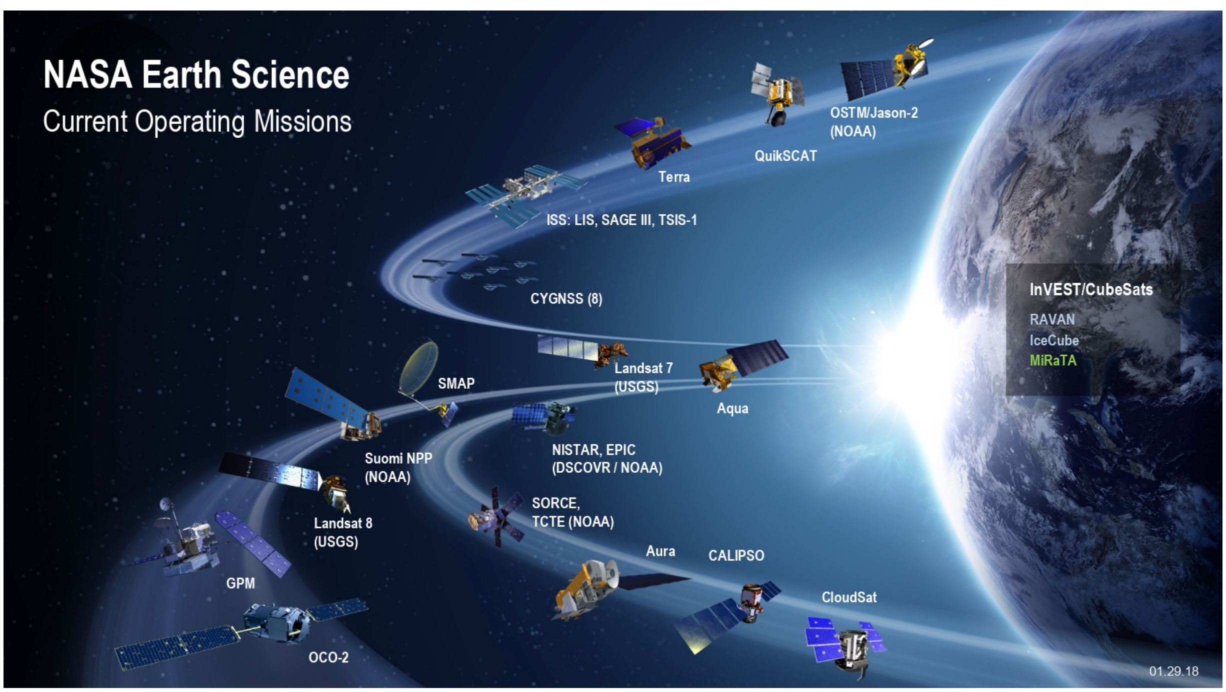
NASA Platforms/Instruments for Agricultural Applications

Compiled by Sean McCartney, NASA Applied Remote Sensing Program (ARSET)

Earth observations (EO) from aerial and satellite-based platforms provide objective, timely, consistent, system-wise, and global data products to monitor Earth's resources across space and time. Since the launch of NASA's first Landsat mission (originally named ERTS) in 1972, satellite imagery has been used for global agricultural monitoring, providing one of the longest operational applications for the Landsat program (Leslie et al., 2017). Below are many of the NASA platforms and instruments which contribute to food security and agriculture, with details provided for each instrument.



NASA/USG Platforms & Instruments with Agricultural Applications

Platform	Instrument	Agricultural Data
Twin Otter International's DHC-6, Scaled Composites' Proteus, NASA's ER-2, NASA's WB-57	AVIRIS & AVIRIS-NG	Crop Type, Crop Health, Chlorophyll, Nitrogen, Leaf Water, Soil Composition, Soil Salinity, Soil Carbon, Non-Photosynthetic Constituents
Aerial (Independent contractors)	NAIP	"Leaf On" Aerial Imagery during the peak growing season
Aqua	AMSR-E, MODIS	Surface Reflectance, Soil Moisture, Vegetation Indices, Leaf Area Index, Evapotranspiration, Albedo, Fire, Land Surface Temperature
Aura	OMI	Impact of surface ozone air pollution on crops
ECOSTRESS	PHyTIR (Prototype HyspIRI Thermal Infrared Radiometer)	Temperature and stress response of vegetation, Evapotranspiration (ET), Evaporative Stress Index (ESI)
GPM	GMI, DPR	Rainfall Detection/Precipitation
GRACE FO	Microwave Ranging System	Runoff and ground water storage on land masses
JPSS-1 (NOAA-20)	VIIRS	Surface Reflectance, Vegetation Indices, Albedo, Fire, Land Surface Temperature
Landsat 1,2,3	MSS	Global Agricultural Monitoring
Landsat 4,5	MSS, TM	Surface Reflectance, Crop Condition, Vegetation Indices, Land Surface Temperature
Landsat 7	ETM+	Surface Reflectance, Crop Condition, Vegetation Indices, Fire, Land Surface Temperature
Landsat 8	OLI, TIRS	Surface Reflectance, Crop Condition, Vegetation Indices, Fire, Land Surface Temperature
POES	AVHRR	Crop Condition, Vegetation Indices
SMAP	L-band radiometer	Soil Moisture

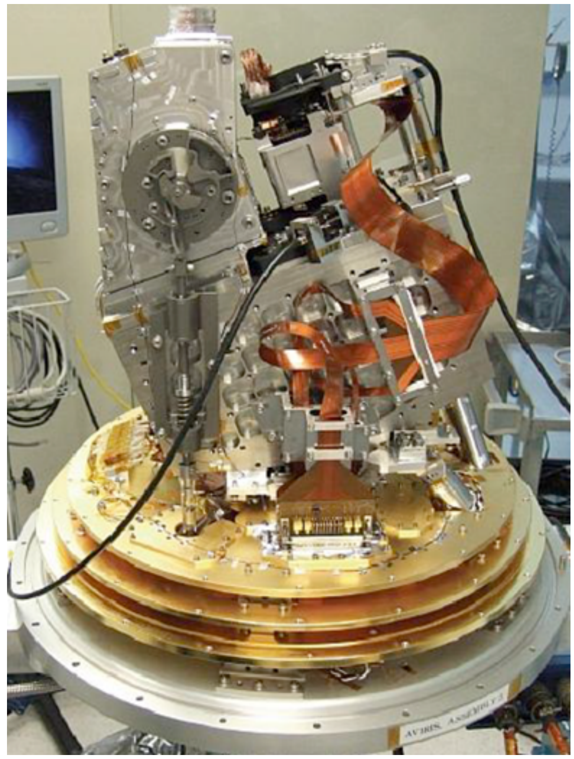
Space Shuttle Endeavour	SRTM	Topography (Elevation)
Suomi-NPP	VIIRS	Surface Reflectance, Vegetation Indices, Albedo, Fire, Land Surface Temperature
Terra	MODIS, ASTER	Surface Reflectance, Vegetation Indices, Leaf Area Index, Evapotranspiration, Albedo, Fire, Land Surface Temperature
TRMM	TMI, PR	Rainfall Detection/Precipitation

Future NASA Missions with Agricultural Applications

Platform	**Instrument**	**Agricultural Data**
SES-Government Solutions communications satellite	GeoCarb	Solar-Induced Fluorescence (SIF)
Landsat 9	OLI-2, TIRS-2	Crop Condition, Vegetation Indices, Land Surface Temperature
NISAR	L-band synthetic aperture radar (SAR), S-band SAR	Hazards and Global Environmental Change
SWOT	Ka-band Radar Interferometer	Reservoir and Lake Surface Water Heights

Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) & Airborne Visible-Infrared Imaging Spectrometer - Next Generation (AVIRIS-NG)

Photo Credit: NASA



AVIRIS is an imaging spectrometer instrument developed at NASA's Jet Propulsion Laboratory (JPL) and flown on an aerial platform. Its optical sensor delivers calibrated images in 224 contiguous spectral channels (bands) with wavelengths from 400 to 2500 nanometers. It uses a scanning mirror ("whisk broom") and four spectrometers to image simultaneously in all 224 bands. AVIRIS produces 677 pixels for the 224 detectors on each scan. The pixel size and swath width of the AVIRIS data depend on the altitude from which the data is collected. When collected by the ER-2 (20 km above the ground) each pixel produced by the instrument covers an area approximately 20 m in diameter on the ground, with some overlap between the pixels, thus yielding a ground swath of about 11 km wide. When collected by the Twin Otter (4 km above the ground), each ground pixel is 4 m square, and the swath is roughly 2 km wide. The AVIRIS sensor collects data that can be applied to studies in the fields of oceanography, snow hydrology, geology, limnology, volcanology, soil and land management, atmospheric and aerosol studies, and agriculture (NASA, 2016).

AVIRIS-NG has been developed at JPL to provide continued imaging spectroscopy measurements in the optical range. AVIRIS-NG is expected to replace the AVIRIS-Classic instrument that has been flying since the 1980s. The instrument measures wavelengths from 380 nm to 2510 nm with 5 nm sampling. Spectra are measured as images with 600 cross-track elements and spatial sampling from 0.3 m to 4.0 m from a Twin Otter platform. In the near future, a high-altitude platform (NASA's ER-2) will be available. AVIRIS-NG has better than 95% cross-track spectral uniformity and >= 95% spectral IFOV uniformity (NASA, 2016).

AVIRIS in the NASA Community

- The AVIRIS Next Generation team is transitioning to replace the AVIRIS-Classic instrument that has been flying since the 1980s.
- AVIRIS data products can be obtained from two separate portals (AVIRIS-Classic & AVIRIS-NG), depending on the instrument.

Data

- Science and agricultural applications include:
    - Crop Type
    - Crop Health
    - Chlorophyll
    - Soil Composition
    - Soil Salinity
    - Soil Carbon

Band	**Spectral Range (μm)**	**Resolution (m)**	**Real-Time Data**
Visible	0.400 - 0.750	4/20	N/A
Near infrared	0.750 - 1.40	4/20	N/A
Shortwave Infrared	1.40 - 2.50	4/20	N/A

Relevant Publications and Citations

Green, Robert O, et al. Imaging Spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). **Remote Sensing of Environment**, vol. 65, no. 3, 1998, pp. 227–248., doi:10.1016/s0034-4257(98)00064-9.

Thompson, David R., et al. A Large Airborne Survey of Earth's Visible-Infrared Spectral Dimensionality. **Optics Express**, Optical Society of America, 11 Apr. 2017, www.osapublishing.org/oe/abstract.cfm?uri=oe-25-8-9186.

Thompson, David R., et al. Atmospheric Correction with the Bayesian Empirical Line. **Optics Express**, vol. 24, no. 3, 2016, p. 2134., doi:10.1364/oe.24.002134.

National Agriculture Imagery Program (NAIP)

Image provided by NAIP

The National Agriculture Imagery Program (NAIP) is administered by the U.S. Department of Agriculture's Farm Service Agency (FSA) through the Aerial Photography Field Office (APFO) in Salt Lake City, Utah. NAIP acquires aerial imagery at a resolution of 0.5-2-meter ground sample distance (GSD) for the United States during the agricultural growing season, or “leaf on” conditions. The NAIP imagery is used to maintain Common Land Unit (CLU) boundaries and assist with farm programs. The images are orthorectified which combines the image characteristics of an aerial photograph with the georeferenced qualities of a map. NAIP projects are contracted each year based upon available funding and the FSA acquisition cycle. The current contract has three primary contractors acquiring imagery for the USDA Farm Service Agency (FSA).

Each individual image tile, or Digital Ortho Quarter Quad (DOQQ), covers a 3.75 x 3.75-minute quarter quadrangle plus a 300-meter buffer on all four sides. Tiles in the NAIP collection come in visible (red, green, and blue bands) or near infrared (red, green, blue, and near infrared bands) and may contain as much as 10 percent cloud cover per tile. The U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center distributes NAIP products in GeoTIFF and JPEG2000 format (USGS, 2015 & USDA, 2017).

NAIP in the Agricultural Community

- NAIP imagery can be obtained from the USGS Earth Explorer website and the Geospatial Data Gateway

Data

- Science and agricultural applications include:
  - Acreage Reporting
  - Conservation Practices
  - Land Classification
  - Canopy Analysis
  - Ground Truth

Band	Spectral Range (μm)	Resolution (m)	Real-Time Data
Visible	0.435 - 0.651*	0.5 - 2	N/A
Near Infrared	0.808 - 0.882*	0.5 - 2	N/A

* Since 2014 imagery has been collected with the Leica ADS100 digital sensor. Spectral and spatial resolutions prior to 2014 vary depending on the year and sensor used.

Advanced Microwave Scanning Radiometer for EOS (AMSR-E)

Photo Credit: JAXA

Launched in 2002 onboard NASA’s second EOS mission, AMSR-E is one of six instruments on the Aqua satellite, one of NASA’s flagship Earth Observing Systems (EOS) missions. The instrument measures geophysical variables related to the Earth's water cycle. AMSR-E is a twelve-channel, six-frequency, total power passive-microwave radiometer system measuring brightness temperatures at 6.925, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz. Spatial resolutions corresponding to each frequency are as follows: 6 x 4 km (89.0 GHz), 14 x 8 km (36.5 GHz), 32 x 18 km (23.8 GHz), 27 x 16 km (18.7 GHz), 51 x 29 km (10.65 GHz), 75 x 43 km (6.925 GHz). The instrument was designed and provided by the National Space Development Agency of Japan (Contractor: Mitsubishi Electric Corporation).

The geophysical record will play an important role in climate change monitoring and will provide valuable information for understanding the Earth's climate system, including water and energy circulation. Various geophysical parameters can be retrieved, including water vapor, cloud liquid water, precipitation, sea surface temperature, sea ice concentration, snow water equivalent, and soil moisture. The lubricant in the bearing assembly gradually deteriorated over the course of the mission leading to the instrument being finally turned off in 2016 (NOAA, 2016 & NASA, 2017).

