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The CORONAL DIAGNOSTIC SPECTROMETER for the SOLAR AND HELIOSPHERIC OBSERVATORY

Scientific Report

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"Busy old fool, unruly Sun, Why dost thou thus? "
from The Sun Rising
John Donne (1572-1631)

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1. INTRODUCTION

"We would never reach the Sun, without trying"
Chris de Burgh, 1988, from 'Leather on my Shoes'

1.1 The Purpose of this Report

The purpose of this report is to act as a focus for the scientific operation of CDS. It should be used as a guide book or brochure for the scientist to construct observation sequences, and to obtain information about the instrument. It also acts as an operations guide for the instrument team, i.e. the scientific demands form the demands on operations planning, on command structure etc... It is a discussion document and this is the sixth version.

The following sections give an overview of the mission, an overview of CDS, details of the CDS operation and characteristics, details of the operations and specific scientific plans. The document is aimed at the solar scientist; the potential user of CDS.

1.2 The SOHO Concept

The Solar and Heliospheric Observatory (SOHO) is the flagship space mission of ESA's Horizon 2000 First Cornerstone. This cornerstone is devoted to solar terrestrial sciences and includes a co-ordinated effort to study the Sun and its influence on the Earth using the SOHO solar observatory and the Cluster spacecraft, which will make field and particle observations in the vicinity of the Earth.

SOHO will be stationed at the L1 Lagrangian point, where the gravitational pull of the Sun and Earth are equal. Thus, the platform has a continuous view of the Sun and sits well within the solar wind streams. The mission lifetime is 2 years extendible to 6 years. Operations will be co-ordinated through the so called Experiment Operations Facility (EOF) at the Goddard Space Flight Center, near Washington, USA. Launch is currently planned for November 7, 1995 aboard an Atlas IIaS rocket from the Kennedy Space Center.

SOHO has three main goals:

- Why does the solar corona exist, how is it heated?

- How are the solar wind streams accelerated?
- What is the nature of the solar interior?

The payload consists of 12 experiments, the details of which are given in Table 1.1. The instruments fall into three groups. The GOLF, VIRGO and MDI instruments make up the helioseismology package whose goal is the study of the Sun's interior. The CELIAS, COSTEP and ERNE instruments make up the in situ particle detector group. The instruments comprise the SOHO coronal package, designed to study the solar corona at all levels in a variety of wavelength ranges.

Table 1.1: The SOHO Payload

Experiment	Principal Investigator	Description
GOLF [Global Oscillations at Low Frequencies]	A. Gabriel, Orsay, France	Global Sun velocity and magnetic field oscillations
VIRGO [Variability of Solar Irradiance]	C. Frölich, Davos, Switzerland	Global and low resolution imaging of oscillations and solar constant
MDI [Michelson Doppler Imager]	P.H. Scherrer, Stanford, USA	High resolution imaging of velocity oscillation
SUMER [Solar UV Measurement of Emitted Radiation]	K. Wilhelm, Lindau, Germany	Plasma flows, temperature and density in the solar atmosphere
CDS [Coronal Diagnostic Spectrometer]	R.A. Harrison, Chilton, UK	Density, temperature and flows in the solar atmosphere
EIT [Extreme UV Imaging Telescope]	J.-P. Delaboudinière, Orsay, France	Evolution of low coronal structure and activity
UVCS [UV Coronagraph and Spectrometer]	J.L. Kohl, Cambridge, USA	Density and temperature in the corona
LASCO [LargeAngle Spectrometer Coronagraph]	G. Brükener, Washington, USA	Structure and evolution of the corona
SWAN [Solar Wind Anisotropies]	J.-L. Bertaux, Paris, France	Solar wind mass flux anisotropies
CELIAS [Charge, Element, Isotope Analysis]	D. Hovestadt, Garching, Germany	Ion composition in the solar wind
COSTEP [Suprathermal & Energetic Particle Analyser]	H. Kunow, Kiel, Germany	Ion and electron composition in the solar wind

ERNE [Energetic Particle Analyser]	J.J. Torsti, Turku, Finland	Ion and electron composition in the solar wind

1.3 The Coronal Diagnostic Spectrometer

CDS addresses two of the three main goals of SOHO, namely, (i) Why does the corona exist, how is it heated, and (ii) How are the solar wind-streams accelerated? Critical to the pursuit of these goals is the determination of plasma characteristics (densities, temperatures, velocities, abundances etc...) on spatial, temporal and spectral scales and ranges appropriate to those of the solar atmosphere.

