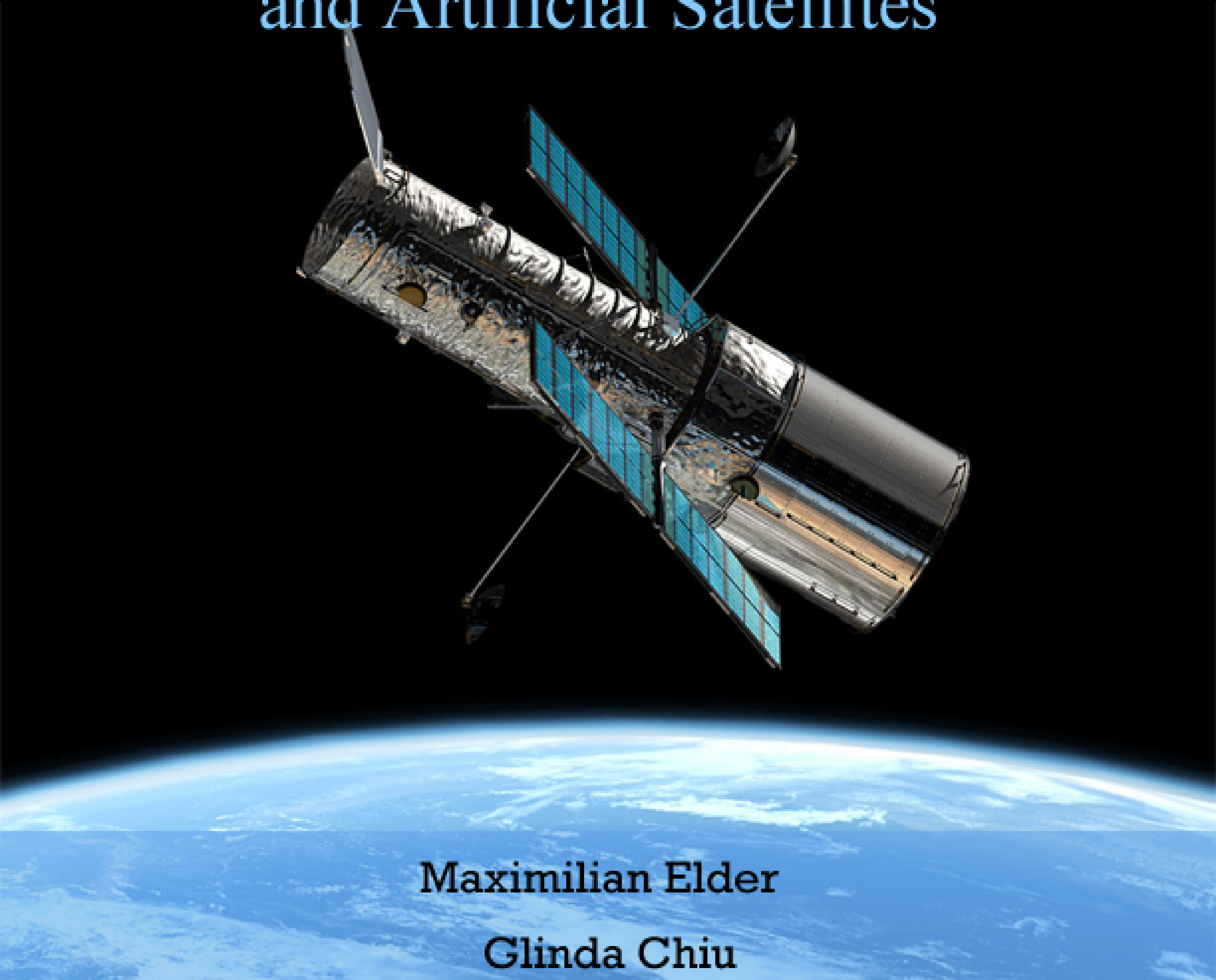
Handbook of

Space Telescopes, Observatories and Artificial Satellites



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Chapter 1

Compton Gamma Ray Observatory

Compton Gamma Ray Observatory

General information

NSSDC ID	1991-027B
Organization	NASA
Major contractors	TRW
Launch date	5 April 1991
Launched from	Kennedy Space Center
Launch vehicle	Space Shuttle *Atlantis* STS-37
Mission length	9 years, 2 months
Deorbited	4 June 2000
Mass	17,000 kg (37,000 lb)

Orbit height	450 km (280 mi)
Orbit period	90 min (1.5 h)
Telescope style	Scintillation detectors
Wavelength	Gamma
Diameter	N/A
Collecting area	Varies by instrument
Focal length	N/A
	Instruments
BATSE	all-sky monitor
OSSE	pointed detectors
COMPTEL	imaging telescope
EGRET	wide field telescope
Website	NASA Compton Gamma Ray Observatory

The **Compton Gamma Ray Observatory** (**CGRO**) was the second of the NASA "Great Observatories" to be launched to space, following the Hubble Space Telescope. CGRO was named after Dr. Arthur Holly Compton (Washington University in St. Louis), Nobel prize winner, for work involved with gamma ray physics. CGRO was built by TRW (now Northrop Grumman Aerospace Systems) in Redondo Beach, CA. Following 14 years of effort, the observatory was launched on the Space Shuttle *Atlantis*, mission STS-37, on 5 April 1991 and operated until its deorbit on 4 June 2000. It was deployed in low earth orbit at 450 km (280 miles) to avoid the Van Allen radiation belt. It was the heaviest astrophysical payload ever flown at that time at 17,000 kilograms (37,000 lb).

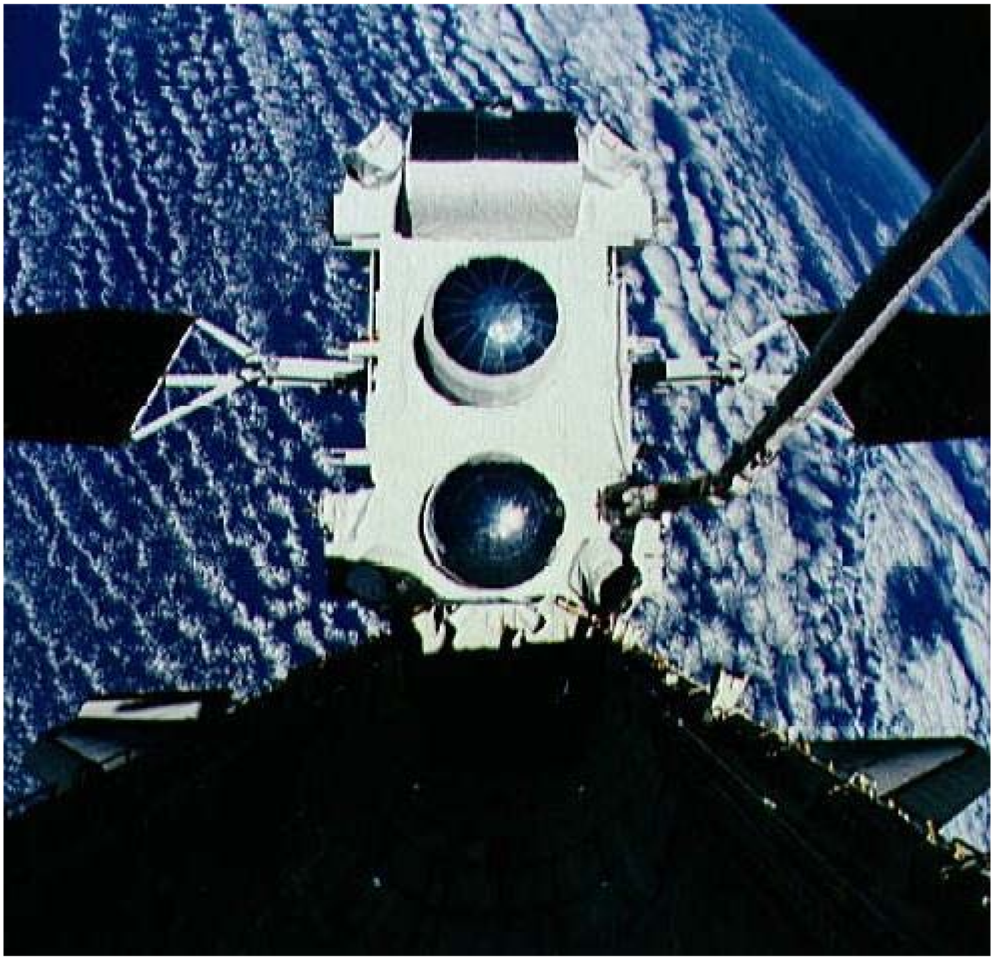
The CGRO is part of NASA's Great Observatories series, with the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

Instruments

CGRO carried a complement of four instruments that covered an unprecedented six decades of the electromagnetic spectrum, from 20 keV to 30 GeV. In order of increasing spectral energy coverage:

BATSE

- The **Burst and Transient Source Experiment**, (**BATSE**) by NASA's Marshall Space Flight Center searched the sky for short duration gamma ray bursts (20 to >600 keV) and conducted full sky surveys for long-lived sources. It consisted of eight identical detector modules, one at each of the satellite's corners (left, right; front and back; top and bottom). Each module consisted of both a NaI(Tl) Large Area Detector (LAD) covering the 20 keV to ~2 MeV range, 50.48 cm in dia by 1.27 cm thick, and a 12.7 cm dia by 7.62 cm thick NaI Spectroscopy Detector, which extended the upper energy range to 8 MeV, all surrounded by a plastic scintillator in active anti-coincidence to veto the large background rates due to cosmic rays and trapped radiation. Sudden increases in the LAD rates triggered a high-speed data storage mode, the details of the burst being read out to telemetry later. Bursts were typically detected at rates of roughly one per day over the 9-year CGRO mission. A strong burst could result in the observation of many thousands of gamma rays within a time interval ranging from ~0.1 s up to about 100 s.



The Compton Gamma Ray Observatory during deployment from STS-37

OSSE

- The **Oriented Scintillation Spectrometer Experiment**, (**OSSE**), by the Naval Research Laboratory detected gamma rays entering the field of view of any of four detector modules, which could be pointed individually, and were effective in the 0.05 to 10 MeV range. Each detector had a central scintillation spectrometer crystal of NaI(Tl) 12 in (303 mm) in diameter, by 4 in (102 mm) thick, optically coupled at the rear to a 3 in (76.2 mm) thick CsI(Na) crystal of similar diameter, viewed by seven photomultiplier tubes, operated as a phoswich: ie, particle and gamma-ray events from the rear produced slow-rise time (~1 μs) pulses, which could be electronically distinguished from pure NaI events from the front, which produced faster (~0.25 μs) pulses. Thus the CsI backing crystal acted as an active anticoncidence shield, vetoing events from the rear. A further barrel-shaped CsI shield, also in electronic anticoincidence, surrounded the central detector on the sides and provided coarse collimation, rejecting gamma rays and charged particles from the sides or most of the forward field-of-view (FOV). A finder level of angular collimation was provided by a tungston slat collimator grid within the outer CsI barrel, which collimated the response to a 3.8° x 11.4° FWHM rectangular FOV. A plastic scintillator across the front of each module vetoed charged particles entering from the front. The four detectors were typically operated in pairs of two. During a gamma-ray source observation, one detector would take observations of the source, while the other would slew slightly off source to measure the background levels. The two detectors would routinely switch roles, allowing for more accurate measurements of both the source and background. The instruments could slew with a speed of approximately 2 degrees per second.

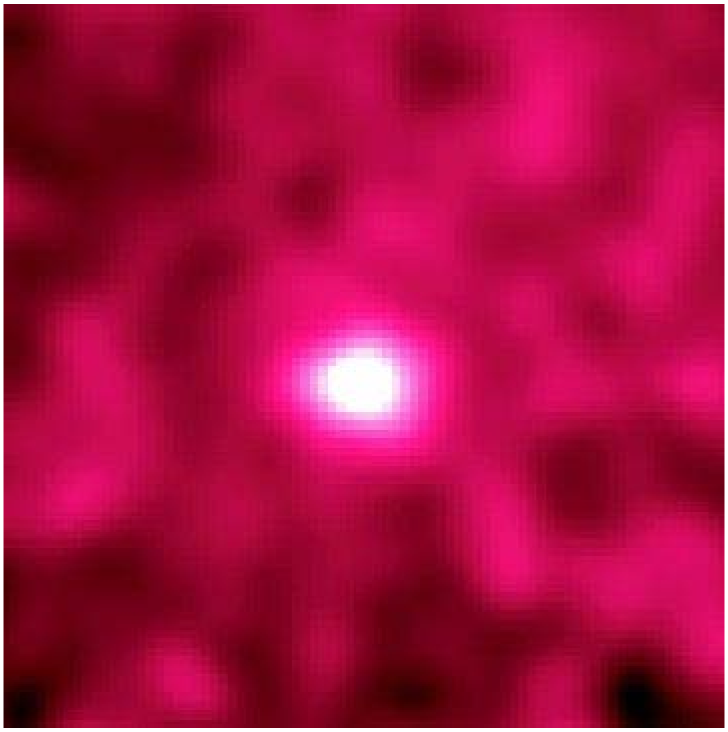
COMPTEL

- The **Imaging Compton Telescope**, (**COMPTEL**) by the Max Planck Institute for Extraterrestrial Physics, the University of New Hampshire, Netherlands Institute for Space Research, and ESA's Astrophysics Division was tuned to the 0.75-30 MeV energy range and determined the angle of arrival of photons to within a degree and the energy to within five percent at higher energies. The instrument had a field of view of one steradian. For cosmic gamma-ray events, the experiment required two nearly simultaneous interactions, in a set of front and rear scintillators. Gamma rays would Compton scatter in a forward detector module, where the interaction energy E_1, given to the recoil electron was measured, while the Compton scattered photon would then be caught in one of a second layer of scintillators to the rear, where its total energy, E_2, would be measured. From these two energies, E_1 and E_2, the Compton scattering angle, angle θ, can be determined, along with the total energy, $E_1 + E_2$, of the incident photon. The positions of the interactions, in both the front and rear scintillators, was also measured. The vector, **V**, connecting the two interaction points determined a direction to the sky, and the angle θ about this direction, defined a cone about **V** on which the source of the photon must lie, and a corresponding "event circle" on the sky. Because of the requirement for a near coincidence between the two interactions, with the correct delay of a few nanoseconds, most modes of background production were strongly suppressed. From the collection of many event energies and event circles, a map of the positions of sources, along with their photon fluxes and spectra, could be determined.

EGRET

- The **Energetic Gamma Ray Experiment Telescope**, (**EGRET**) measured high energy (20 MeV to 30 GeV) gamma ray source positions to a fraction of a degree and photon energy to within 15 percent. EGRET was developed by NASA Goddard Space Flight Center, the Max Planck Institute for Extraterrestrial Physics, and Stanford University. Its detector operated on the principle of electron-positron pair production from high energy photons interacting in the detector. The tracks of the high-energy electron and positron created were measured within the detector volume,and the axis of the *V* of the two emerging particles projected to the sky. Finally, their total energy was measured in a large calorimeter scintillation detector at the rear of the instrument.

Results



The Moon as seen by the Compton Gamma Ray Observatory, in gamma rays of greater than 20 MeV. These are produced by cosmic ray bombardment of its surface. The Sun, which has no similar surface of high atomic number to act as target for cosmic rays, cannot be seen at all at these energies, which are too high to emerge from primary nuclear reactions, such as solar nuclear fusion.

Basic results

- The EGRET instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources, 170 of which were unidentified.
- The COMPTEL instrument completed an all sky map of ^{26}Al (a radioactive isotope of aluminum).
- The OSSE instrument completed the most comprehensive survey of the galactic center, and discovered a possible antimatter "cloud" above the center.
- The BATSE instrument averaged one gamma ray burst event detection per day for a total of approximately 2700 detections. It definitively showed that the majority of gamma-ray bursts must originate in distant galaxies, not nearby in our own Milky Way, and therefore must be enormously energetic.
- The discovery of the first four soft gamma ray repeaters; these sources were relatively weak, mostly below 100 keV and had unpredictable periods of activity and inactivity
- The separation of GRBs into two time profiles: short duration GRBs that last less than 2 seconds, and long duration GRBs that last longer than this.

GRB 990123

Gamma ray burst 990123 (23 January 1999) was one of the brightest bursts recorded at the time, and was the first GRB with an optical afterglow observed during the prompt gamma ray emission (a reverse shock flash). This allowed astronomers to measure a redshift of 1.6 and a distance of 4.5 Gpc (15 Gly). Combining the measured energy of the burst in gamma-rays and the distance, the total emitted energy assuming an isotropic explosion could be deduced and resulted in the direct conversion of approximately two solar masses into energy. This finally convinced the community that GRB afterglows resulted from highly collimated explosions, which strongly reduced the needed energy budget.

Miscellaneous results

- The completion of both a pulsar survey and a supernova remnant survey
- The discovery of terrestrial gamma ray sources in 1994 that came from thunderclouds

De-orbit

After one of its gyroscopes failed, the observatory was deliberately de-orbited. At the time, the observatory was still operational, however the failure of another gyroscope would have made de-orbiting much more difficult and dangerous. With some controversy, NASA decided in the interest of public safety that a controlled crash was preferable to letting the craft come down on its own at random. Unlike the Hubble Space Telescope, it was not designed for on-orbit repair and refurbishment. It entered the Earth's atmosphere on 4 June 2000, with the debris that did not burn up falling harmlessly into the Pacific Ocean.

Chapter 2

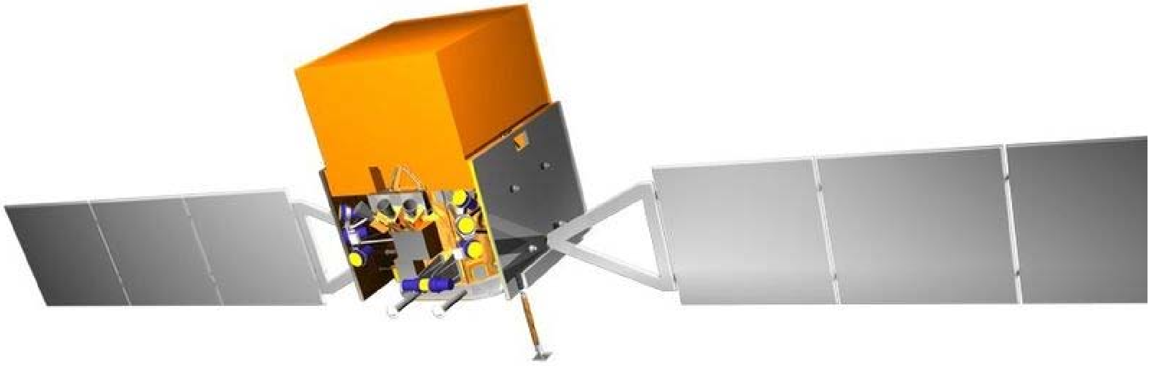
Fermi Gamma-Ray Space Telescope

Fermi Gamma-ray Space Telescope

General information

NSSDC ID	2008-029A
Organization	NASA, United States Department of Energy, and government agencies in France, Germany, Italy, Japan, and Sweden.
Major contractors	General Dynamics
Launch date	2008-06-11 16:05 UTC
Launched	Space Launch Complex 17-B Cape

from	Canaveral Air Force Station
Launch vehicle	Delta II 7920-H
Mission length	elapsed: 2 years, 7 months, and 23 days
Orbit height	550 km (340 mi)
Orbit period	~ 95 minutes
Wavelength	gamma ray
	Instruments
LAT	Large Area Telescope
GBM	Gamma-ray Burst Monitor



Artist's conception of Fermi in orbit

The **Fermi Gamma-ray Space Telescope (FGST)**, formerly referred to as the "Gamma-ray Large Area Space Telescope (GLAST)," is a space observatory being used to perform gamma-ray astronomy observations from low Earth orbit. Its main instrument is the Large Area Telescope (LAT), with which astronomers mostly intend to perform an all-sky survey studying astrophysical and cosmological phenomena such as active galactic nuclei, pulsars, other high-energy sources and dark matter. Another instrument aboard Fermi, the Gamma-ray Burst Monitor (GBM; formerly GLAST Burst Monitor), is being used to study gamma-ray bursts.

FGST was launched on 11 June 2008 at 16:05 GMT aboard a Delta II 7920-H rocket. The mission is a joint venture of NASA, the United States Department of Energy, and government agencies in France, Germany, Italy, Japan, and Sweden.

Overview

Fermi includes two scientific instruments, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT is an imaging gamma-ray detector (a pair-conversion instrument) which detects photons with energy from about 30 million to about 300 billion electron volts (30 MeV - 300 GeV), with a field of view of about 20% of the sky; it may be thought of as a sequel to the EGRET instrument on the Compton gamma ray observatory. The GBM consists of 14 scintillation detectors (twelve sodium iodide crystals for the 8keV to 1MeV range and two bismuth germanate crystals with sensitivity from 150keV to 30MeV), and can detect gamma-ray bursts in that energy range across the whole of the sky not occluded by the Earth.

fermi
Gamma-ray
Space Telescope

Fermi G.S.T. logo

General Dynamics Advanced Information Systems (formerly Spectrum Astro and now Orbital Sciences) in Gilbert, Arizona designed and built the spacecraft that carries the instruments. It travels in a low, circular orbit with a period of about 95 minutes. Its normal mode of operation maintains its orientation so that the instruments will look away from the earth, with a "rocking" motion to equalize the coverage of the sky. The view of the instruments will sweep out across most of the sky about 16 times per day. The spacecraft can also maintain an orientation that points to a chosen target.

Both science instruments underwent environmental testing, including vibration, vacuum, and high and low temperatures to ensure that they can withstand the stresses of launch and continue to operate in space. They were integrated with the spacecraft at the General Dynamics ASCENT facility in Gilbert, Arizona.

Data from the instruments will be available to the public through the Fermi Science Support Center web site. Software for analyzing the data will also be available. Scientists with plans for research will be able to apply to the Guest Investigator program.

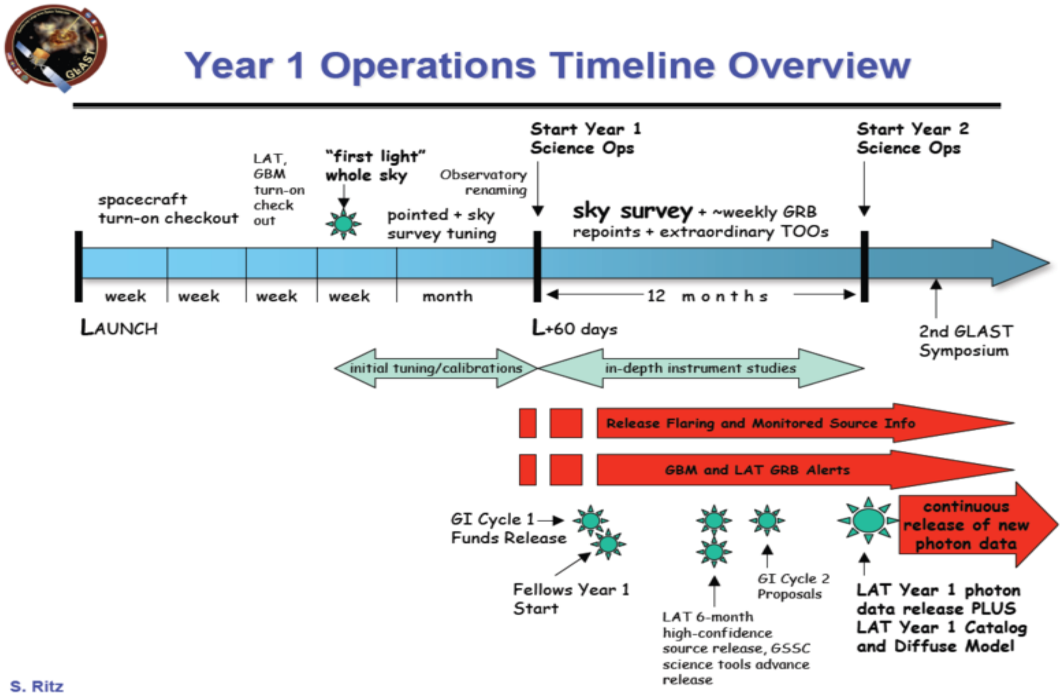
GLAST renamed FGST

Fermi gained its new name in 2008.

NASA's Alan Stern, associate administrator for Science at NASA Headquarters, launched a public competition 7 Feb 2008, closing 31 Mar 2008, to rename GLAST in a way that would "capture the excitement of GLAST's mission and call attention to gamma-ray and high-energy astronomy... something memorable to commemorate this spectacular new astronomy mission... a name that is catchy, easy to say and will help make the satellite and its mission a topic of dinner table and classroom discussion."

On 26 Aug 2008, GLAST was renamed the "Fermi Gamma-ray Space Telescope" in honor of Enrico Fermi, a pioneer in high-energy physics.

Mission



Anticipated operations timeline

The GLAST instrument after arriving at Cape Canaveral in May 2008

NASA designed the mission with a five-year lifetime, with a goal of ten years of operations.

The key scientific objectives of the Fermi mission have been described as:

- To understand the mechanisms of particle acceleration in active galactic nuclei (AGN), pulsars, and supernova remnants (SNR).
- Resolve the gamma-ray sky: unidentified sources and diffuse emission.
- Determine the high-energy behavior of gamma-ray bursts and transients.
- Probe dark matter (e.g. by looking for an excess of gamma rays from the center of the Milky Way) and early Universe.

- Search for evaporating primordial micro black holes (MBH) from their presumed gamma burst signatures [Hawking Radiation component].

The National Academies of Sciences ranked this mission as a top priority. Many new possibilities and discoveries are anticipated to emerge from this single mission and greatly expand our view of the Universe.

- Blazars and active galaxies

  Study energy spectra and variability of wavelengths of light coming from blazars so as to determine the composition of the black hole jets aimed directly at Earth -- whether they are
  (a) a combination of electrons and positrons or
  (b) only protons.

- Gamma-ray bursts

  Study gamma-ray bursts with an energy range several times more intense than ever before so that scientists may be able to understand them better.

- Neutron stars

  Study younger, more energetic pulsars in the Milky Way than ever before so as to broaden our understanding of stars. Study the pulsed emissions of magnetospheres so as to possibly solve how they are produced. Study how pulsars generate winds of interstellar particles.

- Milky Way galaxy

  Provide new data to help improve upon existing theoretical models of our own galaxy.

- Gamma-ray background radiation

  Study better than ever before whether ordinary galaxies are responsible for gamma-ray background radiation. The potential for a tremendous discovery awaits if ordinary sources are determined to be irresponsible, in which case the cause may be anything from self-annihilating dark matter to entirely new chain reactions among intersellar particles that have yet to be conceived.

- The early universe

  Study better than ever before how concentrations of visible and ultraviolet light change over time. The mission should easily detect $E=mc^2$ working in reverse, where energy was actually converted into mass, in the early universe.

- Sun

  Study better than ever before how our own Sun produces gamma rays in solar flares.

- Dark matter

  Search for evidence that dark matter is made up of weakly interacting massive particles, complementing similar experiments already planned for the Large Hadron Collider as well as other underground detectors. The potential for a tremendous discovery in this area is possible over the next several years.

- Fundamental physics

  Test better than ever before certain established theories of physics, such as whether the speed of light in vacuum remains constant regardless of wavelength. Einstein's general theory of relativity contends that it does, yet some models in quantum mechanics and quantum gravity predict that it may not. Search for gamma rays emanating from former black holes that once exploded, providing yet another potential step toward the unification of quantum mechanics and general relativity. Determine whether photons naturally split into smaller photons, as predicted by quantum mechanics and already achieved under controlled, man-made experimental conditions.

- Unknown discoveries

  Scientists estimate a very high possibility for new scientific discoveries, even revolutionary discoveries, emerging from this single mission.

Mission status

Prelaunch

On 4 Mar 2008 the spacecraft arrived at the Astrotech payload processing facility in Titusville, Florida. On 4 Jun 2008, after several previous delays, launch status was retargeted for June 11 at the earliest, the last delays resulting from the need to replace the Flight Termination System batteries. The launch window extended from 11:45 a.m. until 1:40 p.m. EDT (15:45-17:40 GMT) daily, until 7 Aug 2008.

Launch

GLAST launch aboard a Delta II rocket, 11 June 2008.

Launch occurred successfully on 11 Jun 2008 at 16:05, and the spacecraft separated from the carrier rocket about 75 minutes later. The spacecraft departed from pad B at Cape Canaveral Air Force Station Space Launch Complex 17 aboard a Delta 7920H-10C rocket.

Orbit

Fermi resides in a low-earth circular orbit at an altitude of 550 km (340 mi), and at an inclination of 28.5 degrees.

Software modifications

GLAST received some minor modifications to its computer software 2008-06-23.

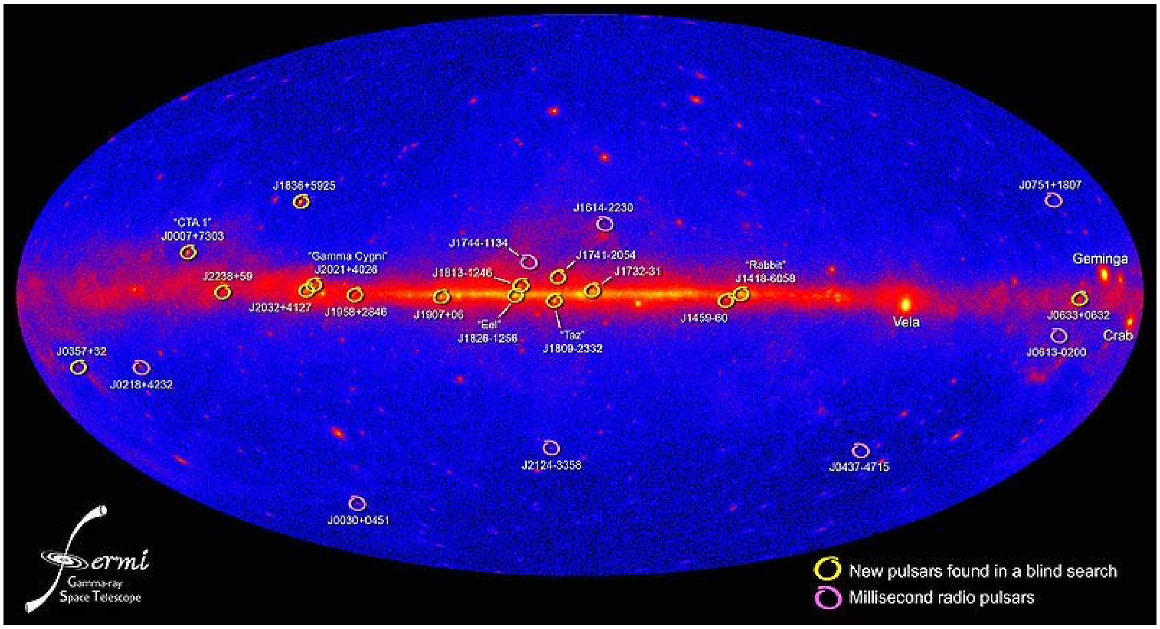
LAT/GBM computers operational

Computers operating both the LAT and GBM and most of the LAT's components were turned on, 2008-06-24. The LAT high voltage was turned on, 2008-06-25, and it began detecting high-energy particles from space, but minor adjustments were still needed to calibrate the instrument. The GBM high voltage was also turned on, 2008-06-25, but the GBM still required one more week of testing/calibrations before searching for gamma-ray bursts.

Sky survey mode

After presenting an overview of the Fermi instrumentation and goals, Jennifer Carson of SLAC National Accelerator Laboratory had concluded that the primary goals were "all achievable with the all-sky scanning mode of observing." Fermi switched to "sky survey mode" on 26 June 2008 so as to begin sweeping its field of view over the entire sky every three hours (every two orbits).

Discoveries



Gamma-ray pulsars detected by the Fermi Gamma-ray Space Telescope

Cycle of pulsed gamma rays from the Vela pulsar. Constructed from photons detected by Fermi's Large Area Telescope.

Pulsar discovery

The first major discovery came when the space telescope detected a pulsar in the CTA 1 supernova remnant that appeared to emit radiation in the gamma ray bands only, a first for its kind. This new pulsar sweeps the earth every 316.86 milliseconds and is about 4,600 light years away.

Greatest GRB energy release

In September 2008, the gamma-ray burst GRB 080916C in the constellation Carina was recorded by the Fermi telescope. This burst is notable as having "the largest apparent energy release yet measured." The explosion had the power of about 9,000 ordinary supernovae, and the relativistic jet of material ejected in the blast must have moved at a minimum of 99.9999% the speed of light. Overall, GRB 080916C had "the greatest total energy, the fastest motions, and the highest-energy initial emissions" ever seen.

Cosmic rays and supernova remnants

In February 2010, it was announced that FGST had determined that supernova remnants act as enormous accelerators for cosmic particles. This determination fulfills one of the stated missions for this project.

Background gamma ray sources

In March 2010 it was announced that active galactic nuclei are not responsible for most gamma-ray background radiation. Though active galactic nuclei do produce some of the gamma-ray radiation detected here on Earth, less than 30% originates from these sources. The search now is to locate the sources for the remaining 70% or so of all gamma-rays detected. Possibilities include star forming galaxies, galactic mergers, and yet-to-be explained dark matter interactions.

Fermi bubbles

In November 2010, it was announced two gamma-ray & x-ray bubbles were detected around Earth's galaxy, the Milky way. The bubbles extend about 25 thousand light years distant above and below the center of the galaxy. The galaxy's diffuse gamma-ray fog hampered prior observations, but the discovery team lead by D. Finkbeiner, building on research by G. Dobler, worked around this problem.

Fermi science packages

Gamma-ray Burst Monitor (GBM)

The Gamma-ray Burst Monitor (GBM) (formerly GLAST Burst Monitor) detects sudden flares of gamma-rays produced by gamma ray bursts and solar flares. Its scintillators are on the sides of the spacecraft to view all of the sky which is not blocked by the earth. The design is optimized for good resolution in time and photon energy.

"Gamma-ray bursts are so bright we can see them from billions of light years away, which means they occurred billions of years ago, and we see them as they looked then," stated Charles Meegan of NASA's Marshall Space Flight Center.

The Gamma-ray Burst Monitor has detected gamma rays from positrons generated in powerful thunderstorms.

