Solar Phys (2007) 243: 3–17
DOI 10.1007/s11207-007-9014-6

The *Hinode* (Solar-B) Mission: An Overview

T. Kosugi · K. Matsuzaki · T. Sakao · T. Shimizu · Y. Sone · S. Tachikawa · T. Hashimoto · K. Minesugi · A. Ohnishi · T. Yamada · S. Tsuneta · H. Hara · K. Ichimoto · Y. Suematsu · M. Shimojo · T. Watanabe · S. Shimada · J.M. Davis · L.D. Hill · J.K. Owens · A.M. Title · J.L. Culhane · L.K. Harra · G.A. Doschek · L. Golub

Received: 1 June 2007 / Accepted: 30 July 2007 / Published online: 12 September 2007

Abstract The *Hinode* satellite (formerly *Solar-B*) of the Japan Aerospace Exploration Agency's Institute of Space and Astronautical Science (ISAS/JAXA) was successfully launched in September 2006. As the successor to the *Yohkoh* mission, it aims to understand how magnetic energy gets transferred from the photosphere to the upper atmosphere and results in explosive energy releases. *Hinode* is an observatory style mission, with all the instruments being designed and built to work together to address the science aims. There

T. Kosugi deceased 26 November 2006.

T. Kosugi · K. Matsuzaki · T. Sakao · T. Shimizu (✉) · Y. Sone · S. Tachikawa · T. Hashimoto · K. Minesugi · A. Ohnishi · T. Yamada
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 229-8510, Japan
e-mail: shimizu@solar.isas.jaxa.jp

S. Tsuneta · H. Hara · K. Ichimoto · Y. Suematsu · M. Shimojo · T. Watanabe
National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

S. Shimada
Kamakura Works, Mitsubishi Electric Corp., Kamakura, Kanagawa 247-8520, Japan

J.M. Davis · L.D. Hill · J.K. Owens
Space Science Office, VP62, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

A.M. Title
Lockheed Martin Solar and Astrophysics Laboratory, B/252, 3251 Hanover Street, Palo Alto, CA 94304, USA

J.L. Culhane · L.K. Harra
UCL Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK

G.A. Doschek
E. O. Hulburt Center for Space Research, Code 7670, Naval Research Laboratory, Washington, DC 20375-5352, USA

L. Golub
Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA

are three instruments onboard: the Solar Optical Telescope (SOT), the EUV Imaging Spectrometer (EIS), and the X-Ray Telescope (XRT). This paper provides an overview of the mission, detailing the satellite, the scientific payload, and operations. It will conclude with discussions on how the international science community can participate in the analysis of the mission data.

1. Introduction

The *Hinode* spacecraft (formerly Solar-B) of the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), was launched on 22 September 2006, at 21:36 GMT, aboard the seventh in JAXA's series of M-V rockets. The principal scientific goals of the *Hinode* mission are the following:

(1) To understand the processes of magnetic field generation and transport including the magnetic modulation of the Sun's luminosity.
(2) To investigate the processes responsible for energy transfer from the photosphere to the corona and for the heating and structuring of the chromosphere and the corona.
(3) To determine the mechanisms responsible for eruptive phenomena, such as flares and coronal mass ejections, and understand these phenomena in the context of the space weather of the Sun – Earth System.

This mission is the follow-on to *Yohkoh,* an ISAS mission with significant NASA and United Kingdom participation that was launched in 1991 (Ogawara *et al.*, 1991) and continued taking observations for nearly a solar cycle. *Yohkoh* demonstrated that the high-temperature corona is highly structured and dynamic and that rapid heating and mass acceleration are common phenomena (Acton *et al.*, 1992). *Yohkoh* was launched shortly after the maximum of solar cycle 22, which was an ideal period for studying large solar flares. The subsequent observations provided considerable evidence to support magnetic reconnection as the driver for energy release in flares. Hard X-ray "above the loop top" sources were found in compact flares (*e.g.*, Masuda *et al.*, 1994) and also in long-duration flares (*e.g.*, Harra *et al.*, 1998). In soft X rays the flaring loops often took on the appearance of cusps, which is to be expected from the standard model where the reconnection occurs high in the corona (*e.g.*, Tsuneta, 1996; Canfield, Hudson, and McKenzie, 1999; Sterling *et al.*, 2000). The edges of the loops were also found to be hotter, as expected if the outer edges are the last to be heated from reconnection. As expected from the reconnection, plasma ejections from flaring sites have been found on many occasions (*e.g.*, Shibata *et al.*, 1995). On smaller scales, many jets were found in soft X rays; these are interpreted as reconnection occurring through the interaction of emerging flux and already existing magnetic field (Shimojo *et al.*, 1996). Many small-scale flares were observed in active region loops (*e.g.*, Shimizu, 1995; Shimizu *et al.*, 2002) and in bright points (Priest *et al.*, 1994). On a more global scale, dramatic coronal waves were observed (*e.g.*, Hudson *et al.*, 2003) and trans-equatorial loops were found to erupt (*e.g.*, Khan and Hudson, 2000) followed by coronal mass ejections or flares (Harra, Matthews, and van Driel-Gesztelyi, 2003).

Hinode is designed to address the fundamental question of how magnetic fields interact with the ionized atmosphere to produce solar variability. Measuring the properties of the Sun's magnetic field is the fundamental observational goal of *Hinode* and differentiates it from previous solar missions. The three instruments were selected to observe the response of the chromosphere and corona to changes in the photospheric magnetic field. To achieve this end *Hinode* makes quantitative measurements of all three components of vector magnetic fields. This allows calculation of the free energy of the magnetic field, which powers solar activity through the action of electric currents. The components of the magnetic field are difficult to resolve, especially from the ground where seeing effects degrade spatial resolution. The major scientific instrument on *Hinode*, the Solar Optical Telescope (SOT), makes these observations from space. The response of the solar atmosphere to magnetic field changes is measured by the EUV Imaging Spectrometer (EIS) and the X-Ray Telescope (XRT).

