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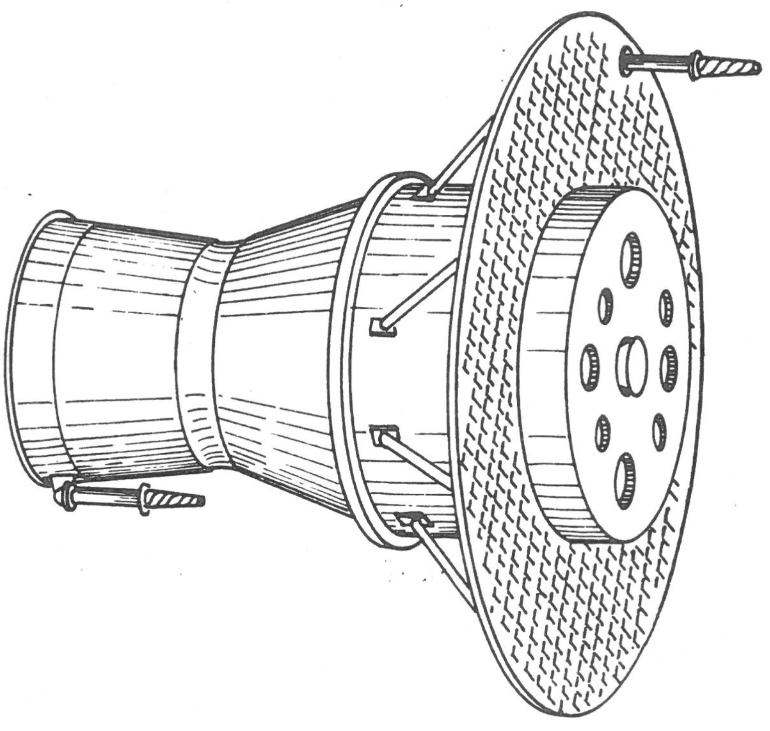
Disco

ASSESSMENT STUDY



FOREWORD

The proposal for the DISCO project was submitted to ESA in response to a call for mission proposals issued in July 1980. The proposers were: R.M. Bonnet, D. Crommelynck, J.P. Delaboudinière, C. Fröhlich, P. Simon and G. Thuillier.

The present document describes the results of an assessment study of DISCO which was conducted in April and May 1981.

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D I S C O

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ABSTRACT

DISCO intends to study, continously and simultaneously over 6 years, the variability of the global oscillations of the Sun in visible light with an accuracy of a few mm s^{-1}, of the total irradiance at 1 AU with an accuracy of 10^{-3} and a precision better than 10^{-4}, of the white light irradiance with a precision of the order of 10^{-6} and of the spectral irradiance in the UV, visible and IR from 20 to 3200 nm with an accuracy of one to a few percent. These capabilities will permit accomplishing major scientific progress in two main areas. First, the measurements of the global solar oscillations and irradiance and of their variations will lead to a concise investigation of the physical as well as dynamical properties of the interior of the Sun. Global oscillations will provide information on the solar model in a region extending from the surface down to the centre. Long-term monitoring of the total irradiance will provide essential information for the understanding of the dynamics of the solar cycle. As a by-product, DISCO will offer the possibility of determining the quadrupolar momentum J2 of the Sun, but the scope of DISCO is more far reaching than that of such missions as the NASA Solar Probe and the ESRO/ESA SOREL studies, since many different integrals of the Sun's interior angular velocity will be obtained with high precision and over long periods of time. These objectives are of relevance not only to Solar Physics but also to stellar evolution, cosmology and general relativity. Limited capabilities in spatial resolution ($\approx$ one arc min) will make it possible to disentangle true global luminosity variations from the effect of time dependent inhomogeneities at the Sun's surface, and to observe Coronal holes and active regions.

Second, the accurate absolute spectral irradiance measurements will provide physical values essential to our understanding of the photochemistry and energy balance of the atmosphere of the Earth as well as of other planets, and of the interplanetary medium and Comets.

Although the direct connection between the changes in the Earth's temperature and several cosmic as well as telluric phenomena is not yet proven, the accurate measurements of the Earth's main source of energy and of its variation is essential to better understand what factors are influencing the climate and the weather. With a designed lifetime of six years, DISCO will not be able to evidence such long-term trends as those connected with the sunspot Maunder Minimum, but it will prove that long-term measurements are possible leading the way to a much longer term investigation, likely to be conducted in the course of the next century.

DISCO will provide references to these more specific programmes which are aimed at the determination of the Earth's radiation budget. It can thereby be considered as a European component of a broader scope international programme for the investigation of solar variability, aeronomy and climatology.

Continuous observations (as opposed to snapshots) are crucial for both the study of global oscillations and for the correct interpretation of the 'solar constant' variations.

The requirements imposed by the scientific objectives of DISCO on the precision and accuracy of the measurements lead to the definition of a strategy which is detailed in the text and is based essentially on the use of balloon, rocket and possibly Space Shuttle flights to obtain highly accurate absolute measurements at various discrete periods during the lifetime of the mission.

Most of the instruments envisaged to fly on DISCO already exist. Some have already been flown on rockets and balloons or will be placed on-board Spacelab. One version of the high resolution spectrometer has been operating on the ground (South Pole) and needs to be adapted to the satellite conditions. There is no major difficulty which is identified for adapting this instrument for DISCO.

The orbit selected after analysis of various alternatives remains in the vicinity of the Lagrangian libration point L1 (or L2), constantly on the Earth-Sun line, at 1.5 million kilometers from the Earth. Thus, the Sun is permanently visible from the spacecraft, without eclipses and, in addition, the radial velocity with respect to the Sun is very low, as required by high-resolution spectrometers.

With a view to decreasing the launching cost, using Ariane-2 or -3, the spacecraft configuration and initial mass are compatible with a dual SYLDA arrangement. Moreover, a "standard" Ariane procedure is foreseen with injection into an intermediate geostationary transfer orbit. Ample mass is available for a second passenger, e.g., in the telecommunications family. At perigee of this intermediate orbit, a solid boost motor, e.g., the GEOS motor, inserts the spacecraft into a cruise orbit towards L1 (or L2).

The spacecraft design has been conceived with the constant objective of minimising the development risks and cost, but fully satisfying the scientific requirements. The technology is conventional and the large majority of equipment exists and is flight qualified.

For reducing the outgassing contamination on the scientific instruments, the boost motor is ejectable after burn-out and a cold trap is provided on the side looking away from the Sun.

The spacecraft is a spinner, with fixed (non-deployable) solar array; the spin axis direction, pointed to the Sun, is controlled by a hydrazine subsystem, used also for orbit correction and maintenance. Telecommunications utilize the standard S-band and are able to transmit 3 kilobits per second of data. In the operational phase, only one ESA ground station is necessary. The total lifetime is 6 years.

A low-risk development schedule, where the real experiments are selected prior to the start of Phase B, shows that the mission can be launched in early 1988.

1. SCIENCE

1.1 Introduction

For more than a century our progress towards understanding the solar phenomena and the physics of the solar atmosphere has been closely associated with our ability to increase the resolving power of our telescopes and spectrographs, first on the Earth , and since the 1960s, in space. Such basic phenomena as the physics of convection, the emergence and concentration of magnetic flux tubes, the heating of the corona, the birth of the solar wind, etc., all occur on spatial scales much below one arc second. Atmospheric turbulence sets a limit of $\simeq$ 0.2 arc sec to the resolution of the best ground-based telescopes, and it is only with the use of solar telescopes in space that we can expect to reduce this limit by the factors which are required to reach the critical spatial scale over which no substantial progress to our understanding of the external layers of the Sun can be expected.

