Chapter 5

Optical, EUV, and X-ray observations

5.1 Satellite orbits

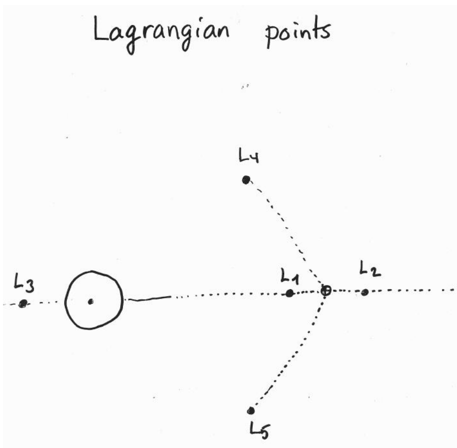


Figure 5.1: The Lagrangian points are positions in an orbital configuration where a small object (like a satellite) is affected only by gravity and can theoretically be stationary relative to the two larger objects (like the Sun and Earth). L1 is a favourable place for solar satellites because it allows a constant view of the Sun and the position is near enough to the Earth to allow good telemetry. L1 is about 1 million km from the Earth and about 148 million km from the Sun.

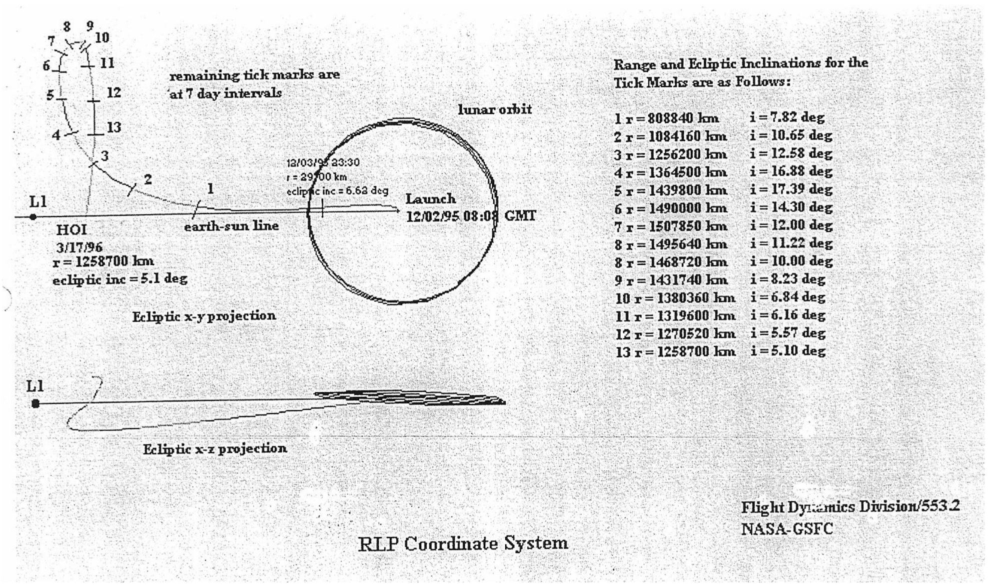
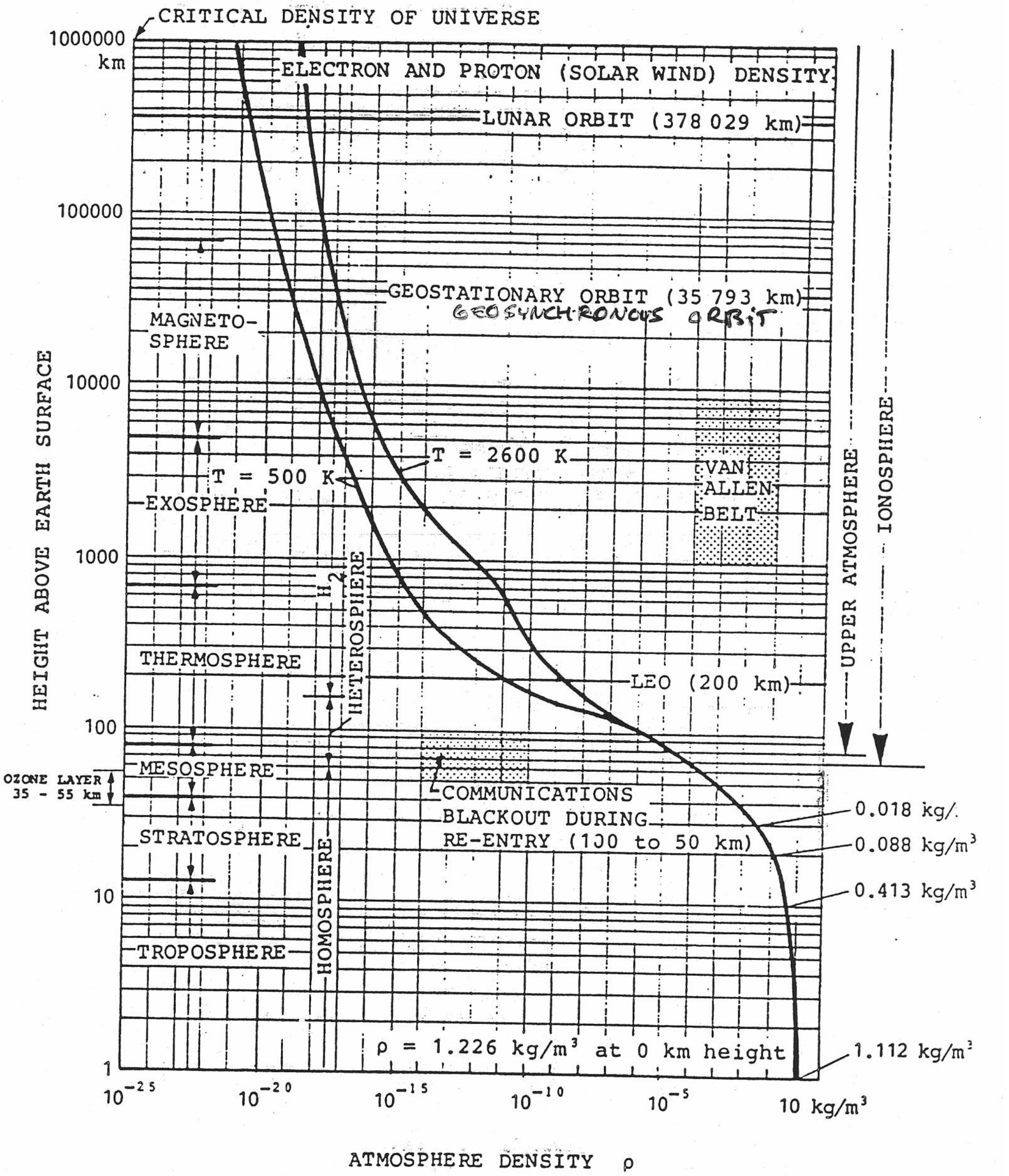


Figure 5.2: SOHO satellite moves around the Sun in step with the Earth, by slowly orbiting around the First Lagrangian Point L1.

Satellites on low-Earth orbits will experience 'satellite night times', i.e., the Sun cannot be observed when the satellite is behind the Earth. The on-off periods get repeated every 40–70 minutes. This affects also the telemetry.



ATMOSPHERIC DENSITY WITHIN EARTH'S INFLUENCE SPHERE

FIGURE 4

Figure 5.3: The NOAA GOES satellites have geosynchronous orbits, near height 36 000 km. The Japanese solar satellite Yohkoh (1991 – 2001) was on a low Earth orbit at height 570 – 730 km, and it regularly passed the van Allen radiation belts so near that the most sensitive instruments had to be turned off. This is the so-called 'South Atlantic Anomaly', SAA region, where the van Allen belt is at 200 km height at the lowest.