<u>Data</u>

- Science and agricultural applications include:
    - Soil Moisture
    - Precipitation
    - Snow Water Equivalent
    - Water Vapor
    - Sea Surface Temperature

- Level-1A, Level-2A, Level-2B, and Level-3 data products from AMSR-E can be obtained from the NASA [National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)]

AMSR-E Performance Characteristics (National Snow and Ice Data Center)

Polarization	Horizontal and Vertical					
Incidence angle	55°					
Cross-polarization	Less than -20 dB					
Swath	1445 km					
Dynamic Range (K)	2.7 to 340					
Precision	1 K (1σ)					
Quantifying Bit Number	12-bit	10-bit				
Center Frequency (GHz)	6.925	10.65	18.7	23.8	36.5	89.0
Bandwidth (MHz)	350	100	200	400	1000	3000
Sensitivity (K)	0.3	0.6	1.1			
Mean Spatial Resolution (km)	56	38	21	24	12	5.4
IFOV (km)	74 x 43	51 x 30	27 x 16	31 x 18	14 x 8	6 x 4
Sampling Interval (km)	10 x 10	5 x 5				
Integration Time (msec)	2.6	1.3				
Main Beam Efficiency (%)	95.3	95	96.3	96.4	95.3	96
Beam width (degrees)	2.2	1.4	0.8	0.9	0.4	0.18

Name	**Frequency (GHz)**	**Resolution (km)**	**Real-Time Data**
Microwave	6.925	12.5 - 25	N/A
Microwave	10.65	12.5 - 25	N/A
Microwave	18.7	12.5 - 25	N/A
Microwave	23.8	12.5 - 25	N/A
Microwave	36.5	12.5 - 25	N/A
Microwave	89.0	12.5 - 25	N/A

Relevant Publications and Citations

Bolten, J. D., Crow, W. T., Zhan, X., Jackson, T. J., & Reynolds, C. A. (2010). Evaluating the Utility of Remotely Sensed Soil Moisture Retrievals for Operational

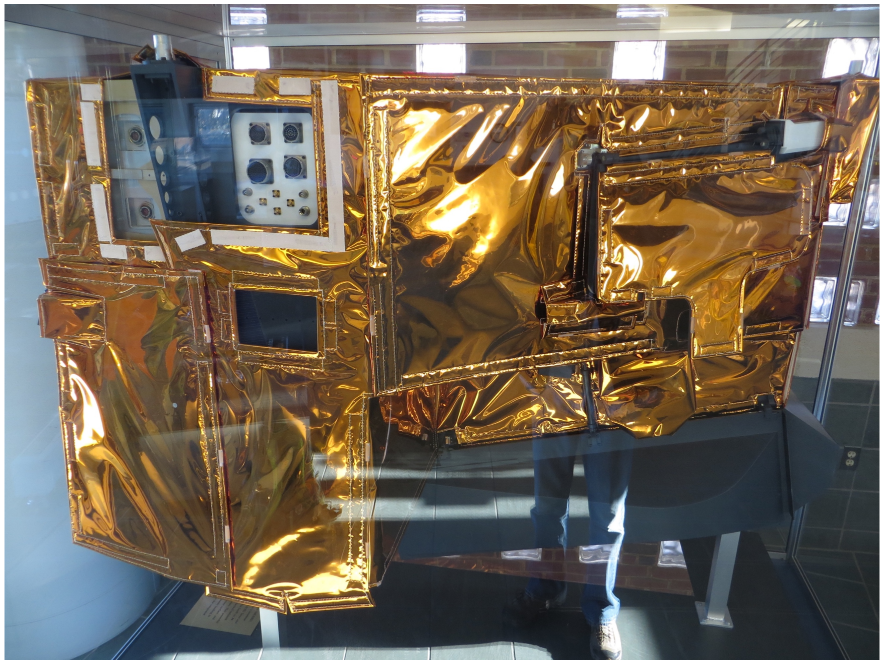
Agricultural Drought Monitoring. **IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing**, 3(1), 57-66. doi:10.1109/jstars.2009.2037163

Liu, D., Mishra, A. K., Yu, Z., Yang, C., Konapala, G., & Vu, T. (2017). Performance of SMAP, AMSR-E and LAI for weekly agricultural drought forecasting over continental United States. **Journal of Hydrology**, 553, 88-104. doi:10.1016/j.jhydrol.2017.07.049

Njoku, E. G. (1999). AMSR Land Surface Parameters. Algorithm Theoretical Basis Document: Surface Soil Moisture, Land Surface Temperature, Vegetation Water Content, Version 3.0 (NASA, Jet Propulsion Laboratory). Pasadena, CA: Jet Propulsion Laboratory.

Moderate Resolution Imaging Spectroradiometer (MODIS)

Photo Credit: Sean McCartney



The Moderate Resolution Imaging Spectro-radiometer (MODIS) is a key instrument aboard the Terra and Aqua satellite missions. Orbiting 705 km above the Earth's surface with a 2,330 km wide swath, MODIS observes almost all points on the planet every 1-2 days. The MODIS instrument collects data within 36 spectral bands, ranging in wave-lengths from 0.4 μm to 14.4 μm and provides us with imagery at a nominal resolution of 250 m at nadir for two bands, 500 m resolution for 5 bands, and the remaining 29 bands at 1 km.

MODIS is ideal for monitoring large-scale changes in the biosphere that are yielding new insights into the workings of the global carbon cycle. Nearly every day across the planet, the instrument monitors changes on the land surface, thereby building upon and extending the heritage begun by Landsat and AVHRR. MODIS' bands are particularly sensitive to fires, providing better estimates of the amounts of aerosols and gases fires release into the atmosphere. The successor to MODIS is the VIIRS instrument first launched in 2011 on the Suomi NPP platform, and followed by the JPSS-1 (NOAA 20) series of satellites (NASA, 2017).

<u>Data</u>

- Science and agricultural applications include:
    - Surface Reflectance
    - Land Cover Type and Extent
    - Snow Cover Extent
    - Land Surface Temperature
    - Evapotranspiration
    - Active Fire
    - Albedo

- NASA MODIS Land Products are available through the [Land Processes DAAC](#) at the USGS Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota.

MODIS Performance Characteristics (NASA)

Primary Use	Band	Bandwidth (µm)	Spectral Radiance	Spatial Resolution (m)
Land/Cloud/Aerosols Boundaries	1	0.620 – 0.670	21.8	250
	2	0.841 – 0.876	24.7	
Land/Cloud/Aerosols Properties	3	0.459 – 0.479	35.3	500
	4	0.545 – 0.565	29	
	5	0.1230 – 0.1250	5.4	
	6	0.1628 – 0.1652	7.3	
	7	0.2105 – 0.2155	1	
Ocean Color/Phytoplankton/Biogeochemistry	8	0.405 – 0.420	44.9	1000
	9	0.438 – 0.448	41.9	
	10	0.483 – 0.493	32.1	
	11	0.526 – 0.536	27.9	
	12	0.546 – 0.556	21	
	13	0.662 – 0.672	9.5	
	14	0.673 – 0.683	8.7	
	15	0.743 – 0.753	10.2	
	16	0.862 – 0.877	6.2	
Atmospheric Water Vapor	17	0.890 – 0.920	10	
	18	0.931 – 0.941	3.6	
	19	0.915 – 0.965	15	
Primary Use	**Band**	**Bandwidth (µm)**	**Spectral Radiance**	**Spatial Resolution (m)**
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	1000
	21	3.929 - 3.989	2.38(335K)	
	22	3.929 - 3.989	0.67(300K)	
	23	4.020 - 4.080	0.79(300K)	
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	
	25	4.482 - 4.549	0.59(275K)	
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6	

	27	6.535 - 6.895	1.16(240K)	
	28	7.175 - 7.475	2.18(250K)	
Cloud Properties	29	8.400 - 8.700	9.58(300K)	
Ozone	30	9.580 - 9.880	3.69(250K)	
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	
	32	11.770 - 12.270	8.94(300K)	
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	
	34	13.485 - 13.785	3.76(250K)	
	35	13.785 - 14.085	3.11(240K)	
	36	14.085 - 14.385	2.08(220K)	

Relevant Publications and Citations

Justice C.O., Vermote E., Privette J., Sei A. The Evolution of U.S. Moderate Resolution Optical Land Remote Sensing from AVHRR to VIIRS. Ramachandran, B., Justice C.O., Abrams M.J. 2011. **Land Remote Sensing and Global Environmental Change:** NASA's Earth Observing System and the Science of ASTER and MODIS. Series: Remote Sensing and Digital Image Processing, Vol. 11, Springer Verlag. 873p. ISBN: 978-1-4419-6748-0

Skakun S., Justice C.O., Vermote E., and Roger J-C, 2017. Transitioning from MODIS to VIIRS: an analysis of inter-consistency of NDVI data sets for agricultural monitoring. **International Journal of Remote Sensing,** 38, 4, 971-992, DOI 10.1080/01431161.2017.1395970

Skakun, S., Franch, B., Vermote, E., Roger, J., Becker-Reshef, I., Justice, C., & Kussul, N. (2017). Early season large-area winter crop mapping using MODIS NDVI data, growing degree days information and a Gaussian mixture model. **Remote Sensing of Environment**, 195, 244-258. doi:10.1016/j.rse.2017.04.026

Whitcraft, A. K., Becker-Reshef, I., & Justice, C. O. (2014). Agricultural growing season calendars derived from MODIS surface reflectance. **International Journal of Digital Earth**, 8(3), 173-197. doi:10.1080/17538947.2014.894147

Ozone Monitoring Instrument (OMI)

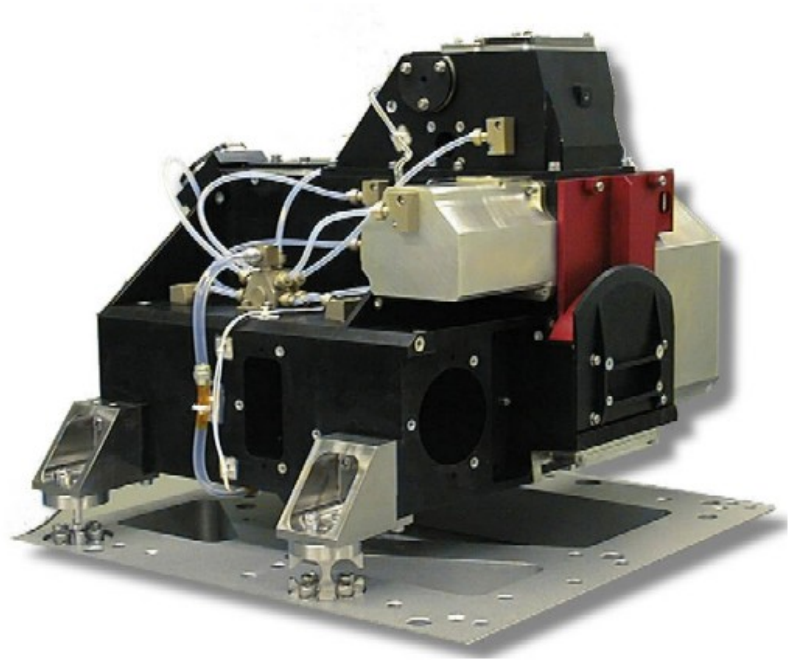


Photo Credit: Netherlands Agency for Aerospace Programmes (NIVR)

The Ozone Monitoring Instrument (OMI) is a key instrument aboard the Aura satellite mission for monitoring the recovery of the ozone layer. Orbiting 705 km above the Earth's surface with a 2,600 km wide swath, the instrument provides daily global coverage. The OMI instrument employs hyperspectral imaging in a push-broom mode to observe solar backscatter radiation in the ultraviolet and visible (270-365 nm). The hyperspectral capabilities improve the accuracy and precision of the total ozone amounts and also allow for accurate radiometric and wavelength self-calibration over the long term. OMI is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the EOS Aura mission and will continue the TOMS record for total ozone and other atmospheric parameters related to ozone chemistry and climate.

OMI measures criteria pollutants such as O3, NO2, SO2, and aerosols. Surface-level O3 reduces crop yields when it enters a plant's stomata and chemically reacts with plant cells. The US Environmental Protection Agency (EPA) has designated these atmospheric constituents as posing serious threats to human health and agricultural productivity. (NASA, 2018)

Data

- Science and agricultural applications include:
    - Ozone pollution causing crop damage

- NASA OMI products are available through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC), located at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

MODIS Performance Characteristics (NASA)

Channel	Spectral range Full performance range	Average spectral	Ground Pixel Size	Data products

		resolution (FWHM)	(along x cross-track)	
UV-1	270 - 314 nm 270 - 310 nm	0.42 nm	13 km x 48 km 13 km x 24 km	O3 Profile
UV-2	306 - 380 nm 310 - 365 nm	0.45 nm	13 km x 24 km 13 km x 12 km	O3 Profile, O3 Column, BrO, OClO, SO2, HCHO, Aerosol, Surface UV-B, Surface Reflectance, Cloud Top Pressure, Cloud Cover
VIS	350 - 500 nm 365 - 500 nm	0.63 nm	13 km x 12 km 13 km x 12 km	NO2, Aerosol, OClO, Surface UV-B, Surface Reflectance, Cloud Top Pressure, Cloud Cover

<u>Relevant Publications and Citations</u>

Avnery, S., Mauzerall, D. L., Liu, J., & Horowitz, L. W. (2011b). Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O3 pollution. Atmospheric Environment, 45(13), 2297-2309.

Schiferl, L. D. and Heald, C. L.: Particulate matter air pollution may offset ozone damage to global crop production, Atmos. Chem. Phys., 18, 5953-5966, https://doi.org/10.5194/acp-18-5953-2018, 2018.

Van Dingenen, R., Dentener, F. J., Raes, F., Krol, M. C., Emberson, L., & Cofala, J. (2009). The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmospheric Environment, 43(3), 604-618

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) / Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)

Photo Credit: NASA/JPL-Caltech/KSC

PHyTIR (Prototype HyspIRI Thermal Infrared Radiometer) is the instrument used for the ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) mission, one of two Pathfinder Programs selected by NASA in 2014 that will observe changes in global vegetation from the International Space Station (ISS). PHyTIR is a high-resolution multiple wavelength imaging spectrometer built by NASA/JPL (Jet Propulsion Laboratory) in Pasadena, CA, to study the effectiveness of water use by vegetation. The instrument was initially developed to support testing and assessment for the HyspIRI (Hyperspectral Infrared Imager) under the auspices of ESTO (Earth Science Technology Office). ECOSTRESS consists of a cross-track, push-whiskbroom, scanning, multiband filter radiometer with six spectral bands between 8 and 12.6 μm, and a high spatial resolution of 38 m in-track by 69 m cross-track, and will be deployed on the JEM (Japanese Experiment Module) External Facility (EF) on the ISS. Because of the precessing orbit of the ISS, the ECOSTRESS will enable vegetation water stress assessments on a diurnal scale. This multispectral TIR (Thermal Infrared) instrument, mounted on the JEM-EF will measure the brightness temperature of plants and use that information to better understand how much water plants need and how they respond to stress (evapotranspiration dynamics).

The ISS orbit of ~400 km altitude and 51.6-degree inclination, ECOSTRESS will provide a repeat cycle of nearly three days and a spatial resolution of ~60 m. Due to the unique orbital path of the ISS, ECOSTRESS will observe the same spot on Earth at different times each day. This configuration will enable an unprecedented view of diurnal trends in vegetation evapotranspiration. ECOSTRESS will provide the highest spatial resolution thermal infrared data ever from the ISS. One of the core products that will be produced by the ECOSTRESS team is the Evaporative Stress Index (ESI). ESI is a leading drought indicator—meaning it can indicate that plants are stressed and that a drought is likely to occur providing the option for decision makers to take action. (NASA & ESA, 2018)

Data

- Science and agricultural applications include:
    - Evapotranspiration
    - Evaporative Stress Index (ESI)

- NASA PHyTIR/ECOSTRESS Land Products are available through the Land Processes DAAC at the USGS Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota.

MODIS Performance Characteristics (NASA)

Description	**Value**	**Unit**	**Notes**
Number of spectral bands	6		
Measured band centers	8.28, 8.79, 9.06, 10.50, 12,05, 12.60	μm	
Measured FWHM per band	0.26, 0.36, 0.4, 0.43, 0.59	μm	
Pixel size at nadir	69 x 38	m	2 pixels in cross track and 1 pixel in down track
Swath width (ISS nominal altitude range is 385 to 415 km)	≥ 360	km	
Radiometric accuracy	≤1 K @ 300 K	K	
Radiometric precision	≤0.3 K @ 300	K	
Dynamic range	270-335	K	
Data coverage	CONUS, twelve 1,000 x 1,000 km key climate zone and twenty-five Flux net sites for all opportunities		
Data collection	On average 1-hour of science data per day		

GPM Microwave Imager (GMI)

Photo Credit: Ball Aerospace & Technology Corporation

The Global Precipitation Measurement (GPM) Microwave Imager (GMI) is a passive instrument that observes the microwave energy emitted by the Earth and atmosphere. GMI is one of two instruments onboard the Global Precipitation Measurement (GPM) core satellite. GPM is a mission between NASA, JAXA, and partnering space agencies. The instrumentation enables the core spacecraft to serve as both a precipitation standard and as a radiometric standard for the other GPM constellation members. The instrument is a multi-channel, conical-scanning, microwave radiometer, characterized by 13 microwave channels ranging in frequency from 10 GHz to 183 GHz. In addition to carrying channels similar to those on the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), which flew from 1997-2015, the GMI carries four high frequency, millimeter-wave channels near 166 GHz and 183 GHz.