GBM participating institutions

US team institution

- NASA's Marshall Space Flight Center, University of Alabama in Huntsville

German team institutions

- Max Planck Institut für Extraterrestrische Physik

Large Area Telescope (LAT)

The Large Area Telescope (LAT) detects individual gamma rays using technology similar to that used in terrestrial particle accelerators. Photons hit thin metal sheets, converting to electron-positron pairs, via a process known as pair production. These charged particles pass through interleaved layers of silicon microstrip detectors, causing ionization which produce detectable tiny pulses of electric charge. Researchers can combine information from several layers of this tracker to determine the path of the particles. After passing through the tracker, the particles enter the calorimeter, which consists of a stack of caesium iodide scintillator crystals to measure the total energy of the particles. The LAT's field of view is large, about 20% of the sky. The resolution of its images is modest by astronomical standards, a few arc minutes for the highest-energy photons and about 3 degrees at 100 MeV. The LAT is a bigger and better successor to the EGRET instrument on NASA's Compton Gamma Ray Observatory satellite in the 1990s. Several countries produced the components of the LAT, who then sent the components for assembly at SLAC National Accelerator Laboratory.

LAT participating institutions

US team institutions

- Stanford University, Physics Department, Fermi group & Hansen Experimental Physics Laboratory
- SLAC National Accelerator Laboratory, Particle Astrophysics group
- NASA Goddard Space Flight Center, Astrophysics Science Division
- U.S. Naval Research Laboratory, High Energy Space Environment (HESE) branch
- Ohio State University, Physics Department
- University of California, Santa Cruz, Physics Department and Institute for Particle Physics
- Sonoma State University, Department of Physics & Astronomy
- University of Washington
- Texas A&M University-Kingsville

German team institutions

- Ruhr-Universität Bochum, Theoretische Physik IV: Theoretische Weltraum- und Astrophysik

Japanese team institutions

- Japan Fermi Collaboration
- University of Tokyo
- Tokyo Institute of Technology
- Institute for Cosmic Ray Research
- Institute for Space and Astronautical Science
- Hiroshima University

Italian team institutions

- Istituto Nazionale di Fisica Nucleare (INFN)
- Italian Space Agency
- Istituto di Fisica Cosmica, Milano, CNR
- INFN and University of Bari
- INFN and University of Padova
- INFN and University of Perugia
- INFN and University of Pisa
- INFN and University of Rome Tor Vergata
- INFN and University of Trieste

- INFN and University of Udine

French team institutions

- Service d'Astrophysique, CEA DAPNIA, CEA Saclay
- Centre National d'Études Spatiales
- Institut National de Physique Nucléaire et de Physique des Particules, IN2P3
- Laboratoire Leprince-Ringuet de l'École Polytechnique
- Centre d'Études nucléaires de Bordeaux Gradignan
- Laboratoire de Physique Théorique et Astroparticules, Montpellier

Swedish team institutions

- Royal Institute of Technology
- Stockholm University

Education and public outreach

Education and public outreach are important components of the Fermi project. NASA's Education and Public Outreach (E/PO) group operates the Fermi education and outreach resources at Sonoma State University.

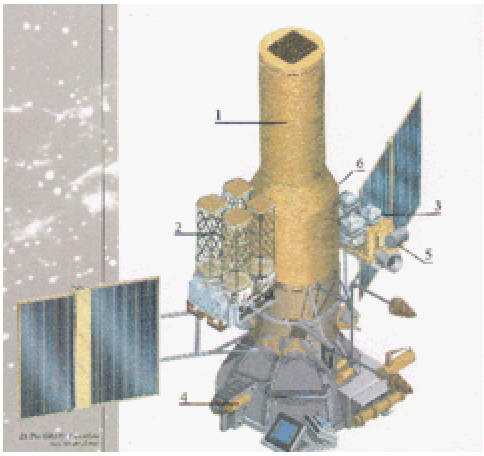
Rossi Prize

The 2011 Bruno Rossi Prize was awarded to Bill Atwood, Peter Michelson and the Fermi LAT team "for enabling, through the development of the Large Area Telescope, new insights into neutron stars, supernova remnants, cosmic rays, binary systems, active galactic nuclei and gamma-ray bursts."

Chapter 3

Granat

International Astrophysical Observatory "GRANAT"



picture credit: NASA

General information

NSSDC ID	1989-096A
Organization	Soviet space program
Major contractors	NPO Lavochkin
Launch date	1 December 1989
Launched from	Baikonur Cosmodrome (LC200/40)
Launch vehicle	Proton rocket
Mission length	9 years
Deorbited	May 25, 1999
Mass	4 metric tons

	(experiments 2.3 metric tons)
Type of orbit	Highly elliptical
Orbit height	apogee 200,000 km perigee 2,000 km (initial values)
Orbit period	4 days
Location	Geocentric orbit
Telescope style	coded mask (SIGMA) coded mask (ART-P)
Wavelength	X-ray to gamma ray
Collecting area	800 cm² (SIGMA)
	Instruments
SIGMA	X-ray/gamma-ray telescope
ART-P	X-ray telescope
ART-S	X-ray spectrometer
PHEBUS	Gamma-burst detector
WATCH	All-sky monitor
KONUS-B **TOURNESOL**	Gamma-ray burst experiments

The **International Astrophysical Observatory "GRANAT"** (usually known as **Granat**; Russian: Гранат), was a Soviet (later Russian) space observatory developed in collaboration with France, Denmark and Bulgaria. It was launched on 1 December 1989 aboard a Proton rocket and placed in a highly eccentric four-day orbit, of which three were devoted to observations. It operated for almost nine years.

In September 1994, after nearly five years of directed observations, the gas supply for its attitude control was exhausted and the observatory was placed in a non-directed survey mode. Transmissions finally ceased on 27 November 1998.

With seven different instruments on board, Granat was designed to observe the universe at energies ranging from X-ray to gamma ray. Its main instrument, SIGMA, was capable of imaging both hard X-ray and soft gamma-ray sources. The PHEBUS instrument was meant to study gamma-ray bursts and other transient X-Ray sources. Other experiments such as ART-P were intended to image X-Ray sources in the 35 to 100 keV range. One instrument, WATCH, was designed to monitor the sky continuously and alert the other instruments to new or interesting X-Ray sources. The ART-S spectrometer covered the X-ray energy range while the KONUS-B and TOURNESOL experiments covered both the X-ray and gamma ray spectrum.

Spacecraft

Granat was a three-axis-stabilized spacecraft and the last of the Venera-class spacecraft produced by the Lavochkin Scientific Production Association. It was similar to the Astron observatory which was functional from 1983 to 1989; for this reason, the spacecraft was originally known as the Astron 2. It weighed 4.4 metric tons and carried almost 2.3 metric tons of international scientific instrumentation. Granat stood 6.5 m tall and had a total span of 8.5 m across its solar arrays. The power made available to the scientific instruments was approximately 400 W.

Launch and orbit

Proton launch vehicle carrying Granat

The spacecraft was launched on 1 December 1989 aboard a Proton rocket from the Baikonur Cosmodrome in Kazakh SSR. It was placed in a highly eccentric 98-hour orbit with an initial apogee/perigee of 200,000 km/2,000 km respectively and an inclination of 51.5 degrees. This meant that solar and lunar perturbations would significantly increase the orbits inclination while reducing its eccentricity, such that the orbit had become near-circular by the time Granat completed its directed observations in September 1994. (By 1991, the perigee had increased to 20,000 km; by September 1994, the apogee/perigee was 59,025 km / 144,550 km at an inclination of 86.7 degrees.)

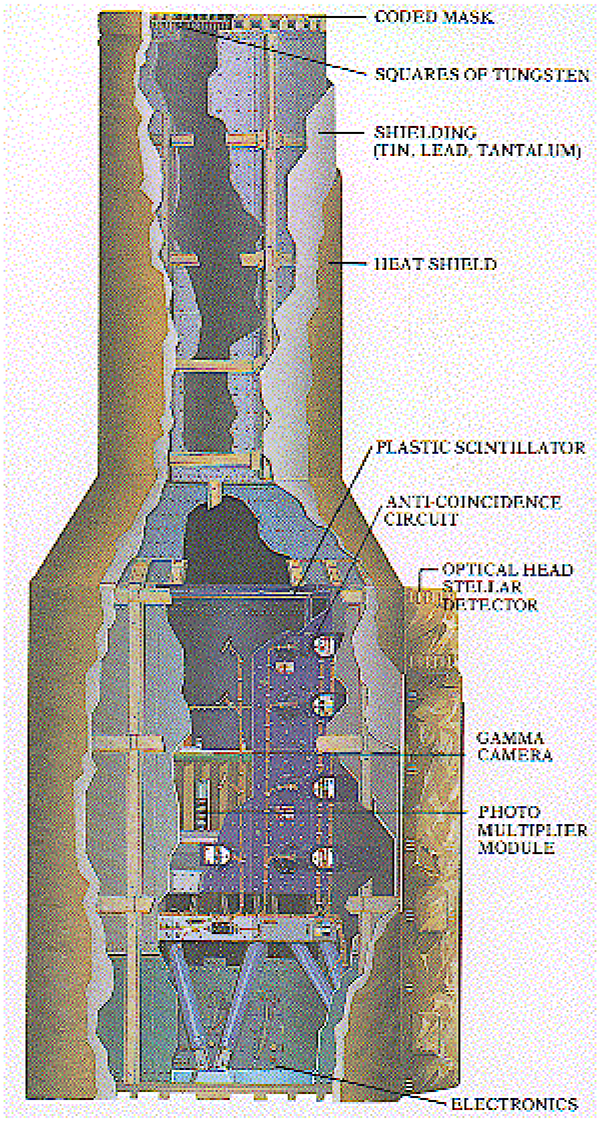
Three days out of the four-day orbit were devoted to observations. After over nine years in orbit, the observatory finally reentered the Earth's atmosphere on May 25, 1999.

Granat observatory orbit change (1994 predictions)

Date	Perigee (km)	Apogee (km)	Arg.perigee (deg)	Inc. (deg)	Long.asc.node (deg)
December 1, 1989	2,000	200,000	285	51.5	20.0
December 1, 1991	23,893	179,376	311.9	82.6	320.3
December 1, 1994	58,959	144,214	343.0	86.5	306.9
December 1, 1996	42,088.8	160,888	9.6	93.4	302.2

Instrumentation

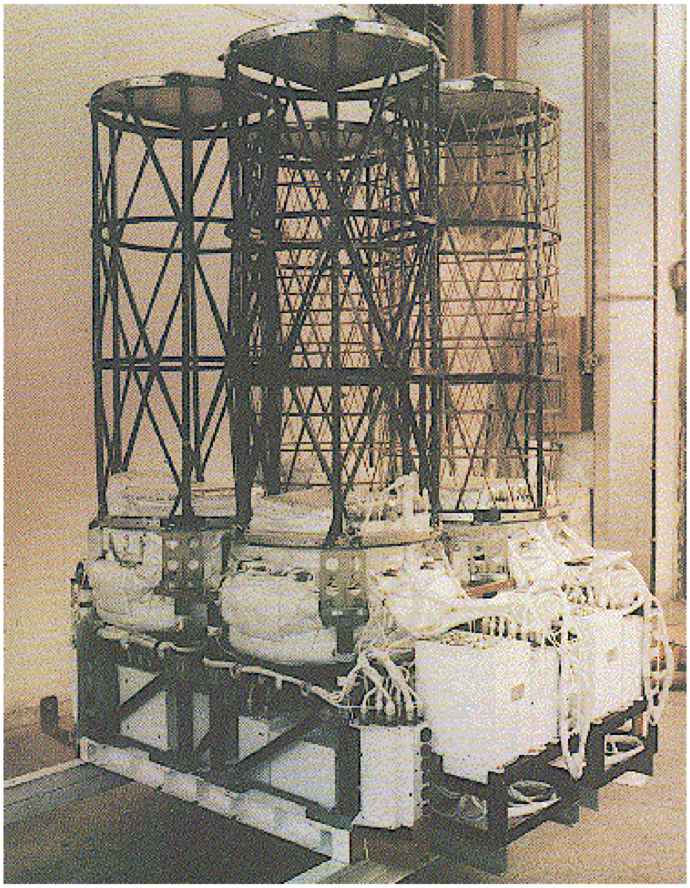
SIGMA



SIGMA instrument

The hard X-ray and low-energy gamma-ray SIGMA telescope was a collaboration between CESR (Toulouse) and CEA (Saclay). It covered the energy range 35–1300 keV, with an effective area of 800 cm^2 and a maximum sensitivity field of view of ~5°×5°. The maximum angular resolution was 15 arcmin. The energy resolution was 8% at 511 keV. Its imaging capabilities were derived from the association of a coded mask and a position sensitive detector based on the Anger camera principle.

ART-P



ART-P instrument

The ART-P X-ray telescope was the responsibility of the IKI in Moscow. The instrument covered the energy range 4 to 60 keV for imaging and 4 to 100 keV for spectroscopy and timing. There were four identical modules of the ART-P telescope, each consisting of a position sensitive multi-wire proportional counter (MWPC) together with a URA coded mask. Each module had an effective area of approximately 600 cm^2, producing a field of view of 1.8° by 1.8°. The angular resolution was 5 arcmin; temporal and energy resolutions were 3.9 ms and 22% at 6 keV, respectively. The instrument achieved a sensitivity of 0.001 of the Crab nebula source (= 1 "mCrab") in an eight-hour exposure. The maximum time resolution was 4 ms.

ART-S

The ART-S X-ray spectrometer, also built by the IKI, covered the energy range 3 to 100 keV. Its field of view was 2° by 2°. The instrument consisted of four detectors based on spectroscopic MWPCs, making an effective area of 2,400 cm^2 at 10 keV and 800 cm^2 at 100 keV. The time resolution was 200 microseconds.

PHEBUS

The PHEBUS experiment was designed by CESR (Toulouse) to record high energy transient events in the range 100 keV to 100 MeV. It consisted of two independent detectors and their associated electronics. Each detector consisted of a bismuth germinate (BGO) crystal 78 mm in diameter by 120 mm thick, surrounded by a plastic anti-coincidence jacket. The two detectors were arranged on the spacecraft so as to observe 4π steradians. The burst mode was triggered when the count rate in the 0.1 to 1.5 MeV energy range exceeded the background level by 8 sigma in either 0.25 or 1.0 seconds. There were 116 energy channels.

WATCH

Starting in January 1990, four WATCH instruments, designed by the Danish Space Research Institute, were in operation on the Granat observatory. The instruments could localize bright sources in the 6 to 180 keV range to within 0.5° using a Rotation Modulation Collimator. Taken together, the instruments' three fields of view covered approximately 75% of the sky. The energy resolution was 30% FWHM at 60 keV. During quiet periods, count rates in two energy bands (6 to 15 and 15 to 180 keV) were accumulated for 4, 8, or 16 seconds, depending on onboard computer memory availability. During a burst or transient event, count rates were accumulated with a time resolution of 1 second per 36 energy channels.

KONUS-B

The KONUS-B instrument, designed by the Ioffe Physico-Technical Institute in St. Petersburg, consisted of seven detectors distributed around the spacecraft that responded to photons of 10 keV to 8 MeV energy. They consisted of NaI(Tl) scintillator crystals 200 mm in diameter by 50 mm thick behind a Be entrance window. The side surfaces were protected by a 5 mm thick lead layer. The burst detection threshold was 500 to 50 microjoules per square meter (5×10^{-7} to 5×10^{-8} erg/cm²), depending on the burst spectrum and rise time. Spectra were taken in two 31-channel pulse height analyzers (PHAs), of which the first eight were measured with 1/16 s time resolution and the remaining with variable time resolutions depending on the count rate. The range of resolutions covered 0.25 to 8 s.

The KONUS-B instrument operated from 11 December 1989 until 20 February 1990. Over that period, the "on" time for the experiment was 27 days. Some 60 solar flares and 19 cosmic gamma-ray bursts were detected.

TOURNESOL

The French TOURNESOL instrument consisted of four proportional counters and two optical detectors. The proportional counters detected photons between 2 keV and 20 MeV in a 6° by 6° field of view. The visible detectors had a field of view of 5° by 5°. The instrument was designed to look for optical counterparts of high-energy burst sources, as well as performing spectral analysis of the high-energy events.

Science results

Over the initial four years of directed observations, Granat observed many galactic and extra-galactic X-ray sources with emphasis on the deep imaging and spectroscopy of the galactic center, broad-band observations of black hole candidates, and X-ray novae. After 1994, the observatory was switched to survey mode and carried out a sensitive all-sky survey in the 40 to 200 keV energy band.

Some of the highlights included:

- A very deep imaging (more than 5 million seconds duration) of the galactic center region.
- Discovery of electron-positron annihilation lines from the galactic microquasar 1E1740-294 and the X-ray Nova Muscae.
- Study of spectra and time variability of black hole candidates.
- Across eight years of observations, Granat discovered some twenty new X-ray sources, i.e. candidate black holes and neutron stars. Consequently, their designations begin with "GRS" meaning "GRANAT source". Examples are GRS 1915+105 (the first microquasar discovered in our galaxy) and GRS 1124-683.

Impact of the dissolution of the Soviet Union

After the end of the Soviet Union, two problems arose for the project. The first was geopolitical in nature: the main spacecraft control center was located at the Yevpatoria facility in the Crimea region. This control center was significant in the Soviet space program, being one of only two in the country equipped with a 70 m dish antenna. With the break up of the Union, the Crimea region, although mostly populated by ethnic Russians, found itself part of the newly independent Ukraine and the center was put under Ukrainian national control, prompting new political hurdles.

The main and most urgent problem, however, was in finding funds to support the continued operation of the spacecraft amid the spending crunch in post-Soviet Russia. The French space agency, having already contributed significantly to the project (both scientifically and financially), took upon itself to fund the continuing operations directly.

Chapter 4

Chandra X-Ray Observatory

Chandra X-ray Observatory

Chandra X-ray Observatory and Inertial Upper Stage sit inside the payload bay on Space Shuttle *Columbia* mission STS-93

General information

NSSDC ID	1999-040B
Organization	NASA, SAO, CXC
Major contractors	TRW, Northrop Grumman
Launch date	23 July 1999
Launched from	Kennedy Space Center
Launch vehicle	Space Shuttle *Columbia* STS-93
Mission length	planned: 5 years elapsed: 11 years, 6 months, and 12 days
Mass	4,790 kg (10,600 lb)
Orbit height	apogee 133,000 km (83,000 mi) perigee 16,000 km (9,900 mi)
Orbit period	64.2 hours
Wavelength	X-ray (0.1 - 10 keV)
Diameter	1.2 m (3.9 ft)
Collecting area	0.04 m^2 (0.43 sq ft) at 1 keV
Focal length	10 m (33 ft)

The **Chandra X-ray Observatory** is a satellite launched on STS-93 by NASA on July 23, 1999. It was named in honor of Indian-American physicist Subrahmanyan Chandrasekhar who is known for determining the maximum mass for white dwarfs. "Chandra" also means "moon" or "luminous" in Sanskrit.

Chandra Observatory is the third of NASA's four Great Observatories. The first was Hubble Space Telescope; second the Compton Gamma Ray Observatory, launched in 1991; and last is the Spitzer Space Telescope. Prior to successful launch, the Chandra Observatory was known as AXAF, the Advanced X-ray Astrophysics Facility. AXAF was assembled and tested by TRW (now Northrop Grumman Space Technology) in Redondo Beach, California. Chandra is sensitive to X-ray sources 100 times fainter than any previous X-ray telescope, due primarily to the high angular resolution of the Chandra mirrors.

Since the Earth's atmosphere absorbs the vast majority of X-rays, they are not detectable from Earth-based telescopes, requiring a space-based telescope to make these observations.

History

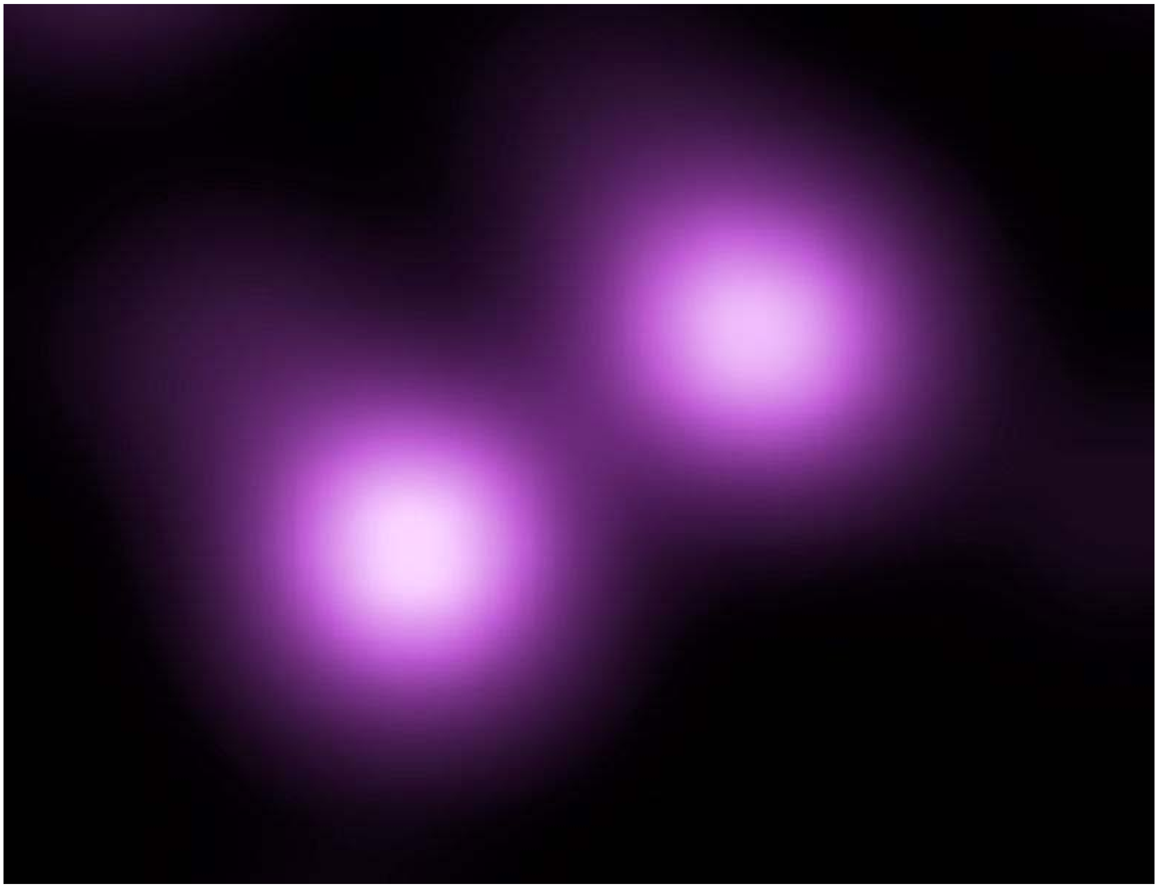
In 1976 the Chandra X-ray Observatory (called AXAF at the time) was proposed to NASA by Riccardo Giacconi and Harvey Tananbaum. Preliminary work began the following year at Marshall Space Flight Center (MSFC) and the Smithsonian Astrophysical Observatory (SAO). In the meantime, in 1978, NASA launched the first imaging X-ray telescope, Einstein (HEAO-2), into orbit. Work continued on the Chandra project through 1980s and 1990s. In 1992, to reduce costs, the spacecraft was redesigned. Four of the twelve planned mirrors were eliminated, as were two of the six scientific instruments. Chandra's planned orbit was changed to an elliptical one, reaching one third of the way to the Moon's at its farthest point. This eliminated the possibility of improvement or repair by the space shuttle but put the observatory above the Earth's radiation belts for most of its orbit.

AXAF was renamed Chandra in 1998 and launched in 1999 by the shuttle *Columbia* (STS-93). At 22753 kg, it was the heaviest payload ever launched by the shuttle, a consequence of the two-stage Inertial Upper Stage booster rocket system needed to transport the spacecraft to its high orbit.

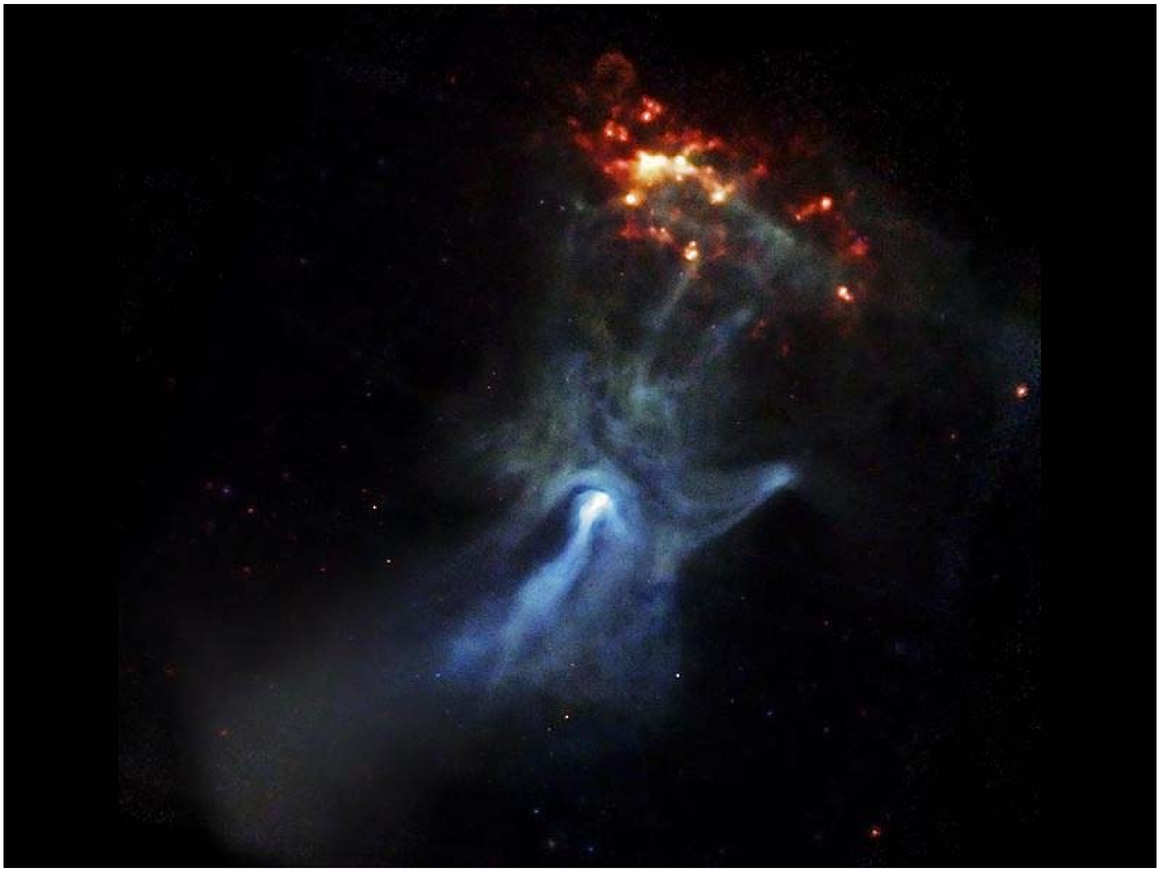
Chandra has been returning data since the month after it launched. It is operated by the SAO at the Chandra X-ray Center in Cambridge, Massachusetts, with assistance from MIT and Northrop Grumman Space Technology. The ACIS CCDs suffered particle damage during early radiation belt passages. To prevent further damage, the instrument is now removed from the telescope's focal plane during passages.

Although Chandra was initially given an expected lifetime of 5 years, on 4 September 2001 NASA extended its lifetime to 10 years "based on the observatory's outstanding results." Physically Chandra could last much longer. A study performed at the Chandra X-ray Center indicated that the observatory could last at least 15 years. On 24 July 2008 the International X-Ray Observatory (IXO), a joint project between ESA, NASA and JAXA, was proposed as the next major X-ray observatory. Its expected launch date is 2020.

Discoveries



SN 2006gy (upper right) and its parent galaxy NGC 1260 (lower left) in false color as observed through the Chandra X-Ray Observatory.



In this image of PSR B1509-58, the lowest energy X-rays that Chandra detects are red, the medium range is green, and the most energetic ones are colored blue.

The data gathered by Chandra have greatly advanced the field of X-ray astronomy.

- The first light image, of supernova remnant Cassiopeia A, gave astronomers their first glimpse of the compact object at the center of the remnant, probably a neutron star or black hole. (Pavlov, *et al.*, 2000)
- In the Crab Nebula, another supernova remnant, Chandra showed a never-before-seen ring around the central pulsar and jets that had only been partially seen by earlier telescopes. (Weisskopf, *et al.*, 2000)
- The first X-ray emission was seen from the supermassive black hole, Sagittarius A*, at the center of the Milky Way. (Baganoff, *et al.*, 2001)
- Chandra found much more cool gas than expected spiralling into the center of the Andromeda Galaxy.
- Pressure fronts were observed in detail for the first time in Abell 2142, where clusters of galaxies are merging.
- The earliest images in X-rays of the shock wave of a supernova were taken of SN 1987A.
- Chandra showed for the first time the shadow of a small galaxy as it is being cannibalized by a larger one, in an image of Perseus A.

- A new type of black hole was discovered in galaxy M82, mid-mass objects purported to be the missing link between stellar-sized black holes and supermassive black holes. (Griffiths, *et al.*, 2000)
- X-ray emission lines were associated for the first time with a gamma-ray burst, Beethoven Burst GRB 991216. (Piro, *et al.*, 2000)
- High school students, using Chandra data, discovered a neutron star in supernova remnant IC 443.
- Observations by Chandra and BeppoSAX suggest that gamma-ray bursts occur in star-forming regions.
- Chandra data suggested that RX J1856.5-3754 and 3C58, previously thought to be pulsars, might be even denser objects: quark stars. These results are still debated.
- Sound waves from violent activity around a supermassive black hole were observed in the Perseus Cluster (2003).
- TWA 5B, a brown dwarf, was seen orbiting a binary system of Sun-like stars.
- Nearly all stars on the main sequence are X-ray emitters. (Schmitt & Liefke, 2004)
- The X-ray shadow of Titan was seen when it transitted the Crab Nebula.
- X-ray emissions from materials falling from a protoplanetary disc into a star. (Kastner, *et al.*, 2004)
- Hubble constant measured to be 76.9 km/s/Mpc using Sunyaev-Zel'dovich effect.
- 2006 Chandra found strong evidence that dark matter exists by observing supercluster collision
- 2006 X-ray emitting loops, rings and filaments discovered around a supermassive black hole within Messier 87 imply the presence of pressure waves, shock waves and sound waves. The evolution of Messier 87 may have been dramatically affected.
- Observations of the Bullet cluster put limits on the cross-section of the self-interaction of dark matter.
- "The Hand of God" photograph of PSR B1509-58.

Technical description

Unlike optical telescopes which possess simple aluminized parabolic surfaces (mirrors), X-ray telescopes generally use a Wolter telescope consisting of nested cylindrical paraboloid and hyperboloid surfaces coated with iridium or gold. X-ray photons would be absorbed by normal mirror surfaces, so mirrors with a low grazing angle are necessary to reflect them. Chandra uses four pairs of nested mirrors, together with their support structure, called the High Resolution Mirror Assembly (HRMA); the mirror substrate is 2 cm-thick glass, with the reflecting surface a 33 nm iridium coating, and the diameters are 65 cm, 87 cm, 99 cm and 123 cm. The thick substrate and particularly careful polishing allowed a very precise optical surface, which is responsible for Chandra's unmatched resolution: between 80% and 95% of the incoming X-ray energy is focused into a one-arcsecond circle. However, the thickness of the substrates limit the proportion of the aperture which is filled, leading to the low collecting area compared to XMM-Newton.

Chandra's highly elliptical orbit allows it to observe continuously for up to 55 hours of its 65 hour orbital period. At its furthest orbital point from earth, Chandra is one of the furthest from earth earth-orbiting satellites. This orbit takes it beyond the geostationary satellites and beyond the outer Van Allen belt.

With an angular resolution of 0.5 arcsecond (2.4 µrad), Chandra possesses a resolution over one thousand times better than that of the first orbiting X-ray telescope.

Instruments

The Science Instrument Module (SIM) holds the two focal plane instruments, the Advanced CCD Imaging Spectrometer (ACIS) and the High Resolution Camera (HRC), moving whichever is called for into position during an observation.

ACIS consists of 10 CCD chips and provides images as well as spectral information of the object observed. It operates in the range of 0.2 - 10 keV. HRC has two micro-channel plate components and images over the range of 0.1 - 10 keV. It also has a time resolution of 16 microseconds. Both of these instruments can be used on their own or in conjunction with one of the observatory's two transmission gratings.

The transmission gratings, which swing into the optical path behind the mirrors, provide Chandra with high resolution spectroscopy. The High Energy Transmission Grating Spectrometer (HETGS) works over 0.4 - 10 keV and has a spectral resolution of 60-1000. The Low Energy Transmission Grating Spectrometer (LETGS) has a range of 0.09 - 3 keV and a resolution of 40-2000.

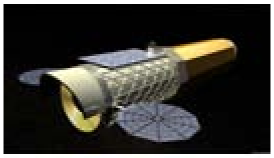
Chapter 5

International X-ray Observatory

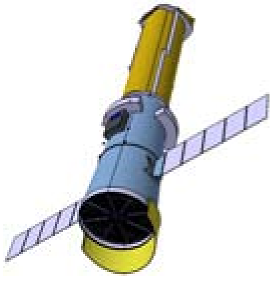
International X-ray Observatory

General information	
Organization	NASA European Space Agency Japan Aerospace Exploration Agency
Launch date	2021
Launch vehicle	Ariane V or Atlas V
Wavelength	X-ray
Collecting area	3 square metres (32 sq ft)
Focal length	20 metres (66 ft)

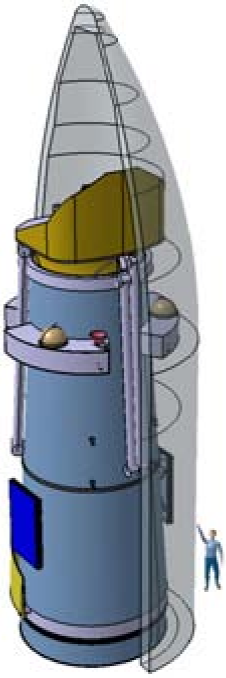
NASA conception of IXO, mirror view, artist's impression



NASA conception of IXO, side view, artist's impression



ESA conception of IXO, schematic diagram of IXO articulated and deployed, artist's impression.