5.2 X-ray and EUV instruments

These instrument designs include:

- Geiger counters (1962-, saturates easily)
- Proportional counters
- Scintillation detectors
- Gas scintillation proportional counters
- Solid state detectors
- Microchannel plates
- Collimators
- Grazing incidence telescopes
- Glancing incidence telescopes
- Grating spectrometers
- Bragg crystal spectrometers

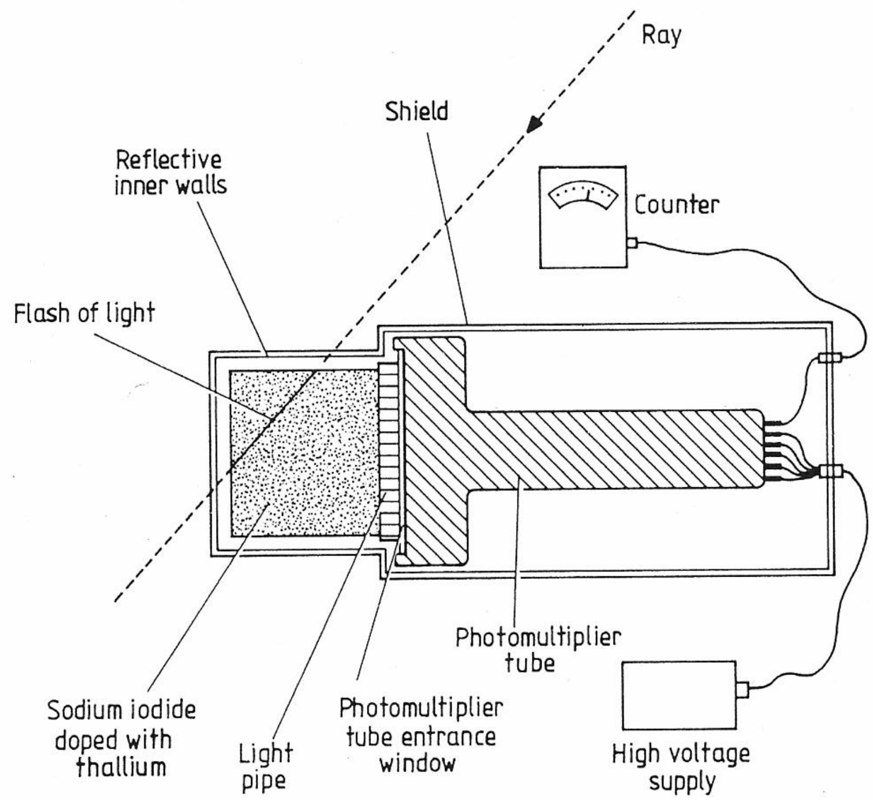


Figure 1.3.2 Schematic experimental arrangement of a scintillation counter.

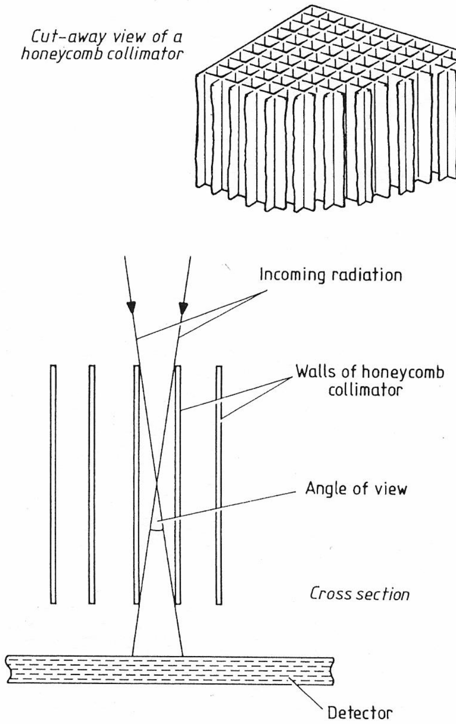


Figure 1.3.5 Honeycomb collimator.

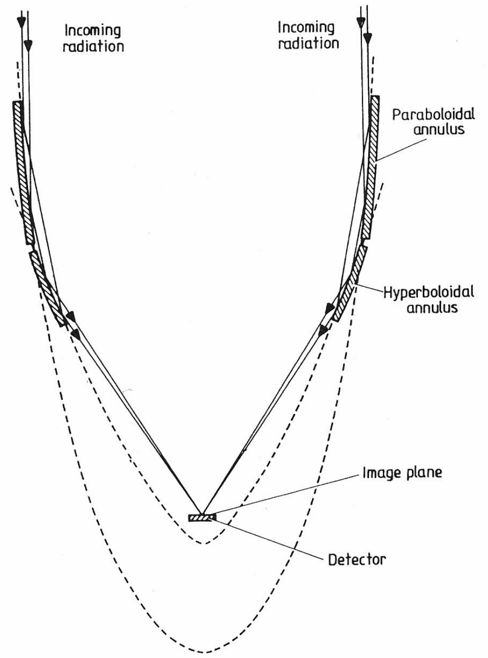


Figure 1.3.8 Cross section through a grazing incidence x-ray telescope.

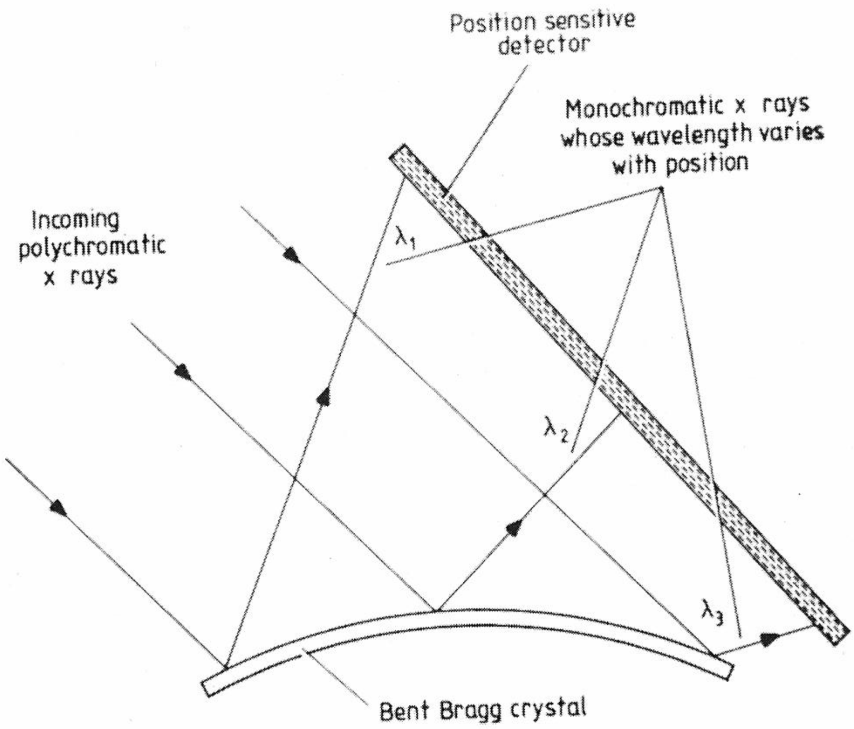


Figure 1.3.15 Bent Bragg crystal x-ray spectrometer.