In recent years, however, we have witnessed the progress of a diametrically different approach which carries in itself a potential of observations which are crucial to our understanding of the Sun and of its interior. This is the study of the global Sun in which the search for better spatial resolution has led the way to that of the highest possible accuracy in the determination of the global phenomena or properties and of their variation with time. The flux of neutrinos from the core of the Sun, the detailed properties of global oscillations with an accuracy of a few cm s^{-1}, the minute variations of the solar radius and the solar constant, the magnetic cycle of the Sun are likely to find their origin far beneath the layers which are accessible to direct optical observation. However. as is the case for the detailed observations of the disc, the Earth's atmosphere presents a physical obstacle to reaching the limit of the accuracy which is necessary to acquire the genuine meaningful information. Here, too, the use of space techniques is a necessary step towards the achievement of scientific progress. In addition, the information which is contained in the temporal variation of these global properties and of their possible respective phases, and which may lead to the refined knowledge of the solar machinery, requires that the observations be conducted over time periods which span a substantial portion of a magnetic cycle.

DISCO intends to study simultaneously the variability of the global oscillations in the visible with an accuracy of a few mm s^{-1}, of the "solar constant" (total irradiance at 1 AU) with an accuracy of 10^{-3} and a precision better than 10^{-4}, of the white light irradiance with a precision of the order of 10^{-6}, and of the ultraviolet, visible and infrared spectral irradiance from 20 to 3200 nm with an accuracy of one to a few percent.

Projects competing with DISCO are described in Annex 1. It has not been possible to identify any which aims at measuring these parameters both simultaneously and continuously over several years.

In addition, DISCO will permit the observations of coronal holes and active regions in the far ultraviolet with a resolution of ~ 1 arc min. Although it might be of interest to relate the global solar properties to the global magnetic structure, there is not yet any solid theoretical justification to substantiate this relationship.

A very important by-product of the global oscillation measurements on DISCO is the possibility to determine the quadrupolar moment J_2 of the Sun.

Our scope is more far-reaching than that of such missions as the NASA Solar Probe and the ESRO/ESA SOREL studies. We plan to obtain many different integrals of the Sun's interior angular velocity with high precision, rather than merely the single integral J_2 whose accuracy would be severely limited by the short interval during which the probes would be near the Sun. Further discussion on this subject is to be found in Section 1.2.

The value of long-term monitoring and long-term observations of the Sun finds a unique illustration in the discovery of the disappearance at several epochs in the past of sunspots over several decades and in the existence of the Maunder minimum which is the manifestation of the detailed mechanics which governs the solar activity cycle.

Of course, with a designed lifetime of six years, DISCO will not be able to evidence any such long-term trends. It is highly possible, however, that in the next century routine observations, such as those envisaged with DISCO, will be conducted from space platforms, especially if the reality of the relationship between the variability of the solar output and climatology and aeronomy are confirmed. In addition to a pure global Sun Observatory, DISCO can, thus, be considered as the probing element of a much longer term investigation, to be conducted in the course of the next century with the aim of understanding the various factors which determine the Earth's climate.

At the present time, the direct connection between the changes in the Earth's temperature and several factors, such as the decreased radiation caused by sunspots, the cosmic ray flux changes, cosmic dust clouds, movements of the Earth's magnetic fields, volcanic aerosols, conjunctions of the planets, etc., is far from being proven. The first objective is to measure accurately the Earth's main source of energy and its variation. With DISCO we intend to prove that these measurements can be envisaged over long time periods while at the same time revealing the detailed behaviour of the global Sun.

Such measurements are, of course, of direct interest also to the study of the aeronomy of the Earth and the planets. In that context, they could serve as references to those programmes which aim at the determination of the Earth's radiation budget, such as the ERBE in the United States. DISCO could thus be considered as a European component of an international programme in the investigation of solar variability, aeronomy and climatology.

Europe must play a role in this growing field of interest. Not only does the expertise exist in the area of accurate absolute radiometry and photometry but the development in Europe of resonance scattering techniques, which have been so remarkably successful in recent South Pole observations of the global solar oscillations, clearly illustrates the fact that European scientists today do possess the tools necessary to properly explore this new and exciting field of research.

Table 1.1 summarizes the main requirements imposed on the instrumentation to fulfil some of the major scientific objectives of DISCO.

1.2 Investigation of the Solar Interior

1.2.1 Relevance to stellar evolution, cosmology and general relativity

Until now our knowledge of the internal structure of the Sun comes from the applications of the theory of stellar evolution. The prime success of that theory is the explanation of the qualitative features of the Hertzprung-Russell diagram for star clusters. But for the quantitative agreement, it is necessary to calibrate the theory against stars whose properties we know well. The most important calibration is with the Sun, a typical Main Sequence star. However, if one disregards the neutrino problem, there is at least a single infinity of solar models that agree with the observations. The standard theory of stellar evolution depends on a set of assumptions that have been chosen for simplicity. For example: the Sun is assumed to be spherically symmetrical, rotation is ignored, and the possibility of material mixing produced either by meridional circulation, turbulence or wave-breaking is usually not taken into account. This is because the manifestation of such processes are difficult to check observationally. Nevertheless, we have already strong indications that something may be wrong with the theory in its present state from the failure to reproduce theoretically the observed neutrino flux with a solar model having an internal composition that most astronomers would believe in: a model can be found with very low helium abundance, but this abundance is lower than that predicted to have been created during the initial stages of the Big Bang.

Table 1.1 : SCIENTIFIC OBJECTIVES AND REQUIRED INSTRUMENTAL PARAMETERS

SCIENTIFIC OBJECTIVES	INSTRUMENTS	INSTRUMENT REQUIREMENTS
Determination of solar angular momentum by rotational splitting of pressure modes	High resolution visible spectrometer	Continuous observations: Velocity measurements of ≃ mm/s. Integration time: ≃ 2 weeks.
Density stratifications beneath convection zone and central internal rotation	High resolution visible spectrometer	Continuous observations. Velocity measurements of ≃ mm/s. Integration time: ≃ 2 weeks.
White light oscillations	Visible light photometer detection	Continuous observations. Precision: ≃ 10^{-5} Integration time: a few seconds. Angular dependence of the modes. Spatial resolution: several arc min.
Variations in the solar constant, short- and long-term	Absolute pyrheliometer	Continuous observations. Accuracy: 10^{-3} Precision: 10^{-4} Integration time: a few minutes.
Spatial distribution of total irradiance	Absolute pyrheliometer	Spatial resolution: 1 minute. Attitude restitution: 1 minute.
Long-term variation of the temperature minimum	Far-infrared or 160 nm radiometer	Observations over the lifetime of the mission. Accuracy: 5% Precision: 2%
Spectral redistribution of solar irradiance: - 160 - 200 nm	160 - 200 nm photometer	Accuracy: 3% - 5% Precision: 0.3% - 1%
- Visible and near-infrared	Sun photometers	Accuracy: 1% - 5% Precision: 5 10^{-5} to 5 10^{-4}
Spectral irradiance variations: - Far ultraviolet for upper atmosphere/aeronomy	Far UV spectrometer	Accuracy: 5% Precision: 1%
- 170 - 3200 nm	170 - 3200 nm spectrometer	Accuracy: 1% - 5% Precision: 0.3% - 1%
Far ultraviolet imaging for coronal hole observations	Far UV spectrometer	Continuous observations. Spin axis stability of DISCO: 1 arc minute.

The ages of globular clusters are determined by comparing the observed position of the departure from the Main Sequence with standard theoretical predictions. If substantial material mixing between the core and the envelope is taking place, central hydrogen burning will continue for longer and the age predicted would be increased. This would increase our estimate of the age of our Galaxy and of the Universe, which has a direct implication on cosmology.

The angular momentum distribution within the Sun is also important. Not only does it raise interesting questions in fluid dynamics, but also the oblateness of the mass distribution produced by centrifugal forces influences the external gravitational field. The measurement of the precession of the perihelion of the orbit of Mercury and other planets is a crucial test of theories of gravitation only if we know the quadrupole momentum of the gravitation field. This was assumed to be zero by Einstein, but it has been questioned in recent times by Dicke.

1.2.2 Helioseismology

In recent years a wealth of new information has become available from observations of oscillations of the Sun. Provided the mode of oscillations can be identified, their frequencies can be used to diagnose certain aspects of the Sun's structure in much the same way as terrestrial seismic waves have been used to probe the interior of the Earth. Both theory and observation have advanced rapidly and already we are beginning to constrain the solar models more severely than had previously been possible. Like in the Earth, the amplitudes of the oscillations are so low that linear theory can be used.