ESA conception of IXO, IXO stowed in an Ariane V fairing, artist's impression.

The **International X-ray Observatory** (**IXO**) is an X-ray telescope to be launched in 2021 as a joint effort by the United States space agency NASA, the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA). In May 2008, ESA and NASA established a coordination group involving all three agencies, with the intent of exploring a joint mission merging the ongoing XEUS and Constellation-X projects. This proposed the start of a joint study for IXO. IXO still faces funding competition from two other missions, the Europa Jupiter System Mission (EJSM) and the Laser Interferometer Space Antenna (LISA). In 2013 only one of these missions will be chosen.

Science with IXO

X-ray observations are crucial for understanding the structure and evolution of the stars, galaxies, and the Universe as a whole. X-ray images reveal hot spots in the Universe—regions where particles have been energized or raised to very high temperatures by strong magnetic fields, violent explosions, and intense gravitational forces. X-ray sources in the sky are also associated with the different phases of stellar evolution such as the supernova remnants, neutron stars, and black holes.

IXO will explore X-ray Universe and address the following fundamental and timely questions in astrophysics:

- What happens close to a black hole?
- How did supermassive black holes grow?
- How do large scale structures form?
- What is the connection between these processes?

To address these science questions, IXO will trace orbits close to the event horizon of black holes, measure black hole spin for several hundred active galactic nuclei (AGN), use spectroscopy to characterize outflows and the environment of AGN during their peak activity, search for supermassive black holes out to redshift $z = 10$, map bulk motions and turbulence in galaxy clusters, find the missing baryons in the cosmic web using background quasars, and observe the process of cosmic feedback where black holes inject energy on galactic and intergalactic scales.

This will allow astronomers to understand better the history and evolution of matter and energy, visible and dark, as well as their interplay during the formation of the largest structures.

Closer to home, IXO observations will constrain the equation of state in neutron stars, black holes spin demographics, when and how elements were created and dispersed into the intergalactic medium, and much more.

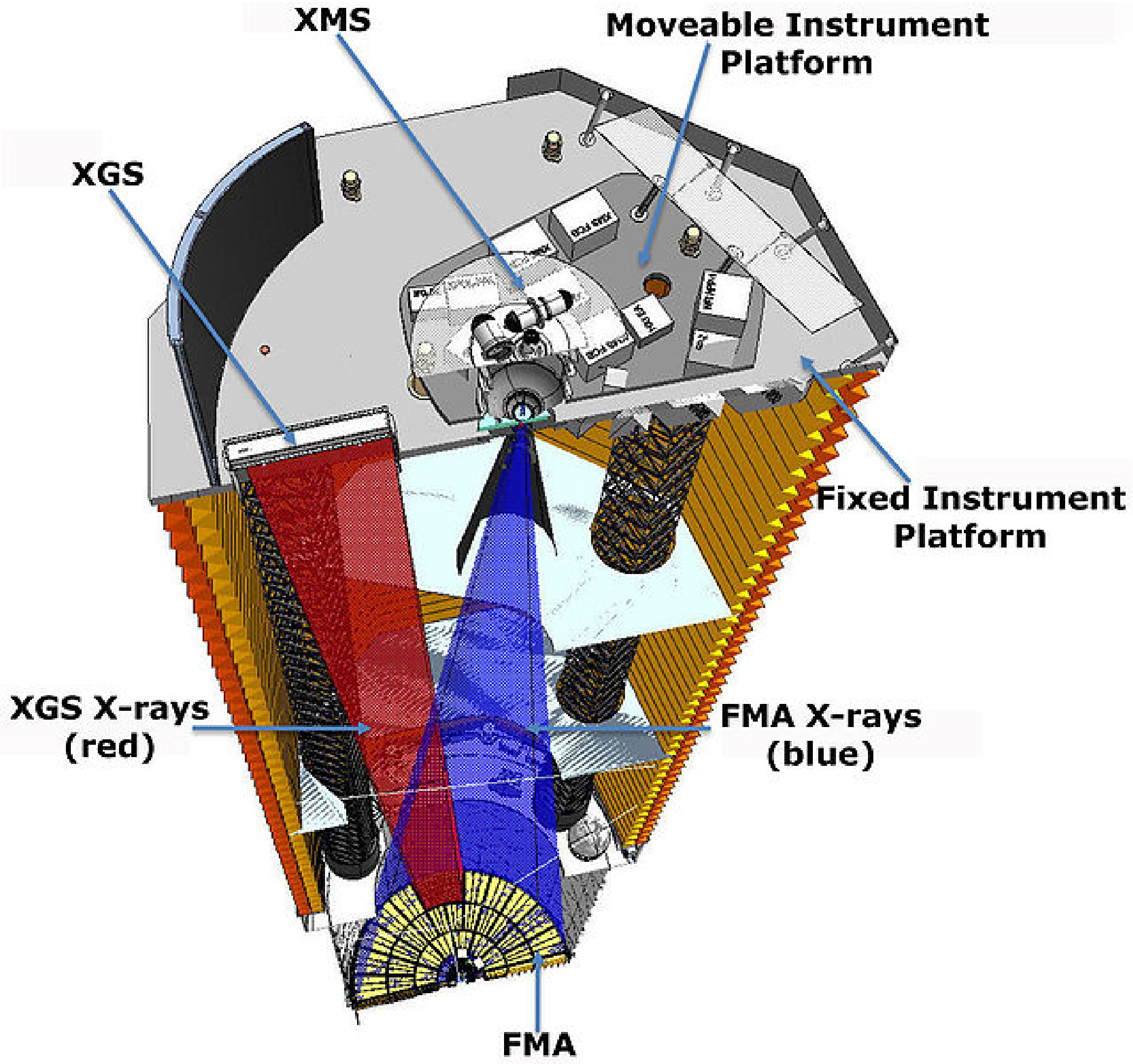
To achieve these science goals, IXO requires extremely large collecting area combined with good angular resolution in order to offer unmatched sensitivities for the study of the high-z Universe and for high-precision spectroscopy of bright X-ray sources.

The large collecting area required because, in astronomy, telescopes gather light and produce images by hunting and counting photons. The number of photons collected puts the limit to our knowledge about the size, energy, or mass of an object detected. More photons collected means better images and better spectra, and therefore offers better possibilities for understanding of cosmic processes.

IXO configuration

The heart of IXO mission is a single large X-ray mirror with up to 3 square meters of collecting area and 5 arcsec angular resolution, which is achieved with an extendable optical bench with a 20 m focal length.

Optics



IXO - cutaway view. X-ray beams reaching detectors, which will provide complementary spectroscopy, imaging, timing, and polarimetry data on cosmic X-ray sources.

A key feature of the IXO mirror design is a single mirror assembly (Flight Mirror Assembly, FMA), which is optimized to minimize mass while maximizing the collecting area, and an extendible optical bench.

Unlike visible light, X-rays cannot be focused at normal incidence, since the X-ray beams would be absorbed in the mirror. Instead, IXO's mirrors, like all prior X-ray telescopes, will use grazing incidences, scattering at a very shallow angle. As a result, X-ray telescopes consist of nested cylindrical shells, with their inner surface being the reflecting surface. However, as the goal is to collect as many photons as possible, IXO will have a bigger than 3m diameter mirror.

As the grazing angle is a function inversely proportional to photon energy, the higher-energy X-rays require smaller (less than 2 degrees) grazing angles to be focused. This implies longer focal lengths as the photon energy increases, thus making X-ray telescopes difficult to build if focusing of photons with energies higher than a few keV is desired. For that reason IXO features an *extendible optical bench* that offers a focal length of 20 m. A focal length of 20 meters was selected for IXO as a reasonable balance between scientific needs for advanced photon collecting capability at the higher energy ranges and engineering constraints. Since no payload fairing is large enough to fit a 20-meter long observatory, thus IXO has a deployable metering structure between the spacecraft bus and the instrument module.

Instrumentation

IXO scientific goals require gathering many pieces of information using different techniques such as spectroscopy, timing, imaging, and polarimetry. Therefore, IXO will carry a range of detectors, which will provide complementary spectroscopy, imaging, timing, and polarimetry data on cosmic X-ray sources to help disentangle the physical processes occurring in them.

Two high-resolution spectrometers, a microcalorimeter (XMS or cryogenic imaging spectrograph (CIS)) and a set of dispersive gratings (XGS) will provide high-quality spectra over the 0.1 – 10 keV bandpass where most astrophysically abundant ions have X-ray lines. The detailed spectroscopy from these instruments will enable high-energy astronomers to learn about the temperature, composition, and velocity of plasmas in the Universe. Moreover, the study of specific X-ray spectral features probes the conditions of matter in extreme gravity field, such as around supermassive black holes. Flux variability adds a further dimension by linking the emission to the size of the emitting region and its evolution over time; the high timing resolution spectrometer (HTRS) on IXO will allow these types of studies in a broad energy range and with high sensitivity.

To extend our view of the high-energy Universe to the hard X-rays and find the most obscured black holes, the wide field imaging & hard X-ray imaging detectors (WFI/HXI) together will image the sky up to 18 arcmin field of view (FOV) with a moderate resolution (<150 eV up to 6 keV and <1 keV (FWHM) at 40 keV.

IXO's imaging X-ray polarimeter will be a powerful tool to explore sources such as neutron stars and black holes, measuring their properties and how they impact their surroundings.

The detectors will be located on two instrument platforms—the Moveable Instrument Platform (MIP) and the Fixed Instrument Platform (FIP). The Moveable Instrument Platform is needed because an X-ray telescopes cannot be folded as it can be done with visible-spectrum telescopes. Therefore, IXO will use the MIP that holds the following detectors—a wide field imaging & hard X-ray imaging detector, a high-spectral-resolution imaging spectrometer, a high timing resolution spectrometer, and a polarimeter — and rotates them into the focus in turn.

The X-ray Grating Spectrometer will be located on the Fixed Instrument Platform. This is a wavelength-dispersive spectrometer that will provide high spectral resolution in the soft X-ray band. It can be used to determine the properties of the warm-hot-intergalactic medium, outflows from active galactic nuclei, and plasma emissions from stellar coronae.

A fraction of the beam from the mirror will be dispersed to a charge-coupled device (CCD) camera, which will operate simultaneously with the observing MIP instrument and collect instrumental background data, which can occur when an instrument is not in the focal position.

To avoid interfering the very faint astronomical signals with radiation from the telescope, the telescope itself and all its instruments must be kept cold. Therefore, the IXO Instrument Platform features a large shield that blocks the light from the Sun, Earth, and Moon, which otherwise would heat up the telescope, and interfere with the observations.

IXO optics and instrumentation will provide up to 100-fold increase in effective area for high resolution spectroscopy, deep spectral, and microsecond spectroscopic timing with high count rate capability.

The improvement of IXO relative to current X-ray missions is equivalent to a transition from the 200 inch Palomar telescope to a 22 m telescope while at the same time shifting from spectral band imaging to an integral field spectrograph.

Launch

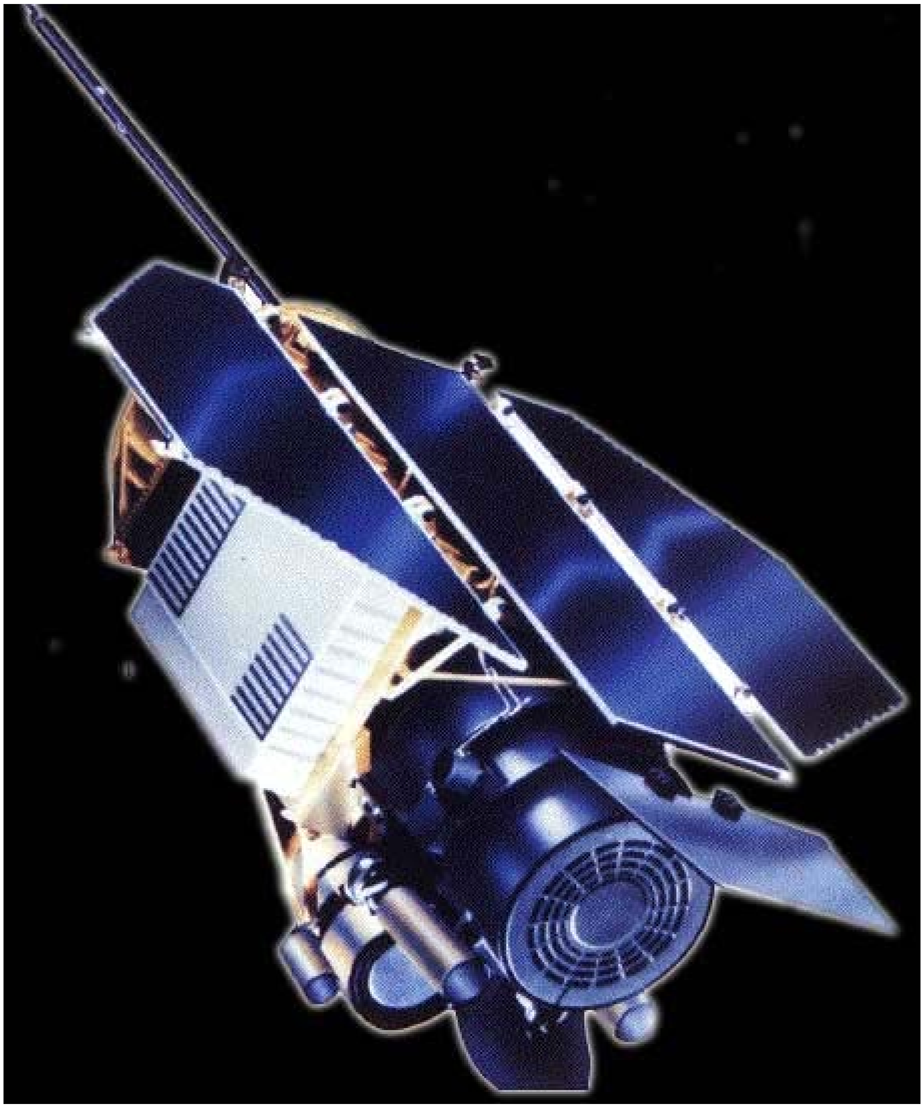
The planned launch date for IXO is 2021, going into an L2 orbit. Studies to determine the launch vehicle, either the Ariane V or Atlas V, are currently underway.

Science operations

IXO will be designed to operate for a minimum of 5 years, with a goal of 10 years, so IXO science operations are anticipated to last from 2021 to 2030.

Chapter 6

ROSAT



ROSAT

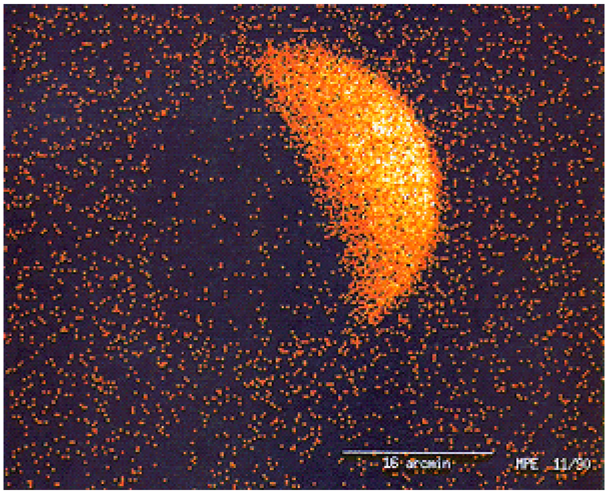
ROSAT (short for **Rö**ntgen**sat**ellit) was a German X-ray satellite telescope. It was named in honour of Wilhelm Röntgen. It was launched on June 1, 1990, with a Delta II rocket from Cape Canaveral, and operated until February 12, 1999.

Overview

The Roentgensatellit (ROSAT) was a joint German, US and British X-ray astrophysics project. ROSAT carried a German-built imaging X-ray Telescope (XRT) with three focal plane instruments: two German Position Sensitive Proportional Counters (PSPC) and the US-supplied High Resolution Imager (HRI). The X-ray mirror assembly was a grazing incidence four-fold nested Wolter I telescope with an 84-cm diameter aperture and 240-cm focal length. The angular resolution was <5 arcsec at half energy width. The XRT assembly was sensitive to X-rays between 0.1 to 2 keV. In addition, a British-supplied extreme ultraviolet (XUV) telescope, the Wide Field Camera (WFC), was coaligned with the XRT and covers the wave band between and 6 angstroms (0.042 to 0.21 keV). ROSAT's unique strengths were high spatial resolution, low-background, soft X-ray imaging for the study of the structure of low surface brightness features, and for low-resolution spectroscopy. The ROSAT spacecraft was a three-axis stablized satellite which can be used for pointed observations, for slewing between targets, and for performing scanning observations on great circles perpendicular to the plane of the ecliptic. ROSAT was capable of fast slews (180 deg. in ~15 min.) which makes it possible to observe two targets on opposite hemispheres during each orbit. The pointing accuracy was 1 arcminute with stability <5 arcsec per sec and jitter radius of ~10 arcsec. Two CCD star sensors were used for optical position sensing of guide stars and attitude determination of the spacecraft. The post facto attitude determination accuracy was 6 arcsec. The ROSAT mission was divided into two phases: (1) After a two-month on-orbit calibration and verification period, an all-sky survey was performed for six months using the PSPC in the focus of XRT, and in two XUV bands using the WFC. The survey was carried out in the scan mode. (2) The second phase consists of the remainder of the mission and was devoted to pointed observations of selected astrophysical sources. In ROSAT's pointed phase, observing time was allocated to Guest Investigators from all three participating countries through peer review of submitted proposals. ROSAT had a design life of 18 months, but was expected to operate beyond its nominal lifetime.

— NASA

Highlights



Earth's Moon on June 29, 1990 by ROSAT

- X-ray all-sky survey catalog, more than 150000 objects
- XUV all-sky survey catalog (479 objects)
- Source catalogs from the pointed phase (PSPC and HRI) containing ~ 100000 serendipitous sources
- Detailed morphology of supernova remnants and clusters of galaxies.
- Detection of shadowing of diffuse X-ray emission by molecular clouds.
- Detection of pulsations from Geminga.
- Detection of isolated neutron stars.
- Discovery of X-ray emission from comets.
- Observation of X-ray emission from the collision of Comet Shoemaker-Levy with Jupiter.

Catalogues

- 1RXS - First ROSAT X-ray Survey

Launch

ROSAT was originally planned to be launched on the Space shuttle but the Challenger disaster caused it to be moved to the Delta platform.

Failures and end of life

Originally designed for a 5 year mission, ROSAT continued in its extended mission for a further 4 years before equipment failure forced an end to the mission. For some months after this, ROSAT completed its very last observations before being finally switched off on 12 February 1999.

There is some recent controversy over the precise causes of ROSAT's demise.

On 25 April 1998, failure of the primary star tracker on the X-ray Telescope led to pointing errors that in turn had caused solar overheating. A contingency plan and the necessary software had already been developed to utilise an alternative star tracker attached to the Wide Field Camera.

ROSAT was soon operational again, but with some restrictions to the effectiveness of its tracking and thus its control. It was severely damaged on September 20, 1998 when a reaction wheel in the spacecraft's Attitude Measuring and Control System (AMCS) achieved its maximum rotational speed, losing control of a slew, damaging the High Resolution Imager by exposure to the sun. This failure was initially attributed to the difficulties of controlling the satellite under these difficult circumstances outside its initial design parameters. A reaction wheel operates by changing its rotational velocity, conservation of angular momentum then causing the more massive satellite to rotate in opposition. Their maximum speed is limited by design, which in turn means they are limited in the velocity they can impart to a satellite. "Reaching maximum speed" thus means merely that it cannot impart any more velocity change, not that it's approaching mechanical damage to itself.

As of April 2009, the satellite continues to orbit approximately 390 km above the Earth.

Allegations of cyber-attacks causing the failure

Ten years later in 2008, NASA investigators were reported to have found that the ROSAT failure was linked to a cyber-intrusion at Goddard Space Flight Center. This was also reported through Bruce Schneier's blog, a highly-regarded commentary on IT security issues.

The root of this allegation is a 1999 advisory report by Thomas Talleur, senior investigator for cyber-security at NASA. This advisory is reported to describe a series of attacks from Russia that reached computers in the X-ray Astrophysics Section (i.e. ROSAT's) at Goddard, and took control of computers used for the control of satellies, not just a passive "snooping" attack. The advisory stated:

"Hostile activities compromised [NASA] computer systems that directly and indirectly deal with the design, testing, and transferring of satellite package command-and-control codes."

The advisory is further reported as claiming that the ROSAT incident was "coincident with the intrusion" and that, "Operational characteristics and commanding of the ROSAT were sufficiently similar to other space assets to provide intruders with valuable information about how such platforms are commanded,". Without public access to the advisory, it is obviously impossible to comment in detail. However it does seem to describe a real intrusion, there is a plausible "no attack" explanation for ROSAT's failure, and the report is claimed to link the two incidents as no more than "coincident". IT security remains a significant issue for NASA, other systems including the Earth Observing System having also been attacked.

Chapter 7

GALEX

Galaxy Evolution Explorer (GALEX)

Artist's impression of GALEX

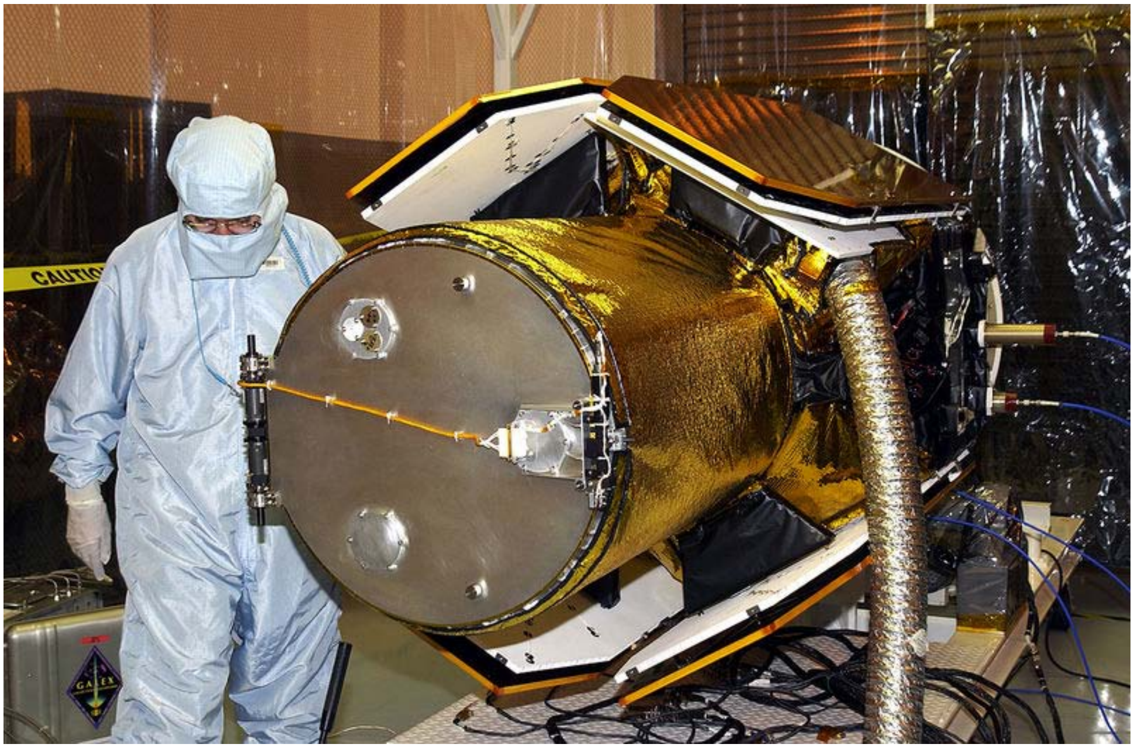
General information

NSSDC ID	2003-017A
Organization	NASA / JPL / Caltech
Major contractors	Orbital Sciences Corporation
Launch date	2003-04-28 11:59:54 UTC

Launched from	~ 60 km offshore from Cape Canaveral Air Force Station
Launch vehicle	L-1011 Stargazer / Pegasus XL
Mass	280 kilograms (620 lb)
Type of orbit	Near-circular
Orbit height	697 kilometres (433 mi)
Location	Low Earth orbit
Telescope style	Richey-Chrétien
Wavelength	135 to 280 nm (Ultraviolet)
Diameter	0.5 m
Focal length	3 m

The **Galaxy Evolution Explorer (GALEX)** is an orbiting ultraviolet space telescope launched on April 28, 2003. A Pegasus rocket placed the craft into a nearly circular orbit at an altitude of 697 kilometres (433 mi) and an inclination to the Earth's equator of 29 degrees.

The first observation was dedicated to the crew of the Space Shuttle Columbia and images the sky in the constellation Hercules, taken on May 21, 2003. This region was selected because it had been directly overhead the shuttle at the time of its last contact with the NASA Mission Control Center.



GALEX at the pre-launch tests

GALEX being mated to a Pegasus XL Rocket

GALEX's Pegasus XL being attached to the L-1011 Stargazer

The Lockheed L-1011 Stargazer take-off with GALEX attached under-belly

Science mission

During its nominal 29-month mission it makes observations at ultraviolet wavelengths to measure the history of star formation in the universe 80 percent of the way back to the Big Bang. Since scientists believe the Universe to be about 13.7 billion years old, the mission will study galaxies and stars across about 10 billion years of cosmic history.

The spacecraft's mission is to observe hundreds of thousands of galaxies, with the goal of determining the distance of each galaxy is from Earth and the rate of star formation in each galaxy. Near- and far-UV emissions as measured by GALEX can indicate the presence of young stars, but may also originate from old stellar populations (e.g. sdB stars).

Partnering with the NASA Jet Propulsion Laboratory (JPL) on the mission are the California Institute of Technology, Orbital Sciences Corporation, University of California, Berkeley, Yonsei University, Johns Hopkins University, Columbia University, and Laboratoire d'Astrophysique de Marseille, France.

Chapter 8

TAUVEX

The **Tel Aviv University Ultraviolet Explorer**, or **TAUVEX**, is a space telescope array designed and constructed in Israel for Tel Aviv University by El-Op , Electro-Optical Industries, Ltd. (a division of Elbit systems), for the exploration of the ultraviolet (UV) sky. TAUVEX was selected in 1988 by the Israel Space Agency (ISA) as its first priority scientific payload. Although originally slated to fly on a national Israeli satellite of the Ofeq series, TAUVEX was shifted in 1991 to fly as part of the Spectrum Roentgen-Gamma (SRG) international observatory, a collaboration of a large number of countries with the Soviet Union (Space Research Institute) leading.

Due to repeated delays of the SRG project, caused by the economic situation in the post-Soviet Russia, ISA decided to shift TAUVEX to a different satellite. In early-2004 ISA signed an agreement with the Indian Space Research Organization (ISRO) to launch TAUVEX on board the Indian technology demonstrator satellite GSAT-4. The launch vehicle slated to be used is the GSLV with a new, cryogenic, upper stage. TAUVEX is a scientific collaboration between Tel Aviv University and the Indian Institute of Astrophysics in Bangalore. Its Principal Investigators are Noah Brosch at Tel Aviv University and Jayant Murthy at the Indian Institute of Astrophysics. Originally, TAUVEX was scheduled to be launched in 2008. but various delays caused the integration with GSAT-4 to take place only in November 2009 for a launch the following year. ISRO decided in January 2010 to remove TAUVEX from the satellite since the Indian-built cryogenic upper stage for GSLV was deemed under-powered to bring GSAT-4 to a geosynchronous orbit. GSAT-4 was subsequently lost in the 15 April 2010 launch failure of GSLV.

Instrumentation

TAUVEX consists of three bore-sighted 20 cm diameter telescopes on a single bezel, called telescopes A, B, and C. Each telescope images the same sky area of 0.9 degree, with an angular resolution of 7-11 arcseconds. The imaging is onto position-sensitive detectors (CsTe cathodes on calcium fluoride windows) equipped with multi-channel plate electron intensifiers. The detectors oversample the point-spread-function by a factor of approximately three. The output is detected by position-sensitive anodes (wedge-and-strip) and is digitized to 12 bits. The full image of each telescope has about 300 resolution elements across its diameter.

The type of cathode (CsTe) assures sensitivity from longward of Lyman α to the atmospheric limit with a peak quantum efficiency of approximately 10%. The operating spectral range is separated in a number of segments selectable with filters. Each telescope [T] is equipped with a four-position filter wheel. Each wheel contains one blocked position (shutter) and three band-selection filters [Fn]. The filter complement, and its distribution among the three telescopes, is as follows:

T	F1	F2	F3	F4
A	BBF	SF1	SF2	Shutter
B	Shutter	SF1	NBF3	SF3
C	BBF	Shutter	SF2	SF3

The approximate characteristics of each filter type are summarized below:

Filter	Wavelength	Width	Normalized transmission
BBF	2300 Å (230 nm)	1000 Å (100 nm)	80%
SF1	1750 Å (175 nm)	400 Å (40 nm)	20%
SF2	2200 Å (200 nm)	400 Å (40 nm)	45%
SF3	2600 Å (260 nm)	500 Å (50 nm)	40%
NBF3	2200 Å (220 nm)	200 Å (20 nm)	30%

TAUVEX was mounted to the GSAT-4 spacecraft on a plate that could rotate around its axis (the MDP), enabling to point the telescopes' line-of-sight to any desired declination. Being on a geostationary satellite, the observation would therefore have been of a scanning type. A 'ribbon' of a constant declination, 0.9 degree wide, would have been scanned as time advanced, completing an entire 360 degree circuit during one sidereal day. In this mode of operation, the dwell time of a source within the detector field of view is a function of the pointing declination and of the exact location in the FOV relative to the detector diameter. The closer a source is to one of the celestial poles, the longer it resides in the TAUVEX field of view during a single scan. The longest theoretically-possible exposure is for sources at |δ|>89°30'; these could be observed all day.

The interface with GSAT-4 ensured that each photon event hitting the detectors would have been transmitted to the ground in real time and processed in a near-real-time pipeline. In-between the photon events a time tag is added every 128 ms. The time between the adjacent time tags is sufficiently short so that the orbital motion of the nadir-pointing platform is much smaller than the TAUVEX virtual pixel.

Given that TAUVEX on GSAT-4 was planned to operate from a geo-synchronous platform that is, essentially, a telecommunications satellite, it is clear that up and downlink telemetry are much less problematic that with other astronomical satellites. In fact, TAUVEX was allowed a dedicated 1 Mbit/s downlink to the ISRO Master Control Facility (MCF) at Hassan, near Bangalore. Command sequences were planned to be uplinked after being generated by IIA and ISRO and the downlink to be analyzed on-line to monitor the payload state of health.

In most situations, TAUVEX would have been able to download all the detected photon events. However, in case of strong straylight or of many bright sources in the field of view, the collected event rate could overload the capacity of the telemetry link. In this case, TAUVEX would have stored the photon events in a solid state memory module (4 GB), from which the events are transmitted at the nominal 1 Mbit/s rate.

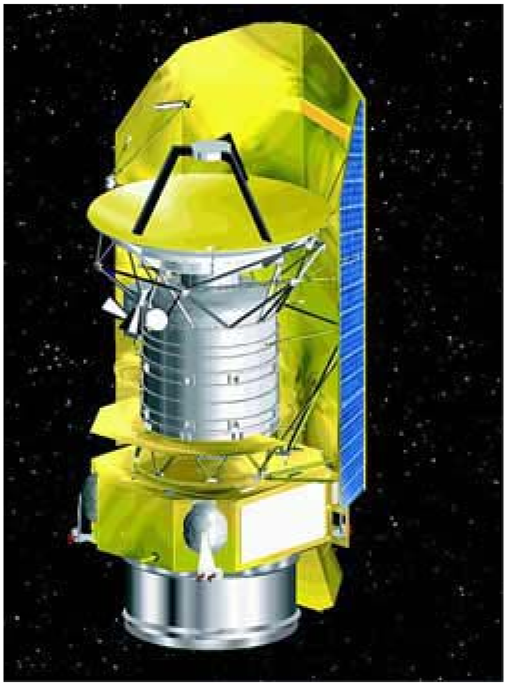
Science with TAUVEX

The science of TAUVEX is based on its unique characteristics: three bore-sighted and independent telescopes able to operate independently, with different filters but measuring the same sources, and reasonably fine time resolution as every detected photon is time-tagged. A unique possibility allows the study of the interstellar dust band at 217.4 nm; the two TAUVEX filters SF2 and NBF3 are centered on this wavelength but have different widths. As the filters are located on different telescopes, it is possible to measure the same sky region with both filters simultaneously, deriving the equivalent width of the band for every star in the field of view. The use of TAUVEX as a scientific instrument is the result of calibration on the ground .This calibration was very difficult and produced unreliable results. The Principal Investigators planned to repeat and improve the calibration in space, following the launch.

Chapter 9

Herschel Space Observatory

Herschel Space Observatory



General information

NSSDC ID	2009-026A
Organization	European Space Agency (ESA) NASA
Major contractors	Thales Alenia Space
Launch date	2009:05:14, 13:12:02 UTC
Launched from	Guiana Space Centre French Guiana

Launch vehicle	Ariane 5 ECA
Mission length	planned: 3 years elapsed: 1 year, 8 months, and 21 days
Mass	3,300 kg (7,300 lb)
Type of orbit	Lissajous orbit
Orbit height	1,500,000 km (930,000 mi)
Orbit period	1 year
Orbit velocity	7,500 m/s (27,000 km/h)
Location	Lagrangian point L_2
Telescope style	Ritchey-Chrétien
Wavelength	60-670 µm (far-infrared)
Diameter	3,500 mm (140 in), f/0.5 (Primary Mirror)
Collecting area	9.6 m^2 (103 sq ft)
Focal length	28.5 m (94 ft), f/8.7
	Instruments
HIFI	Heterodyne Instrument for the Far Infrared
PACS	Photodetector Array Camera and Spectrometer
SPIRE	Spectral and Photometric Imaging Receiver

The **Herschel Space Observatory** is a European Space Agency space observatory sensitive to the far infrared and submillimetre wavebands. It is the largest space telescope ever launched carrying a single mirror of 3.5 meter in diameter.

The observatory was carried into orbit in May 2009, reaching the second Lagrangian point (L2) of the Earth-Sun system, 1,500,000 kilometres (930,000 mi) from the Earth, about two months later. Herschel is named after Sir William Herschel, the discoverer of the infrared spectrum and planet Uranus, and his sister and collaborator Caroline.