Based upon this scientific motivation, *Hinode* was planned and constructed as an international collaborative project including institutions in Japan, the United States, and the United Kingdom. ISAS/JAXA has responsibility for the design, development, test, and integration of the *Hinode* spacecraft with the National Astronomical Observatory of Japan as a domestic partner and the Mitsubishi Electric Corporation as a leading contractor. The participating institutes and their responsibilities are shown in Table 1. The *Hinode* spacecraft was called by its development name Solar-B and the name *Hinode* was given after successful launch according to the Japanese satellite tradition. *Hinode* is a Japanese word meaning sunrise.

In the present paper, we will give an overview of the *Hinode* mission from the viewpoints of the scientific instruments in Section 2, the spacecraft design in Section 3, and the flight operations in Section 4. The scientific objectives will be briefly discussed in Section 5.

2. Scientific Instruments

The scientific payload consists of three instruments: the SOT, the EIS, and the XRT. Each instrument is a result of the combined talents of all the members of the international team. Full technical details of each instrument are described in the separate papers in this special issue. This paper provides a brief summary of each instrument with their main characteristics summarized in Table 2. The instruments usually work together as an "observatory" studying the same target at which the spacecraft is pointed. Optionally, the EIS has the ability to offset its own pointing and the XRT, having a larger field of view than the others, has the ability to observe its own region of interest.

2.1. Solar Optical Telescope

The SOT is the largest solar optical telescope flown in space (Tsuneta *et al.*, 2007). The SOT consists of the Optical Telescope Assembly (OTA) (Suematsu *et al.*, 2007) and its Focal Plane Package (FPP) (Tarbell *et al.*, 2007). The OTA is a 50-cm clear aperture, aplanatic Gregorian, $f/9$ design telescope. The OTA is diffraction limited ($0.2'' - 0.3''$) between 3,880 and 6,700 Å. The primary mirror is fabricated out of ULE and supported by invar/titanium structures to retain thermal stability. Field stops and heat rejection mirrors are located at the focus of the primary mirror and at the Gregorian focus. The secondary field stop limits the field of view to $361'' \times 197''$. The OTA holds the collimating lens unit (CLU), the polarization modulator (PMU), and a tip-tilt mirror (CTM) behind the primary mirror. The PMU is a continuously rotating waveplate optimized for linear and circular polarization at 5,173 and 6,302 Å. The SOT is well designed and calibrated for performing polarization measurements with high accuracy (Ichimoto *et al.*, 2007). With the CLU and the CTM, the OTA provides a pointing-stabilized parallel beam to the FPP. The FPP has four optical paths: the Narrowband Filter Imager (NFI), the Broadband Filter Imager (BFI), the Spectro Polarimeter (SP), and the Correlation Tracker (CT). The BFI and the NFI share a CCD detector and

Table 1 The *Hinode* mission.

Mission objective	Investigation of magnetic activity of the Sun including its generation, energy transfer, and release of magnetic energy
Launch	22 September 2006, 21:36 UTC
Mission life	≥3 years
Organization	
Project manager	T. Kosugi[1] (ISAS/JAXA)
Co-manager	S. Tsuneta (NAOJ)
Project scientists	T. Sakurai (NAOJ), K. Shibata (Kyoto University), J.M. Davis (MSFC), and L.K. Harra (MSSL)[2]
Principal investigators	
Solar Optical Telescope (SOT)	S. Tsuneta (NAOJ) and A.M. Title (LMATC)[3]
EUV Imaging Spectrometer (EIS)	J.L. Culhane (MSSL),[4] G.A. Doschek (NRL), and T. Watanabe (NAOJ)
X-Ray Telescope (XRT)	L. Golub (SAO)[5] and K. Shibasaki (NAOJ)
Responsible institutes	
The Japan Aerospace Exploration Agency's Institute of Space and Astronautical Science (ISAS/JAXA)	Overall mission including the launch vehicle
National Astronomical Observatory of Japan (NAOJ)	Three scientific instruments and support for spacecraft development
The National Aeronautics and Space Administration (NASA)	Three scientific instruments
The Particle Physics and Astronomy Research Council (PPARC)[6]	EIS
European Space Agency (ESA)	Ground station support
Major participating institutions	
Scientific instruments are built by collaborative efforts of the following institutes	
SOT	NAOJ, Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), High Attitude Observatory (HAO), ISAS/JAXA, NASA
EIS	Mullard Space Science Lab. (MSSL), US Naval Research Laboratory (NRL), NAOJ, ISAS/JAXA, Rutherford Appleton Laboratory (RAL), Birmingham University, The University of Oslo
XRT	Smithsonian Astrophysical Observatory (SAO), ISAS/JAXA, NAOJ, NASA

[1] I. Nakatani as project manager and T. Sakao and T. Shimizu as deputy project managers after T. Kosugi passed away in November 2006.

[2] Succeeded by D.R. William in 2006.

[3] Succeeded by T.D. Tarbell in 2004.

[4] Succeeded by L.K. Harra in 2006.

[5] Succeeded by E.E. Deluca in 2005.

[6] Now the Science and Technology Facilities Council (STFC).

Table 2 *Hinode* scientific instruments.