The principal modes of oscillations can be classified according to their physics and according to their geometry. As pointed out by Cowling (1941), there are p-modes whose principal restoring force is provided by pressure, and g-modes whose principal restoring force is buoyancy. The frequencies of p-modes are determined mainly by sound speed whereas the g-modes frequencies are governed by the (potential) density gradient in the stably stratified radiative interior. In addition, there are the surface gravity waves (Cowling's f-modes), but these have little diagnostic value.

Since, to a first approximation, the Sun is spherically symmetrical, the solutions for the normal modes are separable in time, radius, and angular coordinates. The angular structure of each mode is a spherical harmonic of degree l and tesseral order m and the eigen-functions in radius constitute a discrete sequence and can be labelled with an integer n, which is called the order of the mode. The degree l determines an effective horizontal wave number k. The eigen-frequencies ω depend on n and l, but the spherically symmetrical models are degenerate in m. In reality, the Coriolis forces arising from the slow rotation split the degeneracy in m.

The observations fall into two groups: those that detect modes with high l, and those which measure modes with low l. To date, only p-modes have been unambiguously identified. P-modes of high degree have been measured with precision by Deubner (1975), and, more recently, by Harvey (see Fig. 1.1).

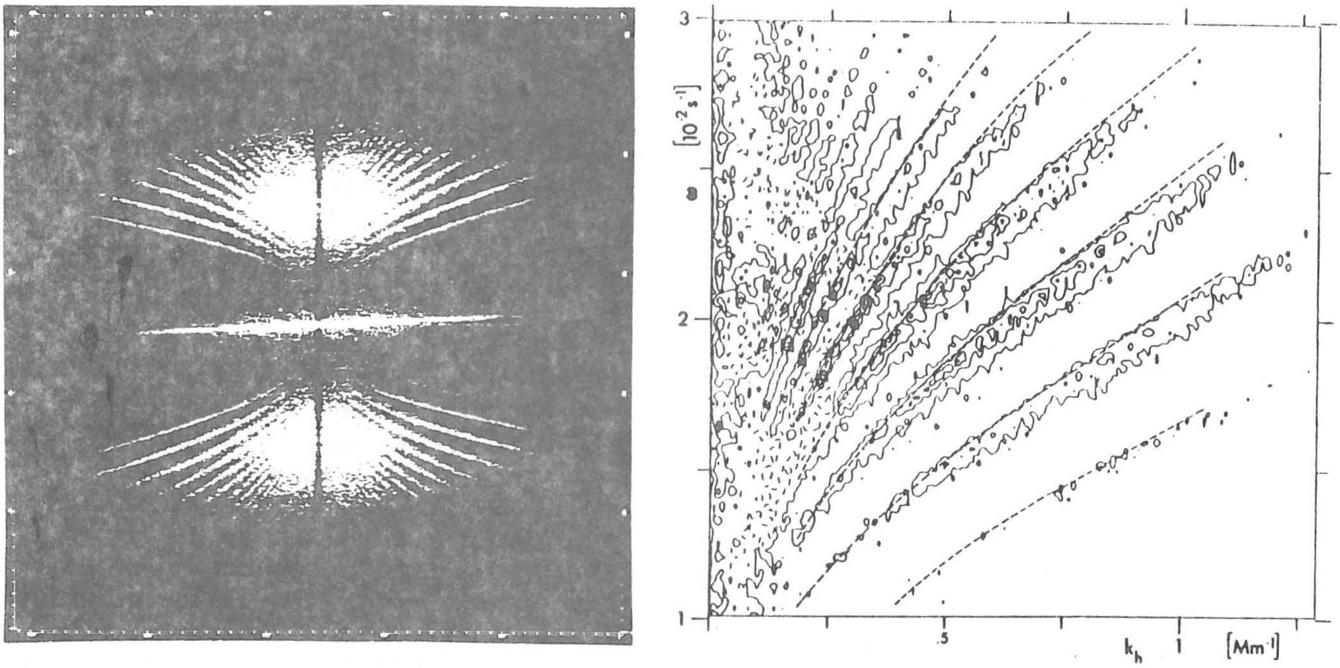

Figure 1.1 Two different examples of the K-ω power spectrum which resolve the discrete ridges corresponding to high-l, low-n oscillating normal modes of the Sun. The figure on the left, from Duvall and Harvey at Kitt Peak (1980, private communication), shows the asymmetry between positive and negative frequency parts, due to rotational splitting. The right-hand figure shows the comparison with the same modes as theoretically calculated.

The observations have determined the relation between k and ω for low order modes ($n \leqslant 10$). Unfortunately, these modes penetrate only a few percent of the solar radius beneath the photosphere, and, therefore, give us no direct information about the deep interior. Nevertheless, the information they provide has enabled us to eliminate standard solar models with low helium abundance. It should be pointed out, however, that this result depends on untested assumptions of the standard theory and must, therefore, be treated with caution. Observations of modes of low degree have been made by integrating light from substantial fractions of the solar disc; in particular, whole disc integrations have led to the discovery of a discrete set of high order eigen-frequencies near 3 mHz (Claverie et al., 1979). Subsequently, by going to the South Pole, Grec et al., (1980) have been able to obtain continuous records sufficiently long for the modes to be identified. This identification was made by detailed comparison of the frequencies and amplitudes of the observed modes with theory.

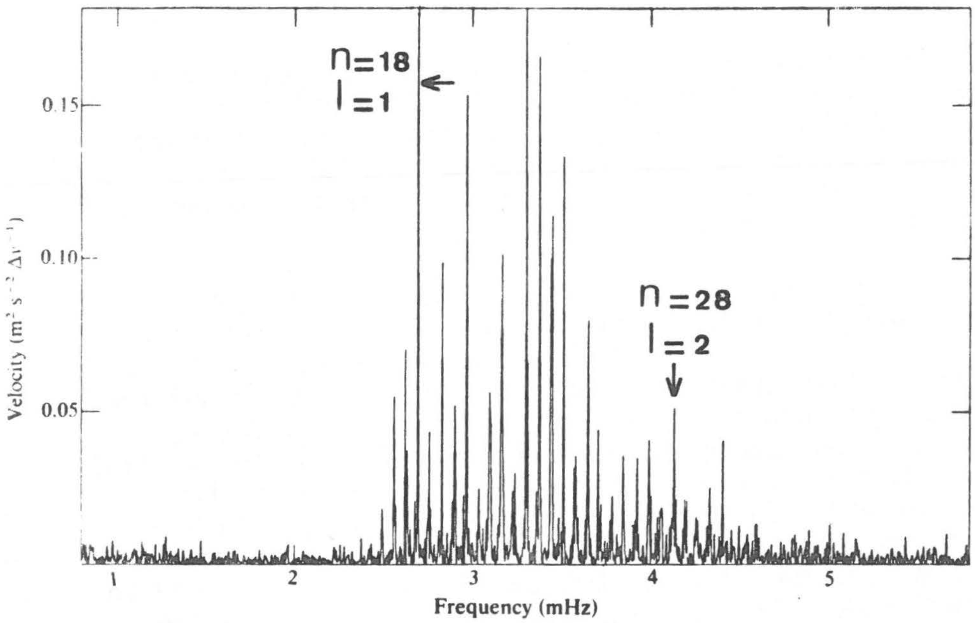

Figure 1.2 Power spectrum of the continuous 5-day full-disc Doppler shift measurements recorded at the South Pole from 31 December 1979 to 5 January 1980. The resolution of the power in the 3 mHz range into many discrete equidistant lines separated by 68 μHz indicates that global p-modes corresponding at least to 1 values of 0 and 1 are observed. Note that the small peaks around 2.4 mHz represent global oscillations with an amplitude $<$ 10 cm s^{-1}, corresponding to motion of the solar radius $<$ 5 m, or 7 x 10^{-6} arc s.

