and services.”

1. **The requirement for different forms of data record**

Whilst inter-calibration of data is vital for operational purposes and, applied to archived data, for a number of climate purposes, the inter-calibrated “Fundamental Climate Data Record” is not in fact the fundamental form of the data record that is needed in some instances. Something closer to the original measurements may be required. This is the case for some important types of data used in reanalysis.

The principal data records for which this applies are those for which analysis is made using a forward radiative transfer model to map geophysical variables, such as the background temperature and humidity fields of a reanalysis, into equivalents of radiance data that have undergone basic radiometric calibration of the raw measurements from one or more satellites. In such cases, the requirement is not for a single record of inter-calibrated radiances from the set of satellites, but rather for a more fundamental set of radiance records, one (or more) for each satellite, to each of which is attached a number of parameters (or metadata) that enable the radiative transfer model to be tailored to the particular instrument (or instruments) flown on that satellite. Even for a particular instrument, drifts and shifts in its characteristics over its active in-orbit lifetime may best be catered for by employing a radiative transfer model that accounts for the instrumental changes that occur over that lifetime.

1. **Terminology**

The 2004 US National Academy of Sciences (NAS) Report on climate data records defines Fundamental Climate Data Records (FCDRs) as “sensor data (e.g., calibrated radiances, brightness temperatures, radar backscatter) that have been improved and quality controlled over time, together with the ancillary data used to calibrate them.” This statement alone does not make it clear that the FCDR is assumed to have been subject to inter-calibration, but the report later states “The third form of calibration is satellite intercalibration”. It further states “The FCDRs will be the ultimate legacy that the long-term satellite programs leave to the next generation.” The Report also introduces the term “sensor data records” (SDRs) and states: “The SDRs are time tagged, geolocated, and calibrated antenna signals, but they will not be created for long-term stability and reliability, and they will therefore not be suitable for climate purposes without reprocessing into FCDRs.”

The final two quotes are incorrect. The FCDR as defined in the NAS report is not the most fundamental form of data record required by some users for climate purposes, at least if the SDR cannot be recovered from the FCDR. Data do not invariably need to be processed into FCDRs to enable them to be used for climate purposes. The fundamental record that provides the legacy must include the SDR for each of the individual instruments involved in the record (which may not map one-to-one to the satellites involved: two VTPRs were included on each of the early NOAA operational polar orbiters). The record must also include as much information as possible both to enable further calibration and to enable the contents of the SDR or further-calibrated records to be modelled in terms of the atmospheric, oceanic and terrestrial state variables to which the measurements are sensitive. The record could include intermediate and fully calibrated records, but these would be more subject to change than the SDRs, and could depend on other observations or reanalysis data.

The definition of the SDR should also be clarified. It should include radiance data that are calibrated with nominal instrument information, such as nominal spectral response functions, antenna emissivity and so on. In this case, recalibration based on improved knowledge of the instrument would still be beneficial for reanalysis. The NOAA presentation to the 14th Session of the GSICS Executive Panel (available from <http://www.wmo.int/pages/prog/sat/meetings/GSICS-EP-14.php>) includes an example of better calibration of CrIS data by improved accounting for nonlinearity of the detector response. In such a case, reprocessing of all or part of the SDR is needed to ensure optimal use of the data in reanalysis and for generation of the FCDR. Depending on circumstances, reprocessing of other SDRs from the same type of instrument may be needed. Moreover, assimilation of the SDR along with other types of data may allow better values of uncertain instrument parameters to be inferred by the reanalysis process.

New terminology is not needed, provided it is understood (as it may already be by many) that the FCDR includes the component SDRs and relevant intermediate calibrated records in addition to the inter-calibrated record. If this is not the case, the Architecture for Climate Monitoring for Space proposed by Dowell *et al.* (2013) needs amendment, as it shows FCDRs as the input to the process of conversion from satellite data to geophysical parameters, a process that includes reanalysis.