Rotating at 32 rotations per minute, the GMI gathers microwave radiometric brightness measurements over a 140-degree sector centered about the spacecraft's ground track vector. The 140-degree GMI swath represents a swath of 904 km (562 miles) on the Earth's surface. GMI is designed to advance precipitation measurements from space, improve knowledge of precipitation systems, improve climate modeling and prediction, improve weather forecasting, and improve hydrological modeling and prediction. Societal applications include disasters, health, agriculture, and climate prediction. The Ball Aerospace and Technology Corporation built the GMI under contract with NASA Goddard Space Flight Center (NASA, 2017).

GMI in the NASA Community

- Precipitation Measurement Missions (PMM) Extreme Weather News is a NASA effort to provide near real-time information and 3-D visualizations of hurricanes to the general public.

Data

- Science and agricultural applications include:
  - Precipitation

- Extreme Weather
- Floods
- Landslides
- Climate Prediction
- Soil Moisture
- Agriculture

- NASA GMI Precipitation Products can be obtained from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC), located in Greenbelt, MD.

GMI Performance Characteristics (NASA)

Channel No	Central Frequency (Ghz)	Central Frequency Stabilization (±MHz)	Bandwidth (MHz)	Polarization	Integration time (ms)	NEDT (K)
1	10.65	10	100	V	9.7	0.96
2	10.65	10	100	H	9.7	0.96
3	18.7	20	200	V	5.3	0.84
4	18.7	20	200	H	5.3	0.84
5	23.8	20	400	V	5	1.05
6	36.5	50	1000	V	5	0.65
7	36.5	50	1000	H	5	0.65
8	89	200	6000	V	2.2	0.57
9	89	200	6000	H	2.2	0.57
10	166	200	3000	V	3.6	1.5
11	166	200	3000	H	3.6	1.5
12	183.31±3	200	3500	V	3.6	1.5
13	183.31±7	200	4500	V	3.6	1.5

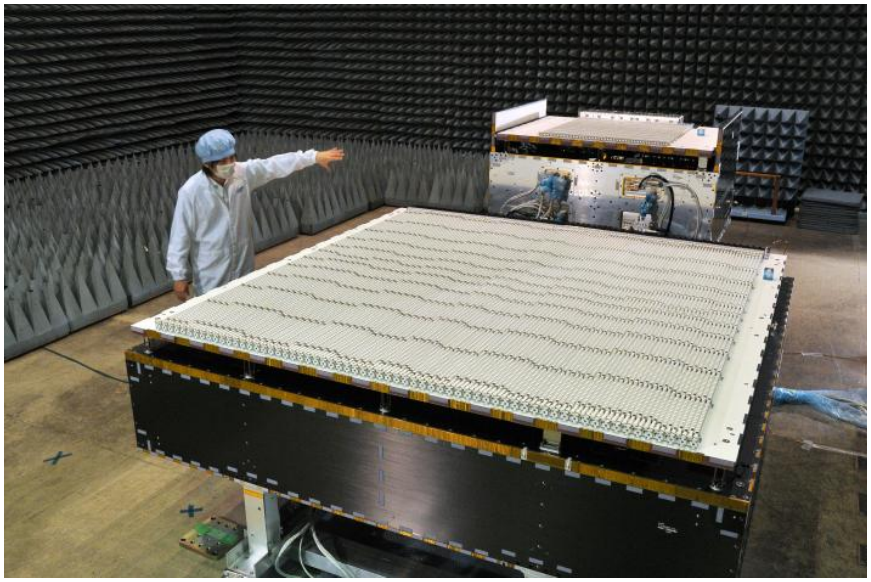
Relevant Publications and Citations

Skofronick-Jackson, G., Petersen, W. A., Berg, W., Kidd, C., Stocker, E. F., Kirschbaum, D. B., . . . Wilheit, T. (2017). The Global Precipitation Measurement (GPM) Mission for Science and Society. **Bulletin of the American Meteorological Society**, 98(8), 1679-1695. doi:10.1175/bams-d-15-00306.1

Kirschbaum, D. B., Huffman, G. J., Adler, R. F., Braun, S., Garrett, K., Jones, E., . . . Zaitchik, B. F. (2017). NASA's Remotely Sensed Precipitation: A Reservoir for Applications Users. **Bulletin of the American Meteorological Society**, 98(6), 1169-1184. doi:10.1175/bams-d-15-00296.1

Dual-frequency Precipitation Radar (DPR)

Photo Credit: JAXA/NASA



The Dual-Frequency Precip-itation Radar (DPR) is one of two instruments onboard the Global Precipitation Measurement (GPM) Core satellite. GPM is a mission between NASA, JAXA, and partnering space agencies. The DPR consists of a Ku-band precipitation radar (KuPR) and a Ka-band precipitation radar (KaPR). The KuPR (13.6 GHz) is an updated version of the highly successful unit flown on the Tropical Rainfall Measuring Mission (TRMM). The DPR provides three-dimensional information about precipitation particles derived from reflected energy by these particles at different heights within the cloud system. The two frequencies of the DPR also allow the radar to infer the sizes of precipitation particles and offer insights into a storm's physical characteristics. The Ka-band frequency scans across a region of 78 miles (125 kilometers) and is nested within the wider scan of the Ku-band frequency of 158 miles (254 kilometers).

The DPR is more sensitive than its TRMM predecessor especially in the measurement of light rainfall and snowfall in high latitude regions. Rain/snow determination is accomplished by using the differential attenuation between the Ku-band and the Ka-band frequencies. These Earth-pointing KuPR and KaPR instruments provide rain sensing over both land and ocean, both day and night. DPR is designed to advance precipitation measurements from space, improve knowledge of precipitation systems, improve climate modeling and prediction, improve weather forecasting, and improve hydrological modeling and prediction. Societal applications include disasters, health, agriculture, and climate prediction. JAXA and Japan's National Institute of Information and Communications Technology (NICT) built the DPR for GPM's Core satellite (NASA, 2017).

DPR in the NASA Community

- Precipitation Measurement Missions (PMM) Extreme Weather News is a NASA effort to provide near real-time information and 3-D visualizations of hurricanes to the general public.

Data

- Science and agricultural applications include:
  - Precipitation
  - Extreme Weather
  - Floods
  - Landslides
  - Climate Prediction
  - Soil Moisture
  - Agriculture

- NASA DPR Precipitation Products can be obtained from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC), located in Greenbelt, MD.

DPR Performance Characteristics (NASA)

Item	**KuPR**	**KaPR**
Swath Width	245 kilometers (km)	120 kilometers (km)
Range Resolution	250 meters (m)	250/500 meters (m)
Spatial Resolution	5 km (Nadir)	5 km (Nadir)
Beam Width	0.71 degrees	0.71 degrees
Transmitter	128 Solid State Amplifiers	128 Solid State Amplifiers
Peak Transmit Power	1013 Watts (W)	146 Watts (W)
Pulse Repetition Frequency	4100 - 4400 Hertz	4100 - 4400 Hertz

Relevant Publications and Citations

Skofronick-Jackson, G., Petersen, W. A., Berg, W., Kidd, C., Stocker, E. F., Kirschbaum, D. B., . . . Wilheit, T. (2017). The Global Precipitation Measurement (GPM) Mission for Science and Society. **Bulletin of the American Meteorological Society**, 98(8), 1679-1695. doi:10.1175/bams-d-15-00306.1

Kirschbaum, D. B., Huffman, G. J., Adler, R. F., Braun, S., Garrett, K., Jones, E., . . . Zaitchik, B. F. (2017). NASA's Remotely Sensed Precipitation: A Reservoir for Applications Users. **Bulletin of the American Meteorological Society**, 98(6), 1169-1184. doi:10.1175/bams-d-15-00296.1

Gravity Recovery and Climate Experiment (GRACE) & Gravity Recovery and Climate Experiment Follow-On (GRACE-FO)

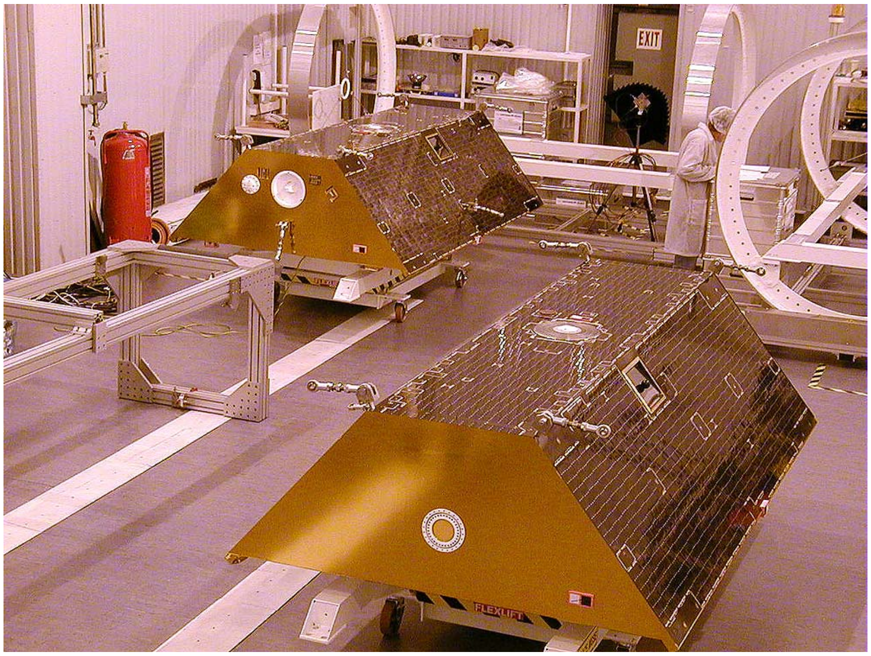


Photo Credit: NASA

The GRACE mission was selected as the second mission under the NASA Earth System Science Pathfinder (ESSP) Program in May 1997. Launched in March of 2002, the GRACE mission is accurately mapping variations in Earth's gravity field. GRACE is different from most Earth observing satellite missions because it doesn't carry a suite of independent scientific instruments on board. It does not take measurements of the electromagnetic energy reflected back to it from the Earth's surface. Instead, the two GRACE satellites themselves act in unison as the primary instrument. Changes in the distance between the twin satellites (nicknamed Tom and Jerry) are used to make gravitational field measurements.

The twin satellites fly about 220 kilometers (137 miles) apart in a polar orbit 500 kilometers (310 miles) above Earth. GRACE maps Earth's gravity field by making accurate measurements of the distance between the two satellites, using GPS and a microwave ranging system (K-band Ranging System). GRACE is providing scientists from all over the world with an efficient and cost-effective way to map Earth's gravity field with unprecedented accuracy. The gravity variations studied by GRACE include: changes due to surface and deep currents in the ocean, runoff and ground water storage on land masses, exchanges between ice sheets or glaciers and the ocean, and variations of mass within Earth. GRACE is a joint NASA/Deutsches Zentrum für Luft- und Raumfahrt (DLR, the German Aerospace Center) mission. Following an age-related battery issue on GRACE-2 in September 2017, the satellite mission has ended scientific operations.
GRACE Follow-On, a joint NASA/Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ) mission, will continue GRACE's legacy. It will also test a new laser-ranging interferometer developed by a joint German/U.S. collaboration for use in

future generations of gravitational research satellites. GRACE-FO is scheduled for launch in early 2018 (NASA, 2017).

Data

- Science and agricultural applications include:
  - Drought Monitoring
  - Flood Potential
  - Groundwater

- NASA GRACE Products can be obtained from the NASA Jet Propulsion Laboratory.

Relevant Publications and Citations

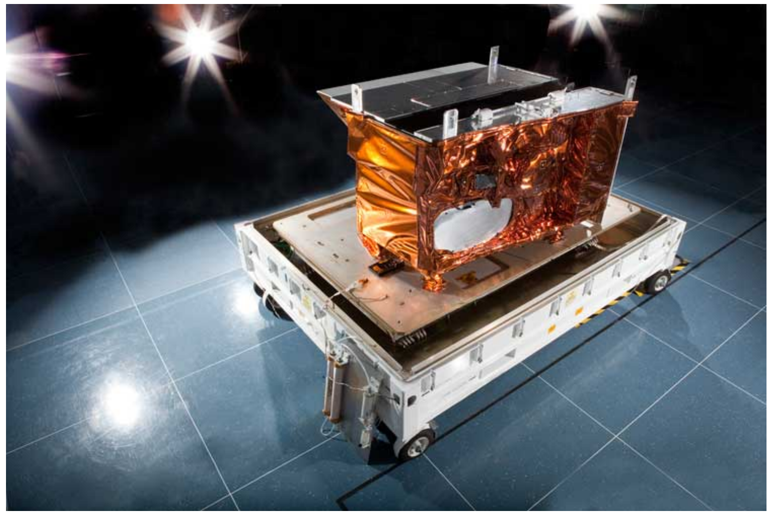
Bernknopf, R., Brookshire, D., Kuwayama, Y., Macauley, M., Rodell, M., Thompson, A., . . . Zaitchik, B. (2018). The Value of Remotely Sensed Information: The Case of a GRACE-Enhanced Drought Severity Index. **Weather, Climate, and Society**, 10(1), 187-203. doi:10.1175/wcas-d-16-0044.1

Girotto, M., G. J. Lannoy, R. H. Reichle, et al. 2017. "Benefits and Pitfalls of GRACE Data Assimilation: A Case Study of Terrestrial Water Storage Depletion in India." **Geophysical Research Letters**, 44: 4107-4115

Lo, M.-H., J. S. Famiglietti, J. T. Reager, M. Rodell, and S. C. Swenson. 2016. "GRACE-based estimates of global groundwater depletion." **Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts**, 137-146, ISBN: 971-1-118-97176-5

The Visible Infrared Imaging Radiometer Suite (VIIRS)

VIIRS Photo, courtesy of Raytheon Space and Airborne Systems



First launched as one of five instruments on the Suomi-National Polar-orbiting Partnership (Suomi-NPP) Mission in 2011, this multispectral imager obtains daily observations from the visible through the thermal. The instrument was designed in part to provide continuity with EOS MODIS and has many of the same characteristics for land monitoring (Justice et al. 2011). The Suomi-NPP Mission shared by NASA and NOAA is a bridging mission to the JPSS-1 (NOAA 20) VIIRS instruments, the NOAA operational polar orbiting imager which replaces the NOAA AVHRR instrument series, which started in 1981. JPSS-1 was launched on November 18, 2017 and is the first of four VIIRS instruments in the JPSS series.

VIIRS observes the entire Earth's surface twice each day from Suomi NPP's polar orbit 824 km above the Earth's surface. The 3,000 km swath width of the VIIRS instrument, which is 710 km greater than that of Moderate Resolution Imaging Spectroradiometer (MODIS), allows for no gaps in coverage, which are observed in MODIS near the equator. The VIIRS instrument provides 22 spectral bands at two spatial resolutions, 375 meters (m) and 750 m, which are resampled to 500 m, 1 km, and 0.05 degrees as NASA data products to promote consistency with the MODIS heritage. Unlike MODIS, VIIRS maintains a uniform pixel size across scan by resampling.

VIIRS in the NASA Community

- The NASA VIIRS Land Science Team is utilizing S-NPP VIIRS to provide continuity with the land products from MODIS.
- NASA VIIRS Land Products can be obtained from the Land Product DAAC at Sioux Falls, South Dakota.
- SPoRT (Short-term Prediction Research and Transition Center) is a NASA project to transition unique observations and research capabilities to the operational weather community to improve short-term forecasts on a regional scale.