The Yohkoh Satellite (1991–2001)
The satellite was launched into space from the Kagoshima Space Center (KSC) in Southern Japan. This satellite, known as Yohkoh ("Sunbeam"), is a project of the Japanese Institute of Space and Astronautical Science (ISAS). There were four instruments on the satellite,

Bragg Crystal Spectrometer (BCS)
Wide Band Spectrometer (WBS)
Soft X-Ray Telescope (SXT)
Hard X-Ray Telescope (HXT).

The BCS consisted of four bent crystal spectrometers. Each was designed to observe a limited range of soft x-ray wavelengths containing spectral lines that are particularly sensitive to the hot plasma produced during a flare. The observations of these spectral lines provide information about the temperature and density of the hot plasma, and about motions of the plasma along the line of sight. Images were not obtained.

The WBS consisted of three detectors: a soft x-ray, a hard x-ray, and a gamma-ray spectrometer. They were designed to provide spectra across the full range of wavelengths from soft x-rays to gamma rays with a time resolution on the order of one second or better. Like the BCS, images were not obtained.

The SXT (glancing incidence mirror/CCD sensor) imaged X-rays in the 0.25 - 4.0 keV range. It used thin metallic filters to acquire images in restricted portions of this energy range. SXT could resolve features down to 2.5 arc seconds in size. Information about the temperature and density of the plasma emitting the observed x-rays is obtained by comparing images acquired with the different filters. Flare images were obtained every 2 seconds. Smaller images with a single filter were obtained as frequently as once every 0.5 seconds.

The HXT (Fourier Synthesis Telescope) observed hard x-rays in four energy bands through sixty-four pairs of grids. These grid pairs provide information about 32 spatial scales of the x-ray emission. This information can be combined on the ground to construct an image of the source in each of the four energy bands. Structures with angular sizes down to about 5 arc seconds can be resolved. These images could be obtained as frequently as once every 0.5 seconds.

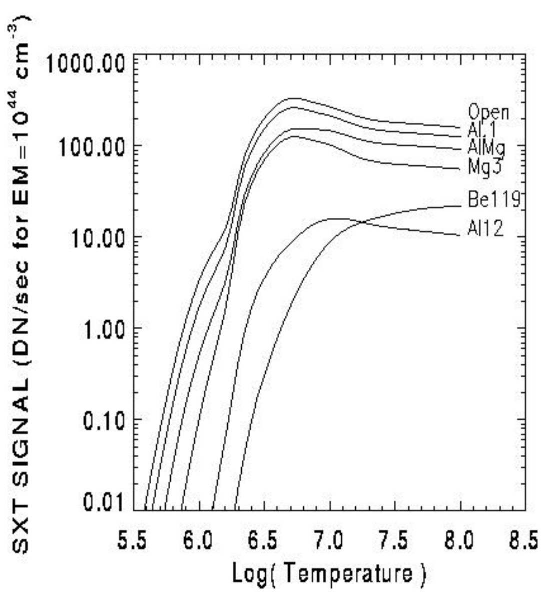


Figure 5.4: The temperature ranges of different Yohkoh SXT filters. The names of the filters come from the materials that were used in their making. The 'AlMg' filter is generally known as the 'sandwich'. The filter ratios can be used to calculate EM and T.

The Yohkoh spacecraft used a slightly elliptical low-earth orbit, with an altitude ranging from approximately 570 km to 730 km. The orbital period was 90 minutes. Sixty-five to seventy-five minutes of this time was spent in sunlight. During five to six of it's orbits per day, Yohkoh passed through the radiation belts of the South Atlantic Anomaly where the instruments using high voltages had to be turned off (the BCS, HXT, and most WBS channels). Otherwise the radiation could have destroyed the instruments or the satellite.

Observations from the instruments were stored in the spacecraft Bubble Data Recorder (BDR). The capacity of the BDR was 10 Mbytes. In order to optimize the recorder, it could operate at several bit-rates; high, medium, and low. Switching between the bit-rates was controlled two different ways, by the on-board deferred commands and automatically. This switching was necessary since the high-bit rate only holds 42 minutes worth of data. Some overwriting of the data was permitted.

The satellite could operate in a large number of spacecraft modes and several different subsystem modes. The two modes of principal interest are the Quiet Mode and Flare Mode. Switching between these two particular modes was controlled by a flare flag generated by the WBS instruments. Allocation of which instruments could collect what data and how much of it depended on which mode Yohkoh was operating in. Generally, more HXT data was taken during the Flare Mode as opposed to the Quiet Mode.

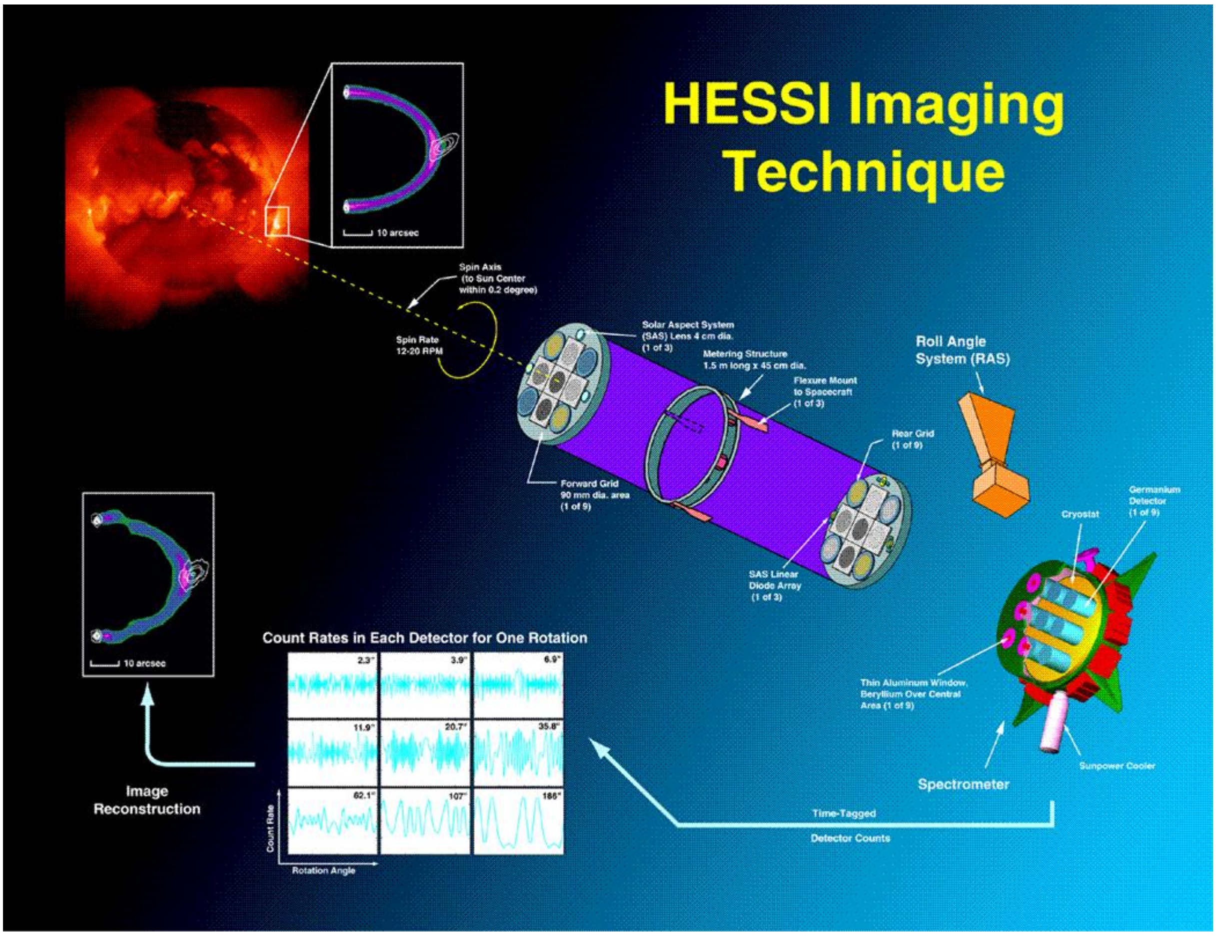
During each orbit, about five or six times a day, Yohkoh passed over the Kagoshima Space Center. Commanding of the satellite could be performed at this time. (The rest of the time the satellite was controlled by on-board deferred command storage.) In addition, Kennedy Space Center also received data from the Data Recorder. At other locations in the orbit, the data got sent to ground stations in the NASA Deep Space Network.