1. **Examples**

Examples are given for three types of data that are assimilated in reanalysis. Although generally satisfactory use of these data has been achieved using variational bias adjustment and there is a suggestion of some additional benefit of using pre-processed inter-calibrated MSU data (Rienecker*et al*., 2011; Simmons *et al*., 2013), there is in each case a potential further improvement to be achieved through modelling the scene-dependence of the differences in measurement from one satellite to another.

*(i) Stratospheric Sounding Unit (SSU)*

Seven SSU instruments provided systematic sounding data for the stratosphere overall total of more than 27 years, but the data have proved challenging to use, in part because of differences between instruments and limited operational overlap from satellite to satellite. Kobayashi *et al*. (2009) showed that differences from one instrument to another in the mean pressures of each instrument’s three pressure-modulated cells could account for much of the inter-satellite differences in data identified for periods when overlap enabled use of the Simultaneous Nadir Overpass technique. In addition to cell-pressure differences at launch, changes in pressure occurred in orbit due to leakage of gas. As the mean cell pressures determine the vertical profiles of the instruments’ weighting functions, the inter-satellite measurement differences depend on the temperature profile. Kobayashi *et al*. also demonstrated improvements (but remaining problems) in the assimilation of SSU data in the ECMWF system when the fast radiative transfer model (RTTOV) used to simulate the data was modified to account for mean cell-pressure differences from satellite to satellite. RTTOV has recently been updated to allow also for the change in cell pressures over time for each instrument (Saunders *et al*., 2013), but the presence of water vapour as well as carbon dioxide in the cell at launch and the subsequent leakage of both gases need to be taken into consideration (Nash and Saunders, 2013).

*(ii) Microwave sounders*

Lu and Bell (2013) present evidence that significant shifts and drifts relative to nominal pass band centre frequencies occur in measurements from channels 6 to 8 of early AMSU A instruments, but not from the actively-stabilised higher-sounding channels of these instruments. They also found large shifts for MSU channel 3. Frequencies had previously been found to be uncertain for the MWTS on FY-3A. The effect on measurements is lapse-rate dependent, as the vertical profiles of weighting functions change from their nominal forms. Lu and Bell argue that these spectral errors are the dominant cause of observation-background biases in the assimilation of these types of data, and that they should be accounted for in the radiative transfer modelling for the instruments.

*(iii)HIRS spectral response functions*

The spectral response functions of the HIRS instruments that have been operated since late 1978 are also known to differ significantly from satellite to satellite, and some of the functions specified from pre‐launch measurement are subject to significant error (Cao *et al*., 2009; Shi and Bates, 2011). Use of revised functions is under consideration for future ECMWF reanalyses, and will at least include changes recently included in RTTOV (Saunders *et al*., 2013). Again, the requirement for reanalysis is for individual sensor records and the best estimates of the spectral response functions for each sensor. This does not obviate the need also for inter-calibrated data records, however. Reanalysis and direct analysis of inter-calibrated records are complementary approaches that provide confidence when their results agree, as in the case of the results of Shi and Bates (2011) and Simmons *et al*. (2013) showing good correlation between surface temperature and upper tropospheric humidity in the tropics. Alternatively, they provide a basis for further investigation when there is disagreement.

1. **Further comment**

The scene dependence of the differences in measurement between different instruments of the same type means that inter-calibration of data records from a set of satellites in some cases cannot be optimally achieved for climate purposes without knowledge of the very geophysical variables to which the data records relate. Assumptions have to be made in practice, and to refer to the inter-calibrated data records that result as “fundamental” seems to be a misnomer. The “ancillary data used to calibrate them”, part of the FCDR, can be complex. Interpretation of the inter-calibrated records may remain difficult as trends in their data may still depend on the trends of multiple geophysical variables, trends of layer-mean temperature, lapse rate and CO2 concentration for example. Inter-calibrated records need to be accompanied by a forward model for the reference measurements to which records from individual instruments have been calibrated.