Data

- Land products relevant for agricultural monitoring include:
    - Surface Reflectance (the input for vegetation indices)

  - Land Surface Remperature
  - Active Fire
  - Albedo

- Near Real Time versions of some of the VIIRS products including surface reflectance and fire can be obtained via the Land Atmosphere Near real time Capability for EOS (LANCE).
- Similar land products offered by NOAA

		Band No.	Driving EDR(s)	Spectral Range (um)	Horiz Sample Interval (km) (track x Scan) Nadir	End of Scan
Reflective Bands	VisNIR	M1	Ocean Color Aerosol	0.402 - 0.422	0.742 x 0.259	1.60 x 1.58
Reflective Bands	VisNIR	M2	Ocean Color Aerosol	0.436 - 0.454	0.742 x 0.259	1.60 x 1.58
Reflective Bands	VisNIR	M3	Ocean Color Aerosol	0.478 - 0.498	0.742 x 0.259	1.60 x 1.58
Reflective Bands	VisNIR	M4	Ocean Color Aerosol	0.545 - 0.565	0.742 x 0.259	1.60 x 1.58
Reflective Bands	VisNIR	I1	Imagery EDR	0.600 - 0.680	0.371 x 0.387	0.80 x 0.789
Reflective Bands	VisNIR	M5	Ocean Color Aerosol	0.662 - 0.682	0.742 x 0.259	1.60 x 1.58
Reflective Bands	VisNIR	M6	Atmosph. Correct.	0.739 - 0.754	0.742 x 0.776	1.60 x 1.58
Reflective Bands	VisNIR	I2	NDVI	0.846 - 0.885	0.371 x 0.387	0.80 x 0.789
Reflective Bands	VisNIR	M7	Ocean Color Aerosol	0.846 - 0.885	0.742 x 0.259	1.60 x 1.58
Reflective Bands	S/MWIR	M8	Cloud Particle Size	1.230 - 1.250	0.742 x 0.776	1.60 x 1.58
Reflective Bands	S/MWIR	M9	Cirrius/Cloud Cover	1.371 - 1.386	0.742 x 0.776	1.60 x 1.58
Reflective Bands	S/MWIR	I3	Binary Snow Map	1.580 - 1.640	0.371 x 0.387	0.80 x 0.789
Reflective Bands	S/MWIR	M10	Snow Fraction	1.580 - 1.640	0.742 x 0.776	1.60 x 1.58
Reflective Bands	S/MWIR	M11	Clouds	2.225 - 2.275	0.742 x 0.776	1.60 x 1.58
Emissive Bands	S/MWIR	I4	Imagery Clouds	3.550 - 3.930	0.371 x 0.387	0.80 x 0.789
Emissive Bands	S/MWIR	M12	SST	3.660 - 3.840	0.742 x 0.776	1.60 x 1.58
Emissive Bands	S/MWIR	M13	SST Fires	3.973 - 4.128	0.742 x 0.259	1.60 x 1.58
Emissive Bands	LWIR	M14	Cloud Top Properties	8.400 - 8.700	0.742 x 0.776	1.60 x 1.58
Emissive Bands	LWIR	M15	SST	10.263 - 11.263	0.742 x 0.776	1.60 x 1.58
Emissive Bands	LWIR	I5	Cloud Imagery	10.500 - 12.400	0.371 x 0.387	0.80 x 0.789
Emissive Bands	LWIR	M16	SST	11.538 - 12.488	0.742 x 0.776	1.60 x 1.58

Band	**Spectral Range (µm)**	**Resolution (km)**	**Real-Time Data**
Visible (I1)	0.600 - 0.680	0.375	✔
Shortwave Infrared (I4)	3.55 - 3.93	0.375	✔
Longwave Infrared (I5)	10.5 - 12.4	0.375	✔
Day/Night Band Radiance		0.75	✔
Day/Night Band Reflectance		0.75	✔

Relevant Publications and Citations

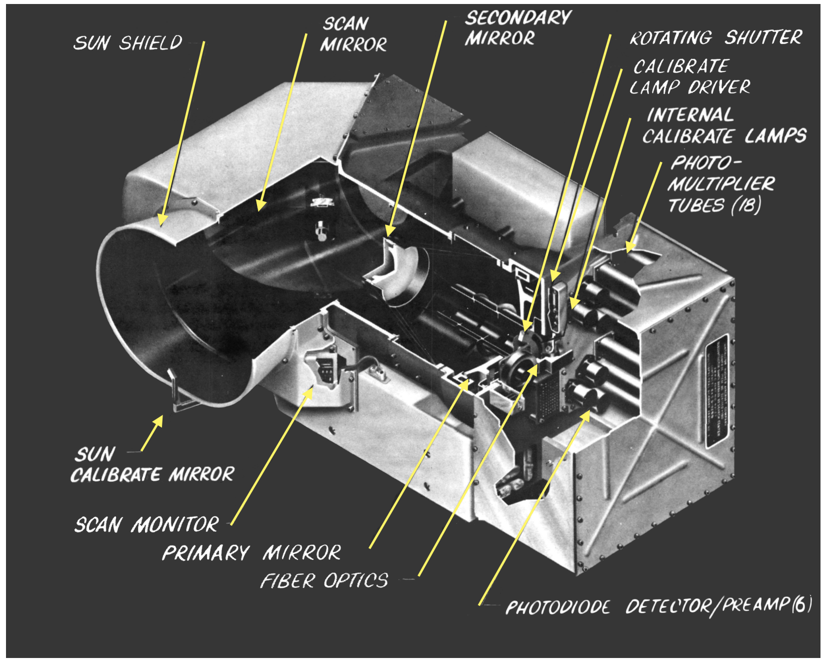
Skakun S., Justice C.O., Vermote E., and Roger J-C, 2017. Transitioning from MODIS to VIIRS: an analysis of inter-consistency of NDVI data sets for agricultural monitoring. **International Journal of Remote Sensing,** 38, 4, 971-992, DOI 10.1080/01431161.2017.1395970

Justice C.O., Vermote E., Privette J., Sei A. The Evolution of U.S. Moderate Resolution Optical Land Remote Sensing from AVHRR to VIIRS. Ramachandran, B., Justice C.O., Abrams M.J. 2011. **Land Remote Sensing and Global Environmental Change:** NASA's Earth Observing System and the Science of ASTER and MODIS. Series: Remote Sensing and Digital Image Processing, Vol. 11, Springer Verlag. 873p. ISBN: 978-1-4419-6748-0

Vermote, E., Justice C., & Csiszar, I. (2014). Early evaluation of the VIIRS calibration, cloud mask and surface reflectance Earth data records. **Remote Sensing of Environment,** *148*, 134-145.

Multispectral Scanner (MSS)

Four-band Multispectral Scanner System that flew on Landsat 1 Photo Credit: Hughes Santa Barbara Remote Sensing / NASA



The Multispectral Scanner (MSS) sensor was onboard Landsats 1 through 5. It acquired images of the Earth nearly continuously from July 1972 to January 1992, with an 18-day repeat cycle for Landsats 1 through 3, and a 16-day repeat cycle for Landsats 4 and 5. Starting with its first Launch on July 23, 1972 aboard Earth Resources Technology Satellite 1 (ERTS-1, later named Landsat 1), the MSS instrument has been crucial to the Landsat mission, a joint effort of the USGS and NASA. Built by Hughes Aircraft Corporation, this scanning spectroradiometric sensor was the backbone of the first three Landsat satellites' data acquisition. It was not until Landsat 4 and 5 that the MSS became subsidiary to the more advantageous Thematic Mapper (TM). The MSS sensor was also the first global monitoring system that used multiple band data in a digital format.

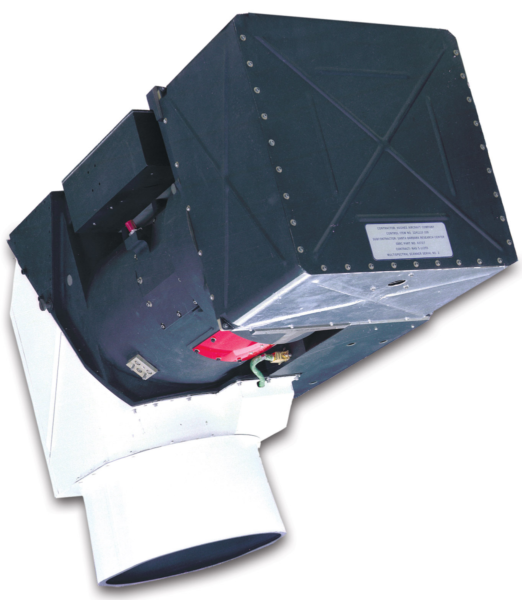


Photo Credit: Hughes Santa Barbara Remote Sensing / NASA

The whisk broom sensor used an oscillating mirror to detect light from four spectral bands ranging from the visible green to the near-infrared (IR) wavelengths (0.5 – 1.1 μm). The sensor collected a swath of 185 km (115 miles) across the orbital track from an orbital altitude of 917 km (~570 miles). The precise location of Landsats 1-3 was not well known, as is now the standard on modern systems carrying a GPS receiver. Therefore, the image processing from these earlier missions often required manual intervention to create products that were

comparable to modern approaches. Using the automated systems, only a small number of MSS scenes could be processed to a terrain-corrected product. To resolve these issues, MSS data products with improved geometric correction were released in fall 2010. The products are processed on the Landsat Product Generation System (LPGS), similar to all other Landsat data types. All MSS products are processed to generate a geolocated, terrain-corrected product (L1T) in the Universal Transverse Mercator (UTM) projection cast on the WGS-84 datum at a 60-meter spatial resolution.
(NASA, USGS, 2017)

Data

- Science and agricultural applications include:
    - Land Use/Land Change
    - Agriculture
    - Forestry
    - Geology

- MSS Level 1T scenes can be obtained from USGS on EarthExplorer or the USGS Global Visualization Viewer (GloVis).

MSS Performance Characteristics (NASA)

Band # (L1-L2)	Band # (L3)	Band # (L4-L5)	Spectral Resolution (μm)	Spatial Resolution (m)	L4/L5 TM Band Equivalent
4 – Green	4	1 – Green	0.5 - 0.6	60	~ 2 (0.52–0.60 μm)
5 – Red	5	2 – Red	0.6 - 0.7	60	~ 3 (0.63–0.69 μm)
6 – NIR	6	3 – NIR	0.7 - 0.8	60	~ 4 (0.76–0.90 μm)
7 – NIR	7	4 – NIR	0.8 - 1.1	60	~ 4 (0.76–0.90 μm)
N/A	8 – Thermal	N/A	10.4 - 12.6	60	~ 6 (10.41-12.5 μm)

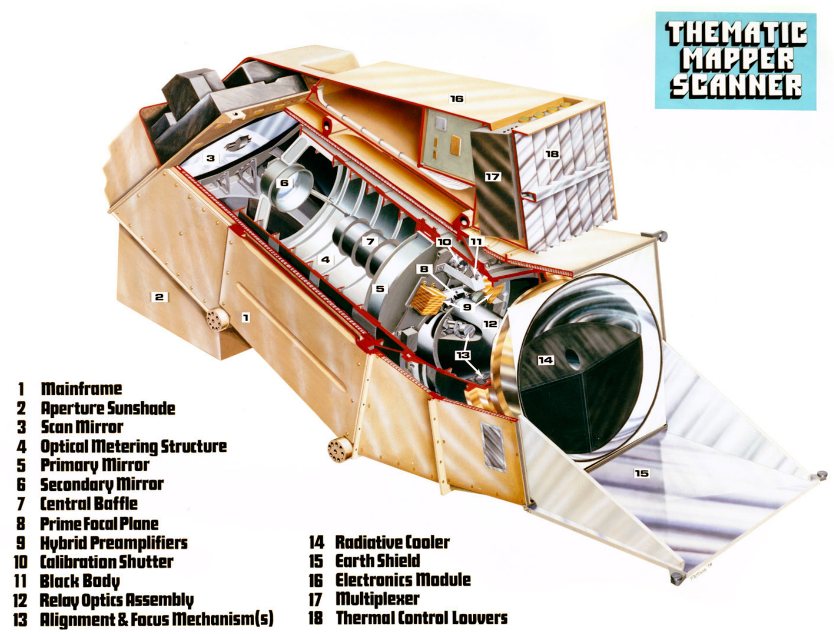
Photo of Landsat 3 spacecraft at GE factory during integration
Photo Credit: GE/NASA

<u>Relevant Publications and Citations</u>

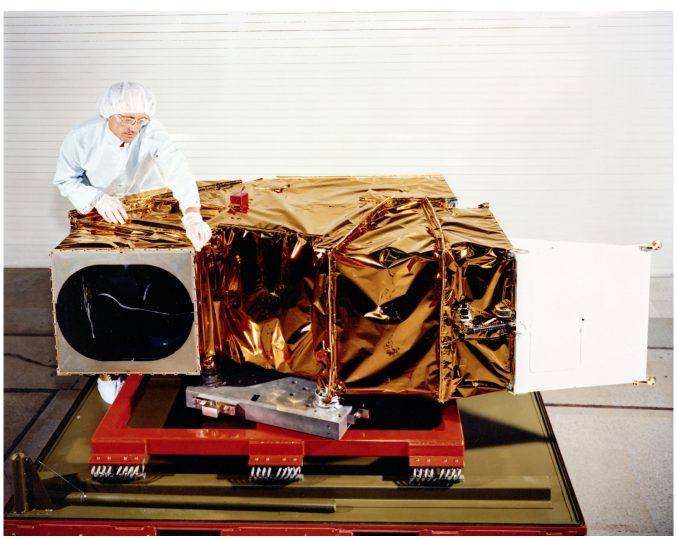
Chander, G., Markham, B. L., & Helder, D. L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM , and EO-1 ALI sensors. **Remote Sensing of Environment**, 113(5), 893-903. doi:10.1016/j.rse.2009.01.007

Thematic Mapper (TM)

Schematic of Landsat 4/5 Thematic Mapper
Photo Credit: Hughes Santa Barbara Remote Sensing



The Thematic Mapper (TM) is a multispectral scanning, whisk broom sensor designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity, and greater radiometric accuracy and resolution than the Multispectral Scanner (MSS). TM flew onboard Landsats 4 and 5 and acquired images of the Earth from 1982 to January 2011, when the instrument stopped acquiring images due to a rapidly degrading electronic component. The instrument operates in the visible and Infra-Red regions of the Electromagnetic Spectrum, consisting of six spectral bands with a spatial resolution of 30 meters for bands 1-5 and band 7, and one thermal band (band 6) collected at 120 meters, later resampled to 30 meters. The instrument had a temporal resolution of 16 days.



Landsat 4 Thematic Mapper during fabrication and test
Photo Credit: Hughes Santa Barbara Remote Sensing

TM products are processed on the Landsat Product Generation System (LPGS), similar to all other Landsat data types. All TM products are processed to generate a geolocated, terrain-corrected product (L1T) in the Universal Transverse Mercator (UTM) projection cast on the WGS-84 datum at a 30-meter spatial resolution. The instrument was built by Santa Barbara Research Centre (SBRC) of Hughes Aircraft Corporation (NASA, USGS, 2017).

Data

- Science and agricultural applications include:
    - Land Use/Land Change
    - Albedo
    - Agriculture
    - Forestry
    - Geology

- TM Level 1T scenes can be obtained from USGS on EarthExplorer or the USGS Global Visualization Viewer (GloVis).