RHESSI (2002 –)
The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) was known as HESSI before launch. It is a NASA Small Explorer (SMEX) mission. Its launch was very much delayed, and it missed most of the last solar activity maximum. Hopefully it will last until the next one.

RHESSI Spectroscopy
Detectors: Nine segmented, hyperpure germanium crystals, cooled to ~ 75 K
Energy Range: ~ 3 keV – ~ 17 MeV
Spectral Resolution: 1 keV (FWHM) in the front segment up to ~100 keV; 3 keV in the rear segment up to ~1 MeV increasing to ~5 keV at 20 MeV

RHESSI Imaging
Technique: Fourier-transform imaging with 9 rotating modulation collimators (grid pairs)
Field of View: Full Sun (~1 degree)
Angular Resolution: 2 arc sec to 100 keV; 7 arc sec to 400 keV; 36 arc sec above 1 MeV
Temporal Resolution: tens of milliseconds for a basic image; 2 seconds (half a rotation of the spacecraft) for a detailed image

RHESSI Aspect System:
Solar Aspect System (SAS) determines the direction to Sun-center to better than 1.5 arc sec.
Roll Angle System (RAS) determines the roll angle to better than 3 arc min.



GRANAT (1989–1999)
The Russian x-ray satellite was launched to a high apogee orbit (200 000 km), where it operated for almost 10 years. It carried 4 major instruments: French SIGMA coded-mask hard x-ray telescope (30-1000 keV), Soviet ART-P coded-mask telescope, Danish all-sky monitor WATCH (6-150 keV), and a gamma-burst detector PHEBUS.

The Danish WATCH experiment was composed of four units. One of these units had the Sun in its field-of-view and observed in the deka-keV range with approximately 6.5 s time resolution. WATCH was based on the rotation-modulation-collimator (RMC) principle. It contained two independent detectors, one based on a NaI- the other on a CsI-scintillator. The direction of the incoming X-rays could thus be derived from the modulation of the detected signal as a function of the rotation phase of the collimator grids. The modulation patterns were used in determining the positions and strengths of the X-ray sources in the field-of-view. The WATCH solar burst catalogue consists of 1551 flares and it was created by systematically going through the approximately 2.5 years of count rate time profile observations. WATCH observations are grouped in dumps associated to telemetry periods. See futher details in Crosby et al., Astron. Astrophys. Suppl. Ser. 130, 233-234 (1998).

The CGRO Mission (1991 - 2000)
The Compton Gamma Ray Observatory was launched on April 5, 1991 aboard the space shuttle Atlantis. Compton was deorbited and it re-entered the Earth's atmosphere on June 4, 2000. Compton had four instruments that covered six decades of the electromagnetic spectrum, from 30 keV to 30 GeV.

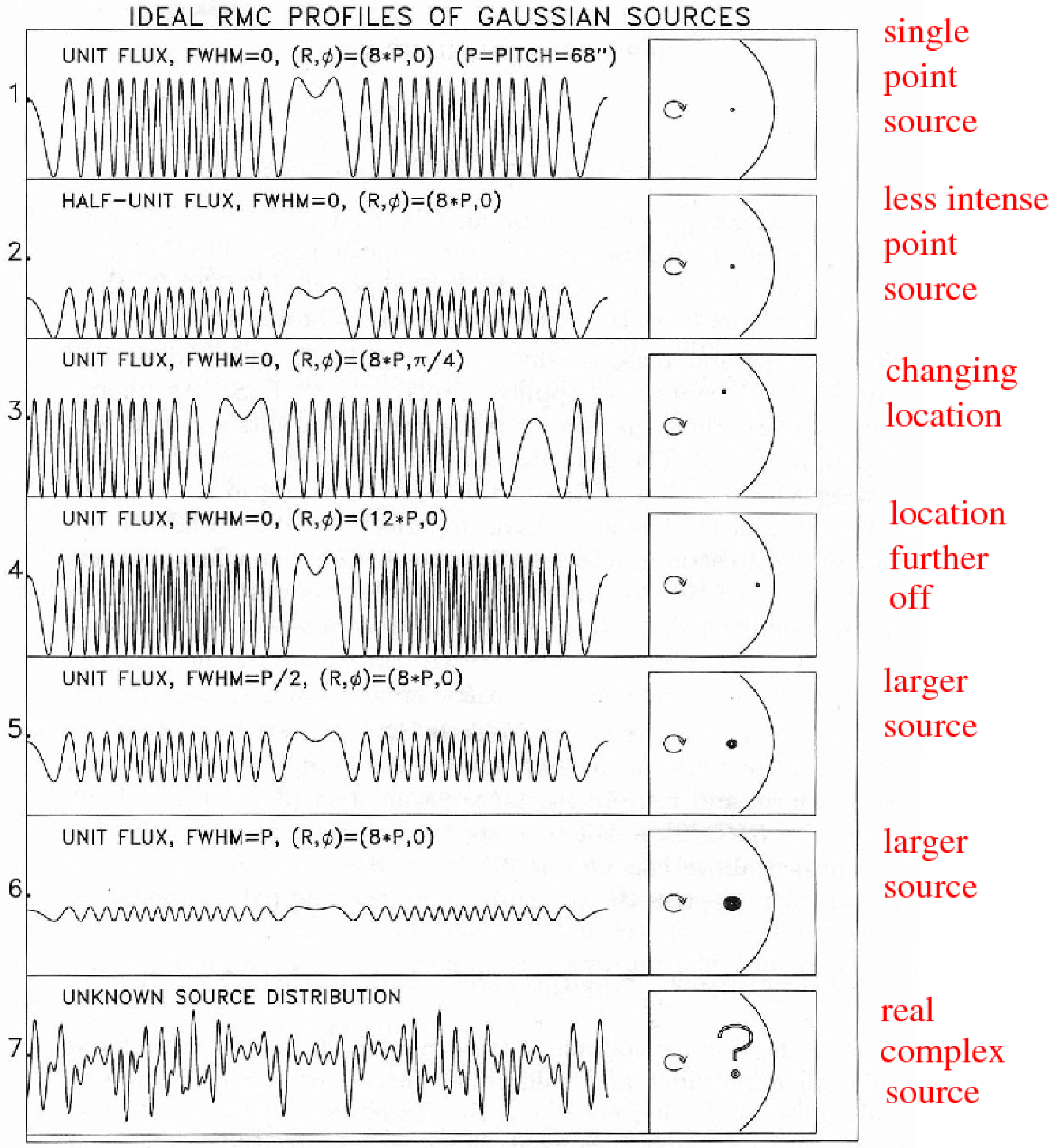


Figure 3. Modulation profiles plotted for one complete rotation for various configurations of an off-axis source, assuming ideal grids of pitch p with equal slits and slats mounted on a collimator that is rotating uniformly about a fixed axis. As discussed in the text, successive panels show the effect on the modulation profile of changing the source characteristics. R and ϕ are the radial offset and the azimuth of the source position relative to the axis of rotation.