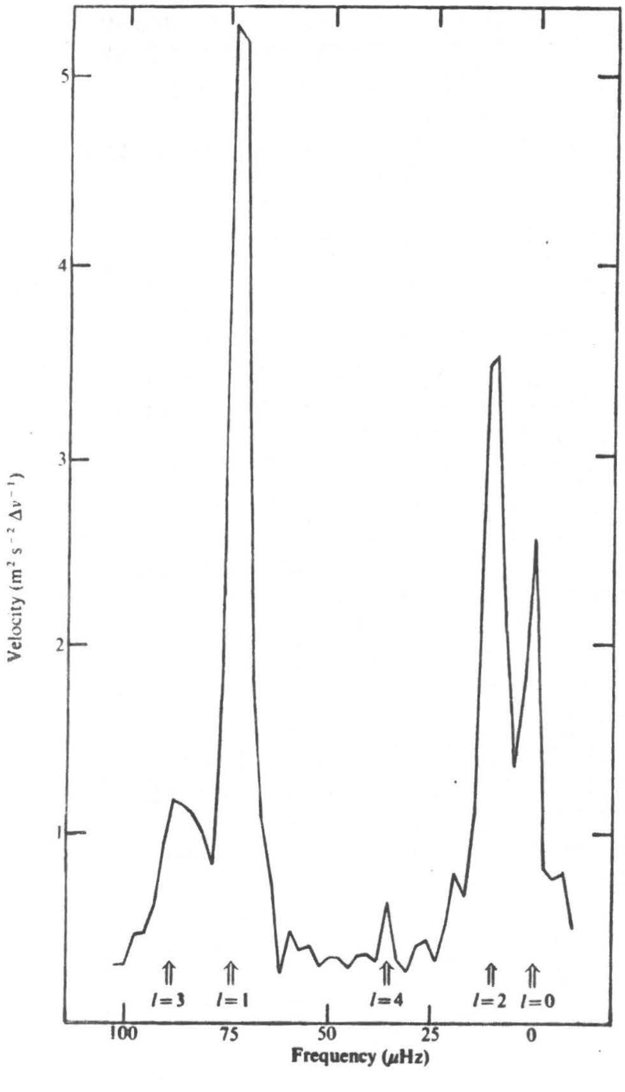

Figure 1.3 A superposed frequency analysis of the frequency range between 2.4 and 4.8 mHz reveals the average shape of spectral lines displayed in the power spectrum of Fig. 1.2. The horizontal axis indicates where the theory predicts the positions of 1 = 1,2,3 and 4 modes if the one on the extreme right is assumed to be 1 = 0. The good agreement leaves no room for doubt. Note that the natural width of each separate mode indicates a Q value of the order of 600.

Unlike the modes of high degree, these modes penetrate to the centre of the Sun and so provide a direct measure of conditions in the interior. The standard solar model that fits the observations best has a relatively high helium content but neither theory nor observation is yet sufficiently precise to preclude other possibilities.

In principle, rotational splitting of the nonaxisymmetrical modes can provide us with information about the internal rotation of the Sun. The splitting of each set of degenerate modes provides a different integral of the angular velocity of the Sun. Thus, with many modes one can perform an inversion to estimate the angular momentum distribution within the solar interior.

Of course, among other things, the oblateness of the gravitational equipotentials can be inferred from the results. To obtain accurate measurements of the rotational splitting requires both that the oscillations maintain phase for several rotation periods and that they are observed continuously throughout that time. Obviously, ground-based observations cannot be made continuously for the several months required. Moreover, the results of Grec et al. have shown that the high order modes do not maintain phase for long enough. One might expect, on theoretical grounds, that the low order modes will maintain phase for much longer, but these have been observed to have very low amplitude. It is, therefore, necessary to make the observations from outside the Earth's atmosphere to reduce the noise to a sufficiently low level, in order to achieve a sensitivity of at least a few mm s^{-1}. It is also hoped that with such sensitivity g-modes will be detected. These would provide a more sensitive measure of the density stratification beneath the convection zone and the internal rotation of the very centre of the Sun.

We should point out that a close Solar Probe is high on NASA's list of future solar missions, and a similar project has also been studied in the past by ESA. The obvious limitations of these projects, aside from their costs, is that they attempt to supply only one integral measure of the internal rotation of the Sun, and that with limited accuracy. If the 2 h 40 min oscillation observed by Severny et al. (1976) is a low degree g-mode, the perturbations in the gravitational potential it produces would be a substantial fraction of the static rotationally induced oblateness if the Sun were rotating approximately uniformly. Since the envisaged probes spend only a very few oscillation periods close to the Sun, with the accuracy available it is impossible to disentangle the oscillatory component of the gravitational field from a measurement of the orbit alone.

It is also proposed here to study these 2 h 40 min oscillations which, as stated above, may be a low degree g-mode, but other possibilities are not excluded. Amplitude modulations have been reported by Severny et al. (1979), which may be a manifestation of rotation splitting. Because the period is so long, the scope of ground-based observations has probably reached its limit, and long continuous sequences from space are now required.

1.2.3 Integrated and spectral irradiance measurements

We divide the discussion according to the time scales of the variations in the intensity of the total Solar Output.

Dynamical time scales (shorter than a few hours)

The dynamical oscillations measured in velocity can also be detected in integrated light. Deubner (1981) has already measured frequencies near 3 mHz in white light with amplitudes of a few parts in 10^5. The radiometers proposed for this mission have a sensitivity of a few 10^{-5} and so will be capable of measuring at least some of the modes of lower order. Since this sensitivity to modes of differing degree is different for velocity and intensity measurements, this additional information will help in identifying the spatial structure of the modes. The relative amplitudes and phases of velocity and white light oscillations will help in our understanding of the reaction of the upper layers of the convection zone to oscillations with periods comparable with the eddy turnover time. This is important for understanding not only the dynamics of the solar convection zone but also the driving and damping of certain classes of intrinsically variable stars, such as the cooler Cepheids and RR Lyrae variables.

Oscillations in the infrared and ultraviolet are indicators of temperature fluctuations in the solar atmosphere near the temperature minimum, and their amplitudes and phases will provide information about the height dependence of the oscillation eigen-functions.

Spatially resolved irradiance fluctuations would provide direct information about the angular dependence of the modes. For studying the low degree modes, which is our principal concern, a resolution of several arc min is optimum.

Time scales of days to weeks

The adjustment of large-scale convection to the appearance and disappearance of sunspots takes place on time scales of days or weeks. Only since the long continuous and precise measurements from SMM (Willson et al., 1981) have been made (see Figure 1.4), has it been demonstrated that variations in the Solar Constant occur in association with the appearance of sunspots. It is now known that luminosity diminutions persist of the order of ten days, which demonstrates that the convective inhibition by the sunspots is deep-seated in the convection zone. Further measurements are required to improve our knowledge of the perturbation in the heat flow. For this purpose, accurate radiometric measurements with spatial resolution comparable with the size of sunspots would be of high value.