TM Performance Characteristics (NASA)

Band Number	**Spectral Resolution (μm)**	**Spatial Resolution (m)**
1 – Blue	0.45 - 0.52	30
2 – Green	0.52 - 0.60	30
3 – Red	0.63 - 0.69	30
4 – Near Infrared (NIR)	0.76 - 0.90	30
5 – Shortwave Infrared (SWIR) 1	1.55 - 1.75	30
6 – Thermal	10.41 - 12.5	120* (30)
7 – Shortwave Infrared (SWIR) 2	2.08 - 2.35	30

* TM Band 6 was acquired at 120-meter resolution, but products are resampled to 30-meter.

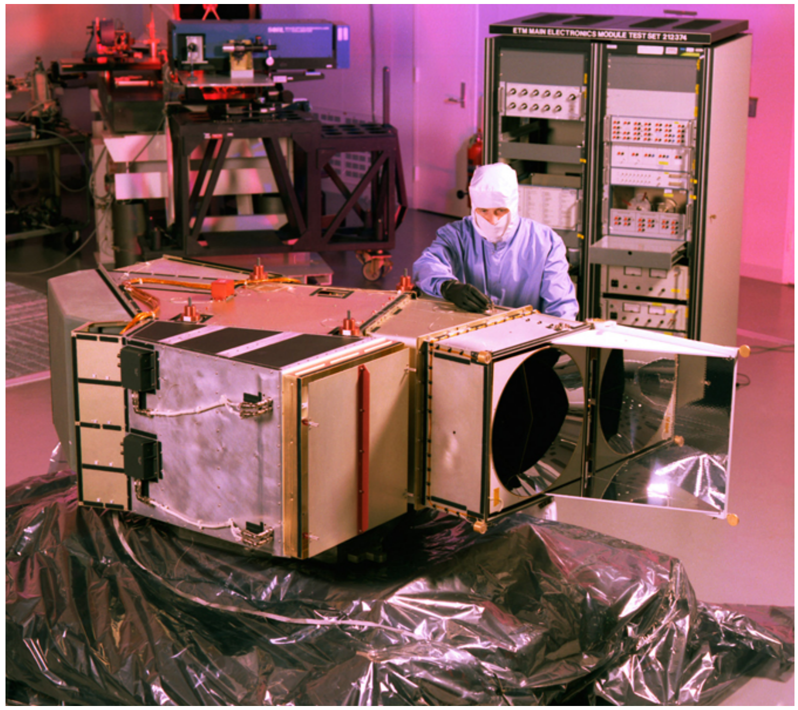
Relevant Publications and Citations

Claverie, M., Vermote, E. F., Franch, B., & Masek, J. G. (2015). Evaluation of the Landsat-5 TM and Landsat-7 ETM surface reflectance products. **Remote Sensing of Environment**, 169, 390-403. doi:10.1016/j.rse.2015.08.030

Huang, J., Tian, L., Liang, S., Ma, H., Becker-Reshef, I., Huang, Y., . . . Wu, W. (2015). Improving winter wheat yield estimation by assimilation of the leaf area index from Landsat TM and MODIS data into the WOFOST model. **Agricultural and Forest Meteorology**, 204, 106-121. doi:10.1016/j.agrformet.2015.02.001

Enhanced Thematic Mapper Plus (ETM+)

Photo Credit: Hughes Santa Barbara Remote Sensing / NASA



The Enhanced Thematic Mapper Plus (ETM+) was launched onboard the Landsat 7 satellite on April 15, 1999, and builds off the success of the Thematic Mapper (TM) flown onboard Landsats 4/5. ETM+ optics contain the Scan Mirror and Scan Line Corrector (SLC), 8-band multispectral scanning radiometer (with a spatial resolution of 30 m for bands 1-7), and 15 m spatial resolution for the panchromatic band 8. The sensor detects spectrally-filtered radiation in the visible, Near Infra-Red (NIR), Shortwave Infra-Red (SWIR), Thermal Infra-Red (TIR), and panchromatic bands in a 183 km wide swath when orbiting at a nominal altitude of 705 km. The instrument has a temporal resolution of 16 days. The primary new features on ETM+ are a panchromatic band with 15 m spatial resolution, 5% absolute radiometric calibration, and a thermal IR channel with a four-fold improvement in spatial resolution over TM. All bands can collect one of two gain settings (low or high) for increased radiometric sensitivity and dynamic range, while band 6 collects both low and high gain (bands 61 and 62, respectively) for all scenes. The ETM+ instrument has been crucial to the Landsat mission, a joint effort of the USGS and NASA.

On May 31, 2003, the SLC, which compensates for the forward motion of Landsat 7, failed. Subsequent efforts to recover the SLC were not successful. Without an operating SLC, the Enhanced Thematic Mapper Plus (ETM+) line of sight now traces a zig-zag pattern along the satellite ground track (see below). As a result, imaged area is duplicated, with width that increases toward the scene edge. All ETM+ products are processed to generate a geolocated, terrain-corrected product (L1T) in the Universal Transverse Mercator (UTM) projection cast on the WGS-84 datum at a 30-meter spatial resolution. The instrument was built by Raytheon SBRS (Santa Barbara Remote Sensing). (NASA, USGS, 2017)

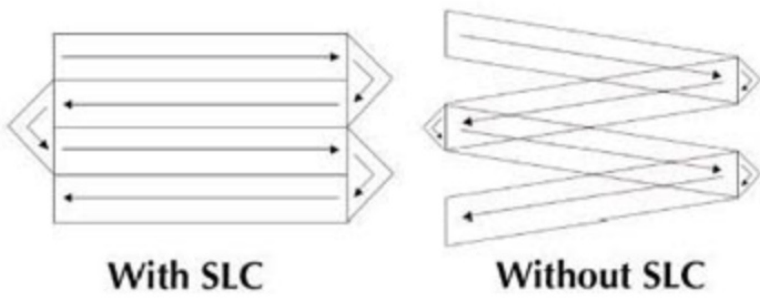


Figure showing result of SLC failure impacting the ETM+ instrument (USGS, 2017).

Data

- Science and agricultural applications include:
    - Surface Reflectance
    - Surface Temperature
    - Land Use/Land Change
    - Agriculture
    - Albedo
    - Forestry
    - Geology

- ETM+ Level 1T scenes can be obtained from USGS on EarthExplorer or the USGS Global Visualization Viewer (GloVis).

ETM+ Performance Characteristics (NASA)

Band Number	**Spectral Resolution (µm)**	**Spatial Resolution (m)**
1 – Blue	0.45-0.515	30
2 – Green	0.525-0.605	30
3 – Red	0.63-0.69	30
4 – Near Infrared	0.775-0.90	30
5 – Shortwave Infrared	1.55-1.75	30
6 – Thermal	10.4-12.5	60* (30)
7 – Shortwave Infrared	2.08-2.35	30
8 – Panchromatic	0.52-0.9	15

* ETM+ Band 6 is acquired at 60-meter resolution, but products are resampled to 30-meters.

Relevant Publications and Citations

Claverie, M., Vermote, E. F., Franch, B., & Masek, J. G. (2015). Evaluation of the Landsat-5 TM and Landsat-7 ETM surface reflectance products. **Remote Sensing of Environment**, 169, 390-403. doi:10.1016/j.rse.2015.08.030

Masek, J., Honzak, M., Goward, S., Liu, P., & Pak, E. (2001). Landsat-7 ETM as an observatory for land cover Initial radiometric and geometric comparisons with Landsat-5 Thematic Mapper [Abstract]. **Remote Sensing of Environment**, 78, 118-130. Retrieved from http://glcfapp.glcf.umd.edu/library/pdf/rse78_p118.pdf

Roy, D., Kovalskyy, V., Zhang, H., Vermote, E., Yan, L., Kumar, S., & Egorov, A. (2016). Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. **Remote Sensing of Environment**, 185, 57-70. doi:10.1016/j.rse.2015.12.024

Operational Land Imager (OLI)

Landsat 8 Operational Land Imager at factory Photo Credit: Ball Aerospace

The Operational Land Imager (OLI) is one of two instruments launched onboard the Landsat 8 satellite on February 11, 2013. The instrument collects visible, near infrared, and short-wave infrared images of the Earth with a 16-day repeat time, and an 8-day offset to ETM+ flown onboard Landsat 7. The spectral bands of the OLI instrument, while similar to the ETM+, provide enhancement from prior Landsat instruments with the addition of two new spectral bands: a deep blue visible channel (band 1) specifically designed for water resources and coastal zone investigation, and a new infrared channel (band 9) for the detection of cirrus clouds. The nine spectral bands have a spatial resolution of 30 m (15 m panchromatic band) over a 185 km swath at a nominal altitude of 705 km.

Landsat 8 Operational Land Imager at factory
Photo Credit: Ball Aerospace

OLI's design is an advancement in Landsat sensor technology and uses an approach demonstrated by the Advanced Land Imager sensor flown on NASA's experimental EO-1 satellite. Instruments on earlier Landsat satellites employed scan mirrors to sweep the instrument fields of view across the surface swath width and transmit light to a few detectors. The OLI instead uses long detector arrays, with over 7,000 detectors per spectral band, aligned across its focal plane to view across the swath. This push broom design results in a more sensitive instrument providing improved land surface information with fewer moving parts. All OLI products are processed to generate a geolocated, terrain-corrected product (L1T) in the Universal Transverse Mercator (UTM) projection cast on the WGS-84 datum at a 30-meter spatial resolution. The instrument was built by Ball Aerospace & Technologies Corporation. The OLI instrument has been crucial to the Landsat mission, a joint effort of the USGS and NASA (NASA, USGS, 2017).

<u>Data</u>

- Science and agricultural applications include:
    - Surface Reflectance
    - Land Use/Land Change
    - Agriculture
    - Albedo
    - Forestry
    - Geology

- OLI Level 1T scenes can be obtained from USGS on [EarthExplorer]() or the [USGS Global Visualization Viewer (GloVis)]().

OLI Performance Characteristics (NASA)

Band Number	**Spectral Resolution (μm)**	**Spatial Resolution (m)**
Band 1 – Coastal / Aerosol	0.433 – 0.453	30
Band 2 – Blue	0.450 – 0.515	30

Band 3 – Green	0.525 – 0.600	30
Band 4 – Red	0.630 – 0.680	30
Band 5 – Near infrared	0.845 – 0.885	30
Band 6 – Shortwave Infrared	1.560 – 1.660	30
Band 7 – Shortwave Infrared	2.100 – 2.300	30
Band 8 – Panchromatic	0.500 – 0.680	15
Band 9 – Cirrus	1.360 – 1.390	30

Relevant Publications and Citations

Irons, J. R., Dwyer, J. L., & Barsi, J. A. (2012). The next Landsat satellite: The Landsat Data Continuity Mission. **Remote Sensing of Environment**, 122, 11-21. doi:10.1016/j.rse.2011.08.026

Roy, D., Kovalskyy, V., Zhang, H., Vermote, E., Yan, L., Kumar, S., & Egorov, A. (2016). Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. **Remote Sensing of Environment**, 185, 57-70. doi:10.1016/j.rse.2015.12.024

Vermote, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. **Remote Sensing of Environment**, 185, 46-56. doi:10.1016/j.rse.2016.04.008

Thermal Infrared Sensor (TIRS)

Photo Credit: NASA/GSFC, Rebecca Roth

Thermal Infrared Sensor (TIRS) is one of two instruments launched onboard the Landsat 8 satellite on February 11, 2013. TIRS was added to the satellite mission when it became clear that state water resource managers rely on the highly accurate measurements of Earth's thermal energy obtained by Landsat 8's predecessors, Landsat 5 and Landsat 7, to track how land and water are being used. The instrument collects imagery for two thermal infrared bands (10.8 μm and 12 μm) with a spatial resolution of 100 m, with the purpose to obtain land surface temperature characteristics. It has a 185 km swath from the nominal altitude of 705 km. TIRS represents an advancement over the single-band thermal data collected by previous Landsat satellites. Similar to OLI, TIRS uses long detector arrays, with roughly 1,850 detectors per spectral band, aligned across its focal plane to view across the swath. This push broom design results in a more sensitive instrument providing improved land surface information with fewer moving parts.

Photo Credit: NASA/GSFC, Rebecca Roth

Since the launch of Landsat 8 in 2013, thermal energy from outside the normal field of view (stray light) has affected the data collected in Bands 10 and 11 of TIRS. This stray light increases the reported temperature by up to four degrees Kelvin (K) in Band 10 and up to eight K in Band 11. The errors vary throughout the scene and depend upon radiance outside the instrument field of view, which users cannot correct in the Landsat Level-1 data product. An algorithm to correct for this issue was developed and implemented into the processing system in February 2017. All TIRS products are processed to generate a geolocated, terrain-corrected product (L1T) in the Universal Transverse Mercator (UTM) projection cast on the WGS-84 datum at a 30-meter spatial resolution. The instrument was built by Ball Aerospace in Boulder, CO, and Goddard Space Flight Center. The TIRS instrument has been crucial to the Landsat mission, a joint effort of the USGS and NASA (NASA, USGS, 2017).

Data

- Science and agricultural applications include:
  - Land Surface Temperature
  - Active Fire

- OLI Level 1T scenes can be obtained from USGS on EarthExplorer or the USGS Global Visualization Viewer (GloVis).

TIRS Performance Characteristics (NASA)

Band Number	**Spectral Resolution (µm)**	**Spatial Resolution (m)**
10 – Thermal Infrared	10.60 - 11.19	100 * (30)
11 – Thermal Infrared	11.50 - 12.51	100 * (30)

* resampled to 30 meters to match multispectral bands

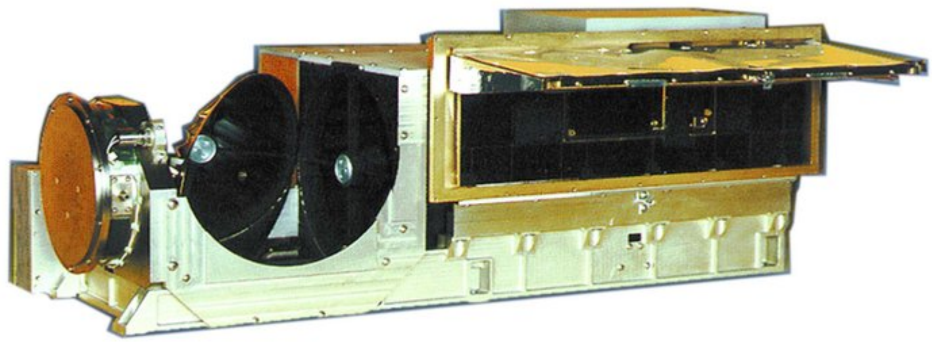
Relevant Publications and Citations

Barsi, J., Schott, J., Hook, S., Raqueno, N., Markham, B., & Radocinski, R. (2014). Landsat-8 Thermal Infrared Sensor (TIRS) Vicarious Radiometric Calibration. **Remote Sensing**, 6(12), 11607-11626. doi:10.3390/rs61111607

Reuter, D., Richardson, C., Pellerano, F., Irons, J., Allen, R., Anderson, M., . . . Thome, K. (2015). The Thermal Infrared Sensor (TIRS) on Landsat 8: Design Overview and Pre-Launch Characterization. **Remote Sensing**, 7(12), 1135-1153. doi:10.3390/rs70101135

Advanced Very High Resolution Radiometer (AVHRR)

Photo Credit: NASA/NOAA



The first Advanced Very High Resolution Radiometer (AVHRR) was a 4-channel radiometer, first carried on TIROS-N (launched October 1978). This was subsequently improved to a 5-channel instrument (AVHRR/2) that was initially carried on NOAA-7 (launched June 1981). The latest instrument version is AVHRR/3, with 6 channels, first carried on NOAA-15 launched in May 1998. The instrument is a cross-track scanning system with a twice daily temporal resolution (0230 and 1430 local solar time). Most AVHRR instruments have been integrated with NOAA's constellation of Polar Operational Environmental Satellites (POES), as well as the European Space Agency's (ESA) MetOp series of polar orbiting satellites. The instrument has provided a continuous long-term record of thermal emissions from the Earth, sea surface temperature, aerosols, and monitoring of land surfaces for almost four decades.