Reanalysis can avoid the above difficulties for key data types by accounting for inter-satellite differences in instrument performance, including in-orbit shifts and drifts. Developments could include variationally adjusting uncertain parameters of the forward radiative transfer model related to instrument characteristics during the course of the data assimilation. Input from the space agencies and their partners in instrument supply is needed for this work, and this is urgent for older instruments because individuals with unique knowledge of these instruments have already retired or are about to retire from employment. Recent documentation by the Met Office (Nash and Saunders, 2013) for the SSU and associated developments of RTTOV provide an example of what can be done. The strategy of GSICS as set out in the preamble places it in a unique position to help, as its monitoring of instrument performance, tying of measurements to absolute references and standards, and lessons learnt in developing inter-calibrations generates much of the information that is needed to use more basic forms of the data in reanalysis. In turn, experience gained in reanalysis may feed into improved inter-calibration by GSICS.

Inter-calibration is nevertheless needed for reanalysis as well as other climate applications. Reanalysis may use inter-calibrated records either directly for assimilation if forward modelling has not been developed for individual instruments of a particular type, or indirectly through assimilation of retrievals for some variables and instruments. A number of fields for the assimilating models used in reanalysis may be derived from a series of data records that benefit from inter-calibration. Requirements are likely to evolve, as research into improving the assimilation of satellite data continues to progress.

**References**

Cao, C., Goldberg, M., and Wang, L., 2009: Spectral Bias Estimation of Historical HIRS Using IASI observations for improved fundamental climate data records. J. Atmos. Ocean. Tech., 26: 1378-1387.doi: 10.1175/2009JTECHA1235.1

Dowell, M., Lecomte, P., Husband, R., Schulz, J., Mohr, T., Tahara, Y., Eckman, R., Lindstrom, E., Wooldridge, C., Hilding, S., Bates, J., Ryan, B., Lafeuille, J., and Bojinski, S., 2013: Strategy Towards an Architecture for Climate Monitoring from Space. Pp. 39. This report is available from: www.ceos.org; www.wmo.int/sat; <http://www.cgms-info.org/>

Kobayashi, S., Matricardi, M., Dee, D., and Uppala, S., 2009: Toward a consistent reanalysis of the upper stratosphere based on radiance measurements from SSU and AMSU-A. Q. J. R. Meteor. Soc., 135: 2086–2099.doi: 10.1002/qj

Lu, Q., and Bell, W., 2013: Characterising channel center frequencies in AMSU-A and MSU microwave sounding instruments. Submitted to J. Atmos. Ocean.Tech..Also available from [www.ecmwf.int](http://www.ecmwf.int)as ECMWF Tech. Memo., 700, 29p.

Nash, J., and Saunders, R.W. 2013:A review of satellite sounding radiance observations in support of climate trends investigations and reanalyses. Forecasting Research Technical Report No XXX, Met Office. *In preparation*

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-J., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., and Woollen, J., 2011: MERRA: NASA’s Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24: 3624-3648. doi: 10.1175/JCLI-D-11-00015.1

Saunders, R., Hocking, J., Rundle, D.,Rayer, P., Matricardi, M., Geer, A., Lupu, C., Brunel, P., and Vidot, J., 2013: RTTOV v11 Science and Validation Report. Available from

http://research.metoffice.gov.uk/research/interproj/nwpsaf/rtm/

Shi, L. and Bates, J.J., 2011: Three decades of intersatellite‐calibrated High‐Resolution Infrared Radiation Sounder upper tropospheric water vapour. J. Geophys. Res., 116, D04108.doi:10.1029/2010JD014847

Simmons, A.J., Poli, P., Dee, D.P., Berrisford, P., Hersbach, H., and Peubey, C.,2013: Estimating low‐frequency variability and trends in atmospheric temperaturefrom the ERA‐Interim reanalysis. Draft paper available from ftp.ecmwf.int/pub/Simmons/ERA-Interim\_temperature\_79-12.pdf