The Herschel Observatory is capable of seeing the coldest and dustiest objects in space; for example, cool cocoons where stars form and dusty galaxies just starting to bulk up with new stars. The observatory will sift through star-forming clouds—the "slow cookers" of star ingredients—to trace the path by which potentially life-forming molecules, such as water, form. The United States through NASA is participating in the ESA built and operated observatory. It is the fourth 'cornerstone' mission in the ESA science program, along with Rosetta, Planck, and the Gaia mission.

Science

Herschel will specialise in collecting light from objects in our Solar System as well as the Milky Way and even extragalactic objects billions of light-years away, such as newborn galaxies, and is charged with four primary areas of investigation:

- Galaxy formation in the early universe and the evolution of galaxies;
- Star formation and its interaction with the interstellar medium;
- Chemical composition of atmospheres and surfaces of Solar System bodies, including planets, comets and moons;
- Molecular chemistry across the universe.

Instrumentation

The mission, formerly titled the **Far Infrared and Sub-millimetre Telescope** (**FIRST**), involves the first space observatory to cover the full far infrared and submillimetre waveband. At 3.5 meters wide, its telescope incorporates the largest mirror (made not from glass but from sintered silicon carbide) ever deployed in space. The light is focused onto three instruments with detectors kept at temperatures below 2 K (−271 °C). The instruments are cooled with liquid helium, boiling away in a near vacuum at a temperature of approximately 1.4 K (−272 °C). The 2,000-litre supply of helium on board the spacecraft will limit its operational lifetime, nonetheless it is expected to be operational for at least 3 years.

Herschel carries three detectors:

PACS (Photodetecting Array Camera and Spectrometer)

An imaging camera and low-resolution spectrometer covering wavelengths from 55 to 210 micrometres. The spectrometer has a spectral resolution between R=1000 and R=5000 and is able to detect signals as weak as −63 dB. It operates as an integral field spectrograph, combining spatial and spectral resolution. The imaging camera can image simultaneously in two bands (either 60–85/85–130 micrometres and 130–210 micrometres) with a detection limit of a few millijanskys.

Herschel in a clean room

SPIRE (Spectral and Photometric Imaging Receiver)

An imaging camera and low-resolution spectrometer covering 194 to 672 micrometre wavelength. The spectrometer has a resolution between R=40 and R=1000 at a wavelength of 250 micrometres and is able to image point sources with brightnesses around 100 millijanskys (mJy) and extended sources with brightnesses of around 500 mJy. The imaging camera has three bands, centered at 250, 350 and 500 micrometres, each with 139, 88 and 43 pixels respectively. It should be able to detect point sources with brightness above 2 mJy and between 4 and 9 mJy for extended sources. A prototype of the SPIRE imaging camera flew on the BLAST high-altitude balloon. NASA's Jet Propulsion Laboratory in

Pasadena, Calif., developed and built the "spider web" bolometers for this instrument, which is 40 times more sensitive than previous versions.

HIFI (Heterodyne Instrument for the Far Infrared)

A heterodyne detector which is able to electronically separate radiation of different wavelengths, giving a spectral resolution as high as $R=10^7$. The spectrometer can be operated within two wavelength bands, from 157 to 212 micrometres and from 240 to 625 micrometres. NASA developed and built the mixers, local oscillator chains and power amplifiers for this instrument.

Service module

A common service module (SVM) was designed and built by Thales Alenia Space in its Turin plant, for the Herschel and Planck missions combined into one single program.

Structurally, the Herschel and Planck SVM's are very similar. Both SVM's are of octagonal shape and for both, each panel is dedicated to accommodate a designated set of warm units, while taking into account the dissipation requirements of the different warm units, of the instruments as well as the spacecraft.

Furthermore, on both spacecraft a common design for the avionics, the attitude control and measurement system (ACMS) and the command and data management system (CDMS), and power subsystem and the tracking, telemetry and command subsystem (TT&C) has been achieved.

All spacecraft units on the SVM are redundant.

Power subsystem

On each spacecraft, the power subsystem consists of the solar array, employing triple-junction solar cells, a battery and the power control unit (PCU). It is designed to interface with the 30 sections of each solar array, provide a regulated 28 V bus, distribute this power via protected outputs and to handle the battery charging and discharging.

For Herschel, the solar array is fixed on the bottom part of the baffle designed to protect the cryostat from the sun. The three-axis attitude control system maintains this baffle in direction of the sun. The top part of this baffle is covered with optical solar reflector (OSR) mirrors reflecting 98% of the sun energy, avoiding heating of the cryostat.

Attitude and orbit control

This function is performed by the attitude control computer (ACC) which is the platform for the ACMS. It is designed to fulfil the pointing and slewing requirements of the Herschel and Planck payload.

The Herschel spacecraft is three-axis stabilized, the absolute pointing error needs to be less than 3.7 arc sec.

The main sensor of the line of sight in both spacecraft is the star tracker.

Launch and orbit

The spacecraft, built in the Cannes Mandelieu Space Center, under Thales Alenia Space Contractorship, was successfully launched from the Guiana Space Centre in French Guiana at 13:12:02 UTC on 14 May 2009, aboard an Ariane 5 rocket, along with the Planck spacecraft, and placed on a very elliptical orbit (perigee: 270.0 km (intended 270.0±4.5), apogee: 1,197,080 km (intended 1,193,622±151,800), inclination 5.99 deg (intended 6.00±0.06)), on its way towards the second Lagrangian point.

On June 14, 2009, ESA successfully sent the command for the cryocover to open which will allow the PACS system to see the sky and transmit images in a few weeks. The lid had to remain closed until the telescope was well into space to prevent contamination. Herschel is reported to have completed 90% of the distance to its orbit 1.5 million km away from Earth.

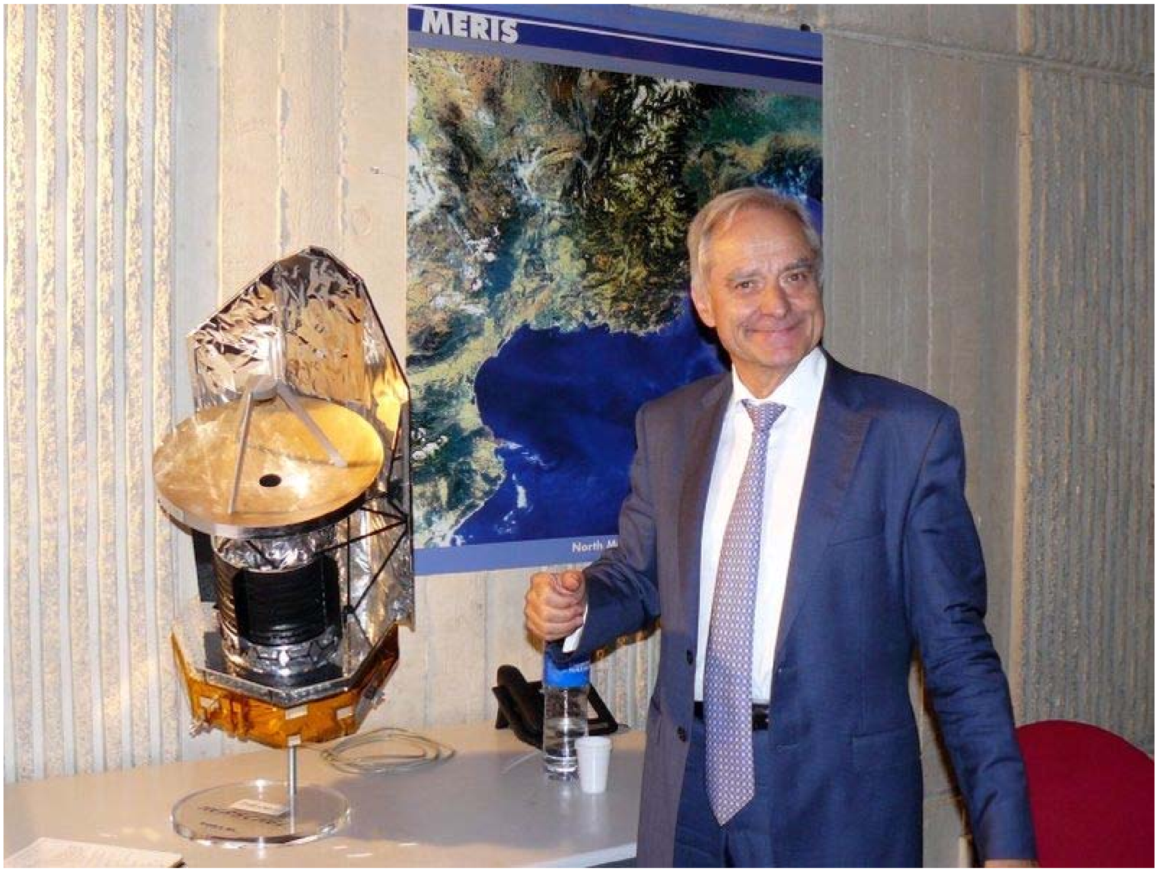
Five days later the first set of test photos, depicting M51 Group, was published by ESA.

In mid-July 2009, approximately sixty days after launch, it entered a Lissajous orbit of 800,000 km average radius around the second Lagrangian point (L2) of the Earth-Sun system, 1.5 million kilometres from the Earth.

Operational mission

On 21 July 2009, Herschel commissioning was declared successful, allowing the start of the operational phase. A formal handover of the overall responsibility of Herschel was declared from the programme manager Thomas Passvogel to the mission manager Johannes Riedinger.

Discoveries



André Brahic, astronomer, one of the fathers of **Herschel** and Planck programmes, during a conference he made in the Cannes Mandelieu Space Center

Herschel was instrumental in the discovery of an unknown and unexpected step in the star forming process. The initial confirmation and later verification via help from ground based telescopes of a vast hole of empty space, previously believed to be a dark nebula, in the area NGC 1999 shed new light in the way newly forming star regions discard the material which surrounds it.

On July 16, 2010, a special issue of *Astronomy and Astrophysics* was published with 152 papers on initial results from the observatory.

Chapter 10

Spitzer Space Telescope

Spitzer Space Telescope

The Spitzer Space Telescope prior to launch

General information

NSSDC ID	2003-038A
Organization	NASA / JPL / Caltech
Major contractors	Lockheed Martin Ball Aerospace
Launch date	25 August 2003

Launched from	Cape Canaveral, Florida
Launch vehicle	Delta II 7920H ELV
Mission length	2.5 to 5+ years (7 years, 5 months, and 10 days elapsed)
Mass	950 kg (2,100 lb)
Type of orbit	Heliocentric
Orbit period	1 year
Location	Orbiting the Sun
Telescope style	Ritchey-Chrétien
Wavelength	3 to 180 micrometers
Diameter	0.85 m (2 ft 9 in)
Focal length	10.2 m
	Instruments
IRAC	infrared camera
IRS	infrared spectrometer
MIPS	far infrared detector arrays

The **Spitzer Space Telescope (SST)**, formerly the **Space Infrared Telescope Facility (SIRTF)** is an infrared space observatory launched in 2003. It is the fourth and final of NASA's Great Observatories.

The planned mission period was to be 2.5 years with a pre-launch expectation that the mission could extend to five or slightly more years until the onboard liquid helium supply was exhausted. This occurred on 15 May 2009. Without liquid helium to cool the telescope to the very cold temperatures needed to operate, most instruments are no longer usable. However, the two shortest wavelength modules of the IRAC camera are still operable with the same sensitivity as before the cryogen was exhausted, and will continue to be used in the Spitzer Warm Mission.

In keeping with NASA tradition, the telescope was renamed after successful demonstration of operation, on December 18, 2003. Unlike most telescopes which are named after famous deceased astronomers by a board of scientists, the name for SIRTF was obtained from a contest open to the general public.

The contest led to the telescope being named in honor of Lyman Spitzer, one of the 20th century's great scientists. Though he was not the first to propose the idea of the space telescope (Hermann Oberth being the first, in *Wege zur Raumschiffahrt,* 1929, and also in *Die Rakete zu den Planetenräumen,* 1923), Spitzer wrote a 1946 report for RAND describing the advantages of an extraterrestrial observatory and how it could be realized with available (or upcoming) technology. He has been cited for his pioneering contributions to rocketry and astronomy, as well as *"his vision and leadership in articulating the advantages and benefits to be realized from the Space Telescope Program."*

The US$800 million Spitzer was launched from Cape Canaveral Air Force Station, on a Delta II 7920H ELV rocket, Monday, 25 August 2003 at 13:35:39 UTC-5 (EDT).

It follows a rather unusual orbit, heliocentric instead of geocentric, trailing and drifting away from Earth's orbit at approximately 0.1 astronomical unit per year (a so-called "earth-trailing" orbit). The primary mirror is 85 centimetres (33 in) in diameter, *f*/12 and made of beryllium and was cooled to 5.5 K (−449.77 °F). The satellite contains three instruments that allowed it to perform imaging and photometry from 3 to 180 micrometers, spectroscopy from 5 to 40 micrometers, and spectrophotometry from 5 to 100 micrometers.

History

By the early 1970s, astronomers began to consider the possibility of placing an infrared telescope above the obscuring effects of Earth's atmosphere. In 1979, a National Research Council of the National Academy of Sciences report, *A Strategy for Space Astronomy and Astrophysics for the 1980s*, identified a Space Infrared Telescope Facility (SIRTF) as "one of two major astrophysics facilities [to be developed] for Spacelab", a Shuttle-borne platform. Anticipating the major results from an upcoming Explorer satellite and from the Shuttle mission, the report also favored the "study and development of ... long-duration spaceflights of infrared telescopes cooled to cryogenic temperatures." The launch in January 1983 of the Infrared Astronomical Satellite, jointly developed by the United States, the Netherlands, and the United Kingdom, to conduct the first infrared survey of the sky, whetted the appetites of scientists worldwide for follow-up space missions capitalizing on the rapid improvements in infrared detector technology.

Earlier infrared observations had been made by both space-based and ground-based observatories. Ground-based observatories have the drawback that at infrared wavelengths or frequencies, both the Earth's atmosphere and the telescope itself will radiate (glow) strongly. Additionally, the atmosphere is opaque at most infrared wavelengths. This necessitates lengthy exposure times and greatly decreases the ability to detect faint objects. It could be compared to trying to observe the stars at noon. Previous space-based satellites (such as IRAS, the Infrared Astronomical Satellite, and ISO, the Infrared Space Observatory) were operational during the 1980s and 1990s and great advances in astronomical technology have been made since then.

Most of the early concepts envisioned repeated flights aboard the NASA Space Shuttle. This approach was developed in an era when the Shuttle program was expected to support weekly flights of up to 30 days duration. A May 1983 NASA proposal described SIRTF as a Shuttle-attached mission, with an evolving scientific instrument payload. Several flights were anticipated with a probable transition into a more extended mode of operation, possibly in association with a future space platform or space station. SIRTF would be a 1-meter class, cryogenically cooled, multi-user facility consisting of a telescope and associated focal plane instruments. It would be launched on the Space Shuttle and remain attached to the Shuttle as a Spacelab payload during astronomical observations, after which it would be returned to Earth for refurbishment prior to re-flight. The first flight was expected to occur about 1990, with the succeeding flights anticipated beginning approximately one year later. However, the Spacelab-2 flight aboard STS-51-F showed that the Shuttle environment was poorly suited to an onboard infrared telescope due to contamination from the relatively "dirty" vacuum associated with the orbiters. By September 1983 NASA was considering the "possibility of a long duration [free-flyer] SIRTF mission".

Spitzer is the only one of the Great Observatories not launched by the Space Shuttle, which had been originally intended. However after the 1986 Challenger disaster, the Centaur LH2/LOX upper stage, which would have been required to place it in its final orbit, was banned from Shuttle use. The mission underwent a series of redesigns during the 1990s, primarily due to budget considerations. This resulted in a much smaller but still fully capable mission which could use the smaller Delta II expendable launch vehicle.

Logo

One of the most important advances of this redesign was an Earth-trailing orbit. Cryogenic satellites that require liquid helium (LHe, $T \approx 4$ K) temperatures in near-Earth orbit are typically exposed to a large heat load from the Earth, and consequently entail large usage of LHe coolant, which then tends to dominate the total payload mass and limits mission life. Placing the satellite in solar orbit far from Earth allowed innovative passive cooling such as the sun shield, against the single remaining major heat source to drastically reduce the total mass of helium needed, resulting in an overall smaller lighter payload, with major cost savings. This orbit also simplifies telescope pointing, but does require the Deep Space Network for communications.

The primary instrument package (telescope and cryogenic chamber) was developed by Ball Aerospace & Technologies Corp., in Boulder, CO. The individual instruments were developed jointly by industrial, academic, and government institutions, the principals being Cornell, the University of Arizona, the Smithsonian Astrophysical Observatory, Ball Aerospace, and Goddard Spaceflight Center. The spacecraft was built by Lockheed Martin. The mission is operated and managed by the Jet Propulsion Laboratory and the Spitzer Science Center, located on the Caltech campus in Pasadena, California.

Instruments

Spitzer has three instruments on-board:

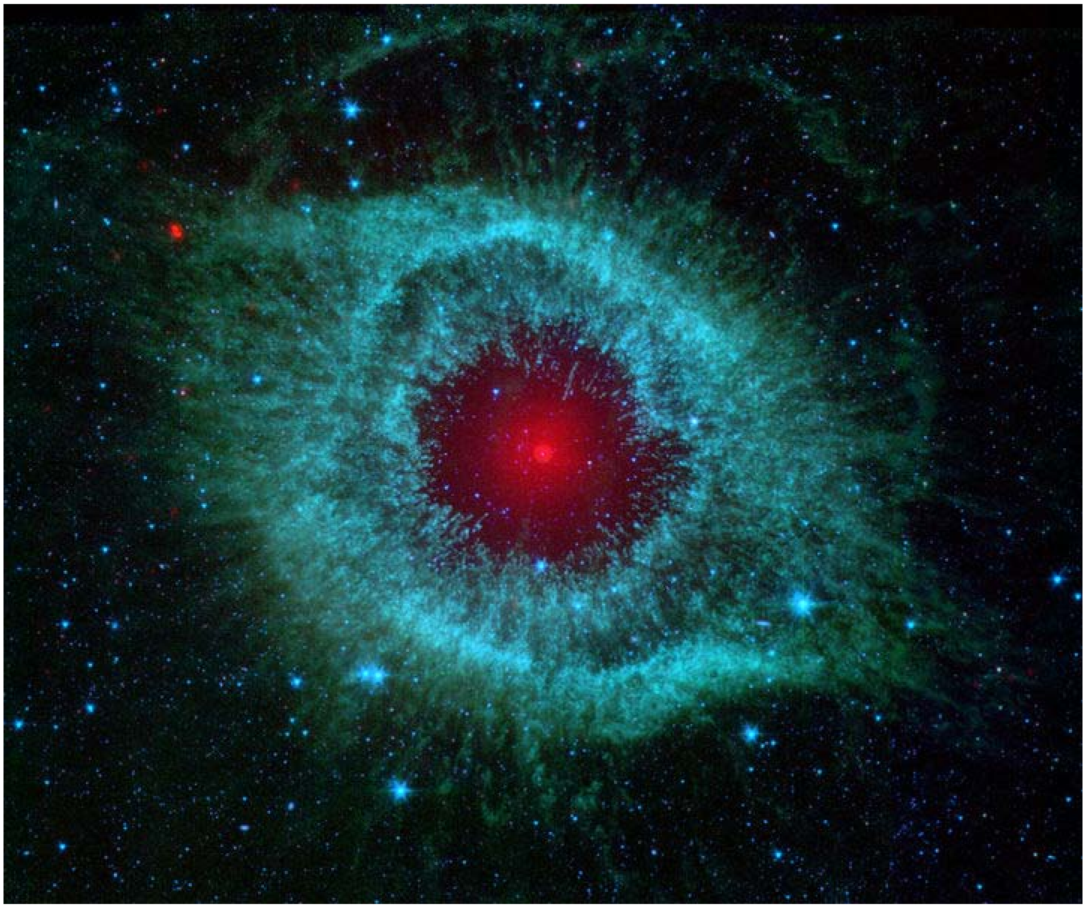
- IRAC (**I**nfra**r**ed **A**rray **C**amera), an infrared camera which operates simultaneously on four wavelengths (3.6 µm, 4.5 µm, 5.8 µm and 8 µm). Each module uses a 256 × 256 pixel detector—the short wavelength pair use indium antimonide technology, the long wavelength pair use arsenic-doped silicon impurity band conduction technology. The two shorter wavelength bands (3.6 um & 4.5 um) for this instrument remain productive after LHe depletion in the spring of 2009, at the telescope equilibrium temperature of around 30 K, so IRAC continues to operate as the "Spitzer Warm Mission".

- IRS (**I**nfra**r**ed **S**pectrograph), an infrared spectrometer with four sub-modules which operate at the wavelengths 5.3-14 µm (low resolution), 10-19.5 µm (high resolution), 14-40 µm (low resolution), and 19-37 µm (high resolution). Each module uses a 128x128 pixel detector—the short wavelength pair use arsenic-doped silicon blocked impurity band technology, the long wavelength pair use antimony-doped silicon blocked impurity band technology.

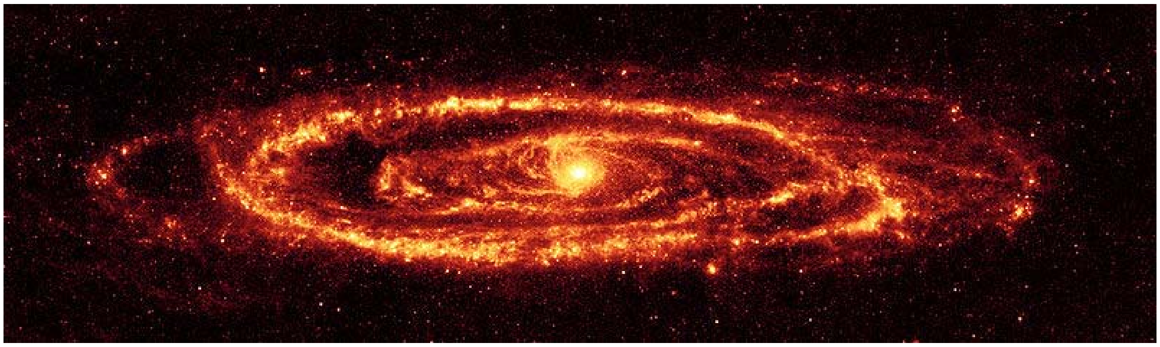
- MIPS (**M**ultiband **I**maging **P**hotometer for **S**pitzer), three detector arrays in the far infrared (128 × 128 pixels at 24 µm, 32 × 32 pixels at 70 µm, 2 × 20 pixels at 160 µm). The 24 µm detector is identical to one of the IRS short wavelength modules. The 70 µm detector uses gallium-doped germanium technology, and the 160 µm detector also uses gallium-doped germanium, but with mechanical stress added to each pixel to lower the bandgap and extend sensitivity to this long wavelength.

As an example of data from the different instruments, the nebula Henize 206 was imaged in 2004, allowing comparison of images from each device.

Results



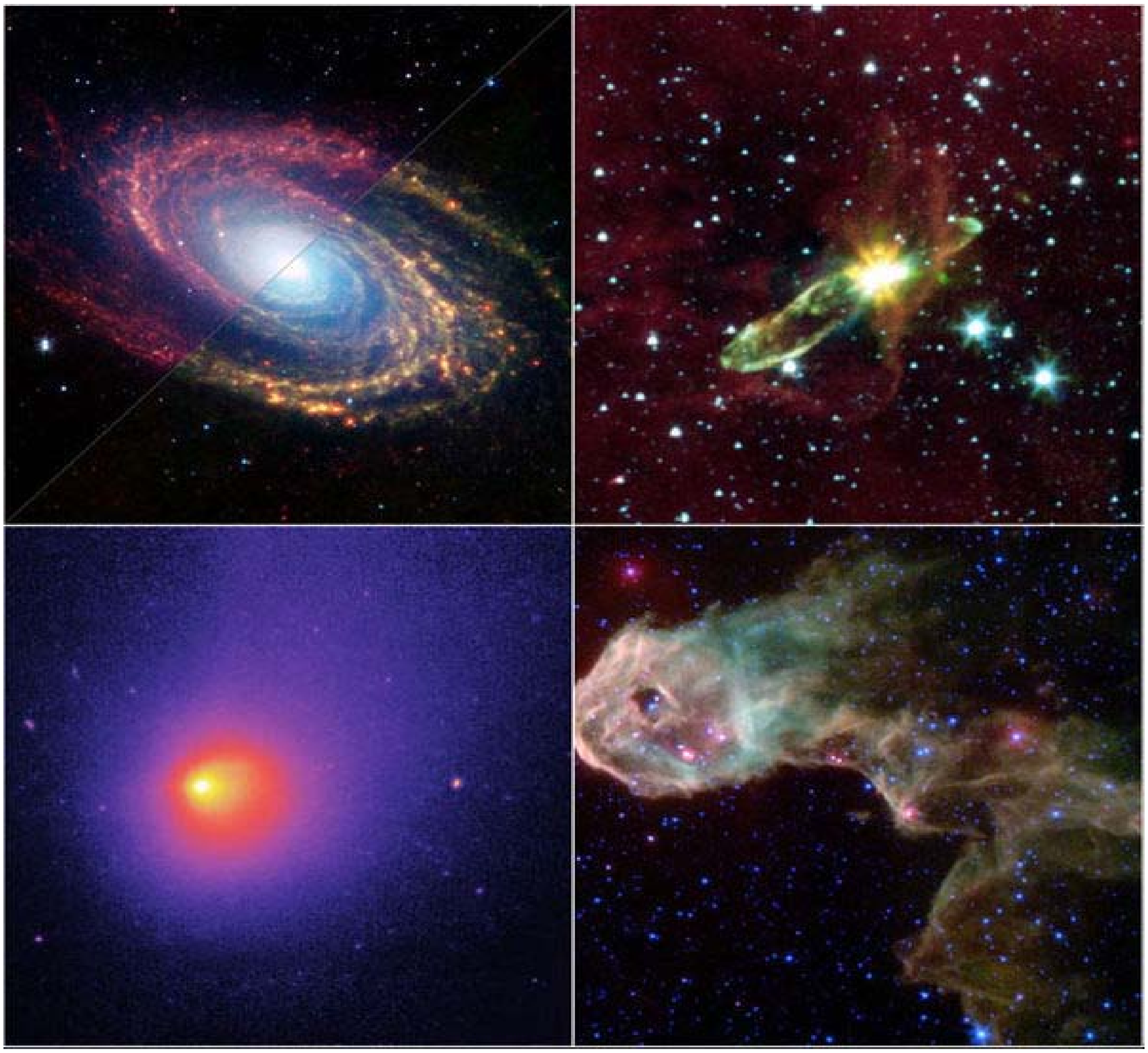
The Helix Nebula. Blue shows infrared light of 3.6 to 4.5 micrometers; green shows infrared light of 5.8 to 8 micrometers; and red shows infrared light of 24 micrometers.



The Andromeda Galaxy (M31) taken by Spitzer in infrared, MIPS, 24 micrometers 2004 August 25.

The first images taken by SST were designed to show off the abilities of the telescope and showed a glowing stellar nursery; a big swirling, dusty galaxy; a disc of planet-forming debris; and organic material in the distant universe. Since then, many monthly press releases have highlighted Spitzer's capabilities, as the NASA and ESA images do for the Hubble Space Telescope.

As one of its most noteworthy observations, in 2005, SST became the first telescope to directly capture the light from extrasolar planets, namely the "hot Jupiters" HD 209458b and TrES-1. (It did not resolve that light into actual images though.) This was the first time extrasolar planets had actually been visually seen; earlier observations had been indirectly made by drawing conclusions from behaviors of the stars the planets were orbiting. The telescope also discovered in April 2005 that Cohen-kuhi Tau/4 had a planetary disk that was vastly younger and contained less mass than previously theorized, leading to new understandings of how planets are formed.



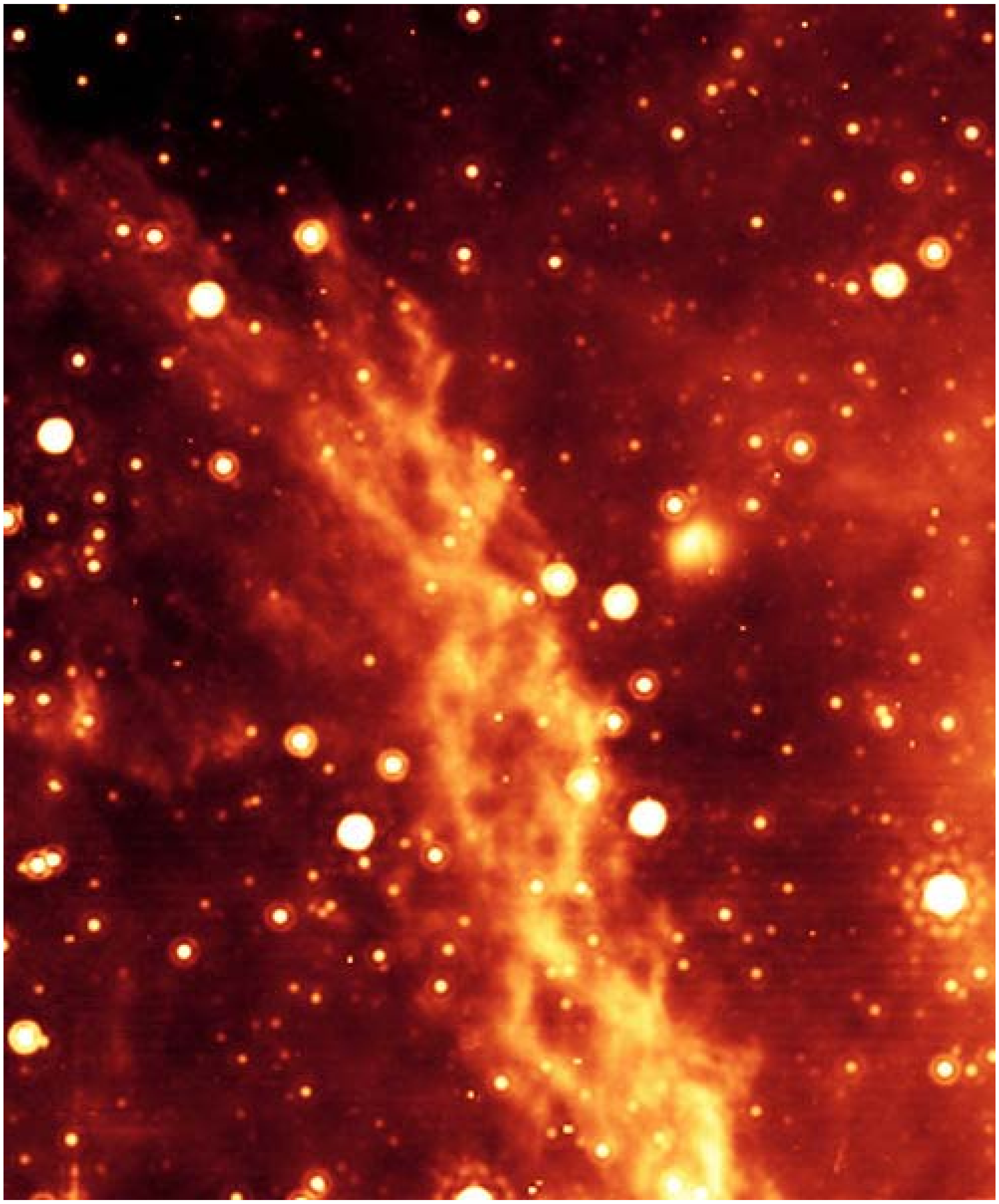
Clockwise from the upper-left: infrared views of spiral galaxy Messier 81; embedded outflows from Herbig-Haro 46/47 protostar; protostars uncovered in multiple views of dark globule in IC1396; and Comet Schwassmann-Wachmann 1.

While some time on the telescope is reserved for participating institutions and crucial projects, astronomers around the world also have the opportunity to submit proposals for observing time. Important targets include forming stars (young stellar objects, or YSOs), planets, and other galaxies. Images are freely available for educational and journalistic purposes.

In 2004, it was reported that Spitzer had spotted a faintly glowing body that may be the youngest star ever seen. The telescope was trained on a core of gas and dust known as L1014 which had previously appeared completely dark to ground-based observatories and to ISO (Infrared Space Observatory), a predecessor to Spitzer. The advanced technology of Spitzer revealed a bright red hot spot in the middle of L1014.

Scientists from the University of Texas at Austin, who discovered the object, believe the hot spot to be an example of early star development, with the young star collecting gas and dust from the cloud around it. Early speculation about the hot spot was that it might have been the faint light of another core that lies 10 times further from Earth but along the same line of sight as L1014. Follow-up observation from ground-based near-infrared observatories detected a faint fan-shaped glow in the same location as the object found by Spitzer. That glow is too feeble to have come from the more distant core, leading to the conclusion that the object is located within L1014. (Young *et al.*, 2004)

In 2005, astronomers from the University of Wisconsin at Madison and Whitewater determined, on the basis of 400 hours of observation on the Spitzer Space Telescope, that the Milky Way Galaxy has a more substantial bar structure across its core than previously recognized.



Artificial color image of the Double Helix Nebula, thought to be generated at the galactic center by magnetic torsion 1000 times greater than the sun's.

Also in 2005, astronomers Alexander Kashlinsky and John Mather of NASA's Goddard Space Flight Center reported that one of Spitzer's earliest images may have captured the light of the first stars in the universe. An image of a quasar in the Draco constellation, intended only to help calibrate the telescope, was found to contain an infrared glow after the light of known objects was removed. Kashlinsky and Mather are convinced that the numerous blobs in this glow are the light of stars that formed as early as 100 million years after the big bang, red shifted by cosmic expansion.

In March 2006, astronomers reported an 80-light-year-long nebula near the center of the Milky Way Galaxy, the Double Helix Nebula, which is, as the name implies, twisted into a double spiral shape. This is thought to be evidence of massive magnetic fields generated by the gas disc orbiting the supermassive black hole at the galaxy's center, 300 light years from the nebula and 25,000 light years from Earth. This nebula was discovered by the Spitzer Space Telescope, and published in the magazine *Nature* on March 16, 2006.

In May 2007, astronomers successfully mapped the atmospheric temperature of HD 189733 b, thus obtaining the first map of some kind of an extrasolar planet.