The instrument has a daily temporal resolution with a 1.1 km spatial resolution in all six bands. AVHRR has a 2,500 km swath and a nominal altitude of 833 or 870 km. There are three data types produced from the POES AVHRR: The Global Area Coverage (GAC), Local Area Coverage (LAC), and the High Resolution Picture Transmission (HRPT). A fourth data type, Full Resolution Area Coverage (FRAC 1.1 km) is now available daily for the entire globe with the launch of MetOp-A (ESA). Research quality data consists of daily, 5-day, 8-day, monthly, and yearly level-3 products on a 4 km global grid. The instrument was built by ITT, Aerospace/Communications Division (NOAA, NASA, 2017).

Data

- Science and agricultural applications include:
  - Agriculture
  - Forestry
  - Land Use/Land Change
  - Sea Surface Temperature
  - Snow Cover

- AVHRR data can be obtained from NOAA through the Comprehensive Large Array-Data Stewardship System (CLASS) and the USGS through Earth Explorer.

AVHRR Performance Characteristics (NOAA)

Band Number	**Spectral Resolution (μm)**	**Spatial Resolution (km)**
1 – Red	0.58 - 0.68	1.1
2 – Near Infrared	0.725 - 1.00	1.1
3A – Shortwave Infrared	1.58 - 1.64	1.1
3B – Midwave Infrared	3.55 - 3.93	1.1
4 – Thermal Infrared	10.30 - 11.30	1.1
5 – Thermal Infrared	11.50 - 12.50	1.1

Relevant Publications and Citations

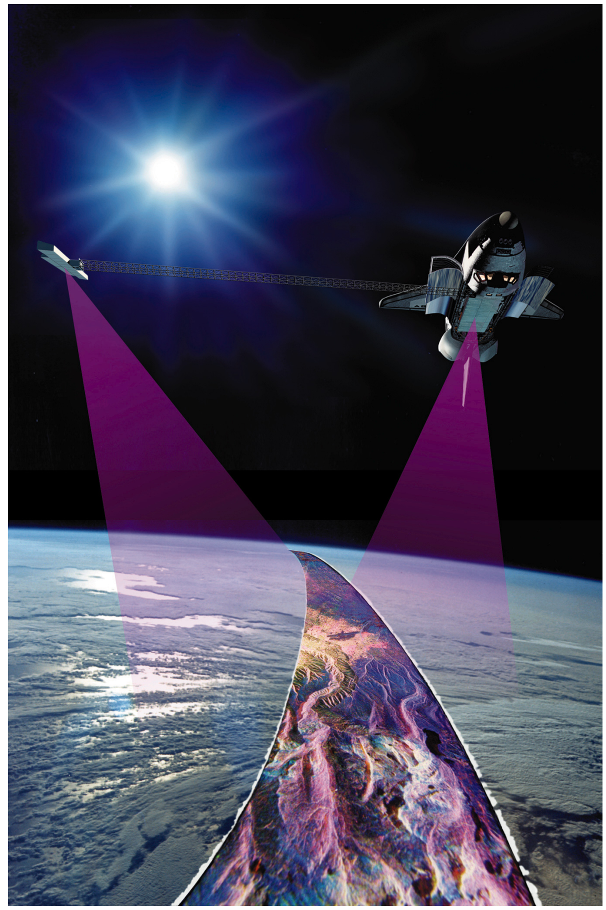
Becker-Reshef, I., Justice, C., Sullivan, M., Vermote, E., Tucker, C., Anyamba, A., . . . Doorn, B. (2010). Monitoring Global Croplands with Coarse Resolution Earth Observations: The Global Agriculture Monitoring (GLAM) Project. **Remote Sensing**, 2(12), 1589-1609. doi:10.3390/rs2061589

Franch, B., Vermote, E., Roger, J., Murphy, E., Becker-Reshef, I., Justice, C., . . . Devadiga, S. (2017). A 30 Year AVHRR Land Surface Reflectance Climate Data Record and Its Application to Wheat Yield Monitoring. **Remote Sensing**, 9(3), 296. doi:10.3390/rs9030296

Pinzon, J., & Tucker, C. (2014). A Non-Stationary 1981–2012 AVHRR NDVI3g Time Series. **Remote Sensing**, 6(12), 6929-6960. doi:10.3390/rs6086929

Shuttle Radar Topography Mission (SRTM)

Photo Credit: AEC-Able/NASA



The Shuttle Radar Topography Mission (SRTM) was flown aboard the space shuttle Endeavour February 11-22, 2000. NASA and the National Geospatial-Intelligence Agency (NGA) participated in an international project to acquire radar data which were used to create the first near-global set of land elevations. To acquire topographic (elevation) data, the SRTM payload was outfitted with two radar antennas. One antenna was located in the shuttle's payload bay, the other on the end of a 60-meter (200-foot) mast that extended from the payload bay once Endeavor was in space.

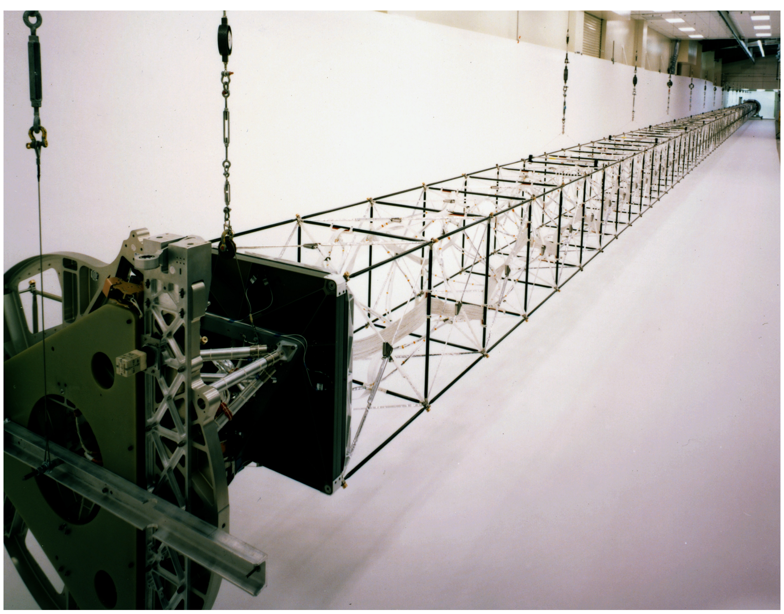


Photo Credit: AEC-Able/NASA

The radars used during the SRTM mission were actually developed and flown on two Endeavour missions in 1994. The C-band Spaceborne Imaging Radar and the X-Band Synthetic Aperture Radar (X-SAR) hardware were used on board the space shuttle in April and October 1994 to gather data about Earth's environment. The technology was modified for the SRTM mission to collect interferometric radar, which compared two radar images or signals taken at slightly different angles. This mission used single-pass interferometry, which acquired two signals at the same time by using two different radar antennas. An antenna located on board the space shuttle collected one data set and the other data set was collected by an antenna located at the end of a 60-meter mast that extended from the shuttle. Differences between the two signals allowed for the calculation of surface elevation.

Endeavour orbited Earth 16 times each day during the 11-day mission, completing 176 orbits. SRTM successfully collected radar data over 80% of the Earth's land surface between 60° north and 56° south latitude with data points posted every 1 arc-second (approximately 30 meters).

Data

- Science and agricultural applications include:
    - Elevation
    - Slope
    - Aspect
    - Runoff potential
    - Flood mapping

- SRTM data can be obtained from USGS EarthExplorer to search, preview, and download 1 arc-second global data.

SRTM Product Specifications

Projection	Geographic
Horizontal Datum	WGS84
Vertical Datum	EGM96 (Earth Gravitational Model 1996)
Vertical Units	Meters
Spatial Resolution	1-arc second for global coverage (~30 m) 3-arc seconds for global coverage (~90 m)
Tile Size	1 degree
C-band Wavelength	5.6 cm

Relevant Publications and Citations

Farr, T.G., Rosen, P.A., Caro, E., . . . Alsdorf, D. (2007). The Shuttle Radar Topography Mission. **Reviews of Geophysics**. 45 (2): doi:10.1029/2005RG000183.

NASA Jet Propulsion Laboratory (2020). Shuttle Radar Topography Mission – The Mission to Map the World. https://www2.jpl.nasa.gov/srtm/index.html

Soil Moisture Active Passive (SMAP) Radiometer

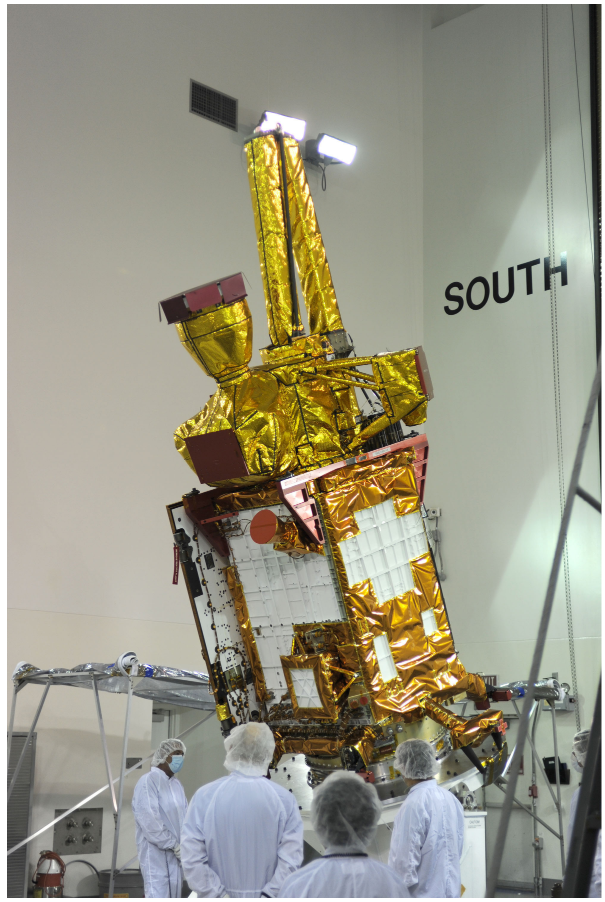


Photo Credit: Northrop Grumman/NASA

Soil Moisture Active Passive (SMAP) is a NASA satellite mission launched on January 31, 2015, measuring the amount of water in the top 5 cm (2 inches) of soil globally. SMAP carries two instruments, an active L-band radar (VV, HH, and HV polarizations) and a passive L-band radiometer (V, H, and 3rd and 4th Stokes parameter polarizations), that together make global measurements of land surface soil moisture and freeze/thaw state. The L-band frequency enables observations of soil moisture through moderate vegetation cover, independent of cloud cover and night or day. Multiple polarizations enable accurate soil moisture estimates to be made with corrections for vegetation, surface roughness, Faraday rotation, and other perturbing factors. SMAP's orbital motion combined with the spin of the antenna sweeps a small field of view in a series of overlapping loops that create a swath 1000 km (621 miles) wide. This large swath coverage allows SMAP to make complete soil moisture maps of the Earth every 2 to 3 days, with a nominal orbit of 685 km (426 miles) in a near-polar, sun-synchronous 6am/6pm, 8-day exact repeat time.

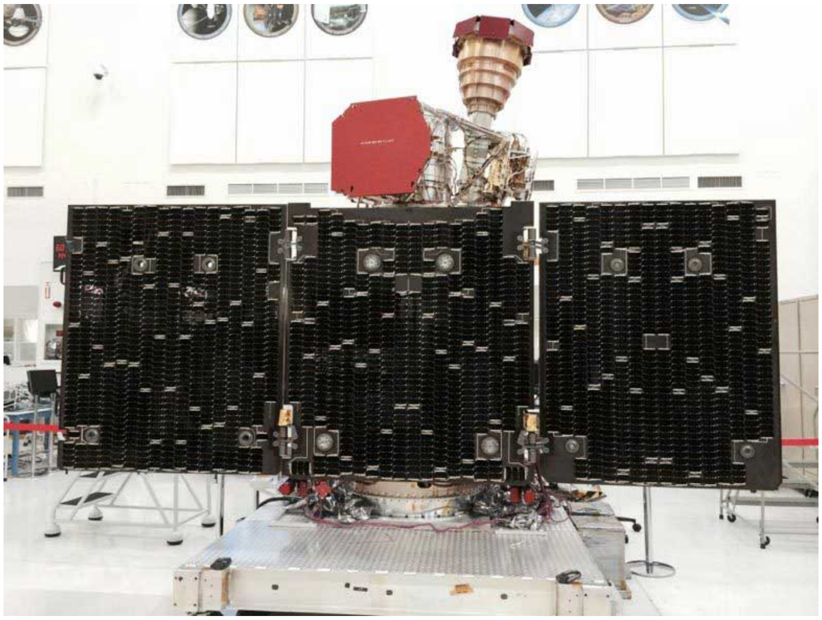


Photo Credit: NASA

The radiometer receives energy in a narrow microwave band. The 1.41 Ghz frequency has been set aside by international agreement for applications which involve only a receiver (no transmitting is allowed in that band). This allows SMAP's radiometer (and, in other frequencies, ground-based radio telescopes) to operate without interference. This frequency band also allows the radiometer to not be much affected by weather or by a moderate amount of vegetation that may cover the soil. Within this frequency band (L-band), water appears relatively 'cold' (about 100K) and dry soil appears relatively 'warm' (about 300K) to the radiometer. With this great difference between wet and dry soils, the radiometer allows SMAP to produce very high soil moisture accuracy (4%) by simply measuring the microwave 'temperature' of the land surface.

On July 7, 2015, SMAP's radar ceased operating leaving data being returned only by the passive radiometer (NASA, 2017).

<u>Data</u>

- Science and agricultural applications include:
  - Agriculture
  - Drought
  - Floods & Landslides
  - Human Health

- SMAP data can be obtained from NASA's [National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)].