(a) Properties of the telescopes

Solar Optical Telescope (SOT)	
Optical Telescope Assembly (OTA)	
Optics	Aplanatic Gregorian with aperture of 50 cm
Focal Plane Package (FPP)	
Wavelength and lines	Broadband Filter Instrument (BFI)
	CN (3883.0), Ca II H (3968.5), CH (4305.0)
	Blue (4504.5), Green (5550.5), Red (6684.0)
	Narrowband Filter Instrument (NFI)
	Mg Ib (5172.7), Fe I (5250.2, 5247.1, 5250.6),
	Fe I (5576.1), Na I (5895.9), Fe I (6302.5, 6301.5),
	H I (6562.8)
	Spectro Polarimeter (SP)
	Fe I (6302.5, 6301.5)
Sensitivity to magnetic fields	longitudinal: 1 – 5 G
	transverse: 30 – 50 G
Typical time cadence	Ranges from tens of seconds for photospheric images and vector magnetographs in particular lines to ≈1 hr for the full Stokes profiles
EUV Imaging Spectrometer (EIS)	
Optics	Off-axis paraboloid with multilayer-coated mirror and concave grating with aperture of 15 cm
Wavelength	170 – 210 Å with spectral resolution of ≈4000
	250 – 290 Å with spectral resolution of ≈4600
Velocity resolution	3 km s^{-1} for Doppler velocity, 20 km s^{-1} for line width
Exposure time	Milliseconds in flares, tens of seconds in active regions
X-Ray Telescope (XRT)	
Optics	Modified Wolter type I grazing incidence mirror and co-aligned optical telescope
Wavelength	X ray: 2 – 200 Å
	Optical: G-band (4305 Å)
Temperature discrimination	$\Delta \mathrm{Log}\, T : 0.2$[1]
Exposure time	4 ms – 10 s

(b) Properties of the focal plane detectors

Instruments	F.O.V. EW × NS (slit/slot width)	Pixel size
SOT		
NFI[2]	$328'' \times 164''$	$0.08''$
BFI[2]	$218'' \times 109''$	$0.053''$
SP	$320'' \times 164''(0.16'')$	$0.16'' \times 21.5$ mÅ
EIS	$590'' \times 512''(1'', 2'', 40'', 266'')$	$1.0'' \times 0.0223$ Å
XRT	$2048'' \times 2048''$	$1.0''$

[1] In the case of isothermal plasma.

[2] NFI and BFI share a CCD.

constitute the Filtergraph (FG). The SP and the CT have their own CCD detectors. The NFI uses a tunable Lyot, birefringent filter to record filtergrams, Dopplergrams, and longitudinal and vector magnetograms across the spectral range from 5170 to 6570 Å. The BFI has interference filters to image the photosphere and low chromosphere and to make blue, green, and red continuum measurements for irradiance studies. The SP is an off-axis Littrow echelle spectrograph that records dual-line, dual-beam polarization spectra of the Fe I 6302.5 Å and 6301.5 Å spectral lines for high-precision Stokes polarimetry. The CT is the high-speed CCD camera to sense jitter of solar features on the focal plane. The jitter signal is fed to the closed-loop control of the tip-tilt mirror (Shimizu *et al.*, 2007). This image-stabilization system prevents the spacecraft jitter from affecting the resolution of the images. The image-stabilization system achieves a stability of $0.007''$ (3σ) below the cross-over frequency of 14 Hz. Time-line sequence of the data acquisitions by the SOT is controlled according to two observation tables (one for FG and the other for SP) on the Mission Data Processor (MDP).

2.2. EUV Imaging Spectrometer

The EIS (Culhane *et al.*, 2007) is an imaging spectrometer designed to observe plasmas in the temperature range from 0.1 MK, the upper transition, to 10 MK, the lower corona. The EIS is an off-axis paraboloid telescope with a focal length of 1.9 m and a mirror diameter of 15 cm. The angular resolution of the optics is $2''$. The total length of the instrument is 3 m. The primary mirror has a mechanism that can offset the field of view of the EIS in the E – W direction relative to the spacecraft pointing. The mirror illuminates various slits that are placed at the focus of two multilayer-coated, toroidal gratings that disperse the spectrum onto two back-side-illuminated CCD detectors. The detectors cover the wavelength ranges of 170 – 210 Å and 250 – 290 Å with spectral resolution of $R \approx 4000$. Four slit or slot widths are available: $1''$ slit, $2''$ slit, $40''$ slot, and $266''$ slot. High-spectral-resolution images can be obtained by rostering with the slit. The slots provide “overlappograms” of the transition region and corona at high cadence. The EIS instrument provides a factor of 3 improvement in spatial and spectral resolution and sensitivity over the CDS (Coronal Diagnostic Spectrometer) aboard the SOHO (*Solar and Heliospheric Observatory*) spacecraft. The velocity resolution is 3 $\mathrm{km\,s^{-1}}$ for Doppler velocities and 20 km $\mathrm{s^{-1}}$ for line widths. With the higher sensitivity and higher telemetry rate of the spacecraft, the EIS can achieve a time cadence of 0.5 s in flares and $\approx$10 s in active regions. The control system is designed to optimize the use of the telemetry allocation. It provides the flexibility to select the mix of spectral lines, image regions, and time cadence of an observation to match specific scientific objectives. A dedicated processor within EIS provides the control function and can operate autonomously to switch observations in response to notification of a flare by the XRT or detection of a flare or a bright point by the EIS processor itself.