The CDS experiment is designed to determine such information through the study of emission line characteristics in the extreme ultraviolet (EUV) - particularly essential for the detection of emission from the hottest plasmas in the (non-flare) solar atmosphere. This is complementary to the remaining coronal instrument package on SOHO which includes a longer-wavelength UV spectrometer, an EUV imager and two coronagraphs (UV and white light).

Specifically, the requirements on the CDS project can be described by the following:

To provide diagnostic information on the solar atmosphere plasmas through the detection and analysis of spectral emission lines in the EUV with the following resolutions and ranges:

- Spectral range of about 150-800Å, to cover lines of formation temperatures in the range 10^4-10^6K.
- Spectral resolution - able to separate lines of prime interest ($\lambda/\Delta\lambda>500$)
- Time resolution - down to ~1s to allow studies of coronal evolution and transient activity.
- Spatial range - field of view able to cover the area of at least one active region, but with pointing to allow studies of the full disc and low corona.
- Spatial resolution - a few arcseconds to cover the smaller structures of the solar atmosphere.
- Lifetime - mission duration of at least several months, to investigate evolution of the corona and to complete a useful programme of observations.

The optical layout of CDS is shown in Figure 1.1 and the CDS performance is summarised in Table 1.2.

CDS consists of a Wolter II grazing incidence telescope which has a focus at a slit assembly which lies beyond a scan mirror. Light stops define two telescope apertures which feed, simultaneously into two spectrometers beyond the slit assembly. One portion of the beam hits a grating in grazing incidence and the spectrum is dispersed onto four 1-D detectors placed around the Rowland circle. This is the grazing incidence spectrometer or GIS. The other portion is fed through to a twin grating in normal incidence and the resulting spectrum is viewed by a 2-D detector system. This is the normal incidence spectrometer or NIS.

The GIS grating is spherical. The system is astigmatic, i.e. there is no spatial focus. Thus, one would use "pinhole" or square slits and build up images by rastering in two directions over the Sun's surface. The rastering is performed by rotating the scan mirror (E-W rastering; i.e. by presenting different portions of the Sun to the slit) and by scanning the slit (N-S rastering). The four detectors sit at specified, fixed locations around the Rowland circle and thus detect the EUV spectrum in four fixed wavelength ranges.

The NIS gratings are toroidal, resulting in a stigmatic system. Thus, we may use long, thin slits and can image, spatially along the slits. Images of the slit are dispersed on the NIS detector producing an image, effectively, of wavelength against a spatial dimension. As a result, one can produce rastered images very quickly by rastering in only one dimension with the scan mirror. Since the NIS spectrum is dispersed by two gratings, slightly angled with respect to one another, two spectral ranges are viewed on the one 2-D detector.

The ideal design for CDS would have been a single NIS system, covering all wavelengths, allowing full advantage of the speed of the NIS system. However, many spectral emission lines produced at the highest temperatures in the quiet solar atmosphere occur at wavelengths much less than 300Å and below this level the efficiency of the normal incidence reflection falls dramatically. Thus, we supplement the NIS system with a GIS spectrometer.

Figure 1.1: The Coronal Diagnostic Spectrometer Optical Layout

For more detailed technical descriptions of the CDS instrument, readers are referred to Harrison et al. (1995), Harrison and Sawyer (1992, 1993) and Patchett et al. (1989).