A cluster of new stars forming in the Serpens South cloud

Since September 2006 the telescope participates in a series of surveys called the Gould Belt Survey, observing the Gould's Belt region in multiple wavelengths. The first set of observations by the Spitzer Space Telescope were completed from September 21, 2006 through September 27. Resulting from these observations, the team of astronomers led by Dr. Robert Gutermuth, of the Harvard-Smithsonian Center for Astrophysics reported the discovery of Serpens South, a cluster of 50 young stars in the Serpens constellation.

In August 2009, the telescope found evidence of a high-speed collision between two burgeoning planets orbiting a young star.

In October 2009, astronomers published findings of the "Phoebe ring" of Saturn, which was found with the telescope; the ring is a huge, tenuous disc of material extending from 128 to 207 times the radius of Saturn.

GLIMPSE and MIPSGAL surveys

GLIMPSE, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, is a survey spanning 300° of the inner Milky Way galaxy. It consists of approximately 444,000 images taken at 4 separate wavelengths using the Infrared Array Camera.

MIPSGAL is a similar survey covering 278° of the galactic disk at longer wavelengths.

On June 3, 2008, scientists unveiled the largest, most detailed infra-red portrait of the Milky Way, created by stitching together more than 800,000 snapshots, at the 212th meeting of the American Astronomical Society in St.Louis, Missouri.

Chapter 11

Miniaturized Satellite and Reconnaissance Satellite

Miniaturized satellite

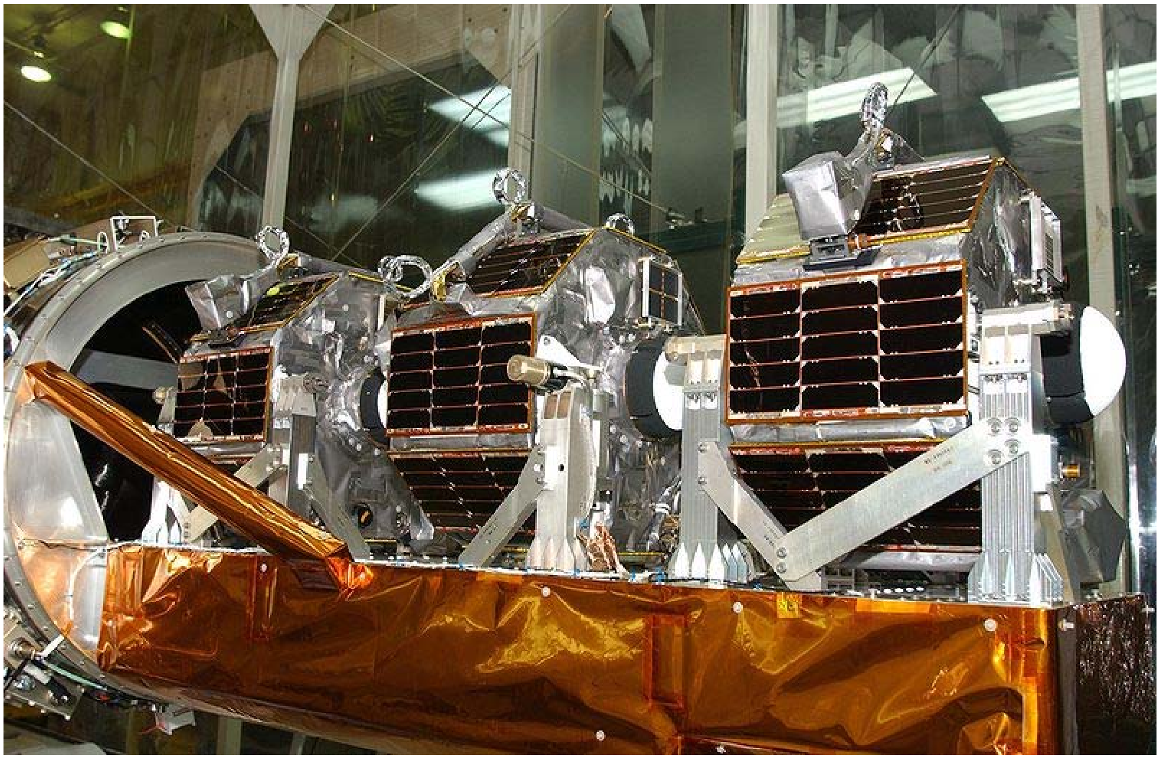
Miniaturized satellites or **small satellites** are artificial satellites of unusually low weights and small sizes, usually under 500 kg (1,100 lb). While all such satellites can be referred to as *small satellites*, different classifications are used to categorize them based on mass.

One reason for miniaturizing satellites is to reduce the cost: heavier satellites require larger rockets of greater cost to finance; smaller and lighter satellites require smaller and cheaper launch vehicles and can sometimes be launched in multiples. They can also be launched 'piggyback', using excess capacity on larger launch vehicles. Miniaturized satellites allow for cheaper designs as well as ease of mass production, although few satellites of any size other than 'communications constellations' where dozens of satellites are used to cover the globe, have been mass produced in practice.

Besides the cost issue, the main rationale for the use of miniaturized satellites is the opportunity to enable missions that a larger satellite could not accomplish, such as:

- Constellations for low data rate communications
- Using formations to gather data from multiple points
- In-orbit inspection of larger satellites.

Classification groups



3 microsatellites of Space Technology 5

Minisatellite

The term "minisatellite" usually refers to an artificial satellite with a "wet mass" (including fuel) between 100 and 500 kg (220 and 1,100 lb), though these are usually simply called "small satellites". Minisatellites are usually simpler but use the same technologies as larger satellites.

Microsatellite

Microsatellite or "microsat" is usually applied to the name of an artificial satellite with a wet mass between 10 and 100 kg (22 and 220 lb). However, this is not an official convention and sometimes microsats can refer to satellites larger than that. Sometimes designs or proposed designs of these types have microsatellites working together or in a formation. The generic term "small satellite" is also sometimes used.

Nanosatellite

The term "nanosatellite" or "nanosat" is usually applied to the name of an artificial satellite with a wet mass between 1 and 10 kg (2.2 and 22 lb). Again designs and proposed designs of these types usually have multiple nanosatellites working together or in formation (sometimes the term "swarm" is applied). Some designs require a larger "mother" satellite for communication with ground controllers or for launching and docking with nanosatellites.

Picosatellite

Picosatellite or "picosat" (not to be confused with the PICOSat series of microsatellites) is usually applied to the name of an artificial satellite with a wet mass between .1 and 1 kg (0.22 and 2.2 lb). Again designs and proposed designs of these types usually have multiple picosatellites working together or in formation (sometimes the term "swarm" is applied). Some designs require a larger "mother" satellite for communication with ground controllers or for launching and docking with picosatellites. The CubeSat design, with 1 kg maximum mass, is an example of a large picosatellite (or minimum nanosat).

Technical challenges

Micro/nanosats usually require innovative propulsion, attitude control, communication and computation systems.

Larger satellites usually use monopropellants or bipropellant combustion rockets for propulsion and attitude control; these systems are complex and require a minimal amount of volume to surface area to dissipate heat. These systems are used on larger microsats, while other micro/nanosats have to use electric propulsion, compressed gas, vaporizable liquids such as butane or carbon dioxide or other innovative propulsion systems that are simple, cheap and scalable.

Microsats can use conventional radio systems in UHF, VHF, the S-band and X-band, although often miniaturized using more up-to-date technology as compared to larger satellites. Tiny satellites such as nanosats and small microsats may lack the power supply or mass for large conventional radio transponders, and various miniaturized or innovative communications systems have been proposed, such a laser receivers, antenna arrays and satellite to satellite communication networks. Few of these have been demonstrated in practice.

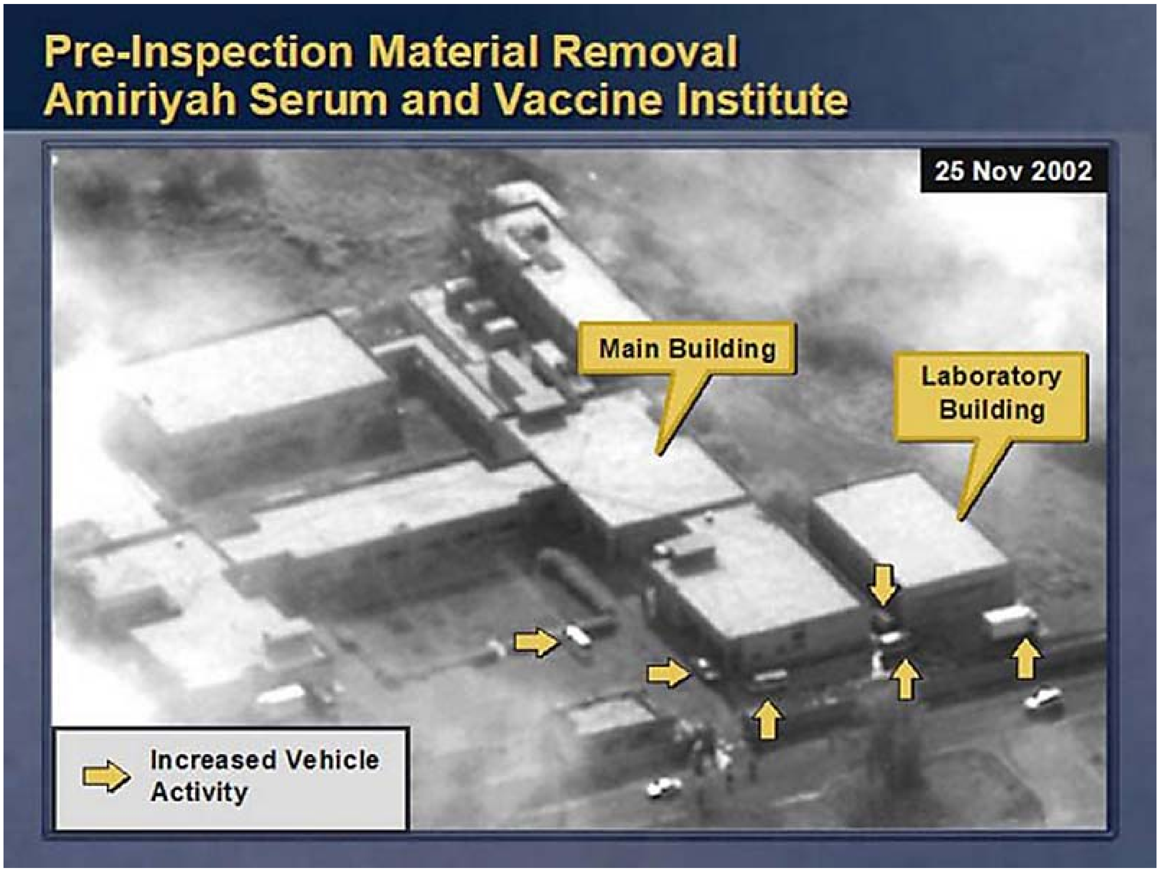
Electronics need to be rigorously tested and modified to be "space hardened" or resistant to the outer space environment (vacuum, microgravity, thermal extremes, and radiation exposure). Miniaturized satellites allow for the opportunity to test new hardware with reduced expense in testing. Furthermore, since the overall cost risk in the mission is much lower, more up-to-date but less space-proven technology can be incorporated into micro and nanosats than can be used in much larger, more expensive missions with less appetite for risk.

Manufacturers of microsatellites include SpaceDev and Surrey Satellite Technology Ltd.

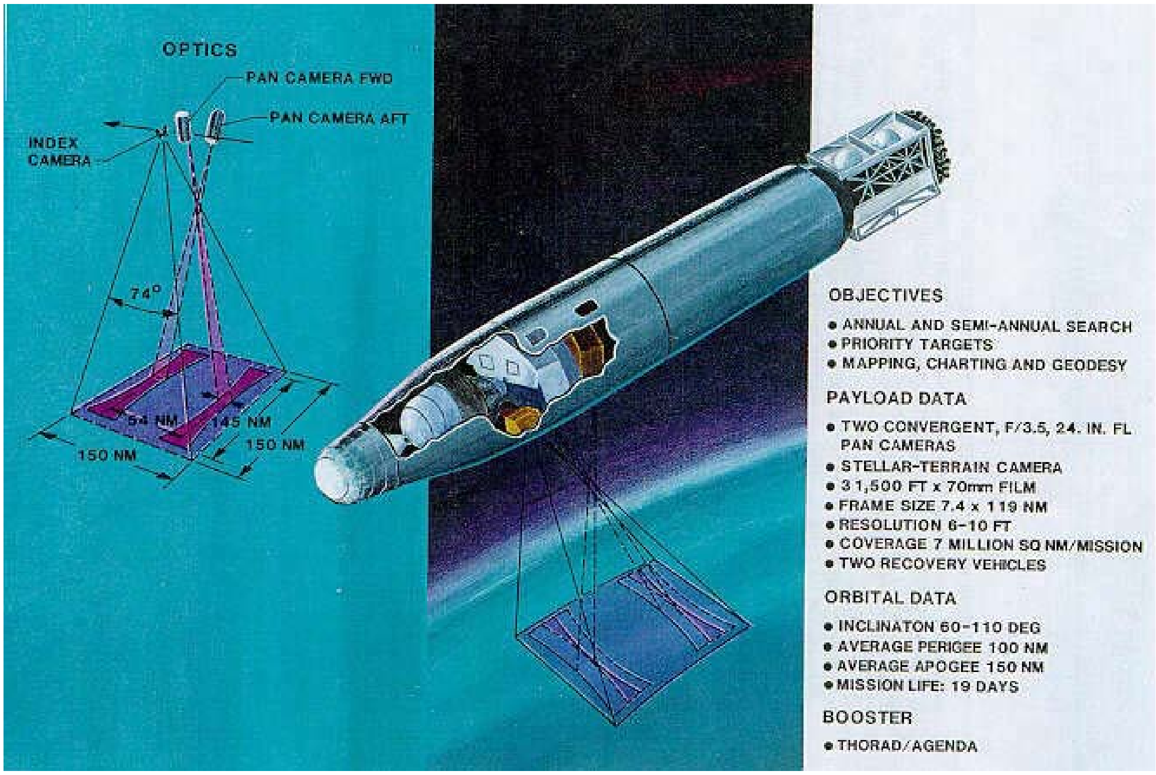
Manufacturers of nanosatellites include GomSpace, ISIS and UTIAS-SFL.

SuitSat, a retired spacesuit fitted with some basic instrumentation and radio transmitting equipment and released into orbit in 2006, was an unconventional example of a low-cost microsatellite test platform.

Reconnaissance satellite



Serum and Vaccine Institute in Al-A'amiriya, Iraq, as imaged by a US reconnaissance satellite in November 2002.



OBJECTIVES
- ANNUAL AND SEMI-ANNUAL SEARCH
- PRIORITY TARGETS
- MAPPING, CHARTING AND GEODESY

PAYLOAD DATA
- TWO CONVERGENT, F/3.5, 24. IN. FL PAN CAMERAS
- STELLAR-TERRAIN CAMERA
- 31,500 FT x 70mm FILM
- FRAME SIZE 7.4 x 119 NM
- RESOLUTION 6-10 FT
- COVERAGE 7 MILLION SQ NM/MISSION
- TWO RECOVERY VEHICLES

ORBITAL DATA
- INCLINATON 60-110 DEG
- AVERAGE PERIGEE 100 NM
- AVERAGE APOGEE 150 NM
- MISSION LIFE: 19 DAYS

BOOSTER
- THORAD/AGENDA

KH-4B Corona satellite

U.S. Lacrosse radar spy satellite under construction

A model of a German SAR-Lupe reconnaissance satellite inside a Cosmos-3M rocket

Reconnaissance satellite is an Earth observation satellite or communications satellite deployed for military or intelligence applications.

These are essentially space telescopes that are pointed toward the Earth instead of toward the stars. The first generation type (i.e. Corona and Zenit) took photographs, then ejected canisters of photographic film, which would descend to earth.

Corona capsules were retrieved in mid-air as they floated down on parachutes. Later spacecraft had digital imaging systems and downloaded the images via encrypted radio links.

In the United States, most information available is on programs that existed up to 1972. Some information about programs prior to that time are still classified, and a small trickle of information is available on subsequent missions.

A few up-to-date reconnaissance satellite images have been declassified on occasion, or leaked, as in the case of KH-11 photographs which were sent to *Jane's Defence Weekly* in 1985.

Origins

On March 16, 1955, the United States Air Force officially ordered the development of an advanced reconnaissance satellite to provide continuous surveillance of 'preselected areas of the earth' in order 'to determine the status of a potential enemy’s war-making capability'. In October 1957, the Russians launched Sputnik. It was the first man made object to be put into Earth's orbit.

Missions

Examples of reconnaissance satellite missions:

- High resolution photography (IMINT)
- Measurement and Signature Intelligence (MASINT)
- Communications eavesdropping (SIGINT)
- Covert communications
- Monitoring of nuclear test ban compliance
- Detection of missile launches

Chapter 12

Tether Satellite

Graphic of the US Naval Research Laboratory's TiPS tether satellite. Note that only a small part of the 4 km tether is shown deployed.

A **tether satellite** is a satellite connected to another by a thin cable called a tether.

History

The "space tether" idea had its origin in the late 19th century. The idea became more popular in the 1960s, and subsequently NASA examined the feasibility of the idea and gave direction to the study of tethered systems, especially tethered satellites.

Some concepts that were brought up during the 1970s were:

- Orbiting antennas
- Shuttle-borne tethered satellites
- Electrodynamic-powered tethers
- Space station tether systems

Description

Tethered satellites are broken up into three parts. There is the base-satellite, tether, and sub-satellite. The base-satellite contains the sub-satellite and tether until deployment. Sometimes the base-satellite is another basic satellite, other times it could be a shuttle, space station, or moon. The tether is what keeps the two satellites connected. The tether is generally a complicated composite that is made up of primarily a copper core and kevlar. The sub-satellite is released from the base-satellite towards an attracting body.

There are, in general, three dynamic phases of a tethered satellite system: the deployment phase, the station-keeping phase, and the retracting phase.

The station-keeping phase and retraction phase need active control for stability, especially when atmospheric effects are taken into account. When there are no simplifying assumptions, the dynamics become overly difficult because they are then governed by a set of ordinary and partial nonlinear, non-autonomous and coupled differential equations. These conditions create a list of problems to consider:

- Three-dimensional rigid body dynamics (librational motion) of the station and subsatellite
- Swinging in-plane and out-of-plane motions of the tether of finite mass
- Offset of the tether attachment point from the base-satellite center of mass as well as controlled variations of the offset
- Transverse vibrations of the tether
- External forces

A NASA artist's rendering of a satellite tethered to the space shuttle.

Tether satellite missions

TSS-1 mission

Tethered Satellite System-1 (TSS-1), a joint NASA-Italian Space Agency project, was flown during STS-46 aboard the Space Shuttle Atlantis from July 31 to August 8, 1992.

The TSS-1 mission discovered a lot about the dynamics of the tethered system, although the satellite was deployed only 260 meters (853 ft). A protruding bolt due to a late-stage modification of the deployment reel system, jammed the deployment mechanism and prevented deployment to full extension. It deployed far enough though, to show that it could be deployed, controlled, and retrieved, and that the TSS was easy to control and even more stable than predicted.

The voltage and current reached using a shorter tether were too low for most of the experiments to be run. However, low-voltage measurements were made, along with recording the variations of tether-induced forces and currents. New information was learned about on the electrons that carry the "return-tether" current. The mission was reflown in 1996 as TSS-1R.

TSS-1R mission

Four years later, as a follow-up mission to TSS-1, the TSS-1R sattelite was released in February 1996 from the Space Shuttle on the STS-75 mission. Over 19 kilometers of the tether were deployed before the tether burned through due to a short-circuit and broke. It remained in orbit for a number of weeks and was easily visible from the ground, appearing something like a small but surprisingly bright fluorescent light traveling through the sky.

SEDS I and II

In 1993 and 1994, NASA launched two "Small Expendable Deployer System" experiments (SEDS-I and SEDS-II), which deployed 20 km tethers attached to a spent Delta second stage. The first fully successful orbital flight test of a long tether system was SEDS-1, which tested the simple deploy-only Small Expendable Deployer System. The tether swung to the vertical and was cut 1 orbit after the start of deployment. This slung the payload and tether from Guam onto a reentry trajectory off the coast of Mexico.The reentry was accurate enough that a pre-positioned observer was able to videotape the payload re-entry and burnup.

SEDS-2 was launched on a Delta (along with a GPS Block 2 satellite) on March 9, 1994. A feedback braking limited the swing after deployment to 4°. The payload returned data for 8 hours until its battery died; during this time tether torques spun it up to 4 rpm. The tether suffered a cut 3.7 days after deployment. The payload reentered (as expected) within hours, but the 7.2 km length at the Delta end survived with no further cuts until re-entry on May 7, 1994. The tether was an easy naked eye object when lit by the sun and viewed against a dark sky.

A follow-on experiment using the SEDS deployer, PMG (Plasma Motor Generator), deployed a 500 m tether to demonstrate electrodynamic tether operation.

In these experiments, not only were tether models verified, the tests successfully showed that a reentry vehicle can be downwardly deployed into a reentry orbit using tethers.

TiPS

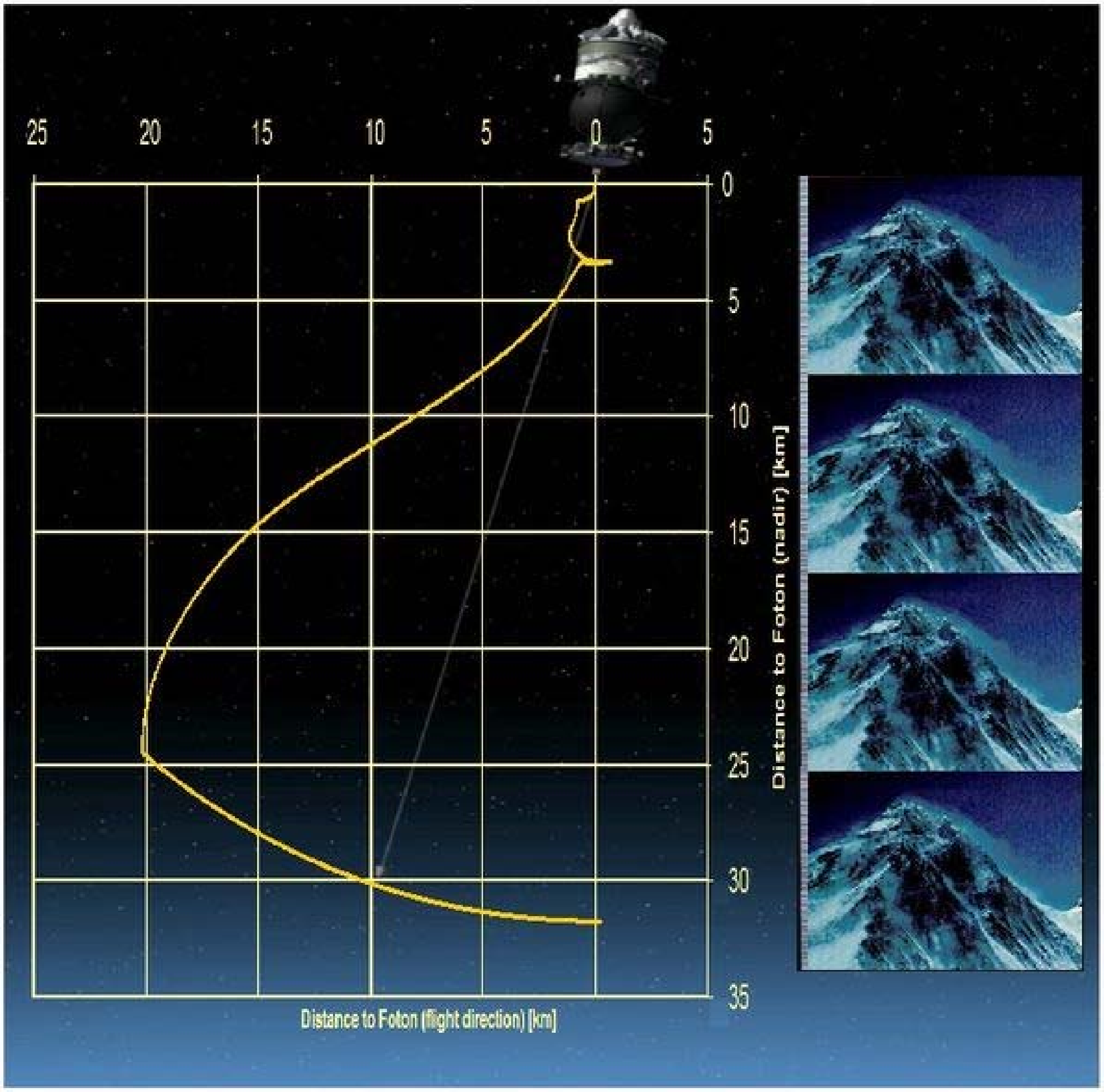
The Tether Physics and Survivability Experiment (TiPS) was the last tethered satellite system in orbit (other than the MAST and YES experimental satellites). It was launched in 1996 as a project of the US Naval Research Laboratory. The tether was four kilometers long. The two tethered objects were called "Ralph" and "Norton". TiPS was visible from the ground with large binoculars or a telescope and was occasionally accidentally spotted by amateur astronomers. The tether broke in July 2006. This long-term statistical data point is in line with debris models published by J. Carroll after the SEDS-2 mission, and ground tests by D. Sabath from TU Muenchen. Predictions of a maximum of two years survivability for TiPS based on some other ground tests have shown to be overly pessimistic (e.g. McBride/Taylor, Penson). The early cut of the SEDS-2 therewith must be considered an anomaly possibly related to the impact of upper stage debris.

JAXA initiatives

A "Foldaway Flat Tether Deployment System" will fly into space, although it won't reach orbit, as part of a mission sponsored by the Japanese Aerospace Exploration Agency (ISAS/JAXA).

Young Engineers' Satellite 2

Delta-Utec SRC



The reconstructed deployment of the YES2 tether, i.e., the trajectory of the Fotino capsule in relationship to the Foton spacecraft. Orbital motion is to the left. The Earth is down. Mount Everest is shown several times for scale. The Fotino was released at the vertical, 32 km below Foton, about 240 km above the surface of the Earth, and made a re-entry towards Kazakhstan.

In 1997, the European Space Agency launched the Young Engineers' Satellite 2 (YES) of about 200 kg into GTO with a 35 km double-strand tether, and planned to deorbit a probe at near-interplanetary speed by swinging deployment of the tether system.{. Due to an electrical fault, the on-board computer failed to register the final length correctly and only a partial deployment was reported. Some weeks after mission completion, analysis of the full data set suggested that the tether deployed to its full length of 31.7 km. No signal was ever received from the "Fotino" re-entry capsule after separation, and it was lost.

Tethered Formation Flying

Tethered SPHERES nano-satellites developed by MIT

Tethered SPHERES nano-satellites developed by MIT

Spacecraft formation flight is becoming a key research area, where distributed computation and decentralized control schemes, as well as information flows between elements, are explored. One such example includes stellar interferometers in which multiple apertures in controlled formation collect light for coherent interferometric beam combination, thereby achieving a fine angular resolution comparable to a large monolithic aperture telescope. The possible architectures of spaceborne interferometers include a structurally connected interferometer (SCI)Space Interferometry Mission, which allows for very limited baseline changes, and a separated spacecraft interferometer (SSI) Terrestrial Planet Finder where the usage of propellant can be prohibitively expensive. A tethered formation flight interferometer represents a balance between SCI and SSI. Such a system is currently being considered for NASA's Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) mission. The dynamics of SSI are coupled by the definition of relative attitude whereas tethered formation spacecraft exhibit inherently coupled nonlinear dynamics.

The MIT Space Systems Laboratory conducted ground experiments that tested a fully decentralized nonlinear control law, which eliminates the need for inter-satellite communications. Contraction theory was used to prove that a nonlinear control law stabilizing a single-tethered spacecraft can also stabilize arbitrarily large circular arrays of tethered spacecraft, as well as a three-spacecraft inline configuration. In order to validate the effectiveness of the decentralized control and estimation framework, a new suite of hardware has been designed and added to the SPHERES (Synchronize Position Hold Engage and Reorient Experimental Satellite) testbed. A 2007 PhD theses introduced a novel relative attitude estimator, in which a series of Kalman filters incorporate the gyro, force-torque sensor, and relative distance measurements. The closed-loop control experiments can be viewed at The MIT team also reported the first propellant-free underactuated control results for tethered formation flight. This is motivated by a controllability analysis that indicates that both array resizing and spin-up are fully controllable by the reaction wheels and the tether motor.

Chapter 13

Balloon Satellite

A **balloon satellite** (Also occasionally referred to as a "satelloon", which is a trademarked name owned by Gilmore Schjeldahl's G.T. Schjeldahl Company) is a satellite that is inflated with gas after it has been put into orbit.

List of Balloon Satellites

List of balloon satellites (sorted by launch date)

Satellite	Launch date (UTC)	Decay	Mass(kg)	Diameter(m)	NSSDC ID	Nation	Usage
Echo 1	1960-08-12 09:36:00	1968-05-24	180	30.48	1960-009A	US	pcr, ado, spc, tri
Explorer 9	1961-02-16 13:12:00	1964-04-09	36	3.66	1961-004A	US	ado
Explorer 19 (AD-A)	1963-12-19 18:43:00	1981-10-05	7.7	3.66	1963-053A	US	ado
Echo 2	1964-01-25 13:55:00	1969-06-07	256	41	1964-004A	US	pcr, tri
Explorer 24 (AD-B)	1964-11-21 17:17:00	1968-10-18	8.6	3.6	1964-076A	US	ado
PAGEOS 1	1966-06-24 00:14:00	1975-07-12	56.7	30.48	1966-056A	US	tri
Explorer 39 (AD-C)	1968-08-08 20:12:00	1981-06-22	9.4	3.6	1968-066A	US	ado
Mylar Balloon	1971-08-07 00:11:00	1981-09-01	0.8	2.13	1971-067F	US	ado
Qi Qiu Weixing 1	1990-09-03 00:53:00	1991-03-11	4	3	1990-081B	PRC	ado
Qi Qiu Weixing 2	1990-09-03 00:53:00	1991-07-24	4	2.5	1990-081C	PRC	ado
Naduvaniy gazovoy	1991-03-30 (?)				1986-017FJ	RU	

balloon

abbreviations:

- pcr = passive communications reflector, satellite reflects microwave signals.
- ado = atmospheric density observations
- spc = solar pressure calculations, estimate impact of solar wind on orbit.
- tri = satellite triangulation, measuring the Earth's surface.

Echo 1 and Echo 2 balloon satellites

The first flying body of this type was Echo 1, which was launched into a 1,600-kilometer (990 mi) high orbit on August 12, 1960 by the United States. It originally had a spherical shape measuring 30 meters (98 ft), with a thin metal-coated plastic shell made of Mylar. It served for testing as a "passive" communication and geodetic satellite. Its international COSPAR number was 6000901 (9th satellite launched in 1960, 1st component).

One of the first radio contacts using the satellite was successful at a distance of nearly 80,000 kilometers (50,000 mi) (between the east coast of the US and California). By the time Echo 1 burned up in 1968, the measurements of its orbit by several dozen earth stations had improved our knowledge of the precise shape of the planet by nearly a factor of ten.

Its successor was the similarly-built Echo 2 (1964 to about 1970). This satellite circled the Earth about 400 kilometers (250 mi) lower, not at an angle of 47° like that of Echo 1, but in a polar orbit with an average angle of 81°. This enabled radio contact and measurements to be made at higher latitudes. Taking part in the Echo orbit checks to analyze disturbances in its orbit and in the Earth's gravitational field were thirty to fifty professional earth stations, as well as around two hundred amateur astronomers across the planet in "Moonwatch" stations; these contributed around half of all sightings.

Range of radio waves, visibility

The Pythagorean theorem allows us to calculate easily how far a satellite is visible at such a great height. It can be determined that a satellite in a 1,500-kilometer (930 mi) orbit rises and sets when the horizontal distance is 4,600 kilometers (2,900 mi). However, the atmosphere causes this figure to vary slightly. Thus if two radio stations are 9,000 kilometers (5,600 mi) apart and the satellite's orbit goes between them, they may be able to receive each other's reflected radio signals if the signals are strong enough.

Optical visibility is, however, lower than that of radio waves, because

- the satellite must be illuminated by the sun
- the observer needs a dark sky (that is, he must be in the Earth's own shadow on the planet's twilight or night side)

- the brightness of a sphere depends on the angle between the incident light and the observer
- the brightness of a sphere is much reduced as it approaches the horizon, as atmospheric extinction swallows up as much as 90% of the light

Despite this there is no problem observing a flying body such as Echo 1 for precise purposes of satellite geodesy, down to a 20° elevation, which corresponds to a distance of 2,900 kilometers (1,800 mi). In theory this means that distances of up to 5,000 kilometers (3,100 mi) between measuring points can be "bridged", and in practice this can be accomplished at up to 3,000–4,000 kilometers (1,900–2,500 mi).

Other balloon satellites

For special testing purposes two or three satellites of the Explorer series were constructed as balloons (possibly Explorer 19 and 38).

Echo 1 was an acknowledged success of radio engineering, but the passive principle of telecommunications (reflection of radio waves on the balloon's surface) was soon replaced by active systems. Telstar 1 (1962) and Early Bird (1965) were able to transmit several hundred audio channels simultaneously in addition to a television program exchanged between continents.

Satellite geodesy with Echo 1 and 2 was able to fulfill all expectations not only for the planned 2–3 years, but for nearly 10 years. For this reason NASA soon planned the launch of the even larger 40-meter (130 ft) balloon Pageos. The name is from "passive geodesic satellite", and sounds similar to "Geos", a successful active electronic satellite from 1965.

Pageos and the global network

Test inflation of PAGEOS

Pageos was specially launched for the "global network of satellite geodesy", which occupied about 20 full-time observing teams all over the world until 1973. All together they recorded 3000 usable photographic plates from 46 tracking stations with calibrated all-electronic BC-4 cameras (1:3 / focal length 30 and 45 cm (12 and 18 in)). From these images they were able to calculate the stations' position three-dimensionally with a precision of about 4 meters (13 ft). The coordinator of this project was Professor H. H. Schmid, from the ETH Zurich.

Three stations of the global network were situated in Europe: Catania in Sicily, Hohenpeißenberg in Bavaria and Tromsø in northern Norway. For the completion of the navigational network exact distance measurements were needed; these were taken on four continents and across Europe with a precision of 0.5 millimeters (0.020 in) per kilometer.

