Chapter 13
Sea Surface Temperature Measurements from Thermal Infrared Satellite Instruments: Status and Outlook

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13.1 Introduction

Thermal Infrared (TIR) sensors have been deployed on earth observing satellites for over 30 years providing measurements of Sea Surface Temperature (SST), clouds and many other products. Developed initially for meteorology and now used widely by the oceanographic and climate communities, TIR derived SST measurements are available in an operational context in Near Real Time (NRT) from a wide variety of satellite missions. TIR sensors have a characteristically high spatial resolution of 0.5–1.1 km (at nadir) with quasi global coverage on a daily basis (using two operational wide swath TIR missions). TIR sensors are typically calibrated using on-board reference blackbody systems alone (e.g. Corlett et al., 2006) or a combination of blackbody and deep-space "cold" views to an accuracy of 0.1–0.2 K (e.g. Robinson, 2004). On-board calibration is sometimes supplemented with vicarious calibration adjustments implicit in some Level-2 SST retrieval algorithms that compensate for the atmospheric attenuation of water leaving radiances using in-situ SST measurements (e.g. Kilpatrick et al., 2001; Zhang et al., 2009). Other approaches to atmospheric correction rely on the use of radiative transfer modes to derive look-up-tables that can be applied to brightness temperature measurements using a suitable SST retrieval algorithm (e.g. Merchant and Le Borgne, 2004).

This approach has the benefit of releasing in-situ observations for use in on-going verification and validation work and for a more detailed investigation of sensor and algorithm biases, essential activities for the production of fundamental climate data records (e.g. Merchant et al., 2008b). Most importantly, well defined and error quantified measurements of SST are required for climate time series (in the form of Fundamental Climate Data Records, or FCDR) that can be analyzed to reveal the role of the ocean in short and long term climate variability.

This chapter first presents a summary of key TIR satellite sensors from 2000 to 2020. In Section 13.3 it outlines the primary on-going challenges and issues

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associated with the use of TIR data for accurate retrieval of SST. In Section 13.4 impact of the Group for High Resolution SST (GHRSST, Donlon et al., 2007) will be reviewed. Finally, conclusions are presented and a forward perspective for the coming decade is provided.

13.2 Key TIR Satellite Sensors Since 2000

Development in the definition, availability, future planning and service provision of TIR satellite sensors and data has matured significantly in the last 10 years. According to the Committee for Earth Observation Satellites (CEOS) on-line database (CEOS, 2008, 2009) over 20 satellite missions capable of measuring SST in a variety of orbits (polar, low inclination and geostationary) have been launched since 1999. The tables reported in Appendix list the main TIR sensors and their basic characteristics for missions operating from 2000 and up to 2020. It is interesting to note the transition of the (A)ATSR instrument series to the Sea and Land Surface Temperature Radiometer (SLSTR) carried by the Sentinel-3 operational mission. The NOAA AVHRR/3 series, a traditional workhorse TIR sensor, will end with NOAA-19, to be replaced with the new NPOESS/NPP VIIRS with enhanced capability. New geostationary imager capability has emerged in the last 10 years in Europe, with the MSG SEVIRI instrument now providing high quality operational SST. Also, the development of new capability in China through the FY-satellite series is noteworthy.

The accuracy that can be obtained for SST derived from TIR data is now at the limit of the capability of available operational in-situ infrastructure (~0.1–0.2 K). Comparisons between the AATSR and drifting-buoy measurements made by the UK Met Office have shown that AATSR is capable of achieving biases in Global SST which typically <0.15 K (O’Carroll et al., 2008). Such error analyses show clearly that AATSR SST data can act as a “benchmark” of accuracy, against which data from other sources can be bias-corrected. This approach has been adopted at operational centres (e.g. Stark et al., 2007).

In summary, Appendix shows that TIR satellite sensors have matured (research instruments are now flown on operational missions), advanced (Sentinel-3 SLSTR has a much wider swath, ~1,400 km, compared to the ENVISAT 512 km swath of AATSR) and both polar and geostationary missions are being sustained until 2020. This is considerable progress since the *Oceans From Space* meeting in 2000.