Table 1.2: Basic CDS Characteristics

Telescope and Geometrical Details:		
	Outer f-number	9.38
	Effective Focal Length	257.831 cm
	Plate Scale	12.5μm/arcsec
	Full Geometric Area	289.28 cm^2
	Field of View	4x4 arcmin
	PSF* FWHM	~ 2 arcsec
	Pointing	Anywhere on disc and low corona
	Step Sizes	E-W = 2.032 arcsec (mirr) N-S = 1.016 arcsec (slit)
The NIS:		
	Telescope Area Used	34.3 cm^2 per grating
	Wavelength Range	308-381Å, 513-633Å
	Prime Slits	2x240, 4x240, 90x240 arcseconds
	Grating Ruling	2400 and 4000 l/mm
	Slit-Grating Distance	736.5 mm
	Grating-Detector Distance	744.6 mm
The GIS:		
	Telescope Area Available	47 cm^2
	Wavelength Range	151-221, 256-338, 393-493, 656-785Å
	Prime Slits	2x2, 4x4, 8x50 arcseconds
	Grating Ruling	1000 l/mm
	Rowland Circle Radius	750 mm
General:		

	Total Mass	100 kg
	Overall Length	1.7 m
	Average Power	58 W
	Telemetry Rates	11.3, 22.6, 1.9 kbit/s

** PSF = Point Spread Function - i.e. the distribution expected when imaging a point source.*

1.4 Pointing

The two rearward legs of CDS contain actuators which govern the pointing of the CDS instrument - the remaining four legs react passively. The actuators are set at 90º to one another, aligned along solar NE-SW and NW-SE. Each actuator has 4096 encoder steps of approximately 1 arcsecond each. Software limits have been set to only allow the use of steps in the range between 512 and 3584 (these values are close to hardware limits). Thus, the full pointing range of CDS is a square centred at Sun-centre with the corners above solar north, south, east and west. The square has sides of length 3073x1 arcseconds = 51 arcminutes or 0.85º. Thus, above solar north, south, east and west, CDS may point up to 36 arcminutes from Sun centre, i.e. to 2.3 solar radii from Sun centre. This is well above the range where we would expect to see counts. In section 3 we give estimates for off-limb counts - they show that we may expect emission up to several tenths of a solar radius. In the worst locations, CDS may only point to 25.5 arcminutes from Sun centre, i.e. 1.6 solar radii. Figure 1.2 shows the area covered by the CDS pointing.

Figure 1.2 The available range of the CDS pointing (large square) with respect to the solar disc. The small square on the solar disc shows the size of the largest CDS raster area.

These pointing capabilities are designed to ensure that despite any potential misalignments after launch, the CDS and SUMER instruments may perform joint scientific operations.

In practice, there are constraints on using the extreme pointing positions, due to stray light problems (A. Richards, 1991). To avoid these problems it is best to restrict pointing in the extremes above the solar north and south poles to within 0.5º from Sun centre, i.e. 2.0 solar radii from Sun centre. This does not influence other directions.

The pointing system of CDS is regarded as a coarse pointing facility and one would expect to acquire the desired pointing to within 10 arcseconds. Fine pointing is achieved through the use of the slit and mirror mechanisms.

For operations planning purposes, the user is expected to use the X, Y coordinate system on the solar disc, where X corresponds to the solar E-W direction, and Y corresponds to the S-N direction (X is positive toward W, Y is positive toward N). The values of X and Y are expressed in arcseconds and they refer to the centre of a CDS raster. The onboard software will then translate X, Y into appropriate positions of the actuators legs, taking into account the pointing of the SOHO spacecraft and any known offset between the spacecraft pointing and the CDS optical axis.

The pointing stability of the SOHO spacecraft is given as 0.99 arcseconds in 15 minutes. Similarly, the roll stability is 21 arcseconds in 15 minutes. The absolute pointing accuracy of the SOHO platform is 1.65 arcminutes.

1.5 Slit Choices and Step Sizes

There are six slits. Although any slit may be used with either the NIS or GIS, each slit is tailored to the needs of a particular spectrometer. The slit selections, their designated slit numbers and purpose are given in Table 1.3. The two prime slits make use of the best possible spectral and spatial characteristics of CDS. However, for lower intensities one can trade the spectral/spatial information for greater counts with wider slits - i.e. the secondary slits listed in Table 1.3. In some cases we may sacrifice spatial information in order to obtain information on very weak lines, using the largest

of the GIS slits, and, for the NIS, we use a wide slit to produce 90x240 arcseconds spatial images dispersed in wavelength, where spectral information is restricted.