Figure 5.5: The RHESSI imaging technique resembles the techniques used in radio interferometry - the 'dirty map' is cleaned uisng CLEAN, MEM or PIXON algorithms.

The CGRO instruments were the Burst And Transient Source Experiment (BATSE), the Oriented Scintillation Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL), and the Energetic Gamma Ray Experiment Telescope (EGRET). For each of the instruments, an improvement in sensitivity of better than a factor of ten was realized over previous missions.

Although BATSE was optimized for the detection of gamma-ray bursts, it was also a sensitive instrument regularly available for the detection of hard X-ray solar flares. As such, it was of great value in providing high time resolution spectral observations over a broad energy range for up to 50% of all flares. A BATSE solar flare catalog was built during the mission. Plots of quick-look orbital data and flare time profiles can be obtained, and ASCII or binary data files can be downloaded for further analysis.

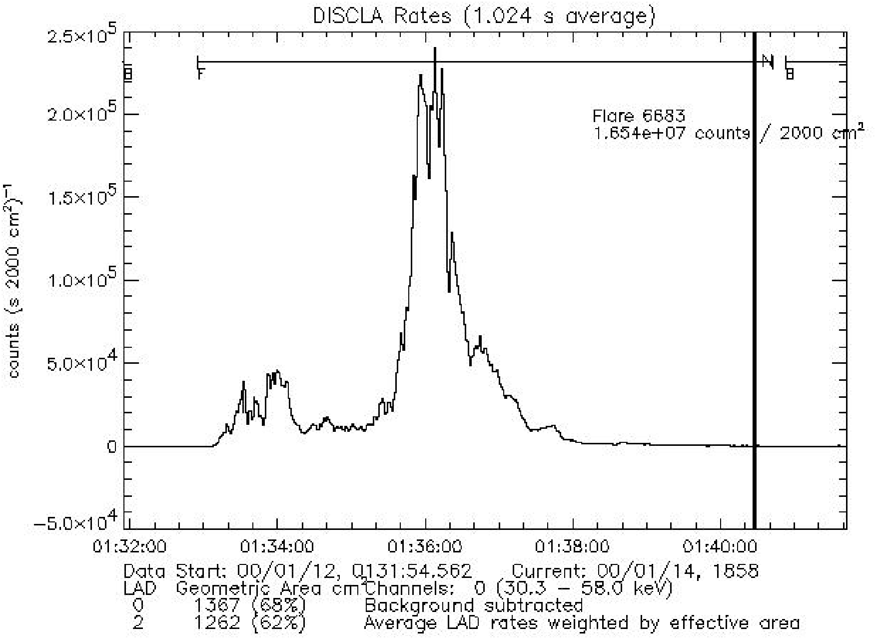


Figure 5.6: A solar flare detected with CGRO BATSE.

SOHO EIT (1995 –)

The SOHO EIT is able to image the solar transition region and inner corona in four, selected bandpasses in the extreme ultraviolet (EUV):

He II, 304 Å (80 000 K)
Fe IX/X, 171 Å (1.3 MK)
Fe XII, 195 Å (1.6 MK)
Fe XV, 284 Å (2 MK)

Using either full-disk or subfield images, the EIT can image active regions, filaments and prominences, coronal holes, coronal "bright points," polar plumes, and a variety of other solar features. The instrument was designed to be used in conjunction with other SOHO instruments, particularly the LASCO visible-light coronagraphs and the SUMER and CDS imaging spectrographs, as well as with ground-based instruments. EIT image cadence is 8 – 12 minutes.

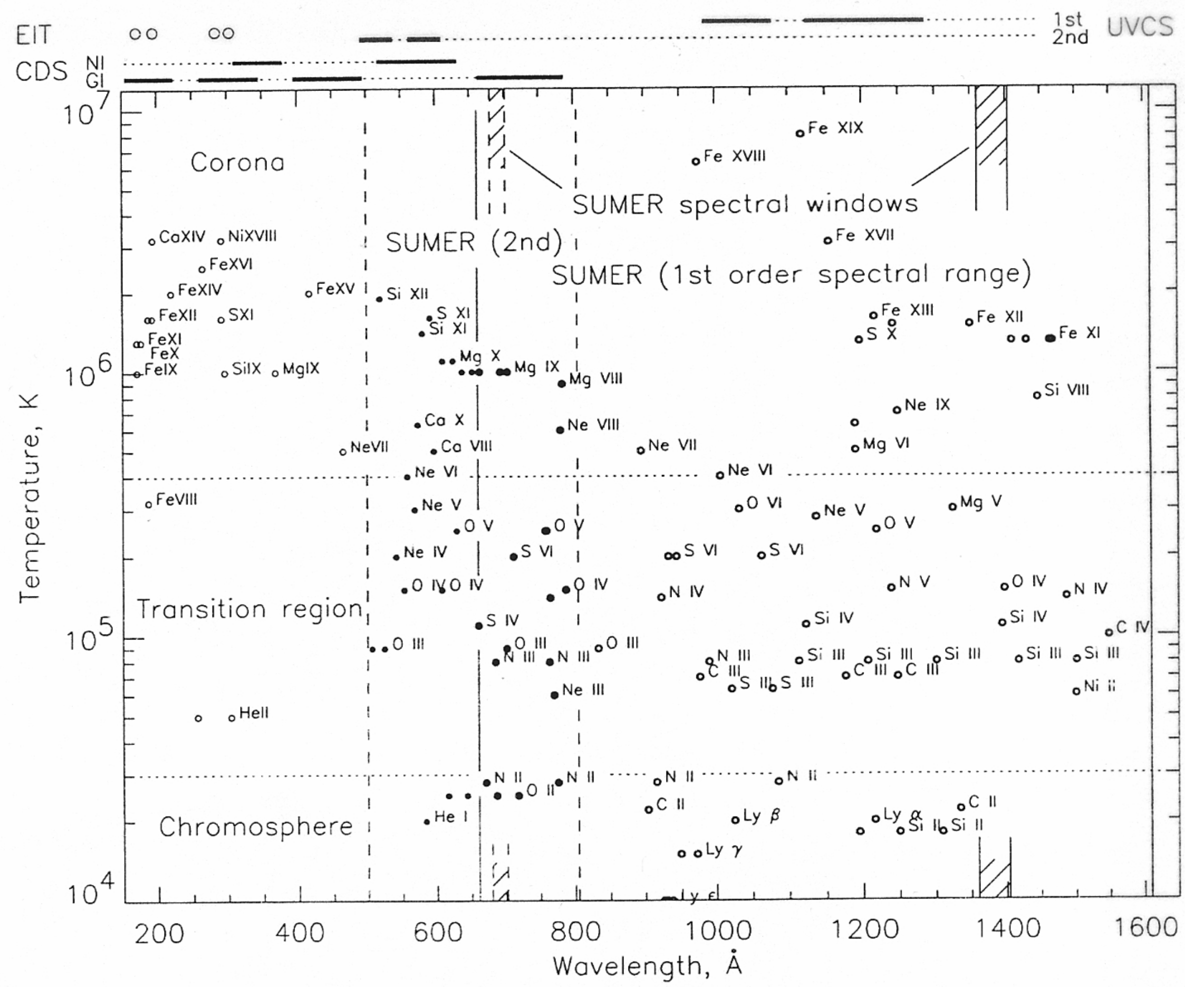


Fig. 1. Selection of emission lines in the wavelength range from 150 to 1610 Å together with the corresponding SUMER, CDS, UVCS and EIT coverages. Observations from 500 to 805 Å can be performed by SUMER in 2nd order and from 661 to 1610 Å in 1st order. The instantaneous coverage is approximately 22 Å in 2nd order and 44 Å in 1st order. This is indicated for a specific wavelength setting (for details see Section 2.1.). The short-wavelength region will be observed by CDS in its NI (normal incidence) and GI (grazing incidence) bands as indicated in the upper margin. Note the overlap in wavelength bands of all instruments, which will be important for inter-calibration.