2.3. X-Ray Telescope

The XRT is a grazing incidence telescope of a Wolter I design made from Zerodur (Golub *et al.*, 2007). The mirror has a 30-cm aperture and a 2.7-m focal length. The surface figure is a modified paraboloid-hyperboloid whose surfaces are optimized to minimize the blur circle radius at large angles. The reflecting surfaces are uncoated and, together with improved entrance filters that reject the Sun’s visible light, provide a lower energy X-ray cutoff than SXT aboard *Yohkoh*. In front of the focal plane, there are two filter wheels containing a total of nine X-ray analysis filters, which pass wavelength bands with different lower cutoff energy. Because of the lower cutoff energy, the XRT can observe plasmas with temperatures as low as 1×10^6 K in the lower corona. The brightness ratio between images taken through two different filters provides a measure of the temperature of the plasma when the observed plasma can be assumed to be isothermal. For flare studies the filter ratio method is capable of measuring temperatures as high as $\approx 30 \times 10^6$ K. In addition to the X-ray optics, the XRT is equipped with visible light optics, to be used with a G-band filter, for the purpose of co-alignment of XRT and SOT images. The X-ray and visible light optics share the focal plane where a back-side-illuminated CCD is located. The CCD has a pixel size of 1 arcsec and the field of view is 34×34 arcmin^2, which covers the whole solar disk when the spacecraft is pointed at sun center. The CCD camera is equipped with an on-orbit focus adjustment mechanism (Kano *et al.*, 2007). The camera is launched out of focus and in addition to moving the camera to the best on-orbit focus it can also be used to optimize across the field of view to compensate for field curvature. For example, for the highest resolution observations an on-axis focus provides an angular resolution of ≈ 1 arcsec within a radius of ≈ 7 arcmin. For the best resolution across the field of view the focus can be moved forward to provide an angular resolution of ≤ 3 arcsec within a radius of ≈ 17 arcmin. The camera, its shutter for exposure control, and the filter wheel are controlled according to an observation sequence defined as the observation table in the MDP. To optimize the use of the telemetry allocation the field of view, filter sequence, and time cadence can be adjusted to match each scientific objective. MDP also has various functions for enhancing XRT observations, including automatic region selection, automatic exposure duration control, flare detection, and memory buffer for storing high-cadence images taken in the pre-flare phase.

3. The Spacecraft

3.1. General

The *Hinode* spacecraft was launched from the Uchinoura Space Center, located at latitude 31 N, longitude 131 E, by the seventh, and last, M-V launch vehicle into an elliptical polar orbit with a perigee of ≈ 280 km and apogee of ≈ 686 km. In the succeeding phase, the *Hinode* spacecraft boosts its perigee and controls the plane of the orbit with its own thrusters to acquire a circular, sun-synchronous, polar orbit of about 680-km attitude, 98.1-deg inclination, and 98-min period. With this orbit, *Hinode* can observe the Sun continuously for a duration of nine months each year.

The major parameters of the spacecraft are summarized in Table 3. The spacecraft, schematically shown in Figure 1, has dimensions of approximately $4000 \times 1600 \times 1600$ mm with two external solar panels (4300×1100 mm each) and weights about 900 kg. Three telescopes are aligned in the Z-axis of the spacecraft and supported by an optical bench unit (OBU). The OBU is a cylinder made up of composite material that supports the OTA internally. The FPP, EIS, and XRT are kinematically mounted on the outside of the OBU with six mounting legs, which constrain the degrees of freedom of the rigid body. The OBU also holds a tower to whose upper surface the sun sensors are attached. The electronics units are located in the bus box attached to the bottom of the OBU. The solar cell panels are designed to supply about 1100 W during each spacecraft day. Excess power is either stored in NiCd batteries to supply the power required during spacecraft night or is consumed by a shunt regulator.

Table 3 Major parameters of *Hinode*.

Size	4000 × 1600 × 1600 mm
Weight	900 kg (wet), 770 kg (dry)
Power	1100 W
Data rate	Up to 2 Mbps (science data), and 32 kbps (housekeeping)
Data recorder	8 Gbits
Telemetry rate	32 kbps (S-band), 4 Mbps (X-band)
Orbit	
Altitude	680 km (circular, Sun-synchronous, polar orbit)
Inclination	98.1 deg
Period	98 min
Attitude control (requirement)	Three-axis stabilized
Absolute pointing	20″
Stability around	X/Y-axes: 0.06″ (>20 Hz), 0.6″/2 s, 4.5″/1 hr
	Z-axis: 200″/1 hr
Pointing determination	X/Y-axes: 0.1″
Offset pointing	Up to 1178″ from the Sun center
Ground stations	
Commanding and downlink	Uchinoura Space Center (131 E, 31 N)
Commanding only	JAXA new Ground Network stations
Downlink only	Svalbard (15 E, 78 N)
Number of downlinks	15 per day (Svalbard)
	4 per day (Uchinoura)

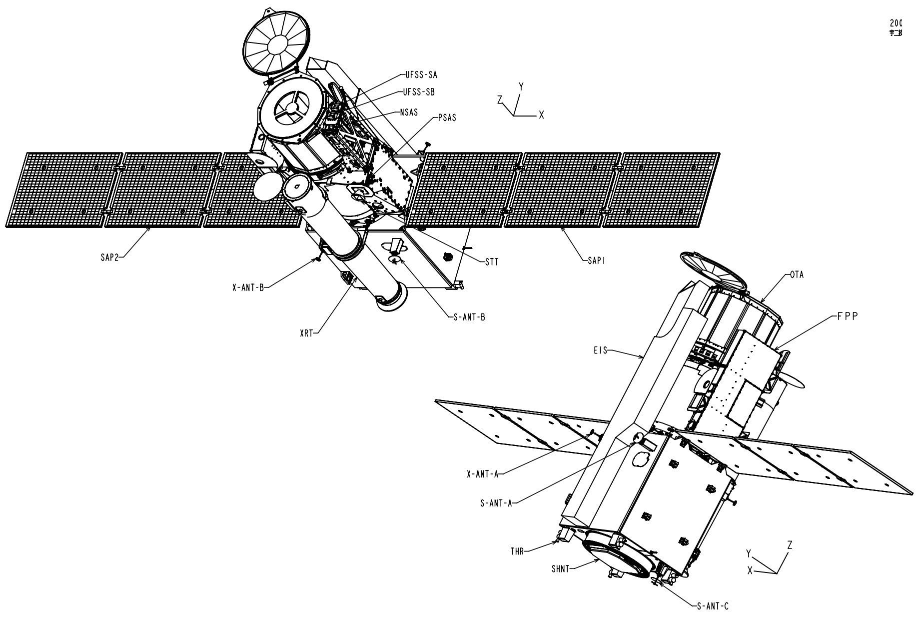

Figure 1 The *Hinode* spacecraft and its scientific instruments.