13.3 On-Going Challenges and Issues

13.3.1 Data Access

Wide and open access in near real time to many TIR satellite SST data products has been established in an operational-like manner using existing data user-driven distribution protocols, tools and services coordinated by the GHRSST project (Donlon et al., 2007). This is a significant development since *Oceans From Space* in 2000 and has led to increased scrutiny, research, development and operational uptake of TIR data. Over 26 Gb of data are provided in NRT every day by GHRSST Services, and over 25,500 international users have accessed GHRSST products. This framework needs to be maintained and evolve as new satellite TIR instruments come on line in the coming decade.

13.3.2 Cloud Flagging of SST Derived from TIR Data

The SST fields obtained TIR sensors are corrupted by clouds, with the temperature of cloud contaminated pixels generally colder than the actual SST. Inclusion of contaminated pixels in final products renders data inaccurate and difficult to use. For these reasons, flagging of cloud contaminated pixels in SST fields has received a great deal of attention over the past 30 years. Despite the effort devoted to such algorithms, significant problems and challenges remain. For applications in which the absolute accuracy of the retrieved SST values is central to their use, it is important to exclude any pixel that is even slightly cloud contaminated.

In contrast, applications in which the location of oceanographic features is important make use of the relative accuracy of adjacent SST values and have some tolerance to cloud contamination. Most cloud screening algorithms are sensitive to large gradients in the retrieved fields and pixels in a high gradient region are generally flagged as cloud contaminated. Approaches make use of the structural characteristics of fronts to either reset the quality mask for those pixels that are believed to be frontal pixels that were falsely flagged as clouds (Cayula and Cornillon, 1996) or add a new flag. One advantage of this test is that it can be applied after the SST retrieval and quality fields have been obtained.

Development of cloud screening algorithms has focused on applications for which the absolute accuracy of the SST value is paramount and typically makes full use of both visible and TIR data available from the sensor in the day time. Only the IR channels are available at night further complicating cloud detection. Algorithms rely on differences in emissivity, reflectivity, temperature and spatial structure between the ocean surface and clouds. Some work well in identifying cloud-contaminated pixels under most open ocean conditions. However, because screening is based on thresholds associated with specific parameters and the underlying distributions are in most cases continuous, there will be ambiguity when one or more of the parameter values is close to a threshold value. The problem is therefore intrinsically probabilistic, with a trade-off between false alarms and hits, a balance that depends critically on the user's application.

Many SST fields are now provided with a separate "quality" field, which is often derived from the cloud screening portion of the retrieval algorithm. This field allows users to mask SST values based on the quality threshold that meets their specific needs. Quality fields are derived differently by different data providers with different meanings that are not always described in sufficient detail making it difficult for the user to apply them consistently. This challenge requires careful attention in the future. In addition to providing quality fields with the SST data, there is a trend toward increasing use of simulations in near-real time from national weather programs to inform the discrimination – either by dynamically calculating thresholds or as input to a probabilistic calculations (Merchant et al., 2005). Further development of this approach is expected in the future.

Cloud screening of TIR satellite data is remains a significant challenge and more effort is required to develop effective systems to minimize the data loss due to inappropriate cloud screening and the increase in error where clouds are not properly detected.

13.3.3 Improved Treatment of Atmospheric Aerosol Contamination

The performance of TIR derived SST retrievals is degraded in the presence of atmospheric aerosols (e.g., Saharan dust, volcanic eruptions). This has been a particular problem for the Meteosat-8 SEVIRI instrument SST retrieval. During the initial phase of operations the occurrence of Saharan dust outbreaks lead to SST bias errors of ~1 K. These problems have been mitigated to a certain degree by upgrading the MSG algorithms to include a Saharan dust index scheme (Merchant et al., 2006) and the use of ENVISAT AATSR data to derive a bias correction for the aerosol (and other) contaminated data. There are several aspects to improving atmospheric aerosol detection and flagging algorithms that will provide increased sensitivity and performance:

1. in strong SST gradient regions,
2. when sub-pixel clouds and optically thin cirrus are present,
3. when only limited instrument channels are available,
4. when aggregated data are used (e.g. AVHRR GAC),
5. when multi-angle view data are available,
6. based on multi-satellite synergy (e.g. use of geostationary data, (A)ATSR, and passive microwave sensors),
7. based on probabilistic techniques,
8. based on improved conventional threshold, histogram and spatial coherence techniques.