### Annex 2: Extract from [Satellite instrument calibration for measuring global climate change](http://map.nasa.gov/documents/CLARREO/BAMSOhringetalSept2005SatelliteClimateCalib%5B3%5D.pdf), Ohring G., Wielecki B., Spencer R., Emery B., Datla R., Bulletin of the American Meteorological Society, September 2005, p.1307-1308

|  |
| --- |
| **TABLE 1. Required accuracies and stabilities for climate variable datasets. Column labeled “signal” indicates the type of climate signal used to determine the measurement requirements.** |
|  | **Signal** | **Accuracy** | **Stability (per decade)** |
| **Solar irradiance, earth radiation budget, and cloud variables** |  |  |  |
| Solar irradiance | Forcing | 1.5 W m–2 | 0.3 W m–2 |
| Surface albedo | Forcing | 0.01 | 0.002 |
| Downward longwave flux: surface | Feedback | 1 W m–2 | 0.2 W m–2 |
| Downward shortwave radiation: surface | Feedback | 1 W m–2 | 0.3 W m–2 |
| Net solar radiation: top of atmosphere | Feedback | 1 W m–2 | 0.3 W m–2 |
| Outgoing longwave radiation: top of atmosphere | Feedback | 1 W m–2 | 0.2 W m–2 |
| Cloud-base height | Feedback | 0.5 km | 0.1 km |
| Cloud cover (fraction of sky covered) | Feedback | 0.01 | 0.003 |
| Cloud particle size distribution | Feedback | TBD | TBD |
| Cloud effective particle size | Forcing: water Feedback: ice | Water: 10%Ice: 20% | Water: 2%Ice: 4% |
| Cloud ice water path | Feedback | 25% | 5% |
| Cloud liquid water path | Feedback | 0.025 mm | 0.005 mm |
| Cloud optical thickness | Feedback | 10% | 2% |
| Cloud-top height | Feedback | 150 m | 30 m |
| Cloud-top pressure | Feedback | 15 hPa | 3 hPa |
| Cloud-top temperature | Feedback | 1 K/cloud emissivity | 0.2 K/cloud emissivity |
| Spectrally resolved thermal radiance | Forcing/climate change | 0.1 K | 0.04 K |
| **Atmospheric variables** |  |  |  |
| Temperature |  |  |  |
| Troposphere | Climate change | 0.5 K | 0.04 K |
| Stratosphere | Climate change | 0.5 K | 0.08 K |
| Water vapor | Climate change | 5% | 0.26% |
| Ozone |  |  |  |
| Total column | Expected trend | 3% | 0.2% |
| Stratosphere | Expected trend | 5% | 0.6% |
| Troposphere | Expected trend | 10% | 1.0% |
| Aerosols |  |  |  |
| Optical depth (troposphere/ stratosphere) | Forcing | 0.01/0.01 | 0.005/0.005 |
| Single scatter albedo (troposphere) | Forcing | 0.03 | 0.015 |
| Effective radius (troposphere/ stratosphere) | Forcing | greater of 0.1 or 10%/0.1 | greater of 0.05 or 5%/0.05 |
| Precipitation |  | 0.125 mm h–1 | 0.003 mm h–1 |
| Carbon dioxide | Forcing/Sources–sinks | 10 ppmv/10 ppmv | 2.8 ppmv/1 ppmv |
| **Surface variables** |  |  |  |
| Ocean color |  | 5% | 1% |
| Sea surface temperature | Climate change | 0.1 K | 0.04 K |
| Sea ice area | Forcing | 5% | 4% |
| Snow cover | Forcing | 5% | 4% |
| Vegetation | Past trend | 3% | 1% |