It is evident from Figure 1.4 that the two dominant dips which lasted approximately ten days would not have been resolved by measurements of the duration that can be provided by balloons or rockets, or even Space Shuttle flights. Had an isolated measurement

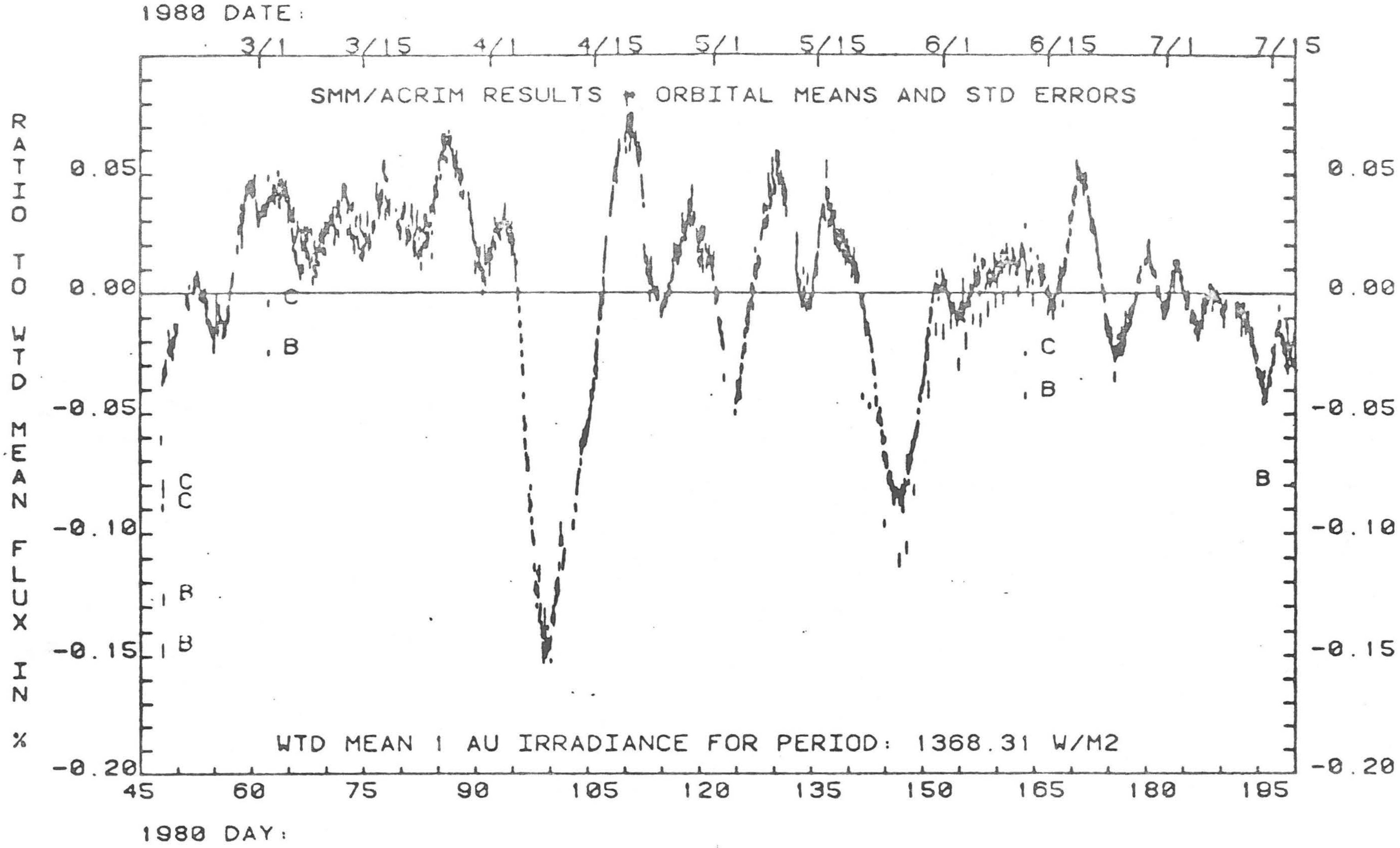

Figure 1.4 The 1 AU total solar irradiance for the ACRIM channel A sensor is shown as a percentage variation about the weighted mean for the first 153 days of the Solar Maximum Mission. The individual tic-marks represent the mean irradiance for the sunlit portion of one orbit. The vertical bars through each tic-mark are the ($\pm$ 1σ) standard errors of the orbital means. The tic-marks with associated "B" and "C" designations are the channel B and C measurements during comparisons with channel A. A similar technique is proposed for DISCO.

been made during the period of such a dip, the result would have been misleading. Therefore, the continuity of the radiometric measurements appears essential here.

Ultraviolet and infrared measurements will diagnose how the solar atmosphere responds to the perturbed heat flux. The infrared measurements, although more difficult to make, are less sensitive to inhomogeneities and are, therefore, a better indicator of the mean structure of the atmosphere. Unlike the ultraviolet, infrared emission is a more direct indicator of the thermodynamical state of the gas and has a direct bearing on the balance of forces in the atmosphere.

Time scales longer than months

The temporary decrease in the solar constant, associated with sunspots mentioned above, leads one to conjecture that there are longer term luminosity variations associated with the solar cycle. Already there is some indication that this is the case from balloon measurements but the issue is not resolved. Theoretically, one might expect a global decrease in the solar energy output when the sunspot number is high (Gough, 1980). Although the amplitude of the variation is expected to be rather less than the direct blocking of radiation by the sunspots, it may, nevertheless, be sufficient to have climatic consequences, as discussed in Section 1.3.

The direct blocking of the radiation by sunspots is not the only process than can cause luminosity variations during the solar cycle. Variations in the mean magnetic stresses in the convection zone, changes in the efficacy of convection brought about by magnetic buoyancy, variations in the depth of the convection zone arising from the inhibition of convection in a boundary layer between the convective and radiative regions, all induce changes in the balance between thermal, gravitational and other forms of energy (Gough, 1980). Such changes modify the hydrostatic structure of the Sun, and, hence, lead to variations in luminosity and radius. Even changes in the solar core, if of sufficient magnitude, could cause temporary variations in the solar luminosity and the radius of the photosphere. This last possibility has been suggested by Dicke (1978) in an attempt to explain the solar cycle, the neutrino flux, and the 12.2 day variation in the Princeton oblateness data in an apparently unified way.

We do not yet understand the dynamics of the solar cycle. Even though dynamo theories are fashionable at present, they do not obviously explain the observations, as Dicke has pointed out. In particular, they do not take into account the global reaction of the Sun to the magnetic variations. Therefore, we do not even know where in the Sun the main controlling forces lie. Attempts to determine whether or not the cycle is controlled by a regular oscillation of the core, by studying statistics of the solar cycle, are inconclusive.

It appears that the Sun's memory is at least several centuries long. This is insufficient to demonstrate that the dynamics is controlled by the core, and, since sunspot numbers were not recorded reliably prior to the Maunder minimum, it appears that sunspot statistics cannot resolve the issue.

Limited theoretical computations suggest that the ratio of the variations in luminosity and radius associated with the cycle depends on the depth in the Sun of the perturbation that produces it. Simultaneous measurements of luminosity and radius are, therefore, of considerable interest. Radius measurements can be made from the ground, and plans to achieve them have already been proposed by Hill in the USA and by Rösch at the Pic-du-Midi Observatory. Accurate luminosity measurements, however, need to be made from above the Earth's atmosphere. Not only does a total radiometric measurement appear to be essential, but the possibility of even moderate spatial resolution in the distribution of the solar flux at the disc surface would allow one to judge whether solar constant variations reflect similar variations in the luminosity or whether they are the result of time-dependent inhomogeneities.

1.3 Relevance to Atmospheric Processes

1.3.1 Relevance to Earth atmosphere photochemistry and energy balance

In the past 1,000 years, there have been significant changes in the Earth's temperature, and in the past 100,000 years, there have been periods when the temperature changed by as much as 0.05^{o} per year for periods of about 100 years. Several authors have made claims to a connection between a variable Sun and the Earth's weather and/or climate. Some have concentrated on local effects as the basis for temperature changes, and there are consequently a host of ingenious ideas ranging from decreased solar radiation caused by black spots on the Sun, through cosmic ray flux changes, cosmic dust clouds, movement of the Earth's magnetic field, volcanic aerosols, conjunctions of the planets, etc., to solar ultraviolet effects on the ozone layer. One thing seems to be clear: to create some order from this chaos it is necessary to establish whether or not there is a variation in the solar radiation, and if there is, to find its size, spectral distribution and period.

Reviews of the solar constant determinations show that no significant change can be detected from the results obtained between 1969 and now: within $\pm$ 2 Wm^{-2} or $\pm$ 0.15% the solar constant stayed constant. The results of the period before 1969 suggest a slight decrease, and one could speculate and try to explain the decrease of the mean global temperature since the 1940s by a decrease in the solar constant. Although this result is in reasonable agreement with model calculations, it is not conclusive, due to the great uncertainties of the measurements in the 1960s.