3.2. Attitude and Orbit Control

The *Hinode* spacecraft is stabilized by the attitude and orbit control system (AOCS) in three axes with its Z-axis pointed to the Sun. The Y-axis is directed toward solar north. As a baseline, the spacecraft tracks a region on the solar surface by correcting for solar rotation. For each tracked target, the angular velocity around the rotation axis of the Sun can be specified. The other mode is the spacecraft pointing to a fixed position on the solar disk. In either case, stability of the Z-axis is $0.3''$ (3σ) per 10 s and $1''$ per min.

The AOCS uses momentum wheels and magnetic torquers as the actuators for attitude control and thrusters for orbital control. The attitude sensors, including two fine sun sensors (UFSS), a star tracker, and geomagnetic sensors are available for determining spacecraft pointing relative to the direction of the Sun and to the ecliptic plane while an inertial reference unit comprising four gyros detects changes of attitude with time. Signals from two UFSS sun sensors with random noise level of $0.3''$ (3σ) can be used to remove the jitter of the satellite Z-axis pointing from the time series of data.

3.3. Command System

An uplink commanding system controls the operation of all the instruments on the spacecraft. Commands are sent from the Uchinoura Space Center as well as from JAXA new Ground Network antennas. There are about three contacts in a day for commanding. Each contact has a duration of up to 10 min. Commands from the ground are received by the command unit and distributed by the data handling unit (DHU). Commands for the scientific instruments are further relayed by the MDP. The DHU can coordinate commands into sequences called organized commands (OGs). The DHU can store up to 512 sets of OGs, each being a set of up to eight commands. First, an OG can be launched by a "real-time OG execute command" from the ground. Second, a series of OGs can be dispatched sequentially with specified time intervals by the DHU itself. Such a series is called an operation program (OP). The OP can contain up to 4096 OG references. The OP is initiated by an "OP start command." The OP can last for up to about 10 days, so that the operation can be programmed beforehand. In addition to the OG, the DHU can store sequences of commands to be executed during spacecraft emergencies. These are triggered by the AOCS or by an autonomous detection of an emergency by the DHU. The latter case includes failure modes of the battery system.

3.4. Onboard Data Processing

Observations of the three scientific instruments are governed by the MDP. Figure 2 is a schematic representation of the onboard observation control system. In the case of the FG, SP, and XRT, the MDP controls the observations. The controls are implemented using observation tables that make use of programs that have a nested loop – call structure. The EIS instrument's observing sequences are controlled by its own processor. In addition to normal observations, the scientific instruments have the capability to switch to autonomous observations when notified by the onboard system of a flare. The MDP continuously analyzes XRT images for large intensity increases indicative of a flare. If a flare is found a flare flag is issued that allows the instruments to terminate their current sequence and switch to a flare observation program. The observation table for flare studies has the same structure as those for normal observations.

The scientific data from the instruments are compressed in the MDP before being stored in the data recorder. Memory space is divided among the SOT, the XRT, and the EIS in

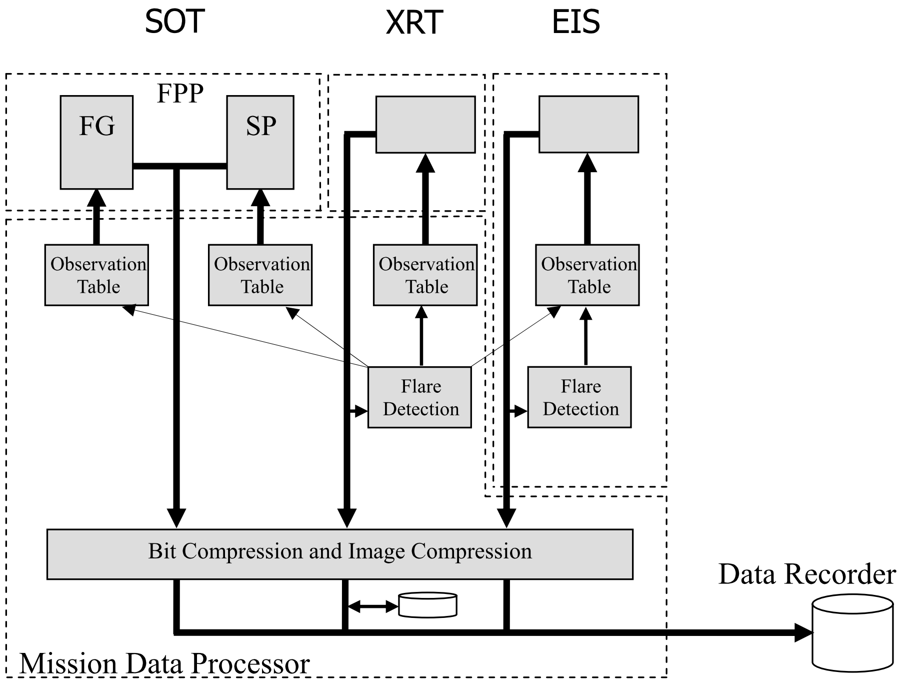

Figure 2 Functional block diagram of onboard observation control system.