It is expected that significant progress will be made in the next decade on these issues as climate quality SST data sets are derived for a variety of TIR sensors.

13.3.4 Improving Current and Future SST Measurements Through Better Uncertainty and Error Estimation

A key user request from all user communities (and in particular the SST community) is the provision of uncertainty estimates to be attached to each pixel in SST products. A framework has emerged from the GHRSST activity called Single Sensor Error

Statistics (SSES) designed to take into account uncertainties for specific instrument/platforms (Donlon et al., 2007). Bias and uncertainty estimates are generally derived from near contemporaneous match ups between satellite and in-situ SST measurements which are periodically analysed to provide SSES. The EUMETSAT OSI-SAF has developed a statistical method to derive SSES bias and standard deviation estimates by associating a confidence level assigned to the retrieved SST estimate. The confidence levels are based on tests to the reliability of the cloud mask and the SST algorithm conditions. Regional (and seasonal) characteristics need to be accounted for in this scheme although it is successfully used in operations.[1]

An alternative approach called the Hypercube has also been developed based on a match-up data base for the Aqua and Terra MODIS sensors. In this case, the MDB includes near-contemporaneous, co-located satellite brightness temperatures, in-situ buoy and radiometer SST, auxiliary data from model or satellite observed fields, and the satellite viewing geometry. A series of quality tests is applied during processing of the MODIS data to identify cloud and dust aerosol contaminated retrievals and assign pixels to one of four different quality levels with quality 0 being the best quality possible. The relative immunity of the MODIS 3.95 and 4.05 μm bands to both water vapour and aerosols as compared to the increased sensitivity to both in the MODIS 11 and 12 μm bands is used to identify aerosol data. After eliminating records with quality levels greater than 1, each match-up database is partitioned into a multi-dimensional array with the following 7 dimensions: time by season (4 values), latitude bands (5 steps in 20° increments from 60°S to 60°N), surface temperature (8 increments in 5° steps), satellite zenith angle (4 increments), brightness temperature difference as a proxy for water vapour (4 intervals for 4 μm and 3 intervals for 11–12 μm SST), retrieved satellite SST quality level (2 intervals) and day/night selection (2 intervals). The bias (satellite-in-situ) and standard deviation are then computed for each element to define a hypercube look up table (LUT). The LUT is then used during satellite data processing to predict the SSES bias and standard deviation of the SST retrieval. The hypercube approach provides more control over the specification of uncertainty estimates and is being actively developed within the framework of GHRSST.

Finally, it is important to recognize that more work is required to ensure that uncertainty values, where possible, are traceable to accepted international reference standards and SI units. Satellite TIR instruments and ground truth instrumentation should also be traceable to the same reference standards. More effort is required in this area.

13.3.5 New SST Retrieval Techniques Using TIR Data

A single-view TIR imager with channels at roughly 3.7, 11 and 12 μm can demonstrate global 1 km accuracy approaching 0.3 K at night-time (i.e., when all three

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[1] See http://www.osi-saf.org

channels are used), although instability of calibration, cloud-detection failures, and episodes of atmospheric aerosol can each degrade this potential significantly. With only the 11 and 12 μm channels available (as in day-time), coefficient-based retrievals have been limited to accuracies of about 0.4 K. Recent work on METOP-A AVHRR data shows that optimal estimation techniques can drive accuracy down to ~0.3 K for SST estimates where the retrieval cost is low (Merchant et al., 2008a). All these quoted errors have a random element, but are in large part correlated on the synoptic scales of the atmosphere. Further research is required to develop and refine SST optimal estimation techniques for TIR sensors that maximize the error reduction from having multiple complementary observing systems in space.

13.3.6 Improving SST Provision in the High Latitude Regions

Accurate retrieval of SST at high latitudes using TIR satellite sensors requires that (a) the discrimination between ice-free and ice-covered water at the resolution, temporal and spatial, of the SST retrieval schemes is well known; and (b) the atmospheric attenuation on the infrared radiation as it propagates from the sea surface to the satellite radiometer is determined. For infrared SST retrievals, during the day, reflected sunlight provides a powerful mechanism for identifying open, cloud-free water.