Although the absolute value of the solar constant is a critical term in the determination of the Earth's radiation budget, the response of the Earth's climate to any solar variability cannot be explained without taking into account the spectral redistribution in the energetic bulk part of the spectrum from 400 to 1500 nm of a variable solar output. This would mainly influence the planetary albedo, which is wavelength dependent, due to the various scattering properties of the atmosphere. Unfortunately, no conclusions about the spectral redistribution during changes of the solar constant can be drawn from existing records.

Furthermore, many properties of the atmosphere depend upon the interaction between the atmosphere and the solar irradiance through fundamental processes which are strongly wavelength dependent. Absorption of solar photons in the Earth atmosphere leads to two basic processes: 1) photoionization, and 2) photodissociation, which initiate all ion and neutral chemistry. Consequently, the action of solar photons on the Earth atmosphere changes the original composition, modifies the temperature, and, hence, the dynamics (movements on all scales).

Above 80 km altitude, the solar photons interact with the atmospheric gases for $\lambda < 175$ nm. At shorter wavelengths ($\lambda < 102.5$ nm), the photoionization becomes dominant. Then the solar EUV creates the ionosphere and heats the neutral gas through various processes involving the ions and the photoelectrons. Those processes now explain the main properties of the thermosphere.

In the lower thermosphere (<150 km), the solar energy absorption occurs mainly in the Schumann-Runge continuum (130-175 nm). As the solar irradiance variation seems smaller at larger wavelengths, the "footprint" of the Sun variability becomes more difficult to exhibit than in the thermosphere. Nevertheless, the link does exist.

In the mesosphere, below 80 km altitude, only Lyman-alpha undergoes photoionization, leading to the creation of the D region. The neutral chemistry is initiated by the O_2 photodissociation in the wavelength range 175-240 nm, leading to O_3 formation which, in turn, can be destroyed by photodissociation ($\lambda < 310$ nm). But the ozone budget is also driven by catalytic cycles involving HO_x, NO_x and ClO_x families (Nicolet, 1975). Some of those trace species are photodissociated in different wavelength intervals, as, for instance, NO_2 ($\lambda < 400$ nm), NO ($\lambda < 190$ nm) and chlorofluorocarbons ($\lambda < 240$ nm).

Thus, it clearly appears that the final composition of the atmosphere is affected by the solar photons. It can easily be shown that the thermal structure is also dependent on the solar photons: for example, the increase of temperature in the stratosphere is due to the UV absorption by O_3. Then, without O_2 dissociation, which initially creates O_3, the stratosphere would not exist.

Atmospheric modelling requires the absolute value of the solar spectral irradiance and its variation as a function of time. Such models can be used to foresee what could be the change in the ozone layer induced by NO_x and/or chlorofluorocarbon injections or induced by solar irradiance variation. For example, a 20% increase in the solar irradiance between 180 and 250 nm would increase the total ozone by 3%. Ozone being a shield against the solar UV, any parameter affecting this layer is of great importance for life on Earth. That is why, among other recommendations, the monitoring of solar radiation has recently been recommended by the Council of Europe (cf. document No. 4558, 1980).

1.3.2 Relevance to solar system photochemistry and energy balance

Any other object within the solar system is also strongly affected by solar irradiance. The thermal balance of planets is dominated by the Sun, although internal sources may also contribute in some cases (Jupiter, Saturn, etc.).

During their journey along elongated orbits, comets are submitted to highly variable heating conditions, as evidenced by the spectacular increase of the coma extent at perihelion.

Photochemical interactions prevail in those layers of the gaseous components where UV radiation can penetrate. Two basic processes must be considered: photodissociation with a threshold of about 200 nm, which dominates the chemistry, and photoionization by photons below 100 nm, which is responsible for the appearance of ionospheres. Quite different photochemical reaction chains are initiated in carbon dioxyde atmospheres (Venus, Mars), the atmospheres of the outer planets dominated by molecular hydrogen, helium, and including CH_4 (Jupiter), or even atmospheres containing sulphur compounds of volcanic origin, like Io.

It has been proposed that solar spectral variations may also induce quite different equilibrium composition in cometary comas as a function of solar cycle phase.

The most tenuous solar system component - the inflowing interstellar gas of hydrogen and helium - is slowly destroyed to a variable extent by solar radiation below 100 nm and its dynamic depends upon the solar flux at 121.6 nm. Ultimately, it is worth mentioning the indirect consequence of variations in solar intensities and spectral distribution upon analysis of fluorescence observations of gases within the solar system.

1.4 Model Payload

Table 1.2 lists the characteristics of a number of instruments that form the model payload. Most of them are already developed, some for space flight, others for balloon, rocket or ground operation. In some cases, further iteration of interfaces with the spacecraft may lead to an optimisation of mass and power requirements.

Because of its importance and the need to ensure a proper continuity with previous and future solar constant observations through comparison of measurements, two pyrheliometers of independent design are proposed to be flown.

The pyrheliometers are absolute instruments based on the use of two identical cylindrical cavities set up differentially. The required knowledge of the intrinsic non-equivalence due to the comparison of two different kinds of energy - radiative and electric - is based on a series of direct laboratory determinations. This allows to guarantee a relative accuracy of better than 10^{-3} associated with a precision better than 10^{-4} in air. In vacuum, this should be improved by at least an order of magnitude. The long-term stability of the design of this instrument is illustrated by the internal consistency and stability of the World Radiation Reference over a period of more than five years, which is better than a few 10^{-4}. With regard to redundancy, there are three instruments of each category, with only one in continuous operation.

The spectral irradiance range from far-ultraviolet to infrared is studied by a set of broad-band spectrometers designed particularly for stability in frequency and time. All of them incorporate in-flight calibrating facilities to control the problem of degradation with time. They consist of:

i) a spectrometer which measures the spectral irradiance from 170 to 3200 nm by the use of three double monochromators. Up to 900 nm, the band pass is 1 nm, and 20 nm from 900 to 3200 nm, with an accuracy of 10^{-2} nm. Calibration lamps are included to monitor any change of sensitivity and wavelength scale. The foreseen precision is 0.3%, while the accuracy is that of the available standard.

ii) a far UV spectrometer which will observe the wavelength range 15 to 175 nm of radiation originating from the solar chromosphere and corona. An appropriate long-term accuracy of 5% can be achieved with the help of in-flight calibration. The instrument itself will include a minimum number of optical components liable to degradation. Strict observance of cleanliness conditions during storage and an economical use of the instrument will guarantee a useful lifetime of over five years. Relative measurement with an accuracy of 1% will be possible, and by inserting once per day a small telescope, it may be possible to reconstruct maps of the highly inhomogeneous solar corona at a resolution of 1 arc min, exploiting the natural motion of a spinning spacecraft.

Table 1.2 : INSTRUMENT CHARACTERISTICS

Instrument	Wavelength range	Bandwidth	Mass (kg)	Power (W)	Telemetry (bit/s)	Status of development
Pyrheliometers						
Radiometer-1	-	-	11.7	20.0	8	Flown on balloons and rockets
Radiometer-2	-	-	6.5	6.5	20	Developed for Spacelab
Visible Sun-photometer	250-1000 nm	5-10 nm	9.7	31.0	30	Flown on balloons and rockets
Infrared Sun-photometer	50-150 um	10 µm	7.2	37.0	2	Flown on balloons
Ultraviolet Sun-photometer	160-200 nm	10 nm	11.0	20.0	256	New
Spectrometer	170-3200 nm	1 nm $\lambda > 1$ µm; 20 nm	32.0	30.0	180 during 3h/day	Developed for Spacelab
Far UV Spectrometer	15-185 nm	0.15-0.3 nm	30.0	20.0	1400	New
High Resolution Spectrometer*	Na 5896 Å line	-	40.0	25.0	1000	Used at ground observatory
Interferometer*	580-780 nm	2 pm	4.5	9.5	10	New

* alternative techniques

To cross-check the stability of the spectrometers, a large fraction of the spectrum is covered simultaneously by sun-photometers. Sun-photometers are used for measurement and long-term monitoring of the solar spectral irradiance at several fixed wavelengths with moderate resolution (∼5 nm) in the wavelength range 250 - 1000 nm. The calibration accuracy is 1% - 5%, depending on wavelength; the single measurement precision is 50 - 500 ppm; and for oscillatory signals, for detectibility with 3-hour integration, the precision is 1 - 25 ppm. In-flight calibration is effected with a laser diode of one of the sun-photometers (820 nm). With regard to redundancy, there are 3 instruments at each wavelength, with only one in continuous operation.