the ratio of 70 : 15 : 15 for many periods of observations. The MDP has a compression speed of 832 kpixel s^{-1} for SOT, 256 kpixel s^{-1} for XRT, and 128 kpixel s^{-1} for EIS, which matches the data acquisition rate and storage capacity for each instrument. Two types of compression are performed sequentially. The first is pixel-by-pixel bit compression followed by image compression. The pixel-by-pixel bit compression is based on look-up tables and implemented by hardware. In the table a smooth function composed of linear and quadratic components can be registered. The image compression is either a lossless compression using a DPCM (Differential Pulse Code Modulation) algorithm or a JPEG (Joint Photographic Experts Group) lossy compression using a DCT (Discrete Cosine Transform) algorithm. These schemes are implemented by an application-specific integrated circuit (ASIC). Parameters for compressions, which affect the compression ratio and data quality, can be optimized on orbit.

The MDP can output compressed data from the SOT, XRT, and EIS at rates of up to 1.3 Mbps, 262 kbps, and 262 kbps, respectively. The actual data rates from the telescopes are determined by the observation tables and compression efficiency. During the preparation of the observation table care has to be taken to ensure that they are consistent with the duration of downlink contacts. The tables should be implemented in scientific operation as described in Section 4.2.

3.5. Data Recording

Telemetry from the spacecraft follows the data packet specification recommended by the Consultative Committee for Space Data Systems (CCSDS). Telemetry packets from the scientific instruments are edited by the MDP; the housekeeping and spacecraft data are edited by the DHU.

The *Hinode* spacecraft has limited-duration ground station contacts. Telemetry packets that cannot be downlinked during a particular ground station contact remain stored in the onboard data reorder and are played back in following contacts. The data recorder has two partitions. Data from the spacecraft and scientific instruments are stored in separate partitions, so that scientific operations do not conflict with maintaining the integrity of the spacecraft data. Each partition has a write pointer for recording and a read pointer for playback and behaves like a first-in-first-out (FIFO) memory. When a partition becomes full, the data recorder either overwrites the oldest data or stops recoding according to its setting.

The recorder memory has a total capacity of 8 Gbits. This capacity is three times greater than the amount of data that can be downlinked during a ground station contact. Distribution of ground contacts in a day can be irregular. With the large capacity of the data recorder, the data rate from telescopes can be determined on a daily basis rather than from the distribution of ground contacts. This feature is well suited for continuous observation in the sun-synchronous orbit of *Hinode*. The three telescopes share their partition of the data recorder. Unexpected data volume from one telescope (*e.g.* from human error in observation planning or degraded compression efficiency) can result in a loss of data for the other telescopes. To prevent this from happening the MDP can be programmed to prevent any of the three telescopes from exceeding its allocation. The MDP monitors the cumulative data recorded by each telescope until a specified limit is reached, at which time it stops further packet addition for that telescope. The assignment of data among the telescopes can be changed on a daily basis.

3.6. Telemetry

Data acquired with the instruments onboard *Hinode* are downlinked to Uchinoura Space Center station as well as the Norwegian high-latitude (78°14′ N) ground station at Svalbard. Svalbard downlinks for every station contact are realized by cooperation between the European Space Agency (ESA) and the Norwegian Space Centre. Two telemetry channels, S-band (2.2 GHz) and X-band (8.4 GHz), are used. The S-band channel transmits real-time status at 32 kbps. The X-band transmits all of the real-time data and recorded data from the data recorder at 4 Mbps. At the Uchinoura station, the two channels are received simultaneously. At the Svalbard station only recorded data are transmitted via the X-band and no real-time data are available. Note that only real-time data are transmitted via the S-band at the JAXA Ground Network stations for commanding purposes. During the downlink, real-time transfer has higher priority than that of recorded data from the data recorder. Real-time data downlinked at Uchinoura are sent to ISAS at Sagamihara, near Tokyo, with the Space Data Transfer Protocol (SDTP) over a TCP/IP network. Recorded data are also sent to ISAS within 90 min of the downlink. Data taken at the Svalbard station are transmitted to ISAS through the Internet, nominally within 90 min of their receipt, where they are combined with the data from the Uchinoura station and placed into the ISAS Sirius database.

From the Sirius database, the data are reformatted into FITS files and classified as Level 0 data and archived on the ISAS DARTS system from where they are made available to the scientific community. The master archive is mirrored to the Solar Data Analysis Center (SDAC) at the Goddard Space Flight Center in Greenbelt, Maryland, and also to data centers in Norway and at MSSL. The principal investigator institutions in Europe and the United States and several co-investigator institutions mirror the data from their instrument to their home institutions.

4. Operations

4.1. Initial Operations and Observations

The month following launch is a period for checking out the spacecraft and the instruments where the spacecraft and the instruments are operated by their builders. After this period, observation with the scientific instruments starts. The first 90 days of observations are planned before the launch and are conducted by the *Hinode* Principal Investigator teams. This provides the instrument teams with the opportunity to learn the operational skills needed to run the mission, including the scheduling of operations and archiving data. During this period there are occasional opportunities to access the data archive to retrieve specific data sets. These opportunities enable the user community to test the system and help identify problems before the full data set is released. This is planned to occur about six months after initial operations begin. At that time all the archived data shall be available and all new observations shall be released as soon as after their acquisition.

4.2. Spacecraft Operation

The *Hinode* orbit provides at least two morning and two evening contacts in Japan. Morning contacts provide quick-look science data and the evening contacts are used for uploading commands to the spacecraft and science instruments. In addition to the Japanese contacts, the ESA provides 15 contacts per day through Svalbard for downloading scientific data. The average contact time at Svalbard is 11.5 min. By allowing 15 s for handshaking, approximately 42.5 Gbits of data are downloaded per day.