TRACE (1998 –)

The Transition Region and Coronal Explorer is also a NASA SMEX mission, to image the solar corona and transition region at high angular and temporal resolution. The TRACE project maintains an Open Data Policy: all data are available from the data archives to the science community as soon as the spacecraft data have been processed.

The 30 cm aperture TRACE telescope uses four normal-incidence coatings for the EUV and UV on quadrants of the primary and secondary mirrors. The segmented coatings on solid mirrors form identically sized and perfectly coaligned images. Pointing is internally stabilized to 0.1 arc second against spacecraft jitter. A 1024 x 1024 CCD detector collects images over an 8.5 x 8.5 arc minute field-of-view (FOV). A powerful data handling computer enables very flexible use of the CCD array including adaptive target selection, data compression, and fast operation for a limited FOV.

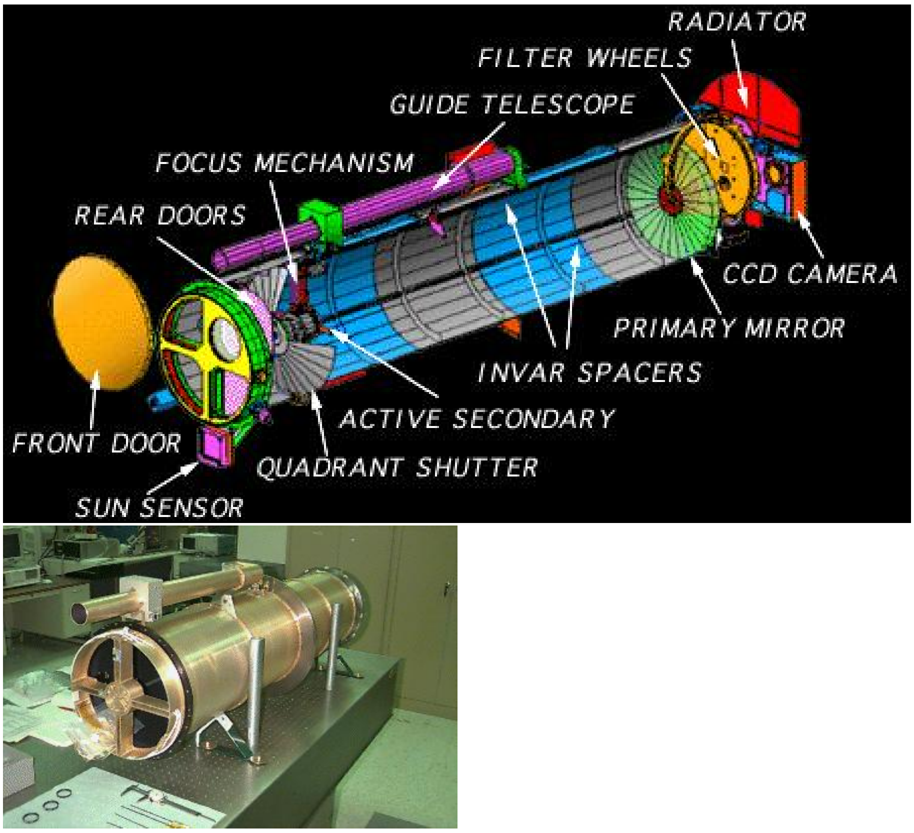


Figure 5.7: TRACE telescope

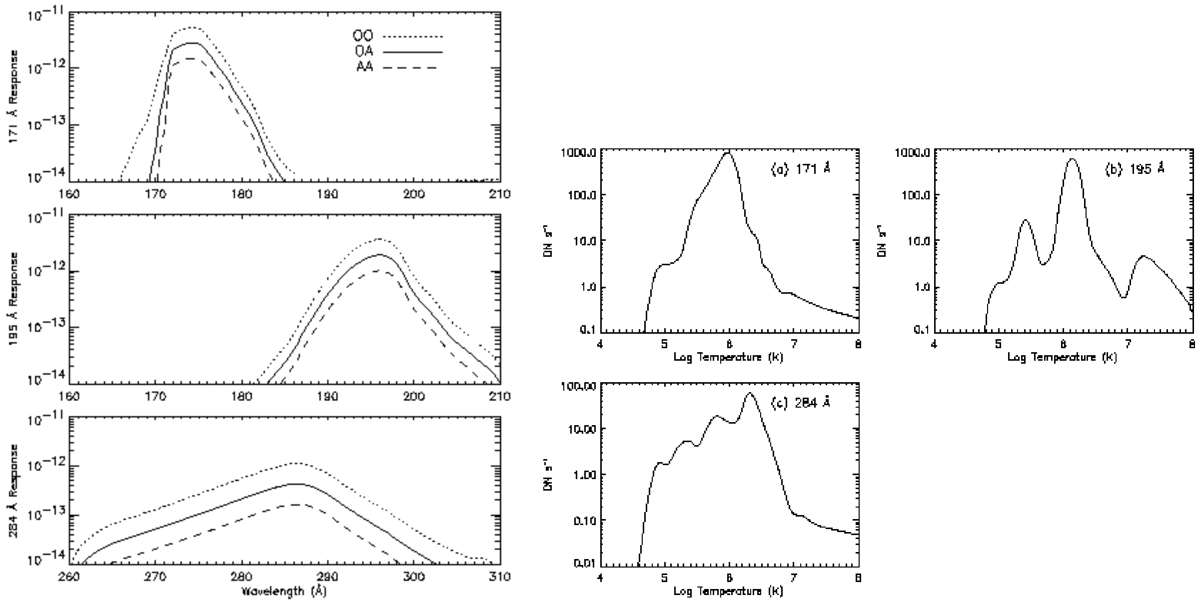


Figure 5.8: Left: Spectral response in the TRACE EUV quadrants (electrons sr cm^2 photon^{-1} pixel^{-1}). Right: Signal at the CCD for each of the TRACE EUV quadrants as a function of source temperature for an emission measure of 10^{44} cm^{-3}.**Conclusion:** plasma diagnostics are possible only from instruments with narrow response functions (like SOHO CDS or SUMER)

Hinode (2006 –)
The Japanese Hinode (Solar-B before launch) is a highly sophisticated observational satellite equipped with three advanced solar telescopes. Its solar optical telescope (SOT) has an unprecedented 0.2 arcsec resolution for the observation of solar magnetic fields. This corresponds to about 140 km on the solar surface. The X-ray telescope (XRT) has a resolution of three times as high as Yohkoh, and the EUV imaging spectrometer (EIS) has sensitivity ten times as high as SOHO EIT. Hinode is a quiet Sun mission, and its aim is to answer questions like why does a hot corona exist above the cool atmosphere, what drives explosive events such as solar flares, and what creates the Sun's magnetic fields.