The global network enabled the calculation of a "geodetic date" (the geocentric position of the measurement system) on different continents, within a few meters. By the early 1970s reliable values for nearly 100 coefficients of the Earth's gravity field could be calculated.

1965-1975: Success with flashing light beacons

Bright balloon satellites are well visible and were measurable on fine-grained (less sensitive) photographic plates, even at the beginning of space travel, but there were problems with the exact chronometry of a satellite's track. In those days it could only be determined within a few milliseconds.

Since satellites circle the earth at about 7–8 kilometers per second (4.3–5.0 mi/s), a time error of 0.002 second translates into a deviation of about 15 meters (49 ft). In order to meet a new goal of measuring the tracking stations precisely within a couple of years, a method of flashing light beacons was adopted around 1960.

To build a three-dimensional measuring network, geodesy needs exactly defined target points, more so than a precise time. This precision is easily reached by having two tracking stations record the same series of flashes from one satellite.

Flash technology was already mature in 1965 when the small electronic satellite Geos (later named Geos 1) was launched; along with its companion Geos 2, it brought about a remarkable increase in precision.

From about 1975 on, almost all optical measurement methods lost their importance, as they were overtaken by speedy progress in electronic distance measurement. Only newly developed methods of observation using CCD and the highly precise star positions of the astrometry satellite Hipparcos made further improvement possible in the measurement of distance.

Chapter 14

Geosynchronous Satellite and Hinotori

Geosynchronous satellite

A **geosynchronous Satellite** is a satellite whose orbit on the Earth repeats regularly over points on the Earth over time. If such a satellite's orbit lies over the equator, the orbit is circular, and its direction is the same as the earth's then it is called a **geostationary satellite**. The orbits of the satellites are known as the geosynchronous orbit and geostationary orbit. Another type of geosynchronous orbit is the Tundra elliptical orbit.

A **geosynchronous network** is a communication network based on communication with or through geosynchronous satellites.

Definition

According to Kepler's Third Law, the orbital period of a satellite in a circular orbit increases with increasing altitude. Space stations and Shuttles in Low Earth orbit (LEO), typically two or four hundred miles above the Earth's surface make between fifteen and sixteen revolutions per day. The Moon, at an altitude of about 238,900 miles (384,400 km), takes about 27 days 7 hours to make a complete revolution . Between those extremes lies the "magic" altitude of 22,236 miles (35,786 km) at which a satellite's orbital period matches, or is an integral part of, the period at which the Earth rotates: once every sidereal day (23 hours 56 minutes 4 seconds). In that case, the satellite is said to be *geosynchronous*.

If a geosynchronous satellite's orbit is not exactly aligned with the equator, the orbit is known as an inclined orbit. It will appear (when viewed by someone on the ground) to oscillate daily around a fixed point. As the angle between the orbit and the equator decreases, the magnitude of this oscillation becomes smaller; when the orbit lies entirely over the equator, the satellite remains stationary relative to the Earth's surface – it is said to be *geostationary*.

Application

There are approximately 300 operational geosynchronous satellites.

Geostationary satellites appear to be fixed over one spot above the equator. Receiving and transmitting antennas on the earth do not need to track such a satellite. These antennas can be fixed in place and are much less expensive than tracking antennas. These satellites have revolutionized global communications, television broadcasting and weather forecasting, and have a number of important defense and intelligence applications.

One disadvantage of geostationary satellites is a result of their high altitude: radio signals take approximately 0.25 of a second to reach and return from the satellite, resulting in a small but significant signal delay. This delay increases the difficulty of telephone conversation and reduces the performance of common network protocols such as TCP/IP, but does not present a problem with non-interactive systems such as television broadcasts. There are a number of proprietary satellite data protocols that are designed to proxy TCP/IP connections over long-delay satellite links—these are marketed as being a partial solution to the poor performance of native TCP over satellite links. TCP presumes that all loss is due to congestion, not errors, and probes link capacity with its "slow-start" algorithm, which only sends packets once it is known that earlier packets have been received. Slow start is very slow over a path using a geostationary satellite.

Another disadvantage of geostationary satellites is the incomplete geographical coverage, since ground stations at higher than roughly 60 degrees latitude have difficulty reliably receiving signals at low elevations. Satellite dishes at such high latitudes would need to be pointed almost directly towards the horizon. The signals would have to pass through the largest amount of atmosphere, and could even be blocked by land topography, vegetation or buildings. In the USSR, a practical solution was developed for this problem with the creation of special Molniya / Orbita inclined path satellite networks with elliptical orbits. Similar elliptical orbits are used for the Sirius Radio satellites.

History

The concept was first proposed by Herman Potočnik in 1928 and popularised by the science fiction author Arthur C. Clarke in a paper in Wireless World in 1945. Working prior to the advent of solid-state electronics, Clarke envisioned a trio of large, manned space stations arranged in a triangle around the planet. Modern satellites are numerous, unmanned, and often no larger than an automobile.

Widely known as the "father of the geosynchronous satellite", Harold Rosen, an engineer at Hughes Aircraft Company, invented the first operational geosynchronous satellite, Syncom 2. It was launched on a Delta rocket B booster from Cape Canaveral July 26, 1963. A few months later Syncom 2 was used for the world's first satellite-relayed telephone call. It took place between United States President John F. Kennedy and Nigerian Prime minister Abubakar Tafawa Balewa.

The first geostationary communication satellite was Syncom 3, launched on August 19, 1964 with a Delta D launch vehicle from Cape Canaveral. The satellite, in orbit near the

International Date Line, was used to telecast the 1964 Summer Olympics in Tokyo to the United States. It was the first television program to cross the Pacific ocean.

Hinotori

Hinotori (ASTRO-A)

Operator	ISAS
Mission type	Orbiter
Satellite of	**Earth**
Launch date	February 21, 1981
Launch vehicle	M-3S
Orbital decay	July 11, 1991
COSPAR ID	1981-017A
Homepage	
Mass	188.0 kg
Orbital elements	
Eccentricity	~0.003952.
Inclination	~31.30 °
Apoapsis	603.0 km
Periapsis	548.0 km
Orbital period	~96.20 min

The **Hinotori (satellite)** (Japanese for "phoenix" or "firebird"), also known as Astronomical Satellite-A or ASTRO-A, was launched on February 21, 1981, at 09:30:00 UTC, using the M-3S vehicle from the Uchinoura Space Center in Japan.

The main objective of the Hinotori mission is the detailed study of solar flares during solar maximum. Principal investigations are (1) imaging of solar flare X-rays in the range 10 to 40 keV by means of rotating modulation collimators and (2) spectroscopy of X-ray emission lines from highly ionized iron in solar flares in the range 0.17 to 0.20 nm by means of a Bragg spectrometer. Wavelength scanning is achieved by the spacecraft revolution, with an offset pointing of the spin axis with respect to the Sun. Investigations (1) and (2) each had a time resolution of 6 s. In addition, the following investigations are included: three solar flare X-ray monitors that recorded the time profile and spectrum of the X-ray flares in the range 2 to 20 keV, a solar flare gamma-ray detector for the range

0.2 to 9.0 MeV, a particle detector that monitored electron flux above 100 keV, and plasma probes for the measurement of electron density and temperature.

Instruments

Hinotori has these eight scientific instruments aboard for specific purposes:

1. solar flare X-ray imager (SXT),
2. solar soft X-ray, bright line spectrum analyzer (SOX),
3. solar soft X-ray monitor (HXM),
4. solar flare monitor (FLM),
5. solar gamma-ray monitor (SGR),
6. particle-ray monitor (PXM),
7. plasma electron density measurement (IMP), and
8. plasma electron temperature measurement (TEL).

The gamma-ray spectrometer (SGR) covering the energy range (0.21 - 6.67 MeV) consists of a phoswich type CsI(Tl) scintillator (8.9 cm dia x 5.1 cm thickness) surrounded by a 0.5 cm thick plastic scintillator.

The hard X-ray spectrometer (HXM) consists of a NaI(Tl) scintillator (8.9 cm dia x 1 cm thick), covering the energy range 17 - 340 keV.

Scientific accomplishments

Each Hinotori instrument has contributed significantly to further understanding of the Sun and solar active regions.

Solar X-ray astronomy

The Hinotori observations of the 1980s pioneered hard X-ray imaging of solar flares.

A new type of X-ray burst which emits thermal hard X-rays with a strong Fe XXVI emission has been found. This thermal burst efficiently forms hot thermal plasma, $T_e = 3 - 5 \times 10^7$K, and becomes dominant after the middle phase of a flare.

Gamma-ray astronomy

Four cosmic gamma-ray bursts were observed between February 1981 and June 1982: on February 21, 1982, lasting 16 s, July 21, 1981, lasting 6 s, February 26, 1982, lasting 32 s, and March 13, 1982, lasting 80 s. Of the four bursts, the first two were also detected by PVO, the second by ISEE-3 and SMM, while the third was corroborated by Venera 14, and the fourth by Venera 13, Venera 14, and SMM.

During solar cycle 21, gamma-ray flares observed by Hinotori and SMM exhibited a 152-158 day periodicity in the occurrence of solar activity. Power-spectrum analyses of daily sunspot areas for the period 1980-1982 show a peak around 159 days, similar to that of solar gamma-ray bursts (GRBs) above 300 keV, soft X-ray bursts (152 d), hard X-ray bursts (158 d) above 30 keV, Hα flare data, microwave bursts (152 d) for the period 1966-1983, but no periodicity in sunspot number, indicating that sunspot area data should be treated as an indicator of solar activity rather than the daily sunspot number.

Eight solar gamma-ray flares observed between April 1981 and June 1982 contained lines at 2.22 MeV and 4.44 MeV produced by particle acceleration where energy spectra do not vary much from flare to flare. The 2.22 MeV line indicates solar surface fusion while the 4.44 MeV line is produced by de-excitation of ^{12}C following the nuclear reactions $^{12}C(p,p'\gamma_{4.438\ \mathrm{MeV}})^{12}C$ and $^{12}C(p,2p\gamma_{4.444\ \mathrm{MeV}})^{11}B$.

Chapter 15

Oceansat-2

Oceansat-2

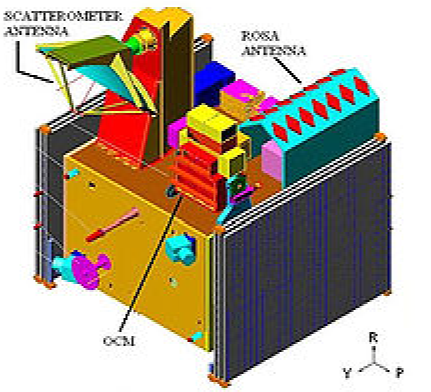


Figure 1. OCEANSAT-2 stowed configuration viewed from +Yaw side

Operator	Indian Space Research Organisation
Bus	IRS
Mission type	Oceanography
Launch date	23 September 2009
Carrier rocket	PSLV-C14
Launch site	Satish Dhawan Space Centre
COSPAR ID	OCEANS2
Mass	960 kilograms (2,100 lb)
	Orbital elements
Regime	Sun-Synchronous Circular orbit
Inclination	98.280^{o}
Apoapsis	720 kilometres (447 mi)
Periapsis	720 kilometres (447 mi)
Orbital period	99.31 minutes

Oceansat-2 is an Indian satellite designed to provide service continuity for operational users of the Ocean Colour Monitor (OCM) instrument on Oceansat-1. It will also enhance the potential of applications in other areas. The main objectives of OceanSat-2 are to study surface winds and ocean surface strata, observation of chlorophyll concentrations, monitoring of phytoplankton blooms, study of atmospheric aerosols and suspended sediments in the water.

Oceansat-2 is ISRO's second in the series of IRS satellites dedicated to ocean research, and will provide continuity to the applications of Oceansat-1 (launched in 1999). Oceansat-2 will carry three payloads including an Ocean Colour Monitor (OCM-2), similar to the device carried on Oceansat-1. Data from all instruments will be made available to the global scientific community after the post-launch sensor characterization, which is expected to be completed within 6 months of the launch. Oceansat-2 was launched from SDSC (SHAR) on 23 September 2009 using PSLV-C14.

Mission

The mission objectives of Oceansat-2 are to gather systematic data for oceanographic, coastal and atmospheric applications. The main objectives of OceanSat-2 are to study surface winds and ocean surface strata, observation of chlorophyll concentrations, monitoring of phytoplankton blooms, study of atmospheric aerosols and suspended sediments in the water.

Oceansat-2 will carry two payloads for ocean related studies, namely, Ocean Colour Monitor (OCM) and Ku-band Pencil Beam Scatterometer. An additional piggy-back payload called ROSA (Radio Occultation Sounder for Atmospheric studies) developed by the Italian Space Agency (ASI) is also proposed to be included. The major applications of data from Oceansat-2 are identification of potential fishing zones, sea state forecasting, coastal zone studies and inputs for weather forecasting and climatic studies.

Payload

The scientific payload contains three instruments. Two are Indian and one is from the Italian Space Agency.

- **Ocean Colour Monitor (OCM)** - OCM is a 8-band multi-spectral camera operating in the Visible – Near IR spectral range. This camera provides an instantaneous geometric field of view of 360 meter and a swath of 1420 km. OCM can be tilted up to + 20 degree along track. The Ku-band pencil beam scatterometer is an active microwave radar operating at 13.515 GHz providing a ground resolution cell of size 50 x 50 km. It consists of a parabolic dish antenna of 1 meter diameter which is offset mounted with a cant angle of about 46 degree with respect to earth viewing axis. This antenna is continuously rotated at 20.5 rpm using a scan mechanism with the scan axis along the +ve Yaw axis. By using two offset feeds at the focal plane of the antenna, two beams are generated which will conically scan the ground surface. The back scattered power in each beam from the ocean surface is measured to derive wind vector. It is an improved version of the one on Oceansat-1.

- **Scanning Scatterometer (SCAT)** - SCAT is an active microwave device designed and developed at ISRO/SAC, Ahmedabad. It will be used to determine ocean surface level wind vectors through estimation of radar backscatter. The scatterometer system has a 1-m parabolic dish antenna and a dual feed assembly to generate two pencil beams and is scanned at a rate of 20.5 rpm to cover the entire swath. The inner beam makes an incidence angle of 48.90° and the outer beam makes an incidence angle of 57.60° on the ground. It covers a continuous swath of 1400 km for inner beam and 1840 km for outer beam respectively. The inner and outer beams are configured in horizontal and vertical polarization respectively for both transmit and receive modes. The aim is to provide global ocean coverage and wind vector retrieval with a revisit time of 2 days.

- **Radio Occultation Sounder for Atmospheric Studies (ROSA)** - ROSA is a new GPS occultation receiver provided by ASI (Italian Space Agency). The objective is to characterize the lower atmosphere and the ionosphere, opening the possibilities for the development of several scientific activities exploiting these new radio occultation data sets.

Current status

India successfully launched its 16th remote-sensing satellite Oceansat-2 and six nano European satellites in 1,200 seconds with the help The Ocean Monitoring Satellite Oceansat-2 is seen 18 minutes after blast off in Sriharikota, AP. of Polar Satellite Launch Vehicle (PSLV- C-14) from Sriharikota on 23 September, 2009. The launch was carried out as per schedule at 11.51 am and ended at 12.06 pm. The 44.4-metre tall, 230-tonne Indian rocket Polar Satellite Launch Vehicle (PSLV) freed itself from the launch pad at the spaceport and lifted itself up, lugging the 960-kg Oceansat-2 and the six nano satellites all together weighing 20 kg.

In copybook style, the rocket first flung out Oceansat-2 at an altitude of 720 km above the earth in a sun-synchronous orbit (SSO), followed by the four nano satellites - also called Cubesats, each weighing one kg. The remaining two, each weighing eight kg, were attached to the rocket's fourth stage. Of the six nano satellites, four are from Germany, one is from Switzerland and one from Turkey. The seventh is a big one, India's Oceansat-2 weighing 960 kg. Soon after the satellites were put into orbit, Indian Space Research Organisation's (ISRO) satellite tracking centres started monitoring them.

Seven satellites in 1,200 seconds. The launch is similar to the one in April 2008 when ISRO launched 10 satellites.

The sequence of ejection is very similar to the April 2008 launch featuring one big satellite - Cartosat-2A and nine other nano satellites - 10 in all: once the PSLV takes off and reaches a certain height and velocity, it will first launch the Oceansat-2 and a few seconds later, the first of four nano satellites. Every 10–12 seconds, the PSLV will launch four satellites one after the other. (Two will remain with the fourth stage).

"The rocket re-orients itself every time a satellite is to be placed in orbit. The re-orientation ensures one satellite doesn't collide with another. The rocket effectively re-orients itself four to five times in the space of one flight," a scientist explained.

The brain of the rocket would have made all calculations in advance - from ejection of first satellite to the fifth. The exact moment of ejection and then re-orientation for the next ejection is worked out in advance. All mathematical calculations on the ground, launch sequence and flight path have to work to zero error. Oceansat-2, India's second satellite to study oceans as well as interaction of oceans and atmosphere, is the 16th remote sensing satellite of India. It is in the shape of a cuboid with two solar panels projecting from its sides. The satellite will map fishing zones around India, measure ocean surface windspeeds as well as atmospheric temperature and humidity.

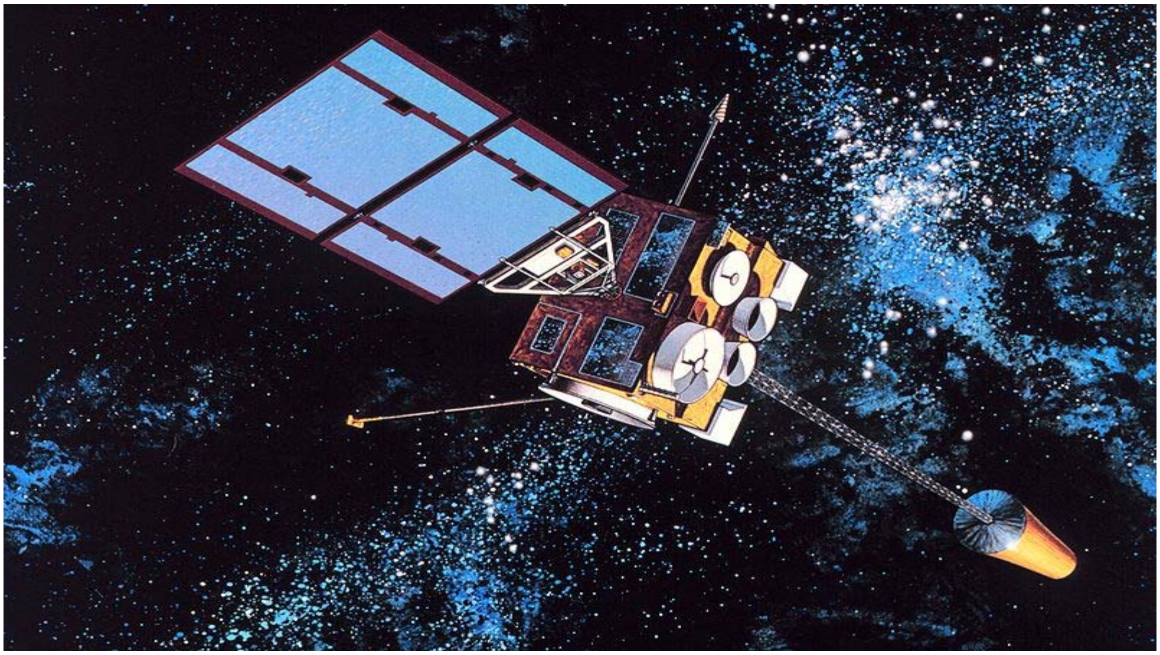
This was the 16th PSLV's mission. From September 1993 to April 2009, PSLV has been launched 15 times. Fourteen launches have been successful continuously while only one has failed so far.

During 2007, the flight model OCM payload electronics was realised, the camera assembly was in progress and scatterometer configuration was finalised. Fabrication of mainframe systems like Core power, RF systems BMU, and sensors had started and DC-DC converters for OCM, earth sensor, TME realized.

As of 2008, mainframe structure had been realised. Preliminary design review of all mainframe systems completed. OCM camera test and evaluation had been completed. Scatterometer qualification model hardware had been realized. ROSA interfaces with spacecraft systems had been finalised. Qualification model of scatterometer scan mechanism and the interface test with electronics had also been completed.

Chapter 16

Weather Satellite



GOES-8, a United States weather satellite

The **weather satellite** is a type of satellite that is primarily used to monitor the weather and climate of the Earth. Satellites can be either polar orbiting, seeing the same swath of the Earth every 12 hours, or geostationary, hovering over the same spot on Earth by orbiting over the equator while moving at the speed of the Earth's rotation. These meteorological satellites, however, see more than clouds and cloud systems. City lights, fires, effects of pollution, auroras, sand and dust storms, snow cover, ice mapping, boundaries of ocean currents, energy flows, etc., and other types of environmental information are collected using weather satellites. Weather satellite images helped in monitoring the volcanic ash cloud from Mount St. Helens and activity from other volcanoes such as Mount Etna. Smoke from fires in the western United States such as Colorado and Utah have also been monitored.

Other environmental satellites can detect changes in the Earth's vegetation, sea state, ocean color, and ice fields. For example, the 2002 oil spill off the northwest coast of

Spain was watched carefully by the European ENVISAT, which, though not a weather satellite, flies an instrument (ASAR) which can see changes in the sea surface.

El Niño and its effects on weather are monitored daily from satellite images. The Antarctic ozone hole is mapped from weather satellite data. Collectively, weather satellites flown by the U.S., Europe, India, China, Russia, and Japan provide nearly continuous observations for a global weather watch.

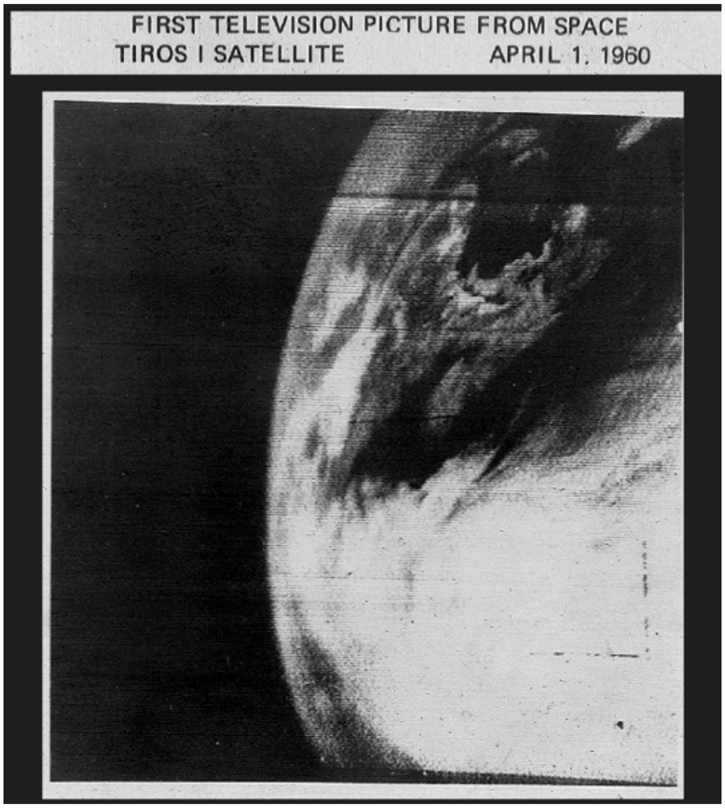
Observation

Observation is typically made via different 'channels' of the Electromagnetic spectrum, in particular, the Visible and Infrared portions.

Some of these channels include :

- *Visible and Near Infrared:* 0.6 µm - 1.6 µm - For recording cloud cover during the day
- *Infrared:* 3.9 µm - 7.3 µm (Water Vapour), 8.7 µm, - 13.4 µm (Thermal imaging)

History



The first television image of Earth from space from the TIROS-1 weather satellite

The first weather satellite, Vanguard 2, was launched on February 17, 1959. It was designed to measure cloud cover and resistance, but a poor axis of rotation kept it from collecting a notable amount of useful data.

The first weather satellite to be considered a success was TIROS-1, launched by NASA on 1 April 1960. TIROS operated for 78 days and proved to be much more successful than Vanguard 2. TIROS paved the way for the Nimbus program, whose technology and findings are the heritage of most of the Earth-observing satellites NASA and NOAA have launched since then.

Visible spectrum

Visible-light images from weather satellites during local daylight hours are easy to interpret even by the average person; clouds, cloud systems such as fronts and tropical storms, lakes, forests, mountains, snow ice, fires, and pollution such as smoke, smog, dust and haze are readily apparent. Even wind can be determined by cloud patterns, alignments and movement from successive photos.

Infrared spectrum

The thermal or infrared images recorded by sensors called scanning radiometers enable a trained analyst to determine cloud heights and types, to calculate land and surface water temperatures, and to locate ocean surface features. Infrared satellite imagery can be used effectively for tropical cyclones with a visible eye pattern, using the Dvorak technique, where the difference between the temperature of the warm eye and the surrounding cold cloud tops can be used to determine its intensity (colder cloud tops generally indicate a more intense storm). Infrared pictures depict ocean eddies or vortices and map currents such as the Gulf Stream which are valuable to the shipping industry. Fishermen and farmers are interested in knowing land and water temperatures to protect their crops against frost or increase their catch from the sea. Even El Niño phenomena can be spotted. Using color-digitized techniques, the gray shaded thermal images can be converted to color for easier identification of desired information.

Types

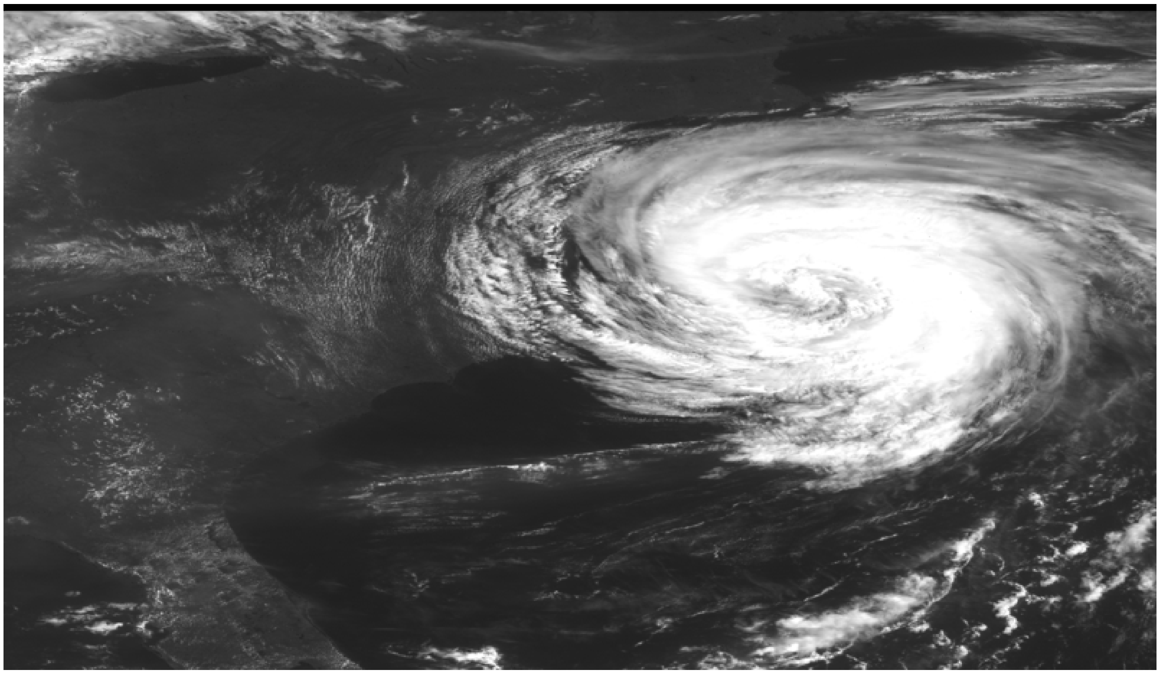


Image from the GOES-9 weather satellite of Hurricane Felix

There are two basic types of meteorological satellites: geostationary and polar orbiting.

Geostationary

Geostationary weather satellites orbit the Earth above the equator at altitudes of 35,880 km (22,300 miles). Because of this orbit, they remain stationary with respect to the rotating Earth and thus can record or transmit images of the entire hemisphere below continuously with their visible-light and infrared sensors. The news media use the geostationary photos in their daily weather presentation as single images or made into movie loops. These are also available on the city forecast pages of noaa.gov (example Dallas, TX).

Several geostationary meteorological spacecraft are in operation. The United States has two in operation; GOES-11 and GOES-12. GOES-12, designated GOES-East, is located over the Amazon River and provides most of the U.S. weather information. GOES-11 is GOES-West over the eastern Pacific Ocean. Russia's new-generation weather satellite Elektro-L 1 operates at 76°E over the Indian Ocean. The Japanese have one in operation; MTSAT-1R over the mid Pacific at 140°E. The Europeans have Meteosat-8 (3.5°W) and Meteosat-9 (0°) over the Atlantic Ocean and have Meteosat-6 (63°E) and Meteosat-7 (57.5°E) over the Indian Ocean. India also operates geostationary satellites called INSAT which carry instruments for meteorological purposes. China operated the Feng-Yun（風雲) geostationary satellites FY-2D at 86.5°E and FY-2E at 123.5°E, which are no longer in use anymore.

Polar orbiting

Computer controlled motorized parabolic dish antenna for tracking LEO weather satellites

Polar orbiting weather satellites circle the Earth at a typical altitude of 850 km (530 miles) in a north to south (or vice versa) path, passing over the poles in their continuous flight. Polar satellites are in sun-synchronous orbits, which means they are able to observe any place on Earth and will view every location twice each day with the same general lighting conditions due to the near-constant local solar time. Polar orbiting weather satellites offer a much better resolution than their geostationary counterparts due their closeness to the Earth.

The United States has the NOAA series of polar orbiting meteorological satellites, presently NOAA 17 and NOAA 18 as primary spacecraft, NOAA 15 and NOAA 16 as secondary spacecraft, NOAA 14 in standby, and NOAA 12. Europe has the Metop-A satellite. Russia has the Meteor and RESURS series of satellites. China has FY-1D and FY-3A. India has polar orbiting satellites as well.

DMSP

Turnstile antenna for reception of 137 MHz LEO weather satellite transmissions

The United States Department of Defense's Meteorological Satellite (DMSP) can "see" the best of all weather vehicles with its ability to detect objects almost as 'small' as a huge oil tanker. In addition, of all the weather satellites in orbit, only DMSP can "see" at night in the visual. Some of the most spectacular photos have been recorded by the night visual sensor; city lights, volcanoes, fires, lightning, meteors, oil field burn-offs, as well as the Aurora Borealis and Aurora Australis have been captured by this 450-mile-high space vehicle's low moonlight sensor.

At the same time, energy monitoring as well as city growth can be accomplished since both major and even minor cities, as well as highway lights, are conspicuous. This informs astronomers of light pollution. The New York City Blackout of 1977 was captured by one of the night orbiter DMSP space vehicles.

In addition to monitoring city lights, these photos are a life saving asset in the detection and monitoring of fires. Not only do the satellites see the fires visually day and night, but the thermal and infrared scanners on board these weather satellites detect potential fire sources below the surface of the Earth where smoldering occurs. Once the fire is detected, the same weather satellites provide vital information about wind that could fan or spread the fires. These same cloud photos from space tell the firefighter when it will rain.

Dramatic photos are provided by all the weather satellites, but even more definitive were the DMSP night visible-light pictures of the 700 oil well fires that Iraq started on 23 February 1991 as they fled Kuwait. These fires were vividly illustrated as huge flashes in the night photos, far outstripping the glow of large populated areas. The fires consumed millions of gallons of oil; the last was doused on November 6.

Uses

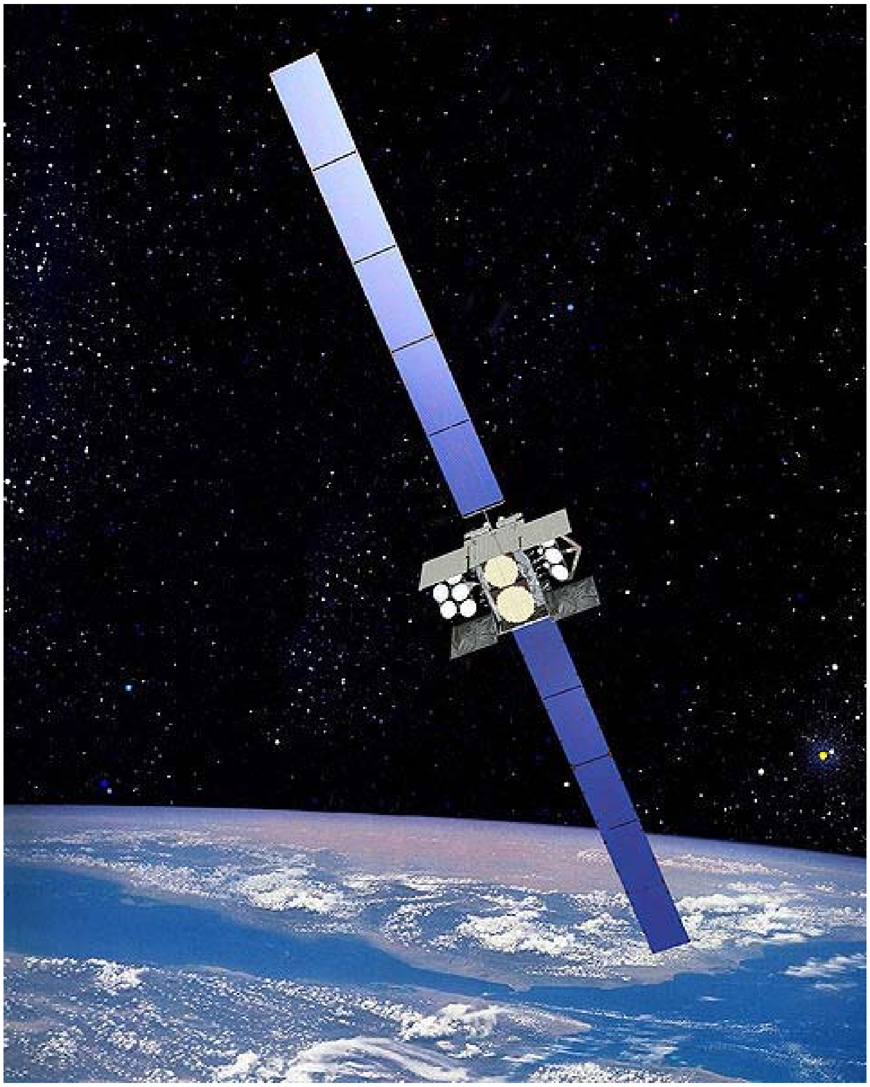
Snowfield monitoring, especially in the Sierra Nevada, can be helpful to the hydrologist keeping track of how much snow is available for runoff vital to the water sheds of the western United States. This information is gleaned from existing satellites of all agencies of the U.S. government (in addition to local, on-the-ground measurements). Ice floes, packs and bergs can also be located and tracked from weather space craft.