The solar output over that point of the spectrum which extends from Lyman-alpha to 200 nm represents only 0.1% of the total solar constant. If the defect of a fraction of a percent observed in the total output were to be totally compensated for in the Lyman-alpha to 200 nm spectrum, we should expect strong fluctuations of factors of 2 or more, and the required accuracy would not be that severe. Our requirements derive, in fact, from the presently achieved accuracy of = ± 25% and from the need for an improvement in absolute UV flux measurements in aeronomy investigations. With a photometer operating in the range 160 - 200 nm, one aims at an accuracy of 5% to 3% and a precision of 1% to 0.3%.

Finally, to measure and resolve small amplitude pulsations, two types of instrument are proposed:

i) a high resolution spectrophotometer devoted to the oscillation measurements utilizing the optical resonance technique. It is derived from the instrument already in use at the ground-based South Pole Observatory. The latter has reached a sensitivity of 4 cm s^{-1} with 5 continuous days of observation, which is a limit imposed by the presence of the Earth atmosphere. Its intrinsic capability is theoretically far better. In space, the sensitivity is, in fact, limited only by photon statistics, and will be around 1 mm s^{-1} for less than two weeks of integration. The intrinsic instrumental noise can be maintained easily below this limit.

ii) a high resolution spectrometer based on a Fizeau interferometer designed to obtain line profiles with a resolution of 2 pm in the wavelength range 580 - 780 nm.

A detailed description of the proposed instruments may be found in Annex 2.

1.5 Mission Strategies

1.5.1 Continuity versus snapshot strategy

The necessity of continuous observations is essential in two respects.

A major progress in the study of the global oscillations has been made with the first continuous set of observations conducted from the South Pole by Grec et al. over 5 consecutive days. There the continuity is mandatory in order to eliminate potential causes of noise in the data and to allow the determination of other modes, in particular those which are associated with long periods. In addition, the need for a low Sun-satellite relative velocity precludes the use of the Space Shuttle for these observations.

With only a few snapshots on the intensity of the solar constant, such as those that might be offered by either balloons or Spacelab-borne instruments, the direct connection between the daily and weekly variations of the solar constant and the appearance or disappearance of sunspots, as evidenced, for example, by the ACRIM instrument on-board SMM, would not have been possible. In addition, the possible correlation between these variations and the spectral redistribution and also the direct correlation with the global oscillations will enable a separation to be made between the different mechanisms leading to solar luminosity variations, and will yield a continuous and accurate survey of the global properties of the Sun. Snapshot observations cannot be interpreted correctly without knowledge of short and intermediate term variations derived from continuous monitoring by means of satellites. In fact, both types of observation are needed to ensure reliable data on solar irradiance and its variations.

1.5.2 Absolute and relative radiometry strategy

The continuous monitoring of the integrated and spectral irradiance fluctuations with the precisions reported in Table 1.1, over more than six years is certainly not trivial and requires a very careful and systematic approach as well as the adherence to strict principles of operation which have never been applied simultaneously to past experiments of this kind. The difficulties are, however, well understood, and their solutions are identified. The goal is to achieve highly accurate absolute measurements and to follow their temporal variations. The obstacles are, on the one hand, the intrinsic limitations of the available absolute standard detectors and sources, and, on the other hand, the degradation of the photometric properties of the instruments once in orbit.

Tables 1.3 and 1.4 give the uncertainty of the presently available transfer and primary detectors and source standards from the National Bureau of Standards. The quoted uncertainty fixes the limits to the accuracy of absolute spectral irradiance measurements.

Table 1.3 : SPECTRAL IRRADIANCE STANDARDS

A. Spectral Irradiance Transfer Detector Standards

Detector	Wavelength Region (nm)	Uncertainty
VUV windowless diode	5-125	8-10%
VUV windowed diode	115-253.7	6-10%
UV-B diode	200-320	10%
silicon photovoltaic diode	257	5%
silicon photovoltaic diode	364	5%
silicon photovoltaic diode	420-700	2%
silicon photovoltaic diode	700-1150	5%

B. Spectral Irradiance High-Level Primary Detector Standards

Detector	Wavelength Region (nm)	Uncertainty
Elect.-calib.	257-2000	1%
pyroelectric	2000-14000	2%

NEP (1 sec) = 1 μW (air), 100 nW (vacuo)

Table 1.4 : SOURCE STANDARDS CURRENTLY AVAILABLE FROM THE U.S. NATIONAL BUREAU OF STANDARDS

A. Spectral Radiance Transfer Source Standards

Source	Wavelength Region (nm)	Uncertainty
argon mini-arc	114-140	10 %
argon mini-arc	140-350	5 %
deuterium lamp	165-350	10 %
tungsten strip lamp	225-2400	
tungsten strip lamp	at 225	2 %
tungsten strip lamp	at 650	0.7%
tungsten strip lamp	at 2400	0.6%

B. Spectral Irradiance Transfer Source Standards

Source	Wavelength Region (nm)	Uncertainty
deuterium lamp	200-350	6 %
mercury lamp	253.7	5 %
tungsten halogen lamp	250-1600	
tungsten halogen lamp	at 250	3 %
tungsten halogen lamp	at 555	1.2%
tungsten halogen lamp	at 1600	1.2%

In order to obtain the required accuracy over the lifetime of DISCO, we propose to:

1) continuously monitor the radiometric properties of the instruments using in-flight on-board calibration standards and techniques;

2) use periodic flights of balloon-, rocket- and Space Shuttle-borne instruments to obtain frequent accurate re-calibration of the spacecraft instruments.

This task will be eased if we succeed in regularly controlling the causes of degradation and in minimizing their consequences. To that effect, the spacecraft and the instruments should satisfy some design, integration and operation requirements, such as:

- the existence of a cold trap on the spacecraft and on each experiment individually,

- the installation of all instruments inside a tight container,

- the use of tight instruments filled with a dry inert gas,

- the use of the highest cleanliness class facilities during all phases of assembly, integration, test and calibration of both the spacecraft and the instruments,

- the obligation not to expose the instruments to sunlight until several weeks after lift-off.

In addition, the design of the instruments must be such as to minimize the number of potentially outgassing surfaces and elements, in particular by completely isolating the electronics from the optics, using tight containers and encapsulated wires and harnesses, and also to minimize the number of optical elements.

The spectrometers and radiometers at present envisaged, and which are described in detail in Annex 2, all have, without exception, on-board calibration sources or detectors and provide the possibility of regularly measuring the stability of their radiometric properties. The solar constant monitors also provide ways of measuring their possible degradation in flight. In addition, two different types of such instruments will measure the total irradiance, with three identical units of each type: one will be continuously exposed to solar light and the other two will be used only once a month for a short period of time, for periodic checks. The absolute re-calibration of the spacecraft instruments can be performed using balloons, rockets or the Space Shuttle. The instruments used for that purpose should keep the same physical characteristics throughout the mission, in order to maintain the highest repeatability and the best continuity in the observations.

For the near-ultraviolet and visible instruments (including the absolute radiometers), balloons provide an excellent opportunity for re-calibration and permit very accurate measurements. A precision of two parts per million is already achieved in solar flux variations using sun-photometers (Fröhlich, 1980). It is, therefore, envisaged to constitute a set of DISCO instruments to fly on balloons (a means that is readily accessible to European scientists). The Space Shuttle will, if possible, also be used.

The following instruments are already assembled in the so-called "Solar Package" intended to fly twice a year on Spacelab:

- an ultraviolet spectrometer
- a visible spectrometer
- a near-infrared spectrometer
- a far-UV spectrometer (SUSIM)
- a number of absolute radiometers.