|  |
| --- |
| **TABLE 2. Required accuracies and stabilities of satellite instruments to meet requirements of Table 1. The instru- ment column indicates the type of instrument used to make the measurement.** |
|  | **Instrument** | **Accuracy** | **Stability (per decade)** |
| **Solar irradiance, earth radiation budget, and cloud variables** |  |  |  |
| Solar irradiance | Radiometer | 1.5 W m–2 | 0.3 W m–2 |
| Surface albedo | VIS radiometer | 5% | 1% |
| Downward longwave flux: surface | IR spectrometer and VIS/IRradiometer | See tropospheric tempera- ture, water vapor, cloud-base height, and cloud cover | See tropospheric temperature water vapor, cloud-base height, and cloud cover |
| Downward shortwave radiation: surface | Broadband solar and VIS/IR radiometer | See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud- top height, and water vapor | See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud-top height, and water vapor |
| Net solar radiation: top of atmosphere | Broadband solar | 1 W m–2 | 0.3 W m–2 |
| Outgoing longwave radiation: top of atmosphere | Broadband IR | 1 W m–2 | 0.2 W m–2 |
| Cloud-base height | VIS/IR radiometer | 1 K | 0.2 K |
| Cloud cover (fraction of sky covered) | VIS/IR radiometer | See cloud optical thickness and cloud-top-temperature | See cloud optical thickness and cloud-top-temperature |
| Cloud particle size distribution | VIS/IR radiometer | TBD | TBD |
| Cloud effective particle size | VIS/IR radiometer | 3.7 *µ*m: water, 5%; ice, 10%1.6 *µ*m: water, 2.5%; ice, 5% | 3.7 *µ*m: Water, 1%; Ice, 2%1.6 *µ*m: Water, 0.5%; Ice, 1% |
| Cloud ice water path | VIS/IR radiometer | TBD | TBD |
| Cloud liquid water path | Microwave and VIS/IR radiometer | Microwave: 0.3 K VIS/IR: see cloud optical thickness and cloud-top height | Microwave: 0.1 K VIS/IR: see cloud optical thickness and cloud-top height |
| Cloud optical thickness | VIS radiometer | 5% | 1% |
| Cloud-top height | IR radiometer | 1 K | 0.2 K |
| Cloud-top pressure | IR radiometer | 1 K | 0.2 K |
| Cloud-top temperature | IR radiometer | 1 K | 0.2 K |
| Spectrally resolved thermal radiance | IR spectroradiometer | 0.1 K | 0.04 K |
| **Atmospheric variables** |  |  |  |
| Temperature |  |  |  |
| Troposphere | MW or IR radiometer | 0.5 K | 0.04 K |
| Stratosphere | MW or IR radiometer | 1 K | 0.08 K |
| Water vapor | MW radiometer IR radiometer | 1.0 K1.0 K | 0.08 K0.03 K |
| Ozone |  |  |  |
| Total column | UV/VIS spectrometer | 2% (*l* independent), 1% (*l* dependent) | 0.2% |
| Stratosphere | UV/VIS spectrometer | 3% | 0.6% |
| Troposphere | UV/VIS spectrometer | 3% | 0.1% |
| Aerosols | VIS polarimeter | Radiometric: 3%Polarimetric: 0.5% | Radiometric: 1.5%Polarimetric: 0.25% |
| Precipitation | MW radiometer | 1.25 K | 0.03 K |
| Carbon dioxide | IR radiometer | 3% | Forcing: 1%; Sources/sinks: 0.25% |
| **Surface variables** |  |  |  |
| Ocean color | VIS radiometer | 5% | 1% |
| Sea surface temperature | IR radiometer | 0.1 K | 0.01 K |
|  | MW radiometer | 0.03 K | 0.01 K |
| Sea ice area | VIS radiometer | 12% | 10% |
| Snow cover | VIS radiometer | 12% | 10% |
| Vegetation | VIS radiometer | 2% | 0.80% |