During the polar night the problem of identifying ice becomes more difficult. A simple temperature threshold test might be adequate to identify pack ice but this would not be sufficient in the more complex marginal ice zone. Surface temperature retrievals below –1.8°C, the freezing point of seawater, can be classified as ice cover. However, this is prone to error as (a) there is noise in the satellite-derived surface temperature, so that ice-free retrievals could fall below the threshold, and ice-covered pixels fall above the threshold; and (b) when melting, sea ice, especially if covered by snow, may remain frozen at temperatures above the threshold. More effort should be given to define and implement ice masking procedures and techniques in Polar Regions for TIR satellite observations.

Considering the impact of atmospheric attenuation on the water leaving signal it is clear that the polar atmosphere is generally very dry and cold, and is thus an extreme in terms of the climatological distribution of atmospheric properties. It represents an anomalous set of conditions for routine SST atmospheric correction algorithms optimized for the global range of atmospheric variability (e.g. Walton et al., 1998; May et al., 1998). It is to be expected that systemic retrieval errors in the derived SSTs will result: bias errors, usually result in warm SST errors that can be greater than 1 K (Vincent et al., 2008b). Loss of the correlation between the brightness temperatures measured at 10.5 and 11.5 μm with the atmospheric water vapour that occurs in very dry atmospheres and Vincent et al. (2008a, b) show using AVHRR brightness temperature data collocated with ship-based radiometric skin SST measurements that a simple, single channel retrieval algorithm can produce improved accuracy in the measurement of skin SST and Ice Surface Temperature. Single-channel algorithms appear to be better suited to the problem than current multi-channel approaches. Satellite SST data providers using infrared systems should review the performance of their atmospheric correction algorithms in polar atmospheres and take steps to develop more appropriate algorithms for these regions.

13.4 Principles and Lessons Learned from the GHRSST International Framework

The GHRSST project (Donlon et al., 2007[2]) was a significant contribution to progress in SST over the last decade as it nurtured a community of scientists from the scientific and operational agencies and institutions. GHRSST established a set of user requirements for all GHRSST activities from a bottom up collaborative and open discussion in five areas: (1) scientific development and applications, (2) operational agency requirements, (3) SST product specifications, (4) programmatic organization of an international SST service and (5) developing and sharing scientific techniques and insight to improve data products and exploit the observing system.

These requirements formed an essential part of the GHRSST evolution and were critical to establishing a framework and a work plan. A consensus GHRSST Data Processing specification (GDS) was developed that described how satellite data providers should process satellite data streams; a common format and content of data products; the basic approaches to providing uncertainty estimates and auxiliary data sets that should be included in products to help users interpret the SST measurements. GHRSST also conducted scientific research and developed a data management framework, including long term stewardship of all products.

GHRSST realised the benefits of creating modular data processing architectures in which many partners around the world can contribute to improve global monitoring. The GHRSST service has also encouraged the development of new SST monitoring and forecasting initiatives by operational agencies that use the new data products. In particular the end-to-end service reveals how a system which enables the complementary use of data from different sources reinforces the importance of each, as it leads to new records of SST with enhanced accuracy and improved spatial and temporal resolution. A full discussion of GHRSST success over the last 10 years is reported in Donlon, 2008; Donlon et al., 2009. The key developments include:

- International agreement on the definition of different SST parameters in the upper layer of the ocean that distinguish between measurements made by infrared radiometers, passive microwave radiometers, in-situ sub-surface observations and SST merged analysis outputs. These definitions have been registered in the Climate Forecast (CF) standard name table (Donlon, 2008).
- Diverse satellite SST data product formats and product content have been homogenised according to international consensus and user requirements to