Even pollution whether it's nature-made or man-made can be pinpointed. The visual and infrared photos show effects of pollution from their respective areas over the entire earth. Aircraft and rocket pollution, as well as condensation trails, can also be spotted. The ocean current and low level wind information gleaned from the space photos can help predict oceanic oil spill coverage and movement. Almost every summer, sand and dust from the Sahara Desert in Africa drifts across the equatorial regions of the Atlantic Ocean. GOES-EAST photos enable meteorologists to observe, track and forecast this sand cloud. In addition to reducing visibilities and causing respiratory problems, sand clouds suppress hurricane formation by modifying the solar radiation balance of the tropics. Other dust storms in Asia and mainland China are common and easy to spot and monitor, with recent examples of dust moving across the Pacific ocean and reaching North America.

In remote areas of the world with few local observers, fires could rage out of control for days or even weeks and consume millions of acres before authorities are alerted. Weather satellites can be a tremendous asset in such situations. Nighttime photos also clearly show the burn-off in the gas and oil fields of the Middle East and African countries. This burn-off throws large amounts of carbon dioxide into the atmosphere.

Chapter 17

Communications Satellite



U.S. military WGSS communications satellite

A **communications satellite** (sometimes abbreviated to **COMSAT**) is an artificial satellite stationed in space for the purpose of telecommunications. Modern communications satellites use a variety of orbits including geostationary orbits, Molniya orbits, other elliptical orbits and low (polar and non-polar) Earth orbits.

For fixed (point-to-point) services, communications satellites provide a microwave radio relay technology complementary to that of submarine communication cables. They are also used for mobile applications such as communications to ships, vehicles, planes and hand-held terminals, and for TV and radio broadcasting, for which application of other technologies, such as cable, is impractical or impossible.

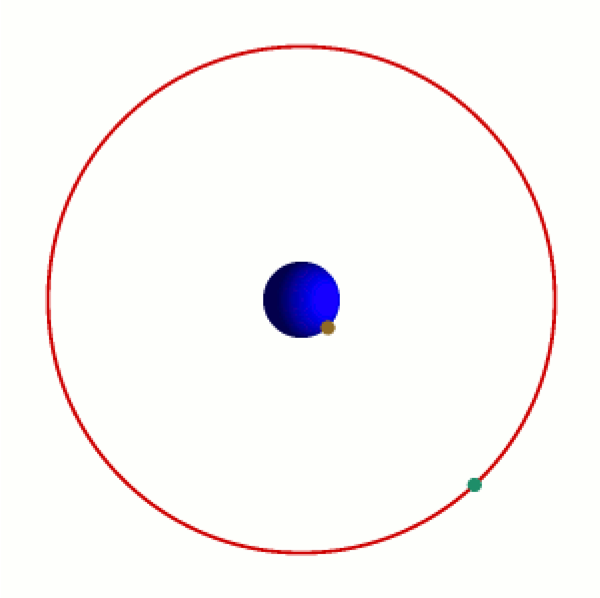
History

The first artificial satellite was the Soviet Sputnik 1, launched on October 4, 1957, and equipped with an on-board radio-transmitter that worked on two frequencies, 20.005 and 40.002 MHz. The first American satellite to relay communications was Project SCORE in 1958, which used a tape recorder to store and forward voice messages. It was used to send a Christmas greeting to the world from U.S. President Dwight D. Eisenhower. NASA launched an Echo satellite in 1960; the 100-foot (30 m) aluminized PET film balloon served as a passive reflector for radio communications. Courier 1B, built by Philco, also launched in 1960, was the world’s first active repeater satellite.

Telstar was the first active, direct relay communications satellite. Belonging to AT&T as part of a multi-national agreement between AT&T, Bell Telephone Laboratories, NASA, the British General Post Office, and the French National PTT (Post Office) to develop satellite communications, it was launched by NASA from Cape Canaveral on July 10, 1962, the first privately sponsored space launch. Telstar was placed in an elliptical orbit (completed once every 2 hours and 37 minutes), rotating at a 45° angle above the equator.

An immediate antecedent of the geostationary satellites was Hughes’ Syncom 2, launched on July 26, 1963. Syncom 2 revolved around the earth once per day at constant speed, but because it still had north-south motion, special equipment was needed to track it.

Geostationary orbits



Geostationary orbit

A satellite in a geostationary orbit appears to be in a fixed position to an earth-based observer. A geostationary satellite revolves around the earth at a constant speed once per day over the equator.

The geostationary orbit is useful for communications applications because ground based antennas, which must be directed toward the satellite, can operate effectively without the need for expensive equipment to track the satellite's motion. Especially for applications that require a large number of ground antennas (such as direct TV distribution), the savings in ground equipment can more than justify the extra cost and onboard complexity of lifting a satellite into the relatively high geostationary orbit.

The concept of the geostationary communications satellite was first proposed by Arthur C. Clarke, building on work by Konstantin Tsiolkovsky and on the 1929 work by Herman Potočnik (writing as Herman Noordung) *Das Problem der Befahrung des Weltraums - der Raketen-motor*. In October 1945 Clarke published an article titled "Extra-terrestrial Relays" in the British magazine *Wireless World*. The article described the fundamentals behind the deployment of artificial satellites in geostationary orbits for the purpose of relaying radio signals. Thus Arthur C. Clarke is often quoted as being the inventor of the communications satellite.

The first truly geostationary satellite launched in orbit was the Syncom 3, launched on August 19, 1964. It was placed in orbit at 180° east longitude, over the International Date Line. It was used that same year to relay experimental television coverage of the 1964 Summer Olympics in Tokyo, Japan to the United States, making these Olympic games the first to be broadcast internationally. Although Syncom 3 is some times credited with the first television transmission to cross the Pacific Ocean, the Relay 1 satellite first broadcast from the United States to Japan on November 22, 1963.

Shortly after Syncom 3, Intelsat I, aka *Early Bird*, was launched on April 6, 1965 and placed in orbit at 28° west longitude. It was the first geostationary satellite for telecommunications over the Atlantic Ocean.

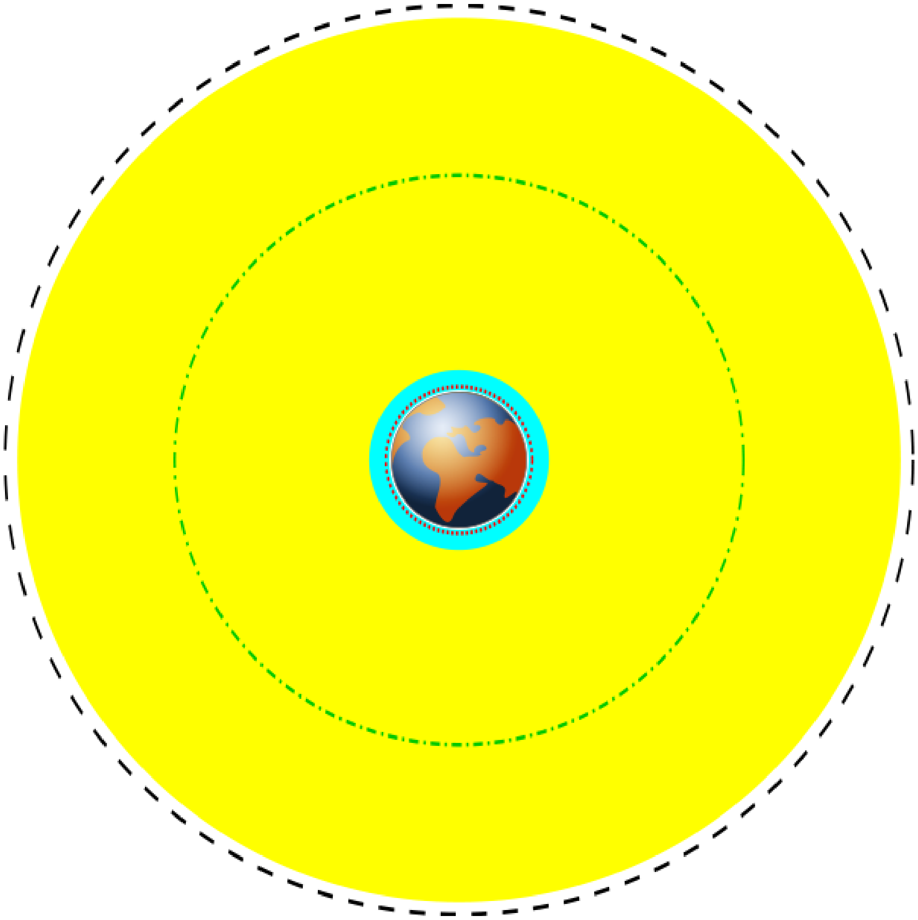
On November 9, 1972, Canada's first geostationary satellite serving the continent, Anik A1, was launched by Telesat Canada, with the United States following suit with the launch of Westar 1 by Western Union on April 13, 1974.

On May 30, 1974, the first geostationary communications satellite in the world to be three-axis stabilized was launched: the experimental satellite ATS-6 built for NASA

After the launches of Telstar, Syncom 3, Early Bird, Anik A1, and Westar 1, RCA Americom (later GE Americom, now SES Americom) launched Satcom 1 in 1975. It was Satcom 1 that was instrumental in helping early cable TV channels such as WTBS (now TBS Superstation), HBO, CBN (now ABC Family), and The Weather Channel become successful, because these channels distributed their programming to all of the local cable TV headends using the satellite. Additionally, it was the first satellite used by broadcast television networks in the United States, like ABC, NBC, and CBS, to distribute programming to their local affiliate stations. Satcom 1 was widely used because it had twice the communications capacity of the competing Westar 1 in America (24 transponders as opposed to the 12 of Westar 1), resulting in lower transponder-usage costs. Satellites in later decades tended to have even higher transponder numbers.

By 2000, Hughes Space and Communications (now Boeing Satellite Development Center) had built nearly 40 percent of the more than one hundred satellites in service worldwide. Other major satellite manufacturers include Space Systems/Loral, Orbital Sciences Corporation with the STAR Bus series, Indian Space Research Organization, Lockheed Martin (owns the former RCA Astro Electronics/GE Astro Space business), Northrop Grumman, Alcatel Space, now Thales Alenia Space, with the Spacebus series, and Astrium.

Low-Earth-orbiting satellites



Low Earth orbit in Cyan

A Low Earth Orbit (LEO) typically is a circular orbit about 400 kilometres above the earth's surface and, correspondingly, a period (time to revolve around the earth) of about 90 minutes. Because of their low altitude, these satellites are only visible from within a radius of roughly 1000 kilometres from the sub-satellite point. In addition, satellites in low earth orbit change their position relative to the ground position quickly. So even for local applications, a large number of satellites are needed if the mission requires uninterrupted connectivity.

Low earth orbiting satellites are less expensive to launch into orbit than geostationary satellites and, due to proximity to the ground, do not require as high signal strength (Recall that signal strength falls off as the square of the distance from the source, so the effect is dramatic). Thus there is a trade off between the number of satellites and their cost. In addition, there are important differences in the onboard and ground equipment needed to support the two types of missions.

A group of satellites working in concert is known as a satellite constellation. Two such constellations, intended to provide satellite phone services, primarily to remote areas, are the Iridium and Globalstar systems. The Iridium system has 66 satellites. Another LEO satellite constellation known as Teledesic, with backing from Microsoft entrepreneur Paul Allen, was to have over 840 satellites. This was later scaled back to 288 and ultimately ended up only launching one test satellite.

It is also possible to offer discontinuous coverage using a low Earth orbit satellite capable of storing data received while passing over one part of Earth and transmitting it later while passing over another part. This will be the case with the CASCADE system of Canada's CASSIOPE communications satellite. Another system using this store and forward method is Orbcomm.

Molniya satellites

As mentioned, geostationary satellites are constrained to operate above the equator. As a consequence, a geostationary satellite will appear low on the horizon, affecting connectivity and causing multipath (interference caused by signals reflecting off the ground and into the ground antenna). The first satellite of the Molniya series was launched on April 23, 1965 and was used for experimental transmission of TV signal from a Moscow uplink station to downlink stations located in Siberia and the Russian Far East, in Norilsk, Khabarovsk, Magadan and Vladivostok. In November 1967 Soviet engineers created a unique system of national TV network of satellite television, called Orbita, that was based on Molniya satellites.

Molniya orbits can be an appealing alternative in such cases. The Molniya orbit is highly inclined, guaranteeing good elevation over selected positions during the northern portion of the orbit. (Elevation is the extent of the satellite's position above the horizon. Thus, a satellite at the horizon has zero elevation and a satellite directly overhead has elevation of 90 degrees).

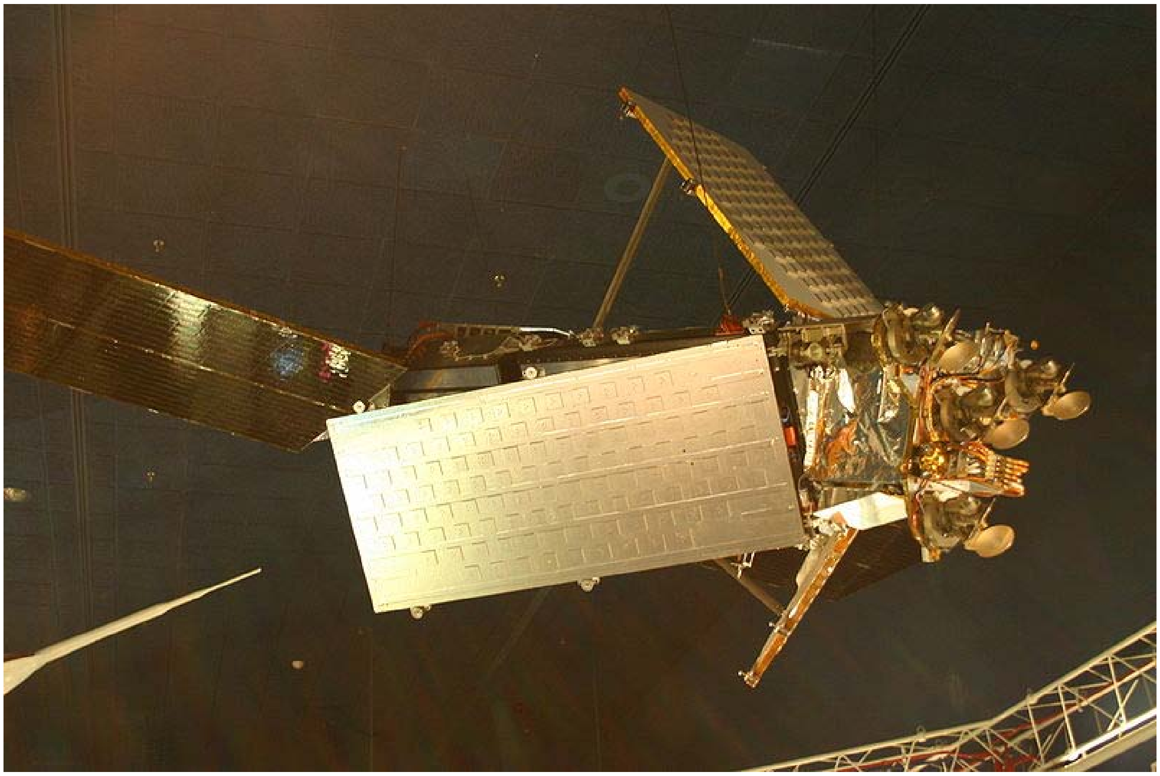
Furthermore, the Molniya orbit is designed so that the satellite spends the great majority of its time over the far northern latitudes, during which its ground footprint moves only slightly. Its period is one half day, so that the satellite is available for operation over the targeted region for sixty-nine hours every second revolution. In this way a constellation of three Molniya satellites (plus in-orbit spares) can provide uninterrupted coverage.

Bandwidth of a satellite

Bandwidth of a satellite depends upon the number of transponders a satellite has. Each service (TV, Voice, Internet, radio) requires different amount of bandwidth for transmission. The bandwidth of transponder is used to carry these services

Applications

Telephone



An Iridium satellite

The first and historically most important application for communication satellites was in intercontinental long distance telephony. The fixed Public Switched Telephone Network relays telephone calls from land line telephones to an earth station, where they are then transmitted to a geostationary satellite. The downlink follows an analogous path. Improvements in submarine communications cables, through the use of fiber-optics, caused some decline in the use of satellites for fixed telephony in the late 20th century, but they still serve remote islands such as Ascension Island, Saint Helena, Diego Garcia, and Easter Island, where no submarine cables are in service. There are also regions of some continents and countries where landline telecommunications are rare to nonexistent, for example large regions of South America, Africa, Canada, China, Russia, and Australia. Satellite communications also provide connection to the edges of Antarctica and Greenland.

Satellite phones connect directly to a constellation of either geostationary or low-earth-orbit satellites. Calls are then forwarded to a satellite teleport connected to the Public Switched Telephone Network

Satellite television

As television became the main market, its demand for simultaneous delivery of relatively few signals of large bandwidth to many receivers being a more precise match for the capabilities of geosynchronous comsats. Two satellite types are used for North American television and radio: Direct Broadcast Satellite (DBS), and Fixed Service Satellite (FSS)

The definitions of FSS and DBS satellites outside of North America, especially in Europe, are a bit more ambiguous. Most satellites used for direct-to-home television in Europe have the same high power output as DBS-class satellites in North America, but use the same linear polarization as FSS-class satellites. Examples of these are the Astra, Eutelsat, and Hotbird spacecraft in orbit over the European continent. Because of this, the terms FSS and DBS are more so used throughout the North American continent, and are uncommon in Europe.

Fixed Service Satellite

Fixed Service Satellites use the C band, and the lower portions of the K_u bands. They are normally used for broadcast feeds to and from television networks and local affiliate stations (such as program feeds for network and syndicated programming, live shots, and backhauls), as well as being used for distance learning by schools and universities, business television (BTV), Videoconferencing, and general commercial telecommunications. FSS satellites are also used to distribute national cable channels to cable television headends.

Free-to-air satellite TV channels are also usually distributed on FSS satellites in the K_u band. The Intelsat Americas 5, Galaxy 10R and AMC 3 satellites over North America provide a quite large amount of FTA channels on their K_u band transponders.

The American DISH Network DBS service has also recently utilized FSS technology as well for their programming packages requiring their SuperDish antenna, due to Dish Network needing more capacity to carry local television stations per the FCC's "must-carry" regulations, and for more bandwidth to carry HDTV channels.

Direct broadcast satellite

A **direct broadcast satellite** is a communications satellite that transmits to small DBS satellite dishes (usually 18 to 24 inches or 45 to 60 cm in diameter). Direct broadcast satellites generally operate in the upper portion of the microwave K_u band. DBS technology is used for DTH-oriented (Direct-To-Home) satellite TV services, such as DirecTV and DISH Network in the United States, Bell TV and Shaw Direct in Canada, Freesat and Sky Digital in the UK, the Republic of Ireland, and New Zealand.

Operating at lower frequency and lower power than DBS, FSS satellites require a much larger dish for reception (3 to 8 feet (1 to 2.5m) in diameter for K_u band, and 12 feet (3.6m) or larger for C band). They use linear polarization for each of the transponders' RF input and output (as opposed to circular polarization used by DBS satellites), but this is a minor technical difference that users do not notice. FSS satellite technology was also originally used for DTH satellite TV from the late 1970s to the early 1990s in the United States in the form of TVRO (TeleVision Receive Only) receivers and dishes. It was also used in its K_u band form for the now-defunct Primestar satellite TV service.

Satellites for communication have now been launched that have transponders in the K_a band, such as DirecTV's SPACEWAY-1 satellite, and Anik F2. NASA as well has launched experimental satellites using the K_a band recently.

Mobile satellite technologies

Initially available for broadcast to stationary TV receivers, by 2004 popular mobile direct broadcast applications made their appearance with that arrival of two satellite radio systems in the United States: Sirius and XM Satellite Radio Holdings. Some manufacturers have also introduced special antennas for mobile reception of DBS television. Using Global Positioning System (GPS) technology as a reference, these antennas automatically re-aim to the satellite no matter where or how the vehicle (on which the antenna is mounted) is situated. These mobile satellite antennas are popular with some recreational vehicle owners. Such mobile DBS antennas are also used by JetBlue Airways for DirecTV (supplied by LiveTV, a subsidiary of JetBlue), which passengers can view on-board on LCD screens mounted in the seats.

Satellite radio

Satellite radio offers audio services in some countries, notably the United States. Mobile services allow listeners to roam a continent, listening to the same audio programming anywhere.

A satellite radio or subscription radio (SR) is a digital radio signal that is broadcast by a communications satellite, which covers a much wider geographical range than terrestrial radio signals.

Satellite radio offers a meaningful alternative to ground-based radio services in some countries, notably the United States. Mobile services, such as Sirius, XM, and Worldspace, allow listeners to roam across an entire continent, listening to the same audio programming anywhere they go. Other services, such as Music Choice or Muzak's satellite-delivered content, require a fixed-location receiver and a dish antenna. In all cases, the antenna must have a clear view to the satellites. In areas where tall buildings, bridges, or even parking garages obscure the signal, repeaters can be placed to make the signal available to listeners.

Radio services are usually provided by commercial ventures and are subscription-based. The various services are proprietary signals, requiring specialized hardware for decoding and playback. Providers usually carry a variety of news, weather, sports, and music channels, with the music channels generally being commercial-free.

In areas with a relatively high population density, it is easier and less expensive to reach the bulk of the population with terrestrial broadcasts. Thus in the UK and some other countries, the contemporary evolution of radio services is focused on Digital Audio Broadcasting (DAB) services or HD Radio, rather than satellite radio.

Amateur radio

Amateur radio operators have access to the OSCAR satellites that have been designed specifically to carry amateur radio traffic. Most such satellites operate as spaceborne repeaters, and are generally accessed by amateurs equipped with UHF or VHF radio equipment and highly directional antennas such as Yagis or dish antennas. Due to launch costs, most current amateur satellites are launched into fairly low Earth orbits, and are designed to deal with only a limited number of brief contacts at any given time. Some satellites also provide data-forwarding services using the AX.25 or similar protocols.

Satellite Internet

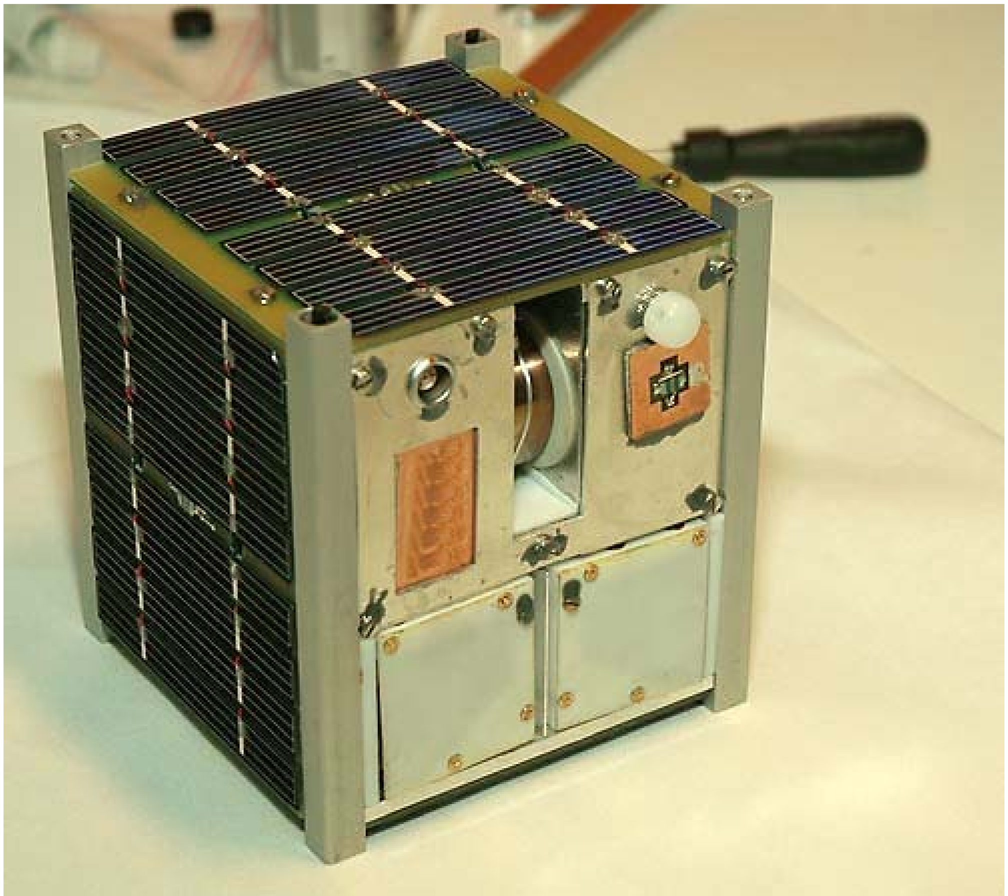
After the 1990s, satellite communication technology has been used as a means to connect to the Internet via broadband data connections. This can be very useful for users who are located in very remote areas, and cannot access a broadband connection.

Military uses

Communications satellites are used for military communications applications, such as Global Command and Control Systems. Examples of military systems that use communication satellites are the MILSTAR, the DSCS, and the FLTSATCOM of the United States, NATO satellites, United Kingdom satellites, and satellites of the former Soviet Union. Many military satellites operate in the X-band, and some also use UHF radio links, while MILSTAR also utilizes Ka band.

Chapter 18

CubeSat



Ncube-2, a Norwegian Cubesat

A **CubeSat** is a type of miniaturized satellite for space research that usually has a volume of exactly one liter (10 cm cube), weighs no more than 1.33 kilograms, and typically uses commercial off-the-shelf electronics components. Beginning in 1999, California Polytechnic State University (Cal Poly) and Stanford University developed the CubeSat specifications to help universities worldwide to perform space science and exploration.

The majority of development comes from academia, however several companies have built CubeSats, including large-satellite-maker Boeing, The CubeSat format is also popular with amateur radio satellite builders.

Design

The term "CubeSat" was coined to denote nano-satellites that adhere to the standards described in the CubeSat design specification. Cal Poly published the standard in an effort led by aerospace engineering professor Jordi Puig-Suari. Bob Twiggs, from the Department of Aeronautics & Astronautics at Stanford University, and most recently, the space science faculty of Morehead State University in Kentucky, has contributed to the CubeSat community. His efforts have focused on CubeSats from educational institutions. The specification does not apply to other cube-like nano-satellites such as the NASA "MEPSI" nano-satellite, which is slightly larger than a CubeSat.

In 2004, with their relatively small size, CubeSats could each be made and launched for an estimated \$65,000–\$80,000. This price tag, far lower than most satellite launches, has made CubeSat a viable option for schools and universities across the world. Because of this, a large number of universities and some companies and government organizations around the world are developing CubeSats — between 40 and 50 universities were developing CubeSats in 2004, Cal Poly reported.

The standard 10×10×10 cm basic CubeSat is often called a "1U" CubeSat meaning one unit. CubeSats are scalable in 1U increments and larger. CubeSats such as a “2U” CubeSat (20×10×10 cm) and a “3U” CubeSat (30×10×10 cm) have been both built and launched.

Since CubeSats are all 10x10 cm (regardless of length) they can all be launched and deployed using a common deployment system. CubeSats are typically launched and deployed from a mechanism called a Poly-PicoSatellite Orbital Deployer (P-POD), also developed and built by Cal Poly. P-PODs are mounted to a launch vehicle and carry CubeSats into orbit and deploy them once the proper signal is received from the launch vehicle. P-PODs have deployed over 90% of all CubeSats launched to date (including unsuccessful launches), and 100% of all CubeSats launched since 2006. The P-POD Mk III has capacity for three 1U CubeSats however, since three 1U CubeSats are exactly the same size as one 3U CubeSat, and two 1U CubeSats are the same size as one 2U CubeSat, the P-POD can deploy 1U, 2U, or 3U CubeSats in any combination up to a maximum volume of 3U.

CubeSat forms a cost-effective independent means of getting a payload into orbit. Most CubeSats carry one or two scientific instruments as their primary mission payload. Several companies and research institutes offer regular launch opportunities in clusters of several cubes. ISC Kosmotras and Eurokot are two companies that offer such services.

Successful projects

One of the earliest launches of CubeSats was 30 June 2003 from Plesetsk, Russia, with Eurockot Launch Services's *Multiple Orbit Mission*. CubeSats were put into a sun-synchronous orbit and included the Danish AAU CubeSat and DTUSat, the Japanese CUTE-1, the Canadian Can X-1, and the US triple-CubeSat Quakesat.

On 27 October 2005, a Kosmos-3M launch vehicle launched from Plesetsk carried three CubeSats into orbit on the European Space Agency's Student Space Exploration & Technology Initiative (SSETI) mission. The SSETI Express Satellite student-built satellite was not a CubeSat as it weighed 136 pounds and was the size of a washing machine. The CubeSats that did make orbit on this launch were the Ncube satellite project from the Norwegian University of Science and Technology and the University of Tokyo's CubeSat XI-V.

Seven CubeSats were launched 17 April 2007 as secondary payloads on a Dnepr rocket. They included a Colombian project from the students at the Universidad Sergio Arboleda. Their satellite, called Libertad 1, was Colombia's first. The Aerospace Corporation had their AeroCube 2, CP-3 & CP-4 were on board from California Polytechnic State University, and CAPE-1 from the University of Louisiana at Lafayette.

In a launch coordinated by the Nanosatellite Launch System, a Polar Satellite Launch Vehicle launched CubeSats on April 28, 2008. One was a 3-unit CubeSat (10x10x30 centimeters) named Delfi-C3 from Delft University of Technology in the Netherlands.

On December 8, 2010, several CubeSats were reported to have deployed successfully from a SpaceX Falcon 9 rocket, the same one that launched their first Dragon spacecraft on COTS Demo Flight 1.

Applications

Development of CubeSat technology

- AAU CubeSat, by Aalborg University - The Danish students in this project, beginning in the summer of 2001, designed a satellite that would evaluate the technology and demonstrate the capabilities of the CubeSat concept. In order to successfully show the technology to the public, the team installed a camera on board the spacecraft, and outfitted it with a magnetically-based attitude control system. But upon reaching orbit, the radio signals were weaker than expected and the batteries failed after only one month of semi-operational activity.

- AAUSAT-II is the second student-built CubeSat built and operated by students from Aalborg University in Denmark. It was launched 28 April 2008 05:54 UTC from Satish Dhawan Space Centre in India on a PSLV rocket. AAUSAT-II carries a radiation sensor.

- AAUSAT3 is the third student-built CubeSat from Aalborg University in Denmark. The primary payload is an AIS receiver which primary task is to receive AIS data from ships around Greenland. Planned launch Q1 2011.

- PW-Sat, by Warsaw University of Technology - This experiment revolves around CubeSats themselves. The test will involve developing a method to deorbit CubeSats by engaging an atmospheric drag device. The mission's focus will be the testing of this foil device; its deployment to intentionally bring the satellite back into the thicker portion of Earth's atmosphere to bring the mission to an end. If successful the satellite will be Poland's first.

- OUFTI-1, by the University of Liège and I.S.I.L (Haute École de la Province de Liège) - This is a 1-unit CubeSat that is being built by Belgian students. The name is an acronym for *Orbital Utility For Telecommunication Innovation*. The Belgian satellite is scheduled to launch on the maiden flight of Vega. The goal of the project is to develop experience in the different aspects of satellite design and operation. In the communications portion of the device, the academic team will be experimenting with the D-STAR digital voice mode and communications protocol that is popular with amateur radio operators. The satellite weighs just 1 kilogram and will utilize a UHF uplink and a VHF downlink.

- CubeSat TestBed 1, by Boeing - Boeing successfully completed all of its design and operational goals with its first nanosatellite. It was built and flown to explore the possibilities with the new CubeSat standard. Boeing satellites are usually much larger; a Boeing 601 or 702 satellite weighs 1,000 times as much as their 1 kilogram CubeSat.

- InnoSAT, by Astronautic Technology Sdn Bhd - This CubeSat will test attitude control and navigation technologies developed by five Malaysian universities.

- XSAS, by University of Michigan - This project, based on graduate research, will house an accordion folded solar array inside a 1U CubeSat. The array will extend into a long solar panel once in orbit, thereby increasing by many times the power available to an attached CubeSat.

Earth remote sensing

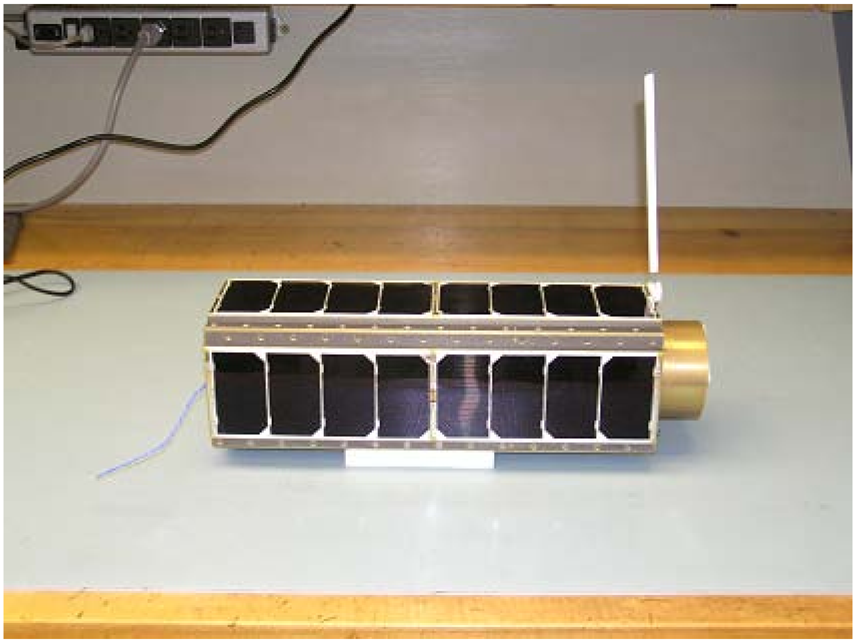
- Quakesat, by Quakefinder - This satellite was set out on a mission to help scientists improve earthquake detection. The students are hoping that the detection of magnetic signals may have value in showing the onset of an earthquake. The company that put the satellites together is from Palo Alto, California. They're gathering data on the extremely low magnetic field fluctuations that are associated with earthquakes to help better understand this area of study that has its skeptics. The 30 June 2003 deployment of Quakesat was alongside other university CubeSats and one commercial CubeSat. The launch occurred on a Rockot rocket from Russia’s Plesetsk launch site.