SMAP Performance Characteristics (NOAA)

Channel No	**Central Frequency (Ghz)**	**Polarizations**
1	1.41	H,V, 3^{rd} & 4^{th} Stokes

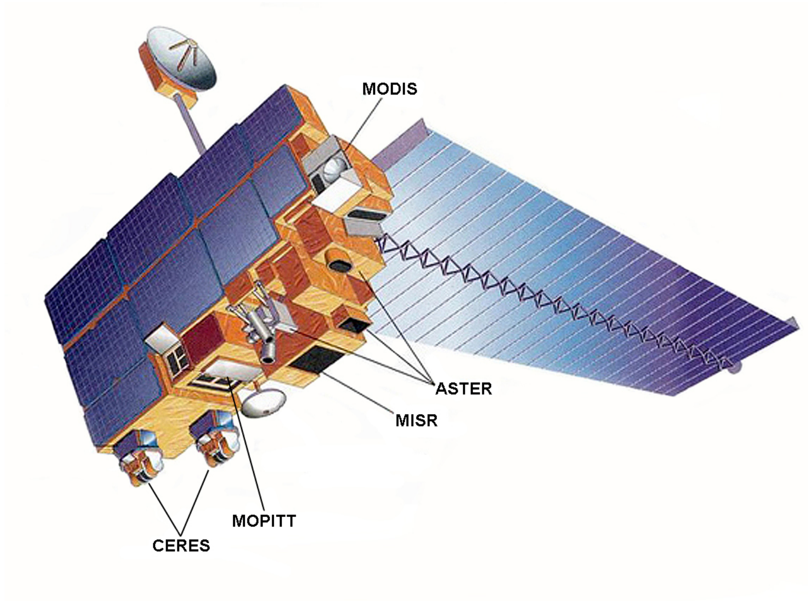
<u>Relevant Publications and Citations</u>

Burgin, M. S., Colliander, A., Njoku, E. G., Chan, S. K., Cabot, F., Kerr, Y. H., . . . Yueh, S. H. (2017). A Comparative Study of the SMAP Passive Soil Moisture Product with Existing Satellite-Based Soil Moisture Products. **IEEE Transactions on Geoscience and Remote Sensing**, 55(5), 2959-2971. doi:10.1109/tgrs.2017.2656859

Piepmeier, J. R., Focardi, P., Horgan, K. A., Knuble, J., Ehsan, N., Lucey, J., . . . Njoku, E. G. (2017). SMAP L-Band Microwave Radiometer: Instrument Design and First Year on Orbit. **IEEE Transactions on Geoscience and Remote Sensing**, 55(4), 1954-1966. doi:10.1109/tgrs.2016.2631978

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

Photo Credit: NASA



The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is one of the five instruments onboard the Terra satellite launched on December 18, 1999. The instrument has a unique combination of wide spectral coverage and high spatial resolution in the visible near-infrared through shortwave infrared to the thermal infrared regions (14 wavelengths). The instrument flies in a sun-synchronous polar orbit, at a nominal altitude of 705 km, crossing the equator in the morning at 10:30. ASTER is the only high spatial resolution instrument on the Terra platform. ASTER's ability to serve as a 'zoom' lens for the other Terra instruments is particularly important for change detection, calibration/validation, and land surface studies. Unlike the other instruments aboard Terra, ASTER will not collect data continuously; rather, it collects an average of 8 minutes of data per orbit. All three ASTER telescopes (VNIR, SWIR, and TIR) are pointable in the crosstrack direction. Given its high resolution and its ability to change viewing angles, ASTER produces stereoscopic images and detailed terrain height models.

The ASTER instrument consists of three separate instrument subsystems. Each subsystem operates in a different spectral region, has its own telescope(s), and was built by a different Japanese company. In April 2008 the SWIR started experiencing anomalous saturation of values in bands 5-9 leading to all data from this date forward being unusable. The ASTER instrument was built in Japan for the Ministry of Economy, Trade, and Industry (METI). A joint United States/Japan Science Team is responsible for instrument design, calibration, and data validation. ASTER data contributes to a wide array of global change-related application areas including vegetation and ecosystem dynamics, hazard monitoring, geology and soils, hydrology, and land cover change (NASA, USGS, 2017).

<u>Data</u>

- Science and agricultural applications include:
    - Surface Temperature

  - Land Use/Land Change
  - Agriculture
  - Disasters
  - Active Fire
  - Geology
  - Digital Elevation Models

- ASTER data can be obtained from NASA's EarthData, USGS EarthExplorer, and USGS Global Visualization Viewer (GloVis).
- The ASTER User Handbook Version 2 was prepared at the Jet Propulsion Laboratory/California Institute of Technology.

ASTER Performance Characteristics (NOAA)

Band	**Bandwidth (μm)**	**Spatial Resolution (m)**
1 – Green	0.52 - 0.60	15
2 – Red	0.63 - 0.69	15
3 – Near infrared	0.76 - 0.86 (Nadir looking)	15
3 – Near infrared	0.76 - 0.86 (Backward looking)	15
4 – Shortwave Infrared	1.600 - 1.700	30
5 – Shortwave Infrared	2.145 - 2.185	30
6 – Shortwave Infrared	2.185 - 2.225	30
7 – Shortwave Infrared	2.235 - 2.285	30
8 – Shortwave Infrared	2.295 - 2.365	30
9 – Shortwave Infrared	2.360 - 2.430	30
10 – Thermal Infrared	8.125 - 8.475	90
11 – Thermal Infrared	8.475 - 8.825	90
12 – Thermal Infrared	8.925 - 9.275	90
13 – Thermal Infrared	10.25 - 10.95	90
14 – Thermal Infrared	10.95 - 11.65	90

Relevant Publications and Citations

Jacob, F., Petitcolin, F., Schmugge, T., Vermote, É, French, A., & Ogawa, K. (2004). Comparison of land surface emissivity and radiometric temperature derived from MODIS and ASTER sensors. Remote Sensing of Environment, 90(2), 137-152. doi:10.1016/j.rse.2003.11.015

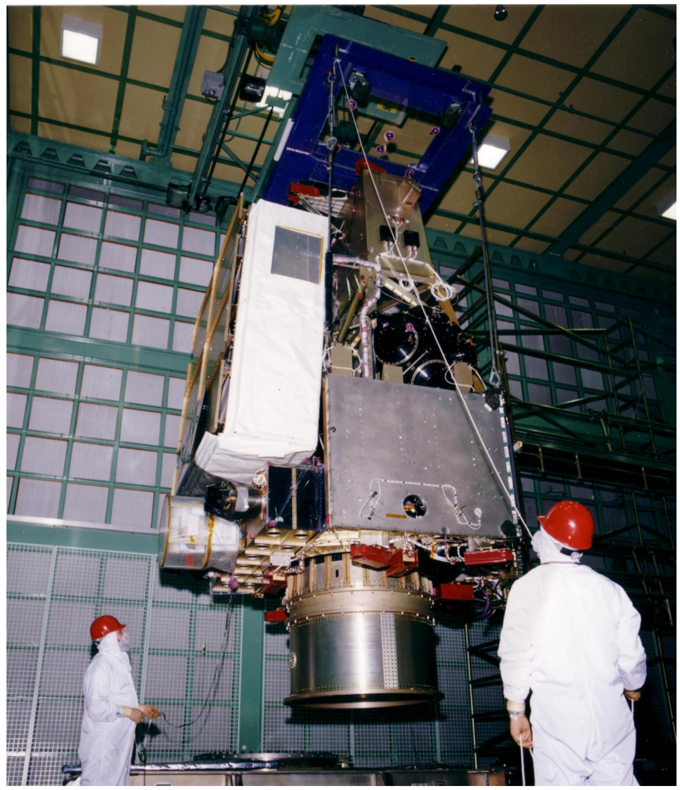
Leslie, C.R., Serbina, L.O., & Miller, H.M. (2017). Landsat and Agriculture—Case Studies on the Uses and Benefits of Landsat Imagery in Agricultural Monitoring and Production. U.S. Geological Survey Open-File Report. https://pubs.usgs.gov/of/2017/1034/ofr20171034.pdf

Schroeder, W., Prins, E., Giglio, L., Csiszar, I., Schmidt, C., Morisette, J., & Morton, D. (2008). Validation of GOES and MODIS active fire detection products using ASTER and ETM data. Remote Sensing of Environment, 112(5), 2711-2726. doi:10.1016/j.rse.2008.01.005

Serbin, G., Hunt, E. R., Daughtry, C. S., McCarty, G., & Doraiswamy, P. (2009). An Improved ASTER Index for Remote Sensing of Crop Residue. Remote Sensing, 1(4), 971-991. doi:10.3390/rs1040971

TRMM Microwave Imager (TMI)

Photo Credit: NASA GSFC



The Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) was a passive microwave sensor built by BSS (Boeing Satellite Systems) to provide quantitative rainfall information over a 547-mile (878-kilometer) wide swath on the surface. TMI consists of nine separate total-power radiometers, each simultaneously measuring the microwave emission coming from the Earth's surface with the intervening atmosphere. This, combined with the wide swath and the good, quantitative information regarding rainfall make TMI the "workhorse" of the rain-measuring package on TRMM. TRMM was a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) and was based on the design of the highly successful Special Sensor Microwave/Imager (SSM/I), which has been flying continuously on Defense Meteorological Satellites since 1987. TMI was one of five instruments onboard the TRMM platform.

TMI employs an offset parabolic reflector (with an antenna aperture size of 61 cm) to collect the microwave radiation. The reflector focuses the radiation into two feedhorns (at 10.7 the other for the 19-85 GHz). The reflector and feedhorns spin as a unit every 1.9 seconds about an axis parallel to the S/X nadir direction. During each scan, the 10.7-37 GHz observations are sampled 104 times over the 130° arc. The 85.5 GHz observations are at a higher spatial resolution and are sampled at 208 observations/scan. TMI flew in a non-sun-synchronous near-circular orbit at an inclination of 35° to observe coverage of the tropics, since the volume of rainfall in the tropics accounts for about two-thirds of the total rainfall on the earth (NASA, ESA, 2018).

<u>Data</u>

- Science and agricultural applications include:
    - Precipitation
    - Sea Surface Temperature
    - Wind Speed

- Columnar Water Vapor
- Landslides
- Floods
- Soil Moisture
- Agriculture

- NASA TMI Precipitation Products can be obtained from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC), located in Greenbelt, MD.

TMI Performance Characteristics

Channel No	**Central Frequency (Ghz)**	**Bandwidth (MHz)**	**Polarization**	**IFOV (km x km)**	**Samples/ scan**
1	10.7	100	V, H	63 x 37	104
2	10.7	100	V, H	63 x 37	104
3	19.4	500	V, H	30 x 18	104
4	19.4	500	V, H	30 x 18	104
5	21.3	200	V	23 x 18	104
6	37	2000	V, H	16 x 9	104
7	37	2000	V, H	16 x 9	104
8	85.5	3000	V, H	7 x 5	104
9	85.5	3000	V, H	7 x 5	208

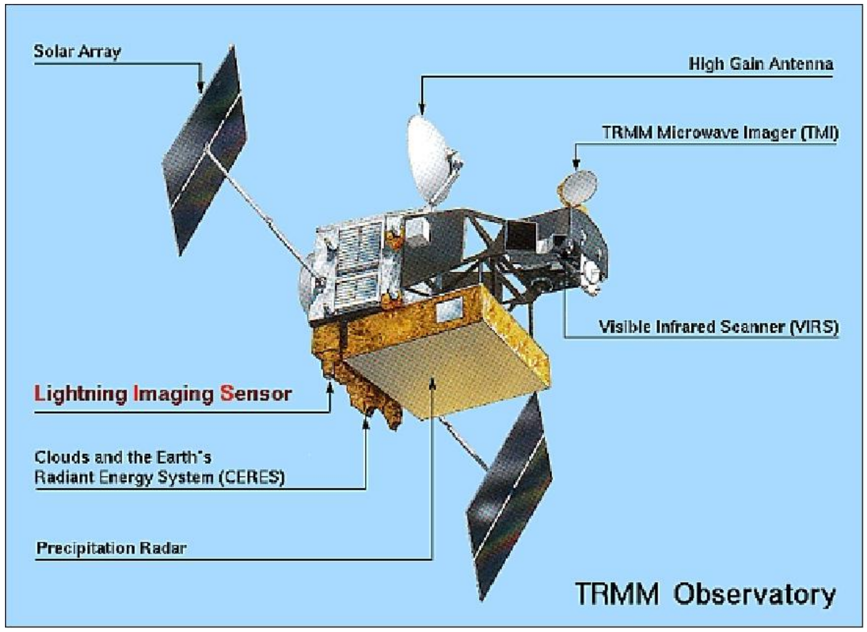
Relevant Publications and Citations

Huffman, G. J., R. F. Adler, B. Rudolf, U. Schneider, and P. R. Keehn, 1995: Global Precipitation Estimates Based on a Technique for Combining Satellite-Based Estimates, Rain Gauge Analysis, and NWP Model Precipitation Information. **J. Climate**, 8, 1284-1295, doi:10.1175/1520-0442(1995)008<1284:GPEBOA>2.0.CO;2.

Carr, N., P. E. Kirstetter, Y. Hong, J. J. Gourley, M. Schwaller, W. Petersen, N. Y. Wang, R. Ferraro, and X. Xue, 2015: The Influence of Surface and Precipitation Characteristics on TRMM Microwave Imager Rainfall Retrieval Uncertainty. **J. Hydrometeor**., 16, 1596–1614, doi:10.1175/JHM-D-14-0194.1.

Precipitation Radar (PR)

Image Credit: UCB



The Tropical Rainfall Measuring Mission's (TRMM) Precipitation Radar (PR) was the first spaceborne instrument designed to provide three-dimensional maps of storm structure. The Precipitation Radar has a horizontal resolution at the ground of about 3.1 miles (five kilometers) and a swath width of 154 miles (247 kilometers). One of its most important features is its ability to provide vertical profiles of the rain and snow from the surface up to a height of about 12 miles (20 kilometers). PR is able to detect fairly light rain rates down to about .027 inches (0.7 millimeters) per hour. At intense rain rates, where the attenuation effects can be strong, new methods of data processing have been developed that help correct for this effect. The Precipitation Radar is able to separate out rain echoes for vertical sample sizes of about 820 feet (250 meters) when looking straight down. It carries out all these measurements while using only 224 watts of electric power—the power of just a few household light bulbs. The objective of PR is to provide a 3-D rainfall distribution over land and oceans (combined with the TMI sensor). PR was built by the Japan Aerospace Exploration Agency (JAXA) as part of its contribution to the joint US/Japan TRMM mission (NASA, ESA, 2018).

<u>Data</u>

- Science and agricultural applications include:
    - Precipitation
    - Landslides
    - Floods
    - Soil Moisture
    - Agriculture

- NASA TMI Precipitation Products can be obtained from the NASA [Goddard Earth Sciences (GES) Data and Information Services Center (DISC)](), located in Greenbelt, MD.

TMI Performance Characteristics

Item	Value	Item	Value
Frequency	13.796 and 13.802 GHz	Antenna Type - Beam Width - Aperture - Scan Angle - Samples Cross-Track - Samples Vertically	128 element WG planar array 0.71° x 0.71° 2.0 m x 2.0 m ±17° (cross track scan) 49 80
Sensitivity	≤ 0.7 mm/h	Transmitter/Receiver - Peak Power - Pulse Width - PRF	SSPA &LNA (128 channels) ≥ 500 W (antenna input) 1.6 μs x 2 channel 2776 Hz
Swath Width	215 km	Dynamic Range	≥ 70 dB
Observable Range	Surface to 15 km	N_S (No of independent samples)	64
Horizontal Resolution	4.3 km (nadir)	Data Rate	93.2 Kbit/s
Range Resolution	250 m (nadir)	Instrument Mass, Power	465 kg (max), 250 W (max)

Relevant Publications and Citations

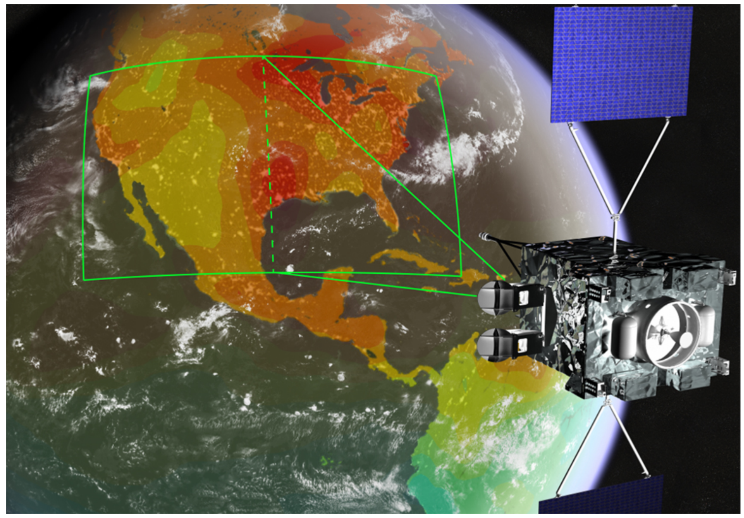
Huffman, G. J., R. F. Adler, B. Rudolf, U. Schneider, and P. R. Keehn, 1995: Global Precipitation Estimates Based on a Technique for Combining Satellite-Based Estimates, Rain Gauge Analysis, and NWP Model Precipitation Information. **J. Climate**, 8, 1284-1295, doi:10.1175/1520-0442(1995)008<1284:GPEBOA>2.0.CO;2.