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[2] See http://www.ghrsst.org

include measurement uncertainty estimates for each derived SST value and supporting auxiliary data sets to facilitate their use by data assimilation systems.
- GHRSST advisory groups have conducted extensive research to ensure that SST diurnal variability (DV) is properly flagged within observational data; developed methods to correct for bias in different satellite data sets; provided uncertainty estimates on a measurement by measurement basis, developed high resolution sea ice data sets and accurate SST products in the marginal ice zone.
- New cost-effective approaches to an integrated and optimised SST measurement system have been developed and are used operationally, to reduce bias error in AVHRR data using targeted global deployment strategies for drifting buoys (Zhang et al., 2009).
- New SST analysis products using new methods to merge in-situ data with complementary microwave and infrared satellite data have been developed and implemented operationally.
- Inter-comparison frameworks – e.g., the GHRSST Multiproduct Ensemble (GMPE)[3] – have been developed at resolutions of 10 km or better for the global ocean and other regions of interest. An operational High Resolution Diagnostic Data Set (HR-DDS)[4] has been established for real time inter-comparisons and validation/verification of GHRSST products allowing real time monitoring of satellite and in-situ SST data streams.
- A delayed-mode intercomparison framework has been established in conjunction with the GCOS SST and Sea Ice Working Group to understand the links between the modern era satellite-based SST record and historical primarily ship-based SST reconstructions.[5]
- Methods to convert between radiometric "skin" SST and the SST at depths measured by ships and buoys have been developed (e.g., Donlon et al., 2002) that are now used by operational SST analysis systems (e.g., Stark et al., 2007).
- An internationally distributed suite of user focussed services are now provided in a sustained Regional/Global Task Sharing (R/GTS) framework that addresses international organisational challenges and recognises the implementing institutional capacities, capabilities and funding prospects. Long term stewardship, user support and help services including standards-based data management and interoperability have been developed that are manned and operated within the R/GTS on a daily basis.
- Methods to manage long-term SST data sets, for use in a reanalyses that considers SST data for the entire satellite era, have begun.

GHRSST has earned broad recognition as the international authority for modern-era SST activities because it has successfully built and nurtured a framework in which the exchange of satellite SST data has flourished and given new life to the study and application of high-resolution SST using TIR satellite and in-situ data.

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[3] See http://ghrsst-pp.metoffice.com/pages/latest_analysis/sst_monitor/daily/ens/index.html

[4] See http://www.hrdds.net

[5] See http://ghrsst.nodc.noaa.gov

Applications have demonstrated positive impact in ocean and atmospheric forecasting systems and a new generation of data products and services to serve these and other users have been built and are operated on a day-to-day basis. The success of GHRSST stems from the Agencies and Offices that have supported the activities of the Pilot Project allowing a dedicated group of scientists and operational entities to successfully work together and bridge the gap between operations and science. All good operational systems are underpinned by excellent science and GHRSST has endeavoured to provide a forum in which operational systems and scientists can meet and discuss problems and solutions to address the real-world challenges associated with the application of high-resolution SST data sets.

13.5 Conclusion and Future Outlook

The future outlook for TIR sensors is very good. Over the last decade there have been many successes in terms of the TIR instruments that are flying in polar and geostationary orbits. Some systems are in the process of transitioning from research to operational systems (e.g. AATSR mobbing to the SLSTR on Sentinel-3). The accuracy of TIR retrievals from space is in some cases better than 0.2 K when using a dual view along track scanning approach. Accuracy of SST from geostationary TIR systems is less than this but still extremely useful especially when bias adjusted using other satellite or in-situ data.

Challenges remain for improved quality of SST products derived from TIR satellite data. These include better cloud clearing, better treatment of atmospheric aerosols that contaminate TIR data, better techniques for SST retrieval and better retrieval algorithms in the polar atmosphere. Better uncertainty estimates for SST data products derived from TIR data are essential and must be continually refined and updated based on the best tools and techniques.

The activities within the SST community over the last decade have transformed the measurement of SST using a complementary satellites and in-situ measurements working in synergy together. The establishment of a GHRSST framework for the exchange and management of international SST data has been successfully implemented and is operating on a daily basis. A thriving user community has developed in which integrated SST data sets are being used at scientific institution and operational agencies. Tools and data services have been developed and implemented to serve this user community. Through the activities of GHRSST many lessons have been learned that provide the basis for an optimal configuration for the SST observing system in the next 10 years.

The major challenges focus on augmenting and maintaining high quality SST measurements from both in-situ and satellite instruments, maintaining and developing the scientific and operational SST community, providing robust and sustained methods and tools that provide uncertainty and error estimates in a format that is easy to use by users and developing and maintaining an SST data stewardship and reanalysis program that is able to tackle the development and validation of SST climate data records.