After the initial period, it is expected that the operation of the spacecraft will become routine. To facilitate safe operation of the spacecraft, patterns of the operations are accumulated and maintained in a knowledge base. In daily operations, a planning tool generates commands for the spacecraft using the knowledge base, predictions of orbital conditions, and specification of the downlink stations. The tool also calculates the telemetry allocation for the scientific instruments to be used in planning the scientific program and merges the spacecraft and scientific operations.

4.3. Scientific Operation

Scientific operations are conducted from the ISAS facility located in Sagamihara, Japan. They are separated into planning and implementation. As shown in Figure 3, the planning process involves monthly, weekly, and daily planning meetings. Monthly meetings or teleconferences establish the high-level objectives for the next three months and more detailed objectives for the next month. The goal of these meetings is to approve and schedule observing proposals from the external community that were submitted to and approved by the Scientific Schedule Coordinators (SSC). The SSCs are senior scientists designated by the instrument Principal Investigators (PIs) who reside at their home institutions. They are responsible for coordinating the monthly observation schedules proposed by the instrument teams with the external proposals. They are also available to assist the external community in preparing proposals and identifying contacts within the instrument teams who can provide proposers with the detailed capabilities of their instruments.

Weekly meetings are held each Friday at ISAS and establish the observing plan, subject to minor changes, for the next week. The plan includes target regions, pointing maneuvers, and data recorder allocations. The plan is placed on the *Hinode* operation Web sites to allow

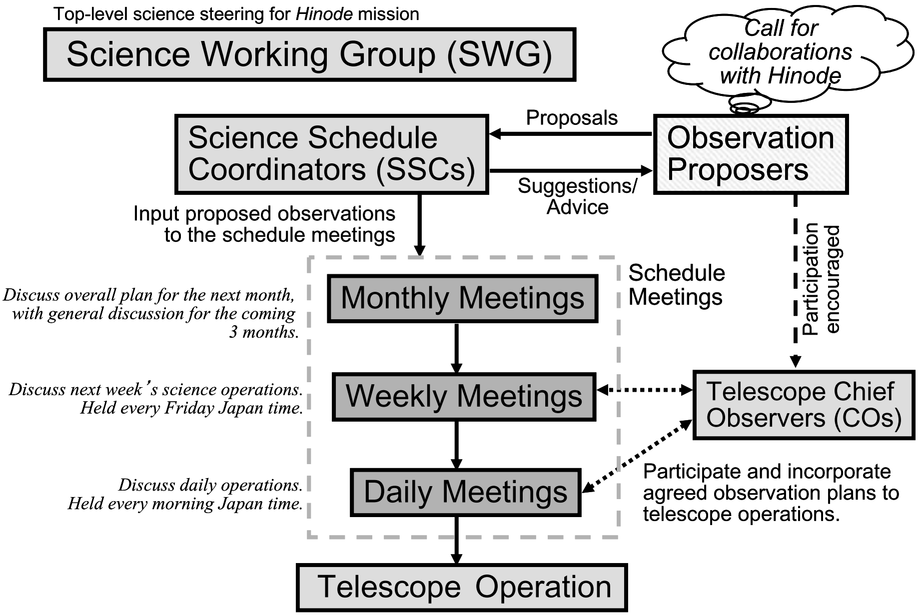

Figure 3 Scientific operation planning flow of *Hinode*.

coordination with other observatories. The daily meetings are held six mornings a week at ISAS at 10:30 AM local time (01:30 UT), during which the daily plan is finalized. In the planning context "days" start at the spacecraft's evening contacts in Japan, which occur at approximately 4:00 – 7:30 PM local time or 7:00 – 10:30 UT. At these contacts the instrument commands and observing tables for the next 24 hours are uplinked to the spacecraft. With this planning schedule it is possible, in principle, to make minor adjustments to the observing plan as little as eight hours before the observations are made.

4.4. Community Involvement

The *Hinode* science teams hope and expect that *Hinode* proves to be a valuable asset to the international scientific community. To expedite collaboration we have created the role of Scientific Schedule Coordinator to provide an interface to the experiment teams and to educate proposers as well as review proposals and schedule observations. Collaboration with other observatories, missions, campaigns, or suborbital programs are given high priority. However, the data from these observations are also freely available to the community (Matsuzaki *et al.*, 2007).

5. Concluding Remarks

Hinode is a complex satellite that is designed to study primarily how changes in the magnetic field as it emerges through the photosphere affect the higher levels in the atmosphere. It is hoped that the high-resolution observations of the vector magnetic field clarify the conditions needed for the onset of magnetic reconnection. The development of the science instruments and objective has been and remains a truly international program and it is hoped that an even broader group of the world's scientists participate in the observations and their analysis.

Acknowledgements The authors would like to acknowledge the people who contributed to the spacecraft design, development, and tests. We express our gratitude to those who were involved in the spacecraft preparation:

ISAS/JAXA: N. Bando, E. Hirokawa, K. Hirose, T. Ichikawa, K. Inoue, N. Ishii, T. Kato, J. Kawaguchi,Y. Maeda, Y. Mochihara, O. Mori, Y. Morita, T. Nagae, H. Nakabe, J. Nakatsuka, H. Saito, S. Sakai, H. Sawai, M. Shida, T. Shimada, K. Shimomura, S. Shimose, K. Shuto, T. Takemae, H. Takeuchi, M. Tamura, M. Tajima, T. Toda, H. Toyoata, H. Yamakawa, T. Yamamoto, Z. Yamamoto, Y. Yoshida, and M. Yoshikawa.