Table 1.3: The CDS Slit Selections

Slit Number	Size (arcseconds)	Main Purpose
1	2 x 2	GIS Prime Slit
2	4 x 4	GIS Secondary
3	8 x 50.8	GIS Wide Slit
4	2 x 240	NIS Prime Slit
5	4 x 240	NIS Secondary
6	90 x 240	NIS Wide Slit

Rastered images are produced by motion of the scan mirror and slit. The step sizes used in these motions are governed by the slit sizes themselves as well as by mechanical and optical restrictions.

The slit mechanism has a range of ±120 steps of 1.016 arcseconds each - we call this a *slitstep.* This gives a range of 4.064 arcminutes in the solar north-south direction.

The mirror mechanism has a range of ±60 steps of 2.032 arcseconds each - we call this a *mirrorstep.* Again, this gives a range of 4.064 arcminutes in the solar east-west direction.

A maximum area covered by a GIS or NIS raster is thus 4 x 4 arcminutes. In order to build a GIS image, it is necessary to move both slit and mirror. For example, a full 4x4 arcminutes image, using 2x2 arcsecond slit, requires 120 different slit positions with 2 arcsecond step and 120 mirror positions with 2 arcsecond step, i.e. 14400 positions in total.

For NIS, when typically used with 2x240 or 4x240 arcsecond slit, no rastering in the N-S direction is necessary, because the image is built along the slit. A NIS image requires changing only the mirror position. In the above example, a 4x4 arcminutes raster requires 120 mirror positions with 2 arcsecond step, when 2x240 slit is used. Clearly NIS takes much less steps (and time) than GIS to cover a 4x4 arcminute area.

To observe a different area on the Sun, CDS needs to be repointed and a raster built around this new location.

1.6 Telemetry

As shown in the last row of Table 1.2, CDS has three telemetry rates. The standard rate is 11.3 kbit/s - and this will be used for the majority of the mission. There are times when the SOHO experiements will *trade* telemetry to allow most of the coronal

instruments to obtain higher rates for short periods of time. There is a CDS high telemetry rate of 22.6 kbit/s. There is a CDS *sleep* telemetry rate of 1.9 kbit/s which is used when either the EIT or SUMER instruments have their high telemetry rate. It should be noted that CDS may perform limited scientific operation during the reduced telemetry periods.

The full NIS spectrum is contained in an array of 120 x 2 x 1024 words, each 16 bits long. These can be truncated to 12 bits, because the 4 bits do not carry significant information. Even so, at 11.3 kbit/s it would take 260 seconds to telemeter the image to the ground. This is for one snapshot, or one location within a raster. For a 10 location raster, it would take 44 minutes to get the image to the ground. This is not acceptable, therefore only a subset of relevant lines will be selected for each observation.

For the GIS the complete spectrum falls onto 4 x 2048 pixels. Given 16 bits each, at 11.3 kbit/s it would take 11.6 seconds to telemeter the data to the ground. Again, this is for one location of a raster. For a 10 x 10 location raster, it would take almost 20 minutes to get the image to ground. This would be acceptable if the exposure time was longer than 11.6 seconds. For shorter exposures, either a subset of lines will have to be selected or subsequent exposures will be delayed untile the previous spectrum has been fully telemetered down.

These calculations assume that all of the telemetry can be devoted to science data, rather than engineering or housekeeping data. So, the actual telemetry time may be longer than given.

To obtain the time resolutions required and to avoid telemetry bottlenecks (the time to telemeter a spectrum should be equal to or shorter than the accumulation time of the subsequent specrum), we must compress data and we must select data. Compression schemes have been developed for CDS but they will not give factors of order more than 2. However, most CDS observations require specific emission line selections and we may expect in any scheme to choose less than 1/10 th of the wavelength range, particularly in the NIS range. Such selections are discussed in detail in Section 2 below.

1.7 Comparison to Past EUV Instrumentation

The CDS experiment really does represent the first thorough examination of the Sun in the EUV range 150-800Å, which is rich in solar coronal emission lines. To illustrate this, Table 1.4 shows a summary of past solar EUV instrumentation.