Appendix

Key TIR sensors and their basic characteristics for missions operating from 2000 and up to 2020 (data obtained from CEOS 2009):

- Along Track Scanning Radiometer 2 (ATSR-2)
- Advanced along Track Scanning Radiometer (AATSR)
- Advanced Very High Resolution Radiometer 3 (AVHRR/3)
- Moderate Resolution Imaging Spectroradiometer (MODIS)
- Spinning Enhanced Visible and Infrared Imager (SEVIRI)
- Visible and Infrared Sounder (VIRS)
- Meteosat Third Generation (MTG)
- MTSAT Imager
- GOES Imager
- Visible/Infrared Imager Radiometer Suite (VIIRS)
- Sea and Land Surface Temperature Radiometer (SLSTR)
- Multispectral Visible and Infrared Scan Radiometer (10 channels)
- Visible and Infra-red Scan Radiometer (VIRR)

The following tables list each instruments' name, mission(s), spatial resolution, swath, wavebands, description, as in:

Instrument		
Mission(s)		
Spatial resolution	Swath width	Spectral bands
Description		

Along track scanning radiometer 2 (ATSR-2)		
ERS-2 (1995-04-21 2011-12-31)		
1.1 km	512 km	VIS – SWIR: 0.65 μm 0.85 μm 1.27 μm 1.6 μm SWIR-TIR: 1.6 μm 3.7 μm 11 μm 12 μm
Imaging Vis/IR radiometer exploiting different viewing conditions		

Advanced along track scanning radiometer (AATSR)

ENVISAT (2002-03-01 2013-12-31)		
1.1 km	512 km	VIS – NIR: 0.555 μm 0.659 μm 0.865 μm SWIR: 1.6 μm MWIR: 3.7 μm TIR: 10.85 μm 12 μm
Imaging Vis/IR radiometer exploiting different viewing conditions		

Advanced very high resolution radiometer 3 (AVHRR/3)

NOAA-12 (1991-05-14 2005-12-31) NOAA-14 (1994-12-30 2005-12-31) NOAA-15 (1998-05-01 2010-12-31) NOAA-16 2000-09-21 2012-12-31 NOAA-17 (2002-06-24 2014-12-31) NOAA-18 (2005-05-20 2015-12-31) NOAA-19 (2009-02-04 2016-03-01)		
EUMETSAT Metop-A (2006-10-19 2011-11-01) Metop-B (2012-04-02 2017-05-01) Metop-C (2016-04-02 2021-12-01)		
1.1 km	~3,000 km ensures full global coverage twice daily	VIS: 0.58–0.68 μm NIR: 0.725–1.1 μm SWIR: 1.58–1.64 μm MWIR: 3.55–3.93 μm TIR: 10.3–11.3 μm 11.5–12.5 μm
Multi-purpose imaging Vis/IR radiometer Imaging multi-spectral radiometers (vis/IR)		

Moderate resolution imaging spectroradiometer (MODIS)

Terra (1999-12-18 2011-09-30) Aqua (2002-05-04 2011-09-30)		
250 m (day)	2,330 km	VIS – TIR:
1,000 m (night) SST: 1,000 m		36 bands in range 0.4–14.4 μm
Medium-resolution spectro-radiometer		

Spinning enhanced visible and infrared imager (SEVIRI)

Meteosat-8 (2002-08-13 2011-06-30)		
Meteosat 9 (2005-12-21 2014-06-30)		
HRV = 1 km all others = 3 km (spatial sampling distance at SSP)	Full earth disk	HRV: ~0.48–0.91 μm VIS: 0.6 μm 0.8 μm NIR: 1.6 μm IR: 3.9 μm 6.3 μm 7.3 μm 8.7 μm 9.7 μm 10.8 μm 12.0 μm 13.4 μm
Multi-purpose imaging Vis/IR radiometer, in geostationary orbit Imaging multi-spectral radiometers (vis/IR)		

Visible and infrared sounder (VIRS)

Tropical rainfall mapping mission (TRMM) (1997-11-27 2011-09-30)		
2 km	720 km	VIS: 0.63 μm SWIR – MWIR: 1.60 μm 3.75 μm TIR: 10.8 μm 12.0 μm
NASA/JAXA Imaging multi-spectral radiometers (vis/IR) Multi-purpose imaging Vis/IR radiometer		