NAOJ: R. Kano, Y. Katsukawa, M. Nakagiri, T. Tamura, and T. Bando.

Mitsubishi Electric Co. (MELCO): J. Akiyama, Y. Aoki, T. Hashizume, K. Hiraide, T. Hayashi, T. Inoue, Y. Ito, H. Izu, T. Kamachi, M. Kasama, K. Kidoguchi, M. Koike, T. Kosuge, K. Nakagawa, M. Mitsutake, T. Sato, Y. Shirahama, T. Shiraishi, K. Takeo, H. Tomoeda, and M. Yoshimura.

NEC Toshiba Space Systems (NTS): T. Abe, K. Fujiwara, T. Gondai, Y. Haruna, I. Kanaoka, N. Kaneko, M. Kubo, T. Kumai, Y. Okada, T. Osashima, M. Matsui, S. Murata, T. Okumura, N. Ogura, T. Saito, T. Shimamura, K. Taniguchi, K. Tsuno, S. Tsuruta, and H. Yamaki.

Furukawa Battery: H. Inafuku.

Mitsubishi Heavy Industries (MHI): K. Furukawa, K. Hisatsune, M. Koyama, and T. Takami.

Panasonic System Solutions: T. Watanabe, G. Furuhashi, and K. Nemoto.

Japan Aviation Electronics Industry (JAE): K. Hattori and S. Miyahara.

Fujitsu: Y. Iizuka, M. Kojima, T. Kosaka, M. Morita, S. Nagata, M. Yokoyama, and M. Yamashita.

GN/JAXA: T. Fuse, S. Hirose, K. Narita, and T. Saito.

We should note that many more engineers, technicians, scientists, and administrators made their contributions to the *Hinode* project. The authors also express their thanks to the M-V rocket team led by Y. Morita for successfully installing the spacecraft into the orbit.

References

Acton, L., Tsuneta, S., Ogawara, Y., Bently, R., Bruner, M., Canfield, R., *et al.*: 1992, *Science* **258**, 618.

Canfield, R.C., Hudson, H.S., McKenzie, D.E.: 1999, *Geophys. Res. Lett.* **26**, 627.

Culhane, J.L., Harra, L.K., James, A.M., Al-Janabi, K., Bradley, L.J., Chaudry, R.A., *et al.*: 2007, *Solar Phys.*, in press.

Golub, L., DeLuca, E., Austin, G., Bookbinder, J., Caldwell, D., Cheimets, P., *et al.*: 2007, *Solar Phys*., in press.

Harra, L.K., Schmieder, B., van Driel-Gesztelyi, L., Sato, J., Plunkett, S.P., Rudawy, P., Rompolt, B., Akioka, M., Sakao, T., Ichimoto, K.: 1998, *Astron. Astrophys.* **337**, 911.

Harra, L.K., Matthews, S.A., van Driel-Gesztelyi, L.: 2003, *Astrophys. J.* **598**, L59.

Hudson, H.S., Khan, J.I., Lemen, J.R., Nitta, N.V., Uchida, U.: 2003, *Solar Phys.* **212**, 121.

Ichimoto, K., Lites, B., Elmore, D., Suematsu, Y., Tsunete, S., Katsukawa, Y., *et al.*: 2007, *Solar Phys.*, submitted.

Kano, R., Sakao, T., Hara, H., Tsuneta, S., Matsuzaki, K., Kumagai, K., *et al.*: 2007, *Solar Phys.*, submitted.

Khan, J.I., Hudson, H.S.: 2000, *Geophys. Res. Lett.* **27**, 1083.

Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., Ogawara, Y.: 1994, *Nature* **371**, 495.

Matsuzaki, K., Shimojo, M., Tarbell, T.D., Harra, L.K., DeLuca, E.: 2007, *Solar Phys.*, in press.

Ogawara, Y., Takano, T., Kato, T., Kosugi, T., Tsuneta, S., Watanabe, T., Kondo, I., Uchida, Y.: 1991, *Solar Phys.* **136**, 1.

Priest, E., Parnell, C., Martin, S.F.: 1994, *Solar Phys.* **427**, 459.

Shibata, K., Masuda, S., Shimojo, M., Hara, H., Yokoyama, T., Tsuneta, S., Kosugi, T., Ogawara, Y.: 1995, *Astrophys. J.* **451**, L83.

Shimizu, T.: 1995, *Publ. Astron. Soc. Japan* **47**, 251.

Shimizu, T., Shine, R.A., Title, A.M., Tarbell, T.D., Frank, Z.: 2002, *Astrophys. J.* **574**, 1074.
Shimizu, T., Nagata, S., Tsuneta, S., Tarbell, T., Edwards, C., Shine, R., *et al.*: 2007, *Solar Phys.*, submitted.
Shimojo, M., Hashimoto, S., Shibata, K., Hirayama, T., Hudson, H.S., Action, L.W.: 1996, *Publ. Astron. Soc. Japan* **48**, 123.
Sterling, A.C., Hudson, H.S., Thompson, B.J., Zarro, D.M.: 2000, *Astrophys. J.* **532**, 628.
Suematsu, Y., Tsuneta, S., Ichimoto, K., Shimizu, T., Otsubo, M., Katsukawa, Y., *et al.*: 2007, *Solar Phys.*, submitted.
Tarbell, T.D., *et al.*: 2007, *Solar Phys.*, submitted.
Tsuneta, S.: 1996, *Astrophys. J.* **456**, 840.
Tsuneta, S., Suematsu, Y., Ichimoto, K., Shimizu, T., Otsubo, M., Nagata, S., *et al.*: 2007, *Solar Phys.*, submitted.