Gebremichael, M., W. F Krajewski, T. M Over, Y. N. Takayabu, P. Arkin, and M. Katayama, 2008: Scaling of tropical rainfall as observed by TRMM precipitation radar. **Atmos. Res.**, 88, 337-354, doi:10.1016/j.atmosres.2007.11.028.

FUTURE NASA MISSIONS

Geostationary Carbon Cycle Observatory (GeoCARB)

Artist's rendition of GeoCARB
Image Credit: NASA



NASA has selected a first-of-its-kind Earth science mission that will extend our nation's lead in measuring key greenhouse gases and vegetation health from space to advance our understanding of Earth's natural exchanges of carbon between the land, atmosphere, and ocean. The Geostationary Carbon Observatory (GeoCarb), targeted for launch in the early 2020s, will build on the success of NASA's Orbiting Carbon Observatory-2 (OCO-2) mission by placing a similar instrument on a commercial SES-Government Solutions communications satellite flying in geostationary orbit. Perched 22,236 miles (35,800 kilometers) above the Americas, GeoCarb will collect 10 million daily observations of the concentrations of carbon dioxide, methane, carbon monoxide, and solar-induced fluorescence (SIF) at a spatial resolution of about 3 to 6 miles (5 to 10 kilometers). The primary goals of GeoCARB, led by Berrien Moore of the University of Oklahoma in Norman, are to monitor plant health and vegetation stress throughout the Americas, and to probe, in unprecedented detail, the natural sources, sinks, and exchange processes that control carbon dioxide, carbon monoxide, and methane in the atmosphere.

The GeoCarb instrument views reflected light from Earth through a narrow slit. When the slit is projected onto Earth's surface, it sees an area measuring about 1,740 miles (2,800 kilometers) from north to south and about 3.7 miles (6 kilometers) from east to west. GeoCarb stares at that area for about 4-1/2 seconds, then the slit is moved half a slit width – 1.9 miles, or 3 kilometers – to the west, allowing for double sampling. With this technique, GeoCarb can scan the entire continental United States in about 2-1/4 hours, and from Brazil to South America's West Coast in about 2-3/4 hours. It is not designed to observe the oceans, as reflectivity over the oceans is too low to provide useful data.

Operational Land Imager 2 (OLI-2)

Landsat 9 Operational Land Imager 2
Photo Credit: Ball Aerospace

The Ball Aerospace & Technologies Corporation is building Landsat 9's Operational Land Imager 2 (OLI-2). OLI-2 will take measurements in the visible, near infrared, and shortwave infrared portions of the electromagnetic spectrum. The spatial resolution of its images will be 15 m (49 ft) for the panchromatic band and 30 m (98 ft) for the multispectral bands. The image swath will be 185 km (115 mi) wide, covering wide areas of the Earth's landscape while providing sufficient resolution to distinguish land cover features like urban centers, farms, and forests. Landsat 9's near-polar orbit precesses at the same rate the Earth rotates around the sun, allowing the entire Earth to fall within view every 16 days at the same local solar time.

The OLI-2 design is a copy of Landsat 8's OLI. The OLI-2 instrument will provide visible and near infrared/shortwave infrared (VNIR/SWIR) imagery consistent with previous Landsat spectral, spatial, radiometric, and geometric qualities. A difference, however, is that Landsat 9 will downlink all 14 bits of data produced by OLI-2, providing a greater bit depth for its imagery as compared to the 12-bit data downlinked from Landsat 8's OLI. An impact of this change is that OLI-2 will provide additional, useful information for dark targets (e.g. dense forests).

OLI-2 will provide both internal calibration sources to ensure radiometric accuracy and stability, as well as the ability to perform solar and lunar calibrations (NASA, USGS, 2017).

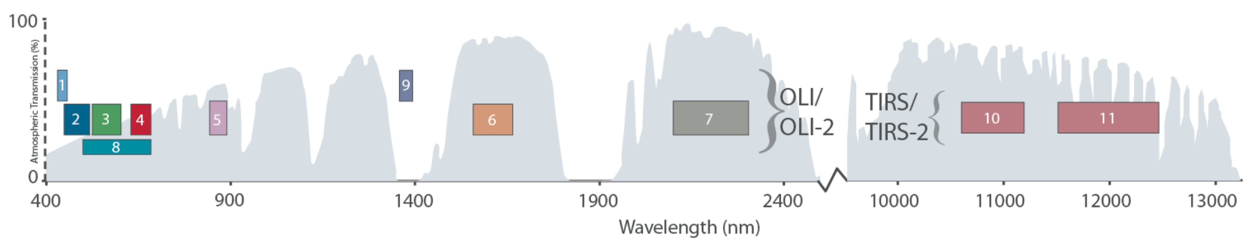
<u>Data</u>

- Science and agricultural applications include:
  - Surface Reflectance
  - Land Use/Land Change
  - Agriculture

- Albedo
- Forestry
- Geology

OLI-2 Performance Characteristics (NASA)

Band Number	**Spectral Resolution (μm)**	**Spatial Resolution (m)**
Band 1 – Coastal / Aerosol	0.433 – 0.453	30
Band 2 – Blue	0.450 – 0.515	30
Band 3 – Green	0.525 – 0.600	30
Band 4 – Red	0.630 – 0.680	30
Band 5 – Near infrared	0.845 – 0.885	30
Band 6 – Shortwave Infrared	1.560 – 1.660	30
Band 7 – Shortwave Infrared	2.100 – 2.300	30
Band 8 – Panchromatic	0.500 – 0.680	15
Band 9 – Cirrus	1.360 – 1.390	30



Thermal Infrared Sensor 2 (TIRS-2)

Landsat 9 Thermal Infrared Sensor 2 sensor inside thermal vacuum chamber at GSFC
Photo Credit: NASA/GSFC

Landsat 9's Thermal Infrared Sensor 2 (TIRS-2) will measure land surface temperature in two thermal infrared bands (10.8 μm and 12 μm) using the same technology that was used for TIRS on Landsat 8, which uses principles of quantum physics to measure emissions of infrared energy.

TIRS-2 will be an improved version of Landsat 8's TIRS, both with regards to instrument class and stray light reduction. However, both the design and specs for TIRS-2 will remain closely aligned with that of TIRS.

The TIRS-2 instrument will be a two-band thermal imaging sensor that will provide imagery consistent with Landsat 8 thermal, spectral, spatial, radiometric, and geometric qualities to enable consistent retrieval of surface temperature.

TIRS-2 will provide two spectral bands with a maximum ground sampling distance, both in-track and cross track, of 100 m (328 ft) for both bands. TIRS-2 provides an internal blackbody calibration source as well as space view capabilities (NASA, USGS, 2017).

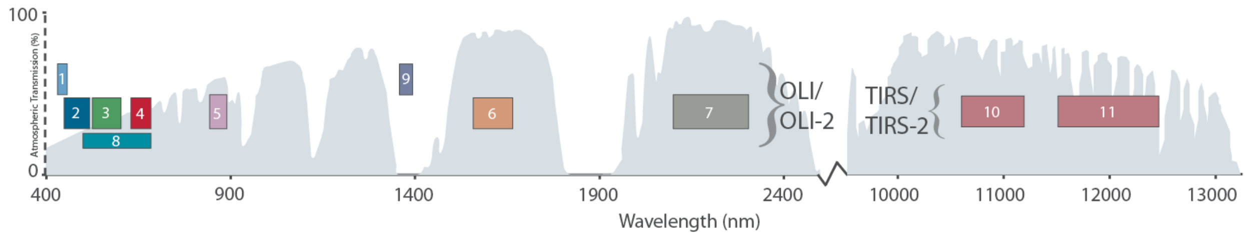
<u>Data</u>

- Science and agricultural applications include:
    - Land Surface Temperature
    - Active Fire

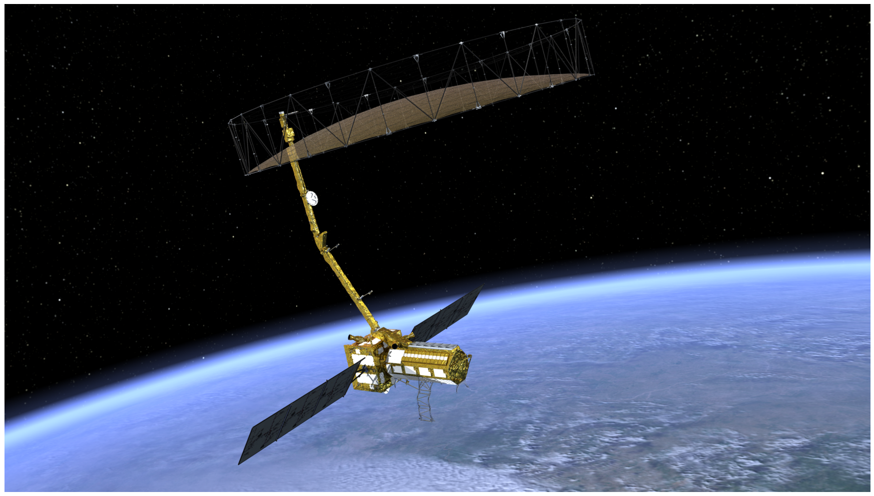
TIRS-2 Performance Characteristics (NASA)

Band Number	**Spectral Resolution (μm)**	**Spatial Resolution (m)**

10 – Thermal Infrared	10.60 - 11.19	100
11 – Thermal Infrared	11.50 - 12.51	100



NASA-ISRO Synthetic Aperture Radar (NISAR)



Artist's rendition of NISAR
Image Credit: NASA

The NASA-ISRO Synthetic Aperture Radar, or NISAR, satellite is designed to observe and take measurements of some of the planet's most complex processes, including ecosystem disturbances, ice-sheet collapse, and natural hazards such as earthquakes, tsunamis, volcanoes, and landslides. The mission is a partnership between NASA and the Indian Space Research Organization (ISRO).

NISAR will be the first satellite mission to use two different radar frequencies (L-band and S-band) to measure changes in our planet's surface less than a centimeter across. This allows the mission to observe a wide range of changes, from the flow rates of glaciers and ice sheets to the dynamics of earthquakes and volcanoes. Under the terms of the new agreement, NASA will provide the mission's L-band SAR (Synthetic Aperture Radar), a high-rate communication subsystem for science data, GPS receivers, a solid state recorder, and a payload data subsystem. ISRO will provide the spacecraft bus, an S-band SAR, and the launch vehicle and associated launch services. The launch of NISAR is targeted in 2021.

NISAR will provide maps of developing crop area on a global basis every two weeks. Observations will be uninterrupted by weather and provide up-to-date information on the large-scale trends that affect international food security. The structures of different crop and land cover types provide a rich variety of responses to radar illumination in terms of varying polarization and frequency signatures. Because of the rapid, time-varying nature of crop rotation, growth, and harvest, frequently repeated radar observations can be used to determine both the type of crop and its stage of growth. Information like this is used to predict the health of the region's crops and the planned agricultural output (NASA, ESA, 2018).

Scientific Instruments

- L-band (24-centimeter wavelength) Polarimetric Synthetic Aperture Radar
- S-band (12-centimeter wavelength) Polarimetric Synthetic Aperture Radar

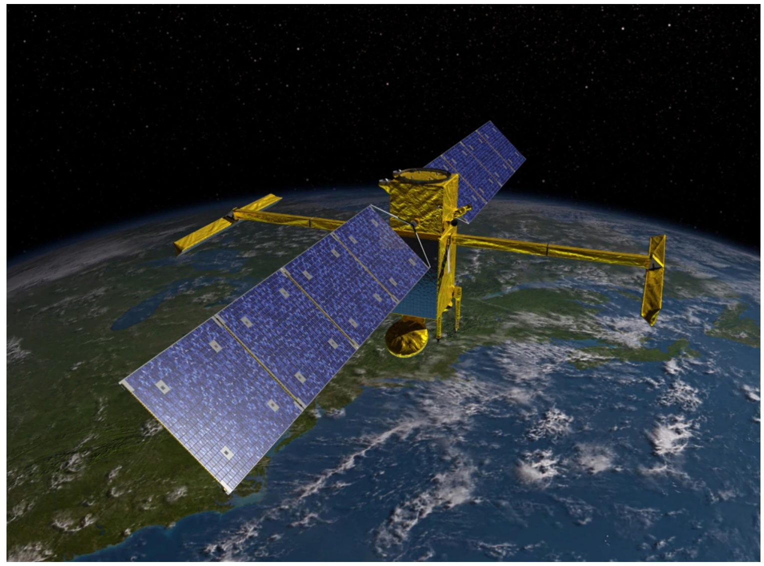
Data

- Science and agricultural applications include:
    - Land Use/Land Change
    - Agriculture
    - Drought
    - Flooding
    - Forestry
    - Geology

NISAR Characteristic:	**Enables:**
L-band (24 cm wavelength)	Foliage penetration and interferometric persistence
S-band (12 cm wavelength)	Sensitivity to light vegetation
SweepSAR technique with Imaging Swath > 240 km	Global data collection
Polarimetry (Single/Dual/Quad)	Surface characterization and biomass estimation
12-day exact repeat	Rapid sampling
3 – 10 meters mode-dependent SAR resolution	Small-scale observations
3 years science operations (5 years consumables)	Time-series analysis
Pointing control < 273 arcseconds	Deformation interferometry
Orbit control < 350 meters	Deformation interferometry
> 30% observation duty cycle	Complete land/ice coverage
Left/Right pointing capability	Polar coverage, north and south

Surface Water Ocean Topography (SWOT)

Artist's rendition of SWOT
Image Credit: NASA



The Surface Water Ocean Topography (SWOT) mission is a proposed NASA mission to make the first global survey of Earth's surface water. SWOT is being developed by an international group of hydrologists and oceanographers to provide a better understanding of the world's oceans and its terrestrial surface waters. It will give scientists their first comprehensive view of Earth's freshwater bodies from space and much more detailed measurements of the ocean surface than ever before.

SWOT is a collaboration between NASA and the French space agency, CNES. It builds on the very successful 25-year partnership between the two agencies to use radar altimetry to measure the surface of the ocean. This partnership began with the TOPEX/Poseidon mission.

The SWOT mission is based on a new type of radar called Ka-band radar interferometry. The satellite will fly two radar antennae at either end of a 10-meter (33-foot) mast, allowing it to measure the elevation of the surface along a 120-kilometer (75-mile) wide swath below. The new radar system is smaller but similar to the one that flew on NASA's Shuttle Radar Topography Mission (SRTM), which made high-resolution measurements of Earth's land surface in 2000 (NASA, ESA, 2018).

Instruments:
1. Ka- or Ku-Band Radar
2. Ku-Band Altimeter
3. MWR (Microwave Radiometer)

Science Goals:
- Provide sea surface heights (SSH) and terrestrial water heights over a 120 km wide swath with a +/-10 km gap at the nadir track.
- Over the deep oceans, provide SSH within each swath with a posting every 2 km x 2 km, and a precision not to exceed 0.5 cm when averaged over the area.
- Over land, download the raw data for ground processing and produce a water mask able to resolve 100-m rivers and 1-km2 lakes, wetlands, or reservoirs.

Associated with this mask will be water level elevations with an accuracy of 10 cm and a slope accuracy of 1 cm/1 km.

- Cover at least 90 percent of the globe. Gaps are not to exceed 10 percent of Earth's surface.

Data

- Science and agricultural applications include:
  - Water Management
  - Reservoirs
  - Drought
  - Flooding
  - Fisheries
  - Agriculture