STEREO (2006 –)
The Solar TErrestrial RElations Observatory (STEREO) is the third mission in NASA's Solar Terrestrial Probes program. The mission employs two nearly identical space-based observatories - one ahead of Earth in its orbit, the other trailing behind - to provide the first-ever stereoscopic measurements to study the Sun and the nature of its coronal mass ejections. Four instrument packages are mounted on each of the two STEREO spacecrafts, including coronagraphs and radio burst trackers (for plasma emission).

In 2011 the two STEREO spacecraft will be separated by more than 90 degrees from the Earth. With the help of observations from SDO and SOHO, a 360-degree view of the Sun is possible for the first time.

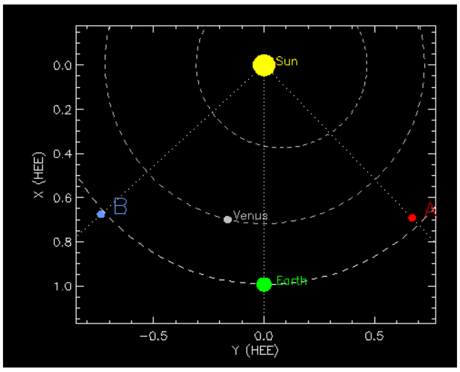


Figure 5.9: Positions of the STEREO Ahead (red) and Behind (blue) spacecraft relative to the Sun (yellow) and Earth (green) on Mar 6, 2009. The dotted lines show the angular displacement from the Sun.

Solar Dynamics Observatory, SDO (2010 –)
SDO has three scientific experiments: Atmospheric Imaging Assembly (AIA), EUV Variability Experiment (EVE), and Helioseismic and Magnetic Imager (HMI). SDO is a sun-pointing semi-autonomous spacecraft that allows nearly continuous observations of the Sun, with a continuous science data downlink rate of 130 Megabits per second. The spacecraft is 4.5 meters high and over 2 meters on each side, weighing a total of 3100 kg (fuel included). SDO's inclined geosynchronous orbit was chosen to allow continuous observations of the Sun, and enable its high data rate through the use of a single dedicated ground station.

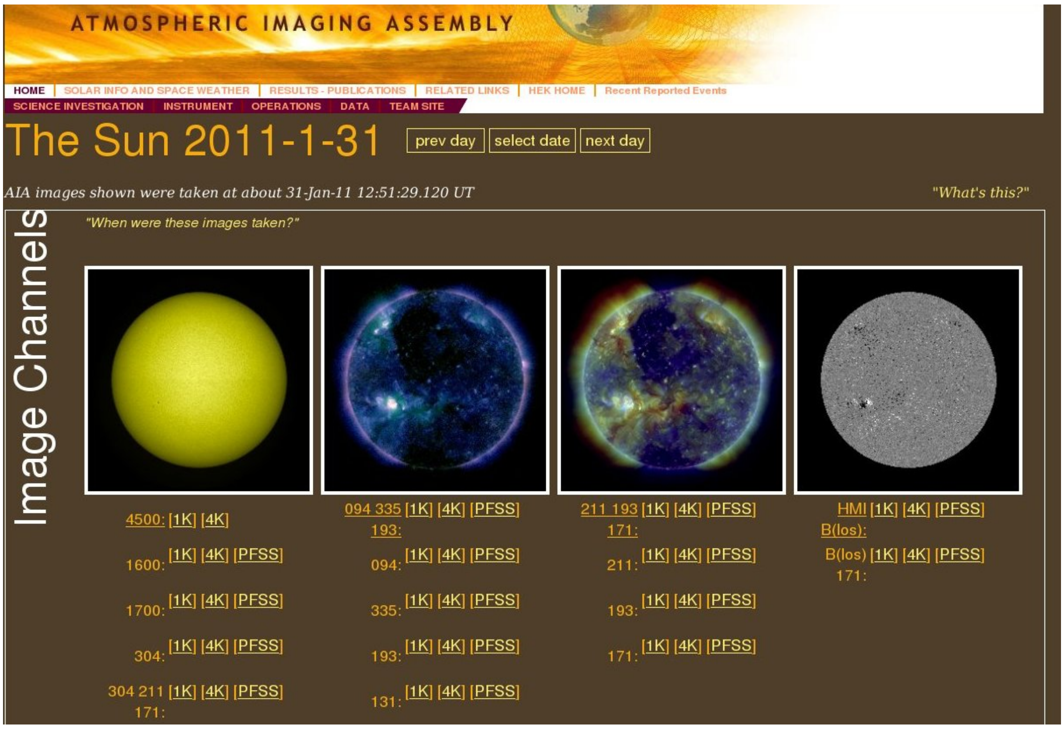


Figure 5.10: The Sun Today - SDO. AIA and HMI data can be accessed through the `http://jsoc.stanford.edu/` website.

5.3 Ground-based optical telescopes

NSST, La Palma

The best spatial resolution obtained from ground-based observations is with the New Swedish Solar Telescope in La Palma, Canary Islands. Adaptive optics are used to clean the images from atmospheric effects. The large, almost 1-meter diameter lens was made by Opteon in Tuorla (Turku, Finland).

In addition to the atmospheric effects, solar telescopes suffer from heating by sunlight of the optics and the air within the telescope tube. This causes the image to shiver and become blurred. Modern solar telescopes are either vacuum telescopes, filled with helium or use careful control of the optic's temperature to reduce heating of the air in the telescope. The NSST is a vacuum telescope.