Table 1.4: Past Solar EUV Instrumentation

EXPT	Dates	λ (Å)	Δλ (Å)	Δt (S)	Δx (arcsec)	FOV (arcmin)
OSO I	1962	150-400			None	Integrated Sun

OSO III	1967	20-400 260-1300	0.6 2.0	180 0.16	None	Integrated Sun
OSO IV	1968	300-1400	3.2	900 full scan	60	1 x 1
OSO V	1969	280-370 465-630 760-1030	Integr-ated	2	None	Integrated Sun
OSO VI	1969	280-1390	3.2	900 full scan	35	1 x 1
OSOVII	1972	120-400	0.8	120	20	5 x 5
Skylab SO55	1973/4	280-1350 Selected Regions	1.6	210(min-imum)	5	5 x 5
Skylab SO82A	1973/4	171-630	0.13	None	>2 Slitless	Full Sun Images
CHASE	1985	150-1335	0.25/0.4	Few Sec (min)	15	3 x 1 max
MSSTA (rocket)	1991	40-2800	SelectedBands	None	0.7	Full Sun Images
NIXT (rocket)	1988	63.5	Wide Band	None	2-3	Full Sun Images
LASP (rocket)	1988	605-635	0.03	0.4	20	0.3 x 0.9
SERTS (rocket)	1989,91, 93	235-450	0.06	None	6	5 x 8
CDS	1995	154-787	0.07-0.12	~1 Sec (min)	~3	4 x 4

To examine the coronal plasmas, their characteristics and evolution, observations below ~300Å are essential in order to include the highest temperature quiet Sun lines. Also, we require spectral information (i.e. not integrated wavelength bands) and some spatial information (i.e. not integrated Sun). Those instruments from Table 1.4 which satisfy those three criteria are: OSOVII, Skylab SO82A, CHASE, SERTS (rocket), and CDS. We are reduced to 5 instruments, including CDS.

Of the remaining instruments listed above -

- The SO82A instrument was a slitless spectrograph - spectral and spatial information cannot be separated unambiguously. Spatial resolution is dependent

on location on the disc, location within the spectrum, the brightness of the feature and confidence that the feature in question is a spatial, not spectral feature.
- The SO82A instrument and SERTS used film and thus have limited temporal capabilities.
- The CHASE and SERTS flights (Shuttle and rocket, respectively) were of short duration.

Thus, we may conclude that CDS is a unique device ideal for tackling the "coronal" goals of SOHO.

1.8 Likely Achievements of CDS

The *likely* achievements of CDS can be discussed by considering the potential target list given in Table 1.5. It should be noted that observation programmes for the examination of most of these targets have been developed thoroughly and are given later in this CDS Science Report.

Table 1.5: Potential CDS Targets

FEATURE	SCALE
Fibrils	**Few Arcsec**
Spicules	**Few Arcsec**
High Velocity Events	**Down to Few Arcsec**
Microflares	**?**
Prominences: Internal Structure	**Few Arcsec**
Sprays/Surges	**Tens of Arcsec**
Bright Points	**Tens of Arcsec**
Active Regions	**One Arcmin**
AR Loops	**Tens of Arcsec**
Prominences	**One Arcmin**
Inter-AR Loops	**Few Arcmin**
Mass Ejecta	**Few Arcmin**

The principal goals of SOHO will most likely be addressed by coronal observations in connection with the finer scale features at the top of the table, i.e. the magnetic structures which pervade the entire chromosphere (spicules, fibrils etc...). It is possible that the interaction of these magnetic structures as they extend into the corona and as they react to photospheric motion, will lead to wave activity, reconnection sites etc.. and thus the acceleration and heating of plasmas. This would appear to require spatial scales of order a few arcsec. This would possibly involve the observation of microflares or jets over the entire low corona - as yet undetected. Again, observation sequences have already been developed to address several questions in this topic area - see later.

Secondary goals would include the determination of the properties and activities in larger scale structures - e.g. the structure and stability of loops (density, temperature, flow mapping of loop structures), the ejection of matter, the expansion of bright points etc... Many observations in this category have been developed and are given later.

The secondary goals are achievable. Observations required for addressing primary goals are often based on modelling, guesswork or projection and thus are more difficult to predict.