Meteosat third generation (MTG)

MTG Imager-1 (2016-12-15 2025-06-15) MTG Imager-2 (2021-06-15 2029-12-15) MTG Imager-3 (2025-01-15 2033-07-15) MTG Imager-4 (2029-06-15 2037-12-15)		
VIS/SWIR: 0.5, 1.0 km IR: 2.0 km	Full earth disk	VIS: 0.4 μm 0.5 μm 0.6 μm 0.8 μm 0.9 μm NIR: 1.3 μm 1.6 μm 2.2 μm 3.8 μm 6.3 μm 7.3 μm 8.7 μm 9.7 μm 10.5 μm 12.3 μm 13.3 μm
Multi-purpose imaging Vis/IR radiometer, in geostationary orbit Imaging multi-spectral radiometers (vis/IR)		

MTSAT imager

MTSAT-1, 2 and 3		
VIS: 1 km TIR: 4 km	Full earth disk (every hour)	VIS – SWIR: 0.55 – 0.80 μm MWIR – TIR: 3.5 – 4 μm 6.5 – 7 μm 10.3 – 11.3 μm 11.5 – 12.5 μm
Imaging multi-spectral radiometers (vis/IR) Multi-purpose imaging Vis/IR radiometer		

GOES imager

GOES-10 GOES-11 GOES-12 GOES-8 GOES-9 GOES-14 GOES-P GOES-13		
10 km	Full earth disk	GOES 8 – 11 VIS: (1 channel, 8 detectors) IR: (4 channels) 3.9 μm 6.7 μm 10.7 μm 12 μm GOES 12 – Q VIS: (1 channel, 8 detectors) IR: (4 channels) 3.9 μm 6.7 μm 10.7 μm 13.3 μm
Imaging multi-spectral radiometers (vis/IR) Multi-purpose imaging Vis/IR radiometer		

Visible/Infrared imager radiometer suite (VIIRS)

NPP NPOESS preparatory project (2010-06-02 2015-06-02) NPOESS-1 (2013-01-31 2020-01-01) NPOESS-2 (2016-01-31 2022-01-01) NPOESS-3 (2018-01-31 2025-01-01) NPOESS-4 (2020-01-31 2027-01-01)		
400 m–1.6 km	3,000 km	VIS – TIR: 22 channels range 0.4–12.5 μm
NASA/NOAA and USA DoD Imaging multi-spectral radiometers (vis/IR) Multi-purpose imaging Vis/IR radiometer		

Sea and land surface temperature radiometer (SLSTR)

Sentinel-3A (2012-10-01 2019-10-01)			
Sentinel-3B (2015-10-01 2022-10-01)			
VNIR/SWIR:	Near-nadir view:	S1	0.555 µm
500 m	1,400 km	S2	0.659 µm
TIR:	Backward view:	S3	0.865 µm
1 km	750 km	S4	1.375 µm
		S5	1.61 µm
		S6	2.25 µm
		S7	3.74 µm
		S8	10.95 µm
		S9	12 µm
ESA/EC			
Imaging multi-spectral radiometers (vis/IR)			
Multi-channel/direction/polarisation radiometer			

Multispectral visible and infrared scan radiometer (10 channels)

FY-1C and 1D		
1.1 km	3,200 km	VIS:
		0.43–0.48 µm
		0.48–0.53 µm
		0.53–0.58 µm
		0.58–0.68 µm
		NIR:
		0.84–0.89 µm
		NIR–SWIR:
		0.90–0.965 µm
		1.58–1.68 µm
		3.55–3.93 µm
		TIR:
		10.3–11.3 µm
		11.5–12.5 µm
Chinese Space Agency		
Imaging multi-spectral radiometers (vis/IR)		
Multi-purpose imaging Vis/IR radiometer		

Visible and infra-red scan radiometer (VIRR)

FY-3A		
FY-3B		
FY-3C		
FY-3D		
FY-3E		
FY-3F		
FY-3G		
1.1 km	2,800 km	10 channels range 0.43–10.5 µm
Chinese space agency		
Visible and infra-red scan radiometer		
Multi-purpose imaging Vis/IR radiometer		

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