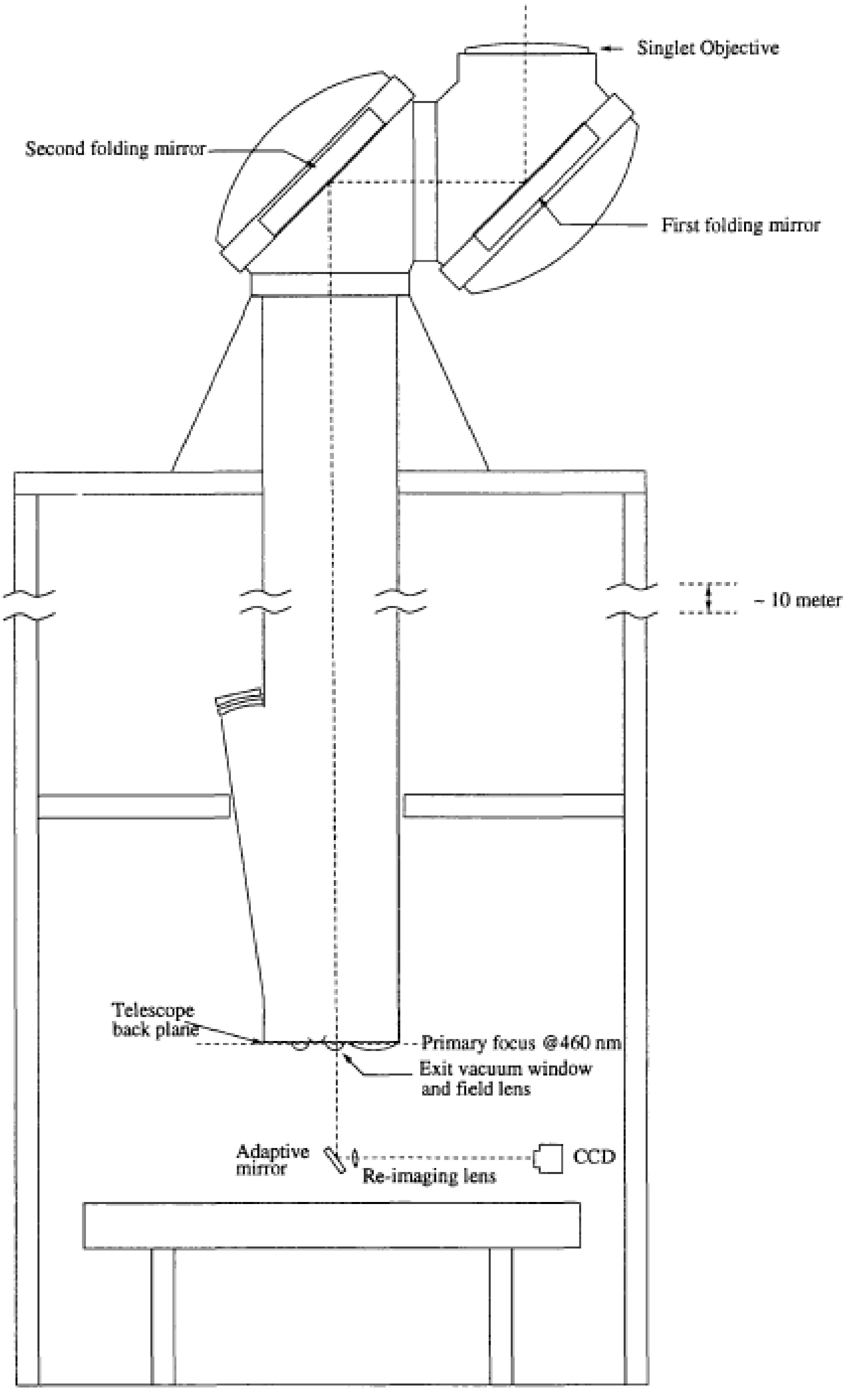


Figure 1. Schematic optics for high-resolution, narrow-band imaging with a a conventional flat adaptive mirror, used also as folding mirror. The combined vacuum window and field lens re-image the singlet objective on a small adaptive mirror. Note the simplicity of the optical system and the small number of optical surfaces.

Figure 5.11: The NSST construction (Scharmer et al., ASP Conference Series 183, 1999)

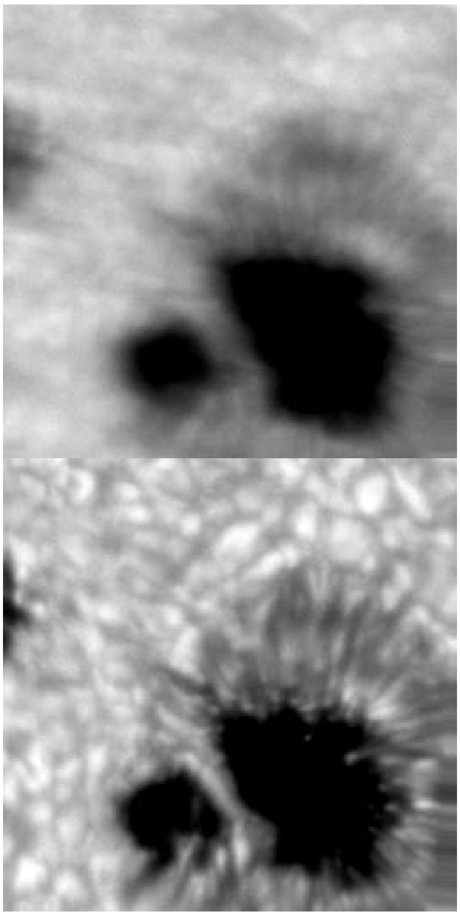


Figure 5.12: The NSST mirror system uses adaptive optics to correct for seeing. The problem is that the atmosphere changes quickly, and the adaptive optics systems have to correct the adaptive mirror at least several hundred and preferably more than 1000 times per second. The obtained diffraction limit is about 100 km on the Sun (0.1 arc sec).

Global High-resolution H-alpha network

The global high-resolution H-alpha (656.3 nm) network utilizes facilities at the Big Bear Solar Observatory (BBSO) in California, the Kanzelhöhe Solar Observatory (KSO) in Austria, the Catania Astrophysical Observatory (CAO) in Italy, Meudon Observatory in France, the Huairou Solar Observing Station (HSOS) and the Yunnan Astronomical Observatory (YNAO) in China. All these observatories have over 300 sunny days a year, good seeing conditions, adequate observing staffs and well established H-alpha telescope systems. Each of the three stations has a 1K x 1K or 2K x 2K CCD detectors available to monitor the Sun with a spatial resolution of 1 arcsec per pixel. Observations of 1 minute cadence are obtained at each station with higher cadence which can be triggered by automated filament eruption detection. The largest time difference in the network is about 9.4 hours between BBSO and YNAO. The difference between BBSO and KSO is about 8.7 hours and that between YNAO and KSO about 5.9 hours. In summer each station can observe 12 hours on clear days. Therefore, normally there is no night gap in the summer. In winter, when each station is expected to operate 8 hours, the BBSO/YNAO gap will be about 1.6 hours and the BBSO / KSO gab about 0.7 hours.

SOONSPOT

The name SOONSPOT stands for SOON Solar Patrol on Tape, where SOON refers to the Solar Observing Optical Network of four solar observatories maintained and operated by the U.S. Air Force 50th Weather Squadron. The refracting telescopes have apertures of 25.3 cm (10-inches) and have vacuum optics. The digitally recorded data are written onto 8-mm Exabyte tapes. The images are written in extended FITS format with header information on timing, pointing coordinates, image scale and sky transparency. The site at Palehua was dismantled and shipped to Sacramento Peak in New Mexico in April of 1997 to facilitate a major upgrade to the SOON system (see map of the sites).

Figure 5.13: Big Bear - Kanzelhöhe - Catania - Meudon - Yunnan - Huairou High resolution H_α network. The number of observatories in the network has been increasing, the network was founded in the 1990s by only three facilities, Big Bear, Kanzelhöhe and Yunnan.

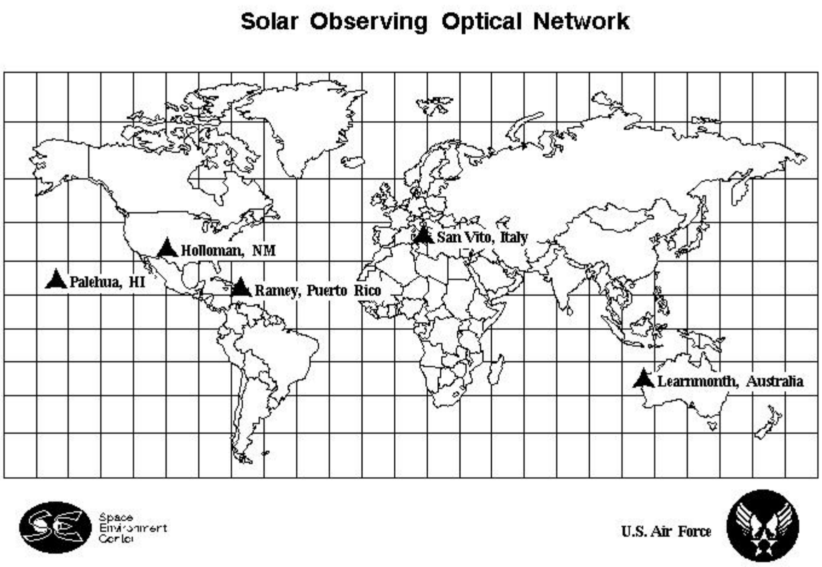


Figure 5.14: The locations of SOON observatories (U.S. Airforce). The data can be searched using the SOONSPOT web archive.