- SwissCube, by École Polytechnique Fédérale de Lausanne - This project has been selected to fly aboard a new expendable launch system being developed for Arianespace jointly by the Italian Space Agency and the European Space Agency. The rocket is called Vega, and takes its name from the star. The Swiss students will conduct experiments with the air glow phenomenon in the Earth's atmosphere. The satellite's downlink radio will transmit at 437 MHz; the uplink will be at 145 MHz.

- PLUME, by the University of Leicester - They plan to launch a CubeSat that will detect cosmic dust, and will be the first English CubeSat to be launched. The students began their project at the beginning of 2007 and if successful will have a method for scientists to look at the smallest ever dust particles from space.

- Firefly, by NASA's Goddard Space Flight Center and Siena College - Terrestrial gamma-ray flashes have been detected from the Compton Gamma Ray Observatory after its launch in 1991. Scientists have theories about their origins and this new CubeSat will have instruments that will observe both photons and electrons simultaneously. This, in turn, will allow scientists to better determine if lightning is the source of the gamma ray bursts.

Space tether



NASA's GeneSat 1

- MAST, by Tethers Unlimited - The *Multi-Application Survivable Tether* experiment, based in the United States, was launched 17 April 2007 aboard a Dnepr rocket. This 1 km multistrand, interconnected tether (Hoytether) is being used to test and prove the long-term survivability for tethers in space. The three

MAST pico-satellites ejected from the P-POD successfully, but the separation mechanism did not function properly, preventing full deployment of the tether. Nonetheless, the experiment operated for over a month and downloaded over 2 MB of data on tethered satellite dynamics as well as images of the tether. While Stanford University formed the academic portion of the team, Tethers Unlimited, from Seattle, Washington, formed the commercial portion of the team.

- Tempo3, by The Mars Society - This operation is called the *Tethered Experiment for Mars inter-Planetary Operations* and is meant to demonstrate the generation of artificial gravity. The project seeks to enhance knowledge about long term space flight.

Biology

- GeneSat 1, by the NASA Ames Research Center - In December 2006, a Minotaur launch vehicle carried this satellite into orbit from NASA's Wallops Flight Facility to carry out a genetics experiment. The team assembled the biological growth and analysis systems to perform experiments with E. coli bacteria. The project is not cheap by CubeSat standards: the total spent on the satellite and its experiments were $6 million before the launch took place. The goal is to establish methods for studying the genetic changes that come from being exposed to a space environment. The satellite was outfitted with a UHF beacon.

Other

- StudSat, first Indian satellite of Pico-Category was developed by a group of 50 under graduate students at Nitte Meenakshi Institute of Technology, Bangalore, India, and was launched 12 July 2010 by Polar Satellite Launch Vehicle.
- Cubesat ROBUSTA, by Montpellier 2 University - A mission to test the effects of radiation on electronics. The goal is to specifically check the deterioration of electronic components based on bipolar transistors when exposed to the space radiation environment. The results of this experiment will be used to validate a test method proposed in the laboratory. The French satellite is scheduled to launch on the maiden flight of Vega.
- TJ^{3}Sat, by Thomas Jefferson High School for Science and Technology, Alexandria, Va., which aims to be the first CubeSat by high school students.
- Xatcobeo, by University of Vigo and Instituto Nacional de Técnica Aeroespacial - The goal for this project is to test software defined radio and to experiment with solar panel deployment. The Spanish satellite is scheduled to launch on the maiden flight of Vega.
- CINEMA, a collaborative effort between the UC Berkeley Space Sciences Laboratory, Imperial College London, Kyung Hee University, and the Interamerican University of Puerto Rico. The project's goal is to develop a cubesat that monitors space weather using a combination of magnetometers and particle detectors.

Launch failures

Dnepr

The Falcon 1 rocket lifting off at Omelek Island on July 14, 2009

On 26 July 2006, 14 CubeSats from 11 universities and a private company were launched aboard a Dnepr rocket, the largest planned deployment of CubeSats to date. The rocket failed and was destroyed during launch, obliterating the CubeSats and four other satellites aboard. The launch was lost after the first stage engine shut down prematurely. All satellite parts are believed destroyed.

The committee investigating the failed launch concluded that the failure was caused by a malfunctioning hydraulic drive unit on the rocket's first stage. The control malfunctioning brought about the disturbances, which led to the roll instability, excessive dispersions of the yaw and pitch angles. Thrust termination occurred at 74 seconds after lift off.

The launch had been postponed numerous times because the primary payload, EgyptSat 1, was not ready. Due to ITAR concerns, the CubeSats were moved to a different launch site, with the primary payload being BelKA, which was to be the first satellite from Belarus.

The launch carried Rincon 1 and SACRED, both from the University of Arizona. Other projects came from the Norwegian University of Science and Technology, Hankuk Aviation University, Seoul, Korea and Polytechnic University of Turin, Italy. The Aerospace Corporation, from the United States, also had its own commercial project onboard.

Falcon 1

On 3 August 2008, a SpaceX Falcon 1 launched from the Kwajalein Atoll launch facility (US) with two NASA Ames CubeSats. They were the PREsat from NASA's Ames Research Center, and the NanoSail-D from both NASA's Marshall Space Flight Center and Ames Research Center. These CubeSats were lost due to a launch vehicle failure when the rocket's first stage inadvertently made contact with the second stage after separation.

Planned projects

NASA Educational Launch of Nanosatellites

A February 23, 2011, launch (setback from a November 2010 launch date due to delays) was scheduled for three university CubeSats to be launched by NASA in their mission called ELaNa (Educational Launch of Nanosatellites). These university satellites include the Space Science and Engineering Laboratory's Explorer-1 PRIME (E1P) developed by students at Montana State University, Kentucky Space's KySat-1 which was developed by multiple Kentucky universities plus several organizations and companies, and the University of Colorado-Boulder's HERMES. The backup for the launch is University of Florida's ASTREC-1. The satellites were lost when the Glory satellite launch failed 5 minutes after take off.

QB50

The goal of the QB50 project is to use an international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere (90–300 km) and re-entry research. QB50 is an iniative of the Von Karman Institute, ESA and NASA. Double-unit CubeSats (10x10x20 cm) are foreseen, with one unit (the 'functional' unit) providing the usual satellite functions and the other unit (the 'science' unit) accommodating a set of standardised sensors for lower thermosphere and re-entry research. 35 CubeSats are envisaged to be provided by universities in 19 European countries, 10 by universities in the US, 2 by universities in Canada and 3 by Japanese universities. All 50 CubeSats will be launched together on a single launch vehicle, a Russian Shtil-2.1. The launch is planned for mid 2013.

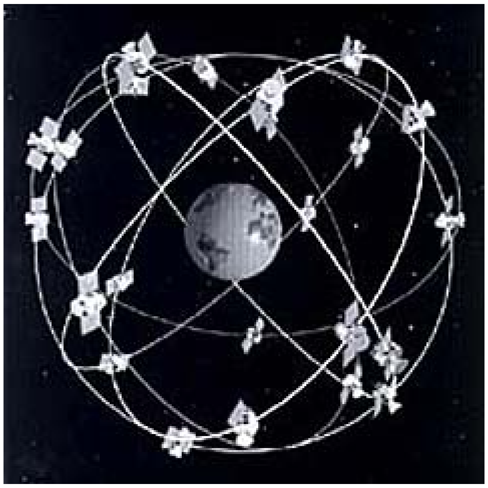
Releasing CubeSats from International Space Station

JAXA is planning of releasing CubeSats from International Space Station using Japanese Experiment Module's robot hand.

Chapter 19

Satellite Constellation and Zero-Drag Satellite

Satellite constellation



The GPS constellation calls for 24 satellites to be distributed equally among six circular orbital planes

A group of artificial satellites working in concert is known as a **satellite constellation**. Such a constellation can be considered to be a number of satellites with coordinated ground coverage, operating together under shared control, synchronised so that they overlap well in coverage and complement rather than interfere with other satellites' coverage.

Overview

Low Earth orbiting satellites (LEOs) are often deployed in satellite constellations, because the coverage area provided by a single LEO satellite only covers a small area that moves as the satellite travels at the high angular velocity needed to maintain its orbit. Many LEO satellites are needed to maintain continuous coverage over an area. This contrasts with geostationary satellites, where a single satellite, moving at the same angular velocity as the rotation of the Earth's surface, provides permanent coverage over a large area.

Examples of satellite constellations include the Global Positioning System (GPS), Galileo and GLONASS constellations for navigation and geodesy, the Iridium and Globalstar satellite telephony services, the Disaster Monitoring Constellation and RapidEye for remote sensing, the Orbcomm messaging service, Russian elliptic orbit Molniya and Tundra constellations, the large-scale Teledesic and Skybridge broadband constellation proposals of the 1990s, and the proposed LEO global backhaul constellation named COMMStellation™.

Broadband applications benefit from low-latency communications, so LEO satellite constellations provide an advantage over a geostationary satellite, where minimum theoretical latency is about 125 milliseconds, compared to 1–4 milliseconds for a LEO satellite. A LEO satellite constellation can also provide more system capacity by frequency reuse across its coverage, with spot beam frequency use being analogous to the frequency reuse of cellular radio towers.

Satellite constellation coverage and geometry – determining the minimum number of satellites needed to provide a service, and their orbits – is a field in itself.

A group of formation-flying satellites very close together and moving in almost identical orbits is known as a satellite cluster or Satellite formation flying.

Walker Constellation

There are a large number of constellations that may satisfy a particular mission. Usually constellations are designed so that the satellites have similar orbits, eccentricity and inclination so that any perturbations affect each satellite in approximately the same way. In this way, the geometry can be preserved without excessive station keeping thereby reducing the fuel usage and hence increasing the life of the satellites. Another consideration is that the phasing of each satellite in an orbital plane maintains sufficient separation to avoid collisions or interference at orbit plane intersections. Circular orbits are popular, because then the satellite is at a constant altitude requiring a constant strength signal to communicate.

A class of circular orbit geometries that has become popular is the Walker Delta Pattern constellation. This has an associated notation to describe it which was proposed by John Walker. His notation is:

i: t/p/f

where: **i** is the inclination, **t** is the total number of satellites. **p** is the number of equally spaced planes **f** is the relative spacing between satellites in adjacent planes. The change in true anomaly (in degrees) for equivalent satellites in neighbouring planes is equal to **f***360/**t**.

For example, the Galileo Navigation system is a Walker Delta 56°:27/3/1 constellation. This means there are 27 satellites in 3 planes inclined at 56 degrees, spanning the 360 degrees around the equator. The "1" defines the phasing between the planes, and how they are spaced. The Walker Delta is also known as the Ballard rosette, after A. H. Ballard's similar earlier work. Ballard's notation is (t,p,m) where m is a multiple of the fractional offset between planes.

Another popular constellation type is the near-polar Walker Star, which is used by Iridium. Here, the satellites are in near-polar circular orbits across approximately 180 degrees, travelling north on one side of the Earth, and south on the other. The active satellites in the full Iridium constellation form a Walker Star of 86.4°:66/6/2, i.e. the phasing repeats every two planes. Walker uses similar notation for stars and deltas, which can be confusing.

Zero-drag satellite

Zero-drag satellites or equivalently "drag-free satellites" are satellites where the payload follows a geodesic path through space only affected by gravity and not by non-gravitational forces such as drag of the residual atmosphere, light pressure and solar wind. A zero-drag satellite has two parts, an outer shell and an inner mass called the "proof mass". The proof mass, containing the payload, is floating freely inside the outer shell. The distance between the outer shell and the proof mass is constantly measured. When a change in the distance between the outer shell and the proof mass is detected, it means that the outer shell has been influenced by non-gravitational forces and moved relative to the proof mass. Thrusters on the outer shell will then reposition the outer shell relative to the proof mass so that its distance is the same as before the external influence changed it. The outer shell thus protects the proof mass from nearly all interactions with the outside that can cause acceleration, except those mediated by gravity.

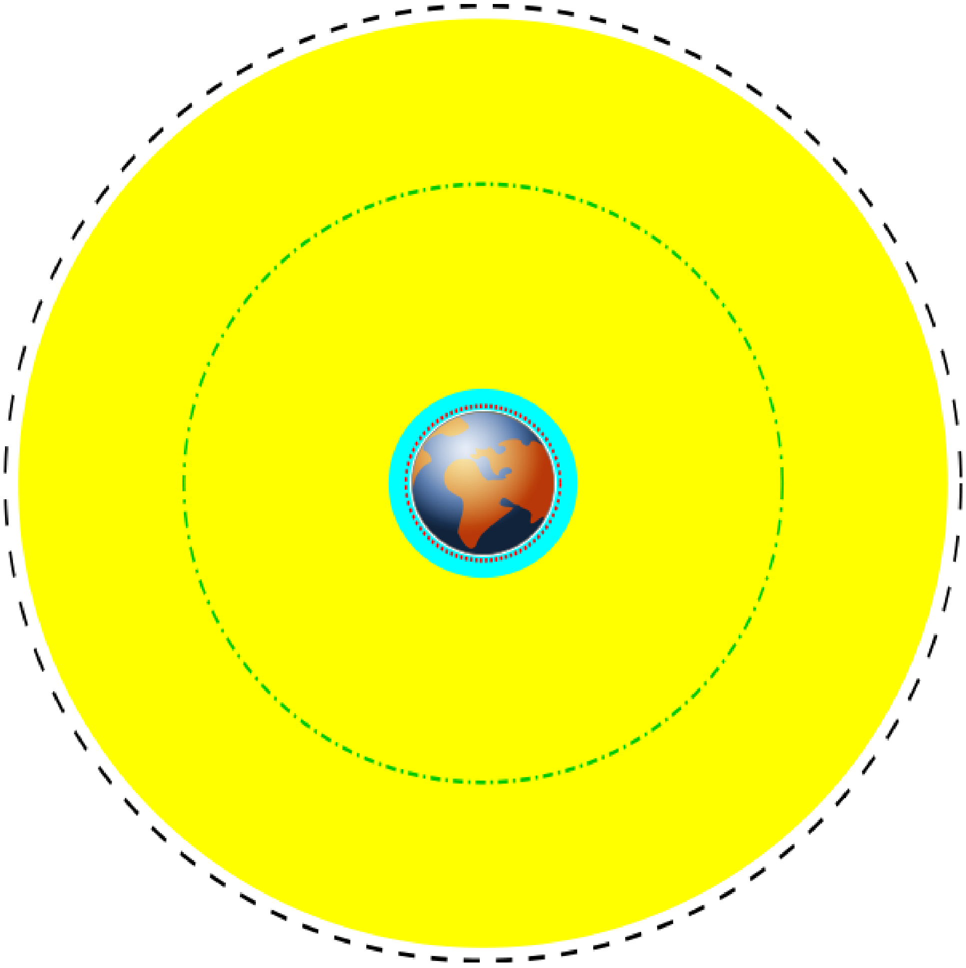
One way to think about a zero-drag satellite is to see the shell/proof mass setup as being an accelerometer, measuring the acceleration of the outer shell. The input from the accelerometer is then used to control the satellites thruster to exactly compensate for the measured acceleration, ensuring that over time the satellite has zero acceleration. Since the proof mass is floating free within the outer shell, neither the initial drag nor the thruster's compensation for it is experienced by the proof mass.

Zero-drag satellites are used in situations where it is instrumental for the satellite's mission that the payload remains on a near perfect geodesic path. Two such missions are the LISA gravity wave observatory and the ESA GOCE spacecraft that measures variations in the Earth's gravitational field.

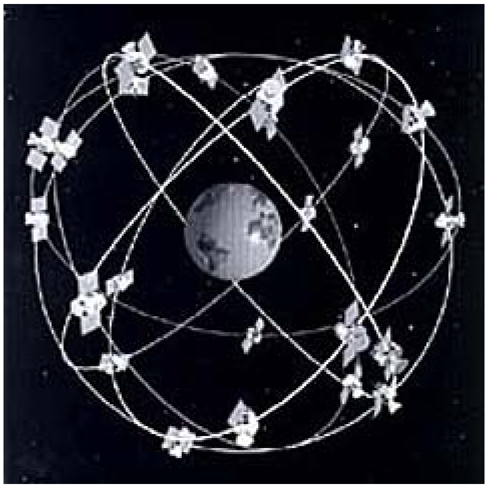
Chapter 20

GPS (Satellite) and GLONASS-K

GPS



Various earth orbits to scale; green dash-dot line is medium earth orbit, a typical GPS orbit.



GPS satellite constellation (not to scale)

A **GPS satellite** is a satellite used by the NAVSTAR Global Positioning System (GPS). The first satellite in the system, Navstar 1, was launched February 22, 1978. The GPS satellite constellation is operated by the 50th Space Wing of the United States Air Force.

Block I satellites

Beginning with Navstar 1 in 1978, ten "Block I" GPS satellites were successfully launched. One satellite, "Navstar 7", was lost due to an unsuccessful launch on December 18, 1981. The Block I satellites were launched from Vandenberg Air Force Base using Atlas rockets that were converted intercontinental ballistic missiles. The satellites were built by Rockwell International at the same plant in Seal Beach, CA where the S-II second stages of the Saturn V rockets had been built. The final Block I launch was conducted on October 9, 1985.

The last Block I satellite was taken out of service on November 18, 1995.

Block II satellites

Initial Block II series

The first of the nine satellites in the initial Block II series was launched February 14, 1989; the last was launched October 1, 1990. The final satellite of the series to be taken out of service was decommissioned March 15, 2007.

Block IIA series

Nineteen satellites in the Block IIA series were launched, the first on November 26, 1990 and the last on November 6, 1997. As of January 17, 2009, six satellites of this series have been removed from service.

Two of the satellites in this series, numbers 35 and 36, are equipped with laser retro-reflectors, allowing them to be tracked independently of their radio signals, providing unambiguous separation of clock and ephemeris errors.

Block IIR series

The Block IIR series are "replenishment" satellites developed by Lockheed Martin. Each satellite weighs 4,480 pounds (2,030 kg) at launch and 2,370 pounds (1,080 kg) once on orbit. The first attempted launch of a Block IIR satellite failed on January 17, 1997 when the Delta II rocket exploded 12 seconds into flight. The first successful launch was on July 23, 1997. Twelve satellites in the series were successfully launched.

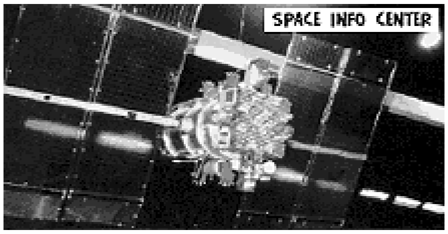
Block IIR-M series

The Block IIR-M satellites include a new military signal and a more robust civil signal, known as L2C. There are eight satellites in the Block IIR-M series, which were built by Lockheed Martin. The first Block IIR-M satellite was launched on September 26, 2005. The final launch of a IIR-M was on August 17, 2009.

Block IIF series

The Block IIF series are "follow-on" satellites developed by Boeing. On September 9, 2007 Boeing announced that it had completed assembly of the first satellite in the Block IIF series. Boeing is under contract to build a total of twelve Block IIF satellites. The first was launched in May 2010 on a Delta IV rocket.

GLONASS-K



GLONASS

GLONASS-K is the latest satellite design intended as a part of the Russian GLONASS radio-based satellite navigation system. Developed by Reshetnev Information Satellite Systems and first launched on 26 February 2011, it is a substantial improvement of the previous GLONASS-M second-generation satellites, having a longer lifespan and better accuracy.

History

The *Federal Targeted Program "Global Navigation System" 2002–2011*, introduced in 2001, stipulated the development of a third-generation navigation satellite design, called GLONASS-K, as part of the overall GLONASS upgrade program in the time frame 2005–2011. The new satellite followed the second generation GLONASS-M, introduced in 2003. The Russian Federal Space Agency (Roscosmos) initially ordered 27 GLONASS-K satellites from Reshetnev Information Satellite Systems, the developer of all the previous GLONASS satellites. On 7 December 2010, the company announced it had completed ground tests of the first GLONASS-K satellite. The satellite was launched to orbit on 26 February 2011.

Satellites

GLONASS-K is the first unpressurised GLONASS satellite—all of its equipment is able to operate in a vacuum. Due to this, the satellite's mass has been substantially reduced: GLONASS-K has a mass of just 750 kg compared to its predecessor GLONASS-M, which had a mass of 1,450 kg. The new satellite has an operational lifetime of 10 years, three years longer than that of GLONASS-M and seven years longer than the lifetime of the original GLONASS satellite. GLONASS-K will transmit 5 navigation signals, 3 more than its predecessor, to improve the system's accuracy. 4 military signals will be transmitted on the L1 and L2 bands, while the civilian signal will use the L3 band. The new satellite's advanced equipment—made solely from Russian components—will allow the doubling of GLONASS' accuracy.

Launches

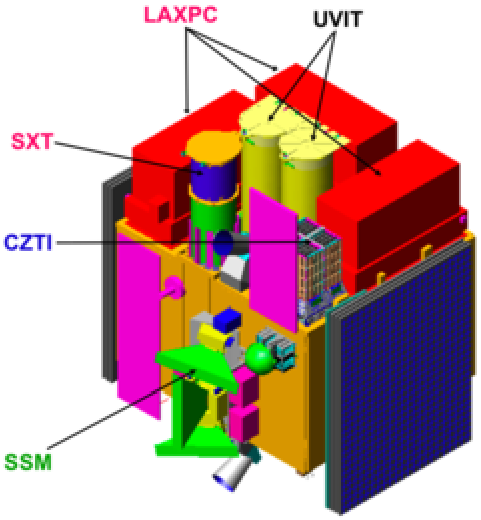
For launching the satellites, two options are planned: six satellites simultaneously from Baikonur Cosmodrome on the heavy-lift Proton-M, or two simultaneously from Plesetsk Cosmodrome on a Soyuz-2 with a Fregat upper stage. In comparison, the previous GLONASS-M satellites could only be launched three at a time on a Proton-M. The new launch scheme is expected to cut orbiting costs by 50%. The launch of the first GLONASS-K satellite did however not conform to the general plan, as it was launched alone on a Soyuz-2.1b instead of in a pair.

At 06:07 Moscow Time on 26 February 2011, the first GLONASS-K satellite was launched. The launch took place from Plesetsk Cosmodrome on a Soyuz-2.1b rocket with a Fregat upper stage. The satellite reached the correct orbit at 09:39. At 09:44, ground stations established control over the satellite. A Space Forces spokesman told Interfax: "we have established and are maintaining steady telemetry communications with the spacecraft... the on-board systems of the Glonass-K satellite are functioning normally."

Chapter 21

Astrosat

Astrosat



Astrosat

General information

Organization	ISRO
Launch date	2011
Launched from	Satish Dhawan Space Centre
Launch vehicle	PSLV-XL
Mission length	5 years
Mass	1,650 kg (3,600 lb)
Type of orbit	Near-equatorial
Orbit height	650 km (400 mi)
Orbit period	5 years
Wavelength	Multi-wavelength

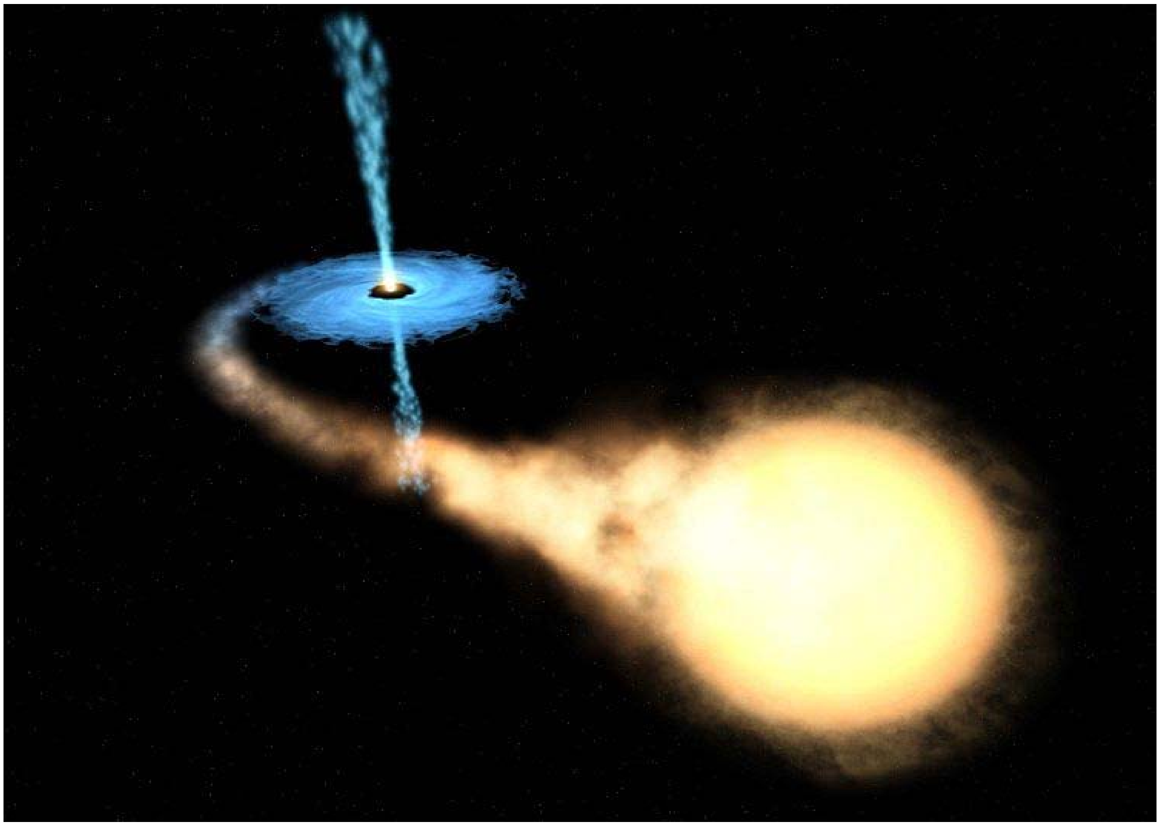
Instruments	
UVIT	UltraViolet Imaging Telescope
SXT	Soft X-ray telescope
LAXPC	X-ray timing and low-resolution spectral studies
CZTI	Hard X-ray imager

Astrosat is India's first dedicated astronomy satellite and is scheduled to launch on board the PSLV in 2011 After the success of the satellite-borne Indian X-ray Astronomy Experiment (IXAE), which was launched in 1996, the Indian Space Research Organization (ISRO) has approved further development for a full fledged astronomy satellite - Astrosat.

A large number of leading astronomy research institutions in India and abroad are jointly building various instruments for the satellite. Important areas requiring broad band coverage include studies of astrophysical objects ranging from the nearby solar system objects to distant stars, to objects at cosmological distances; timing studies of variables ranging from pulsations of the hot white dwarfs to active galactic nuclei (AGN) with time scales ranging from milliseconds to few hours to days.

Astrosat is currently proposed as a multi-wavelength astronomy mission on an IRS-class satellite into a near-Earth, equatorial orbit by the PSLV. The 5 instruments on-board cover the visible (320-530 nm), near UV(180-300 nm), far UV(130-180 nm), soft X-ray (0.3-8 keV and 2-10 keV) and hard X-ray (3-80 keV and 10-150 keV) regions of the electromagnetic spectrum.

Mission



Artist's conception of a binary star system with one black hole and one main sequence star

Astrosat will be a proposal-driven general purpose observatory, with main scientific focus on:

- Simultaneous multi-wavelength monitoring of intensity variations in a broad range of cosmic sources
- Monitoring the X-ray sky for new transients
- Sky surveys in the hard X-ray and UV bands
- Broadband spectroscopic studies of X-ray binaries, AGN, SNRs, clusters of galaxies and stellar coronae
- Studies of periodic and non-periodic variability of X-ray sources

Astrosat will carry out multi-wavelength observations covering spectral bands from radio, optical, IR, UV, X-ray and Gamma ray regions both for study of specific sources of interest and in survey mode. While radio, optical, IR observations would be coordinated through ground-based telescopes, the high energy regions, i.e., UV, X-rays and Gamma rays would be covered by the dedicated satellite borne instrumentation of Astrosat.

The mission would also study near simultaneous muti-wavelength data from different variable sources. In a binary system for example regions near the compact object emit predominantly in X-rays, the accretion disc emitting most of its light in the UV/ optical waveband, and the mass donating star being brightest in the optical band.

The observatory will also carry out (a) low to moderate resolution spectroscopy over wide energy band with the primary emphasis on studies of X-ray emitting objects, (b) Timing studies of periodic and aperiodic phenomenon in X-ray binaries, (c) Studies of pulsations in X-ray pulsars, (d) QPOs, flickering. Flaring and other variations in X-ray binaries, (e) short and long term intensity variations in AGNs, (f) time lag studies in low/hard X-rays and UV/optical radiation, (g) detection and study of x-ray transients. In particular, the mission will train its instruments at active galactic nuclei at the core of the Milky Way that is believed to have a super massive black hole.

Payloads

The scientific payload has a total mass of 750 kg and contains six instruments.

- **The UltraViolet Imaging Telescope (UVIT)** - The UltraViolet Imaging Telescope will perform imaging simultaneously in three channels: 130-180 nm, 180-300 nm, and 320-530 nm. The field of view is a circle of ~ 28 arcmin diameter and the angular resolution is 1.8" for the ultraviolet channels and 2.5" for the visible channel. In each of the three channels a spectral band can be selected through a set of filters mounted on a wheel; in addition, for the two ultraviolet channels a grating can be selected in the wheel to do slitless spectroscopy with a resolution of ~ 100.

- **Soft X-ray imaging Telescope (SXT)**- The soft X-ray telescope on Astrosat will employ focussing optics and a deep depletion CCD camera at the focal plane to perform X-ray imaging in 0.3-8.0 keV band. The optics will consist of 41 concentric shells of gold-coated conical foil mirrors in an approximate Wolter-I configuration. The focal plane CCD camera will be very similar to that flown on SWIFT XRT. The CCD will be operated at a temperature of about -80oC by thermoelectric cooling.

- **The LAXPC Instrument** - For X-ray timing and low-resolution spectral studies over a broad energy band (3-80 keV) Astrosat will use a cluster of 3 co-aligned identical Large Area X-ray Proportional Counters (LAXPCs), each with a multi-wire-multi-layer configuration and a Field of View of 1^o X 1^o. These detectors are designed to achieve (I) wide energy band of 3-80 keV, (II) high detection efficiency over the entire energy band, (III) narrow field of view to minimize source confusion, (IV) moderate energy resolution, (V) small internal background and (VI) long lifetime in space.

- **Cadmium Zinc Telluride Imager (CZTI)** - Astrosat will carry a hard X-ray imager in the form of CZTI. It will consist of a Pixellated Cadmium-Zinc-

Telluride detector array of ~1000 cm^2 geometric area. These detectors have very good detection efficiency, close to 100% up to 100 keV, and have a superior energy resolution (~2% at 60 keV) compared to scintillation and proportional counters. Their small pixel size also facilitates medium resolution imaging in hard x-rays. The CZTI will be fitted with a two dimensional coded mask, for imaging purposes. The sky brightness distribution will be obtained by applying a deconvolution procedure to the shadow pattern of the coded mask recorded by the detector.

- **Scanning Sky Monitor (SSM)** - The Scanning Sky Monitor will consist of three position sensitive proportional counters, each with a one-dimensional coded mask, very similar in design to the All Sky Monitor on NASA's RXTE satellite. The gas-filled proportional counter will have resistive wires as anodes. The ratio of the output charge on either ends of the wire will provide the position of the x-ray interaction, providing an imaging plane at the detector. The coded mask, consisting of a series of slits, will cast a shadow on the detector, from which the sky brightness distribution will be derived.

- **Charged Particle Monitor (CPM)** - A charged particle monitor (CPM) will be included as a part of Astrosat payloads to control the operation of the LAXPC, SXT and SSM. Even though the orbital inclination of the satellite will be 8 deg or less, in about 2/3rd of the orbits, the satellite will spend a considerable time (15 – 20 minutes) in the South Atlantic Anomaly (SAA) region which has high fluxes of low energy protons and electrons. The high voltage will be lowered or put off using data from CPM when the satellite enters the SAA region to prevent damage to the detectors as well as to minimize ageing effect in the Proportional Counters.

Ground support

The Ground Command and Control Centre for Astrosat will be located at ISTRAC, Bangalore, India. Commanding and data download will be possible during every visible pass over Bangalore. Ten out of 14 orbits per day will be visible to the ground station. The satellite is capable of gathering 420 gigabits of data every day that can be down loaded in 10 to 11 orbits visible at Tracking and Data receiving center of ISRO in Bangalore.

Current status

Scientists from Tata Institute of Fundamental Research (TIFR) have completed the developmental phase of complex science payloads and have begun integrating them before delivery of the 1,650 kg satellite Astrosat.A payload from RRI (Raman Research Institute) is under development, awaiting delivery. The challenges in the design of payloads and Attitude Control System have been overcome and in a recent review committee meeting, it was decided that the delivery of the payload to ISRO satellite Centre will begin from the middle of 2009 and continue till early 2010 to enable the launch of ASTROSAT in 2010 using ISRO workhorse PSLV. As of Sept 2010, launch is been rescheduled to 2011.

A third 11-meter antenna at the IDSN is under construction specifically for the Astrosat mission. It will be operational by 2009.

Participants

The Astrosat project is a collaborative effort of a growing list of research institutions. The current participants are:

- Indian Space Research Organization
- Tata Institute of Fundamental Research, Mumbai
- Indian Institute of Astrophysics, Bangalore
- Raman Research Institute, Bangalore
- Inter-University Centre for Astronomy and Astrophysics, Pune
- Bhabha Atomic Research Centre, Mumbai
- S.N. Bose National Centre for Basic Sciences, Kolkata
- Canadian Space Agency
- University of Leicester