In addition, these are also assembled in the SIMBA international project, which is at present under review in Belgium, France, Germany and Switzerland.

Between flights the instruments will be carefully compared and calibrated on the ground against absolute standards.

The various spectrometers and photometers will be calibrated by each investigator, and a cross-calibration will be made on the ground of these instruments in their spectral overlaps. A common absolute reference will also be used such as, for example, the NBS-SURF calibration facility.

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2. TECHNICAL ASSESSMENT

2.1 Mission Analysis

2.1.1 Selection of a Baseline Orbit

2.1.1.1 Requirements

The main requirements governing the choice of a preferred orbital configuration are as follows:

i) as the scientific objectives aim at continuous measurement of solar variability over a long period of time (say five to six years), quasi-continuous visibility of the sun is obviously required. Although some short eclipses might be acceptable, the ideal operational orbit should stay permanently in sunlight;

ii) the background noise due to particle flux must be minimised; therefore, the spacecraft should remain either below the radiation belt (e.g. at an altitude smaller than 500 km), or above it;

iii) the high-resolution spectrometer in the model payload requires a low radial velocity of the spacecraft with respect to the sun;

iv) the injection procedure into the final orbit shall preferably be compatible with a "standard" Ariane procedure, i.e. geostationary transfer orbit or sunsynchronous orbit; thus, the selection of a second passenger, e.g. an application spacecraft, will be eased;

v) in order to minimise the operational costs, use of only one ground station of the ESA S (or X) band shall be foreseen.

Three types of orbits were therefore identified during the assessment study as potential solutions and weighted against the above-mentioned criteria: sunsynchronous, geosynchronous and close to the Lagrangian libration points L1 and L2. Recently, the attention of the study team was drawn to a fourth type of orbit: Earth-like orbit (see section 2.1.1.4).

2.1.1.2 Sunsynchronous orbit

Sunsynchronous orbits (i.e. circular orbits, with an equatorial inclination close to 100°), whose plane precesses at a rate of about 1° per day, can remain in full sunlight during extended periods of time. However, when the altitude is low (e.g. 500 km), eclipses occur periodically (see for example the TD1-A satellite). Permanent sun visibility would need higher altitudes, inside the radiation belt. In addition, due to the inclination to the ecliptic plane, criterium iii) cannot be satisfactory met. Also contrary to criteria iv), there is at the present time no planned application satellite requiring a full sunlight orbit.

For these reasons, the sunsynchronous type of orbits is not considered as a preferred option.

2.1.1.3 Geosynchornous Orbits

A circular geostationary or geosynchronous orbit perfectly satisfies criteria iv) and v). However, it is well known that eclipse periods of maximum duration of about 72 minutes are unavoidable twice yearly; in addition, the background noise (criterium ii) may be high. But, most important, the relative velocity with respect to the sun reaches such large values (3 kms^{-1}) that the high resolution spectrometer cannot provide valid measurements.

Therefore, assuming in the model payload this last instrument, this type of orbit cannot be selected as the primary choice in the assessment study.

2.1.1.4 Orbits like Earth Orbit (Earth-orbits)

A spacecraft can be placed in the Earth-Moon barycentre orbit, either ahead or behind the Earth. In order to minimize the perturbation by the Earth-Moon system, the spacecraft has to be placed outside the sphere of influence of the Earth which has a radius of about 10^6 km. One main advantage of this orbit is that some problems of the orbits around L1 and L2 (see section 2.1.1.5), namely radio interference of the sun or penumbra are eliminated. However, the antenna system will be quite different of that in the L1 or L2 orbit. It appears that all five criteria listed in section 2.1.1.1 are perfectly or satisfactorily met.

It has not been possible during the assessment study to fully investigate the orbital mechanics of this configuration, nor the technical design. It will therefore be an important task of a phase-A study to reconsider this type of orbit. In the following sections, only orbits close to L1 or L2 are assumed, as they lead to a feasible (and already flown) solution.

2.1.1.5 Orbit close to Libration Points L1 and L2

An orbit close to the Lagrangian libration point L1 (between the Sun and the Earth, at a distance of about 0.01 AU from the Earth) has been successfully flown by the NASA ISEE-3 spacecraft. A similar point L2 exists, symetrical to L1 with respect to the Earth. For both, the injection, insertion and maintenance requirements are similar. Both obviously perfectly satisfy the important criterium i) (uninterrupted sun visibility). The radial velocity with respect to the sun is quite low (50 ms^{-1}) and adequately meets criterium iii). Criterium iv) is also covered, as injection to the Lagrangian orbit is feasible via a velocity increment at the perigee of a geostationary transfer orbit; criterium v) is satisfactorily met, as a single ground station will communicate with the spacecraft at least 8 hours per day.

In the present assessment study, both orbital configurations close to L1 or L2 are considered as baseline solution. The technical design in each case will slightly differ, and the final selection is left to the Phase A study.

2.1.2 Libration Point Orbits

The two libration points which come into consideration for stationing a solar observation satellite are the interior L1 and the exterior L2 point. Both lie on the line connecting Sun and Earth/Moon barycentre, each at a distance of about 1 500 000 km from the Earth (figure 2.1.1). DISCO cannot be placed exactly in these libration points, because in L1 the solar radio noise will interfere with the downlink telemetry and in L2 the spacecraft will be in the penumbra of the Earth, thus preventing the observation of the full solar disk.

There exist quasiperiodic orbits around both libration points L1 and L2. For small amplitudes the motions in the ecliptic and normal to the ecliptic are independent in the first approximation. The motion normal to the ecliptic is harmonic with a period of about 181 days (L1). The motion in the ecliptic is coupled and has an oscillatory and a divergent mode. If only the oscillatory mode is excited the period will be about 175 days (L1). Because of the different periods of the oscillation in and normal to the ecliptic, the spacecraft will describe a Lissajous-trajectory (figure 2.1.2).

In order to avoid excessive solar interference with the S-band downlink the apparent distance of the spacecraft from the sun must be at least 2° to 3.5°. The amplitudes in the y- and z-direction should therefore be at least 55 000 km to 92 000 km. (z is normal to the ecliptic plane, x is along the Earth-Sun line, and y perpendicular to x and z). By proper phasing the in-plane and out-of-plane motion and selecting the proper amplitudes the Lissajous orbit stays outside the exclusion zone for several years (for A_z = 200 000 km and A_y = 200 000 km about 4 years, for A_y = 500 000 km even 6.7 years)

Another way to avoid the interference zone are out-of-plane manoeuvres in order to synchronise the out-of-plane motion with the in-plane motion. With A_y = 200 000 km and A_z = 115 000 km the cost is about 20 m/s per year.

Another type of orbits that avoids the exclusion zone is a Halo orbit. For large amplitudes the basic frequencies are no longer independent and it is possible to find orbits with equal in-plane and out-of-plane frequencies. This requires large amplitudes in the y-direction, e.g. for A_z = 100 000 km we have A_y = 663 000 km.

From the point of view of telecommunications it is desirable to keep the amplitudes in the y and z-direction as small as possible. Since the spin axis of the spacecraft is pointing to the sun the line spacecraft-Earth has an offset which equals about the elongation of the spacecraft from the Sun. A fixed antenna should therefore have a large beam width. An amplitude of 100 000 km requires a total beam width of 7.6°. In Halo orbit the beam width must be about 63°.

Orbits around the exterior L2-point have a much smaller exclusion zone, since the penumbra of the Earth has a radius of only 13 000 km, so that

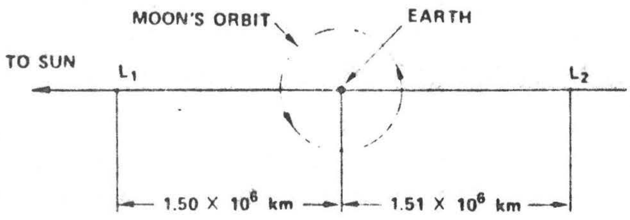


Figure 2.1.1: Sun-Earth co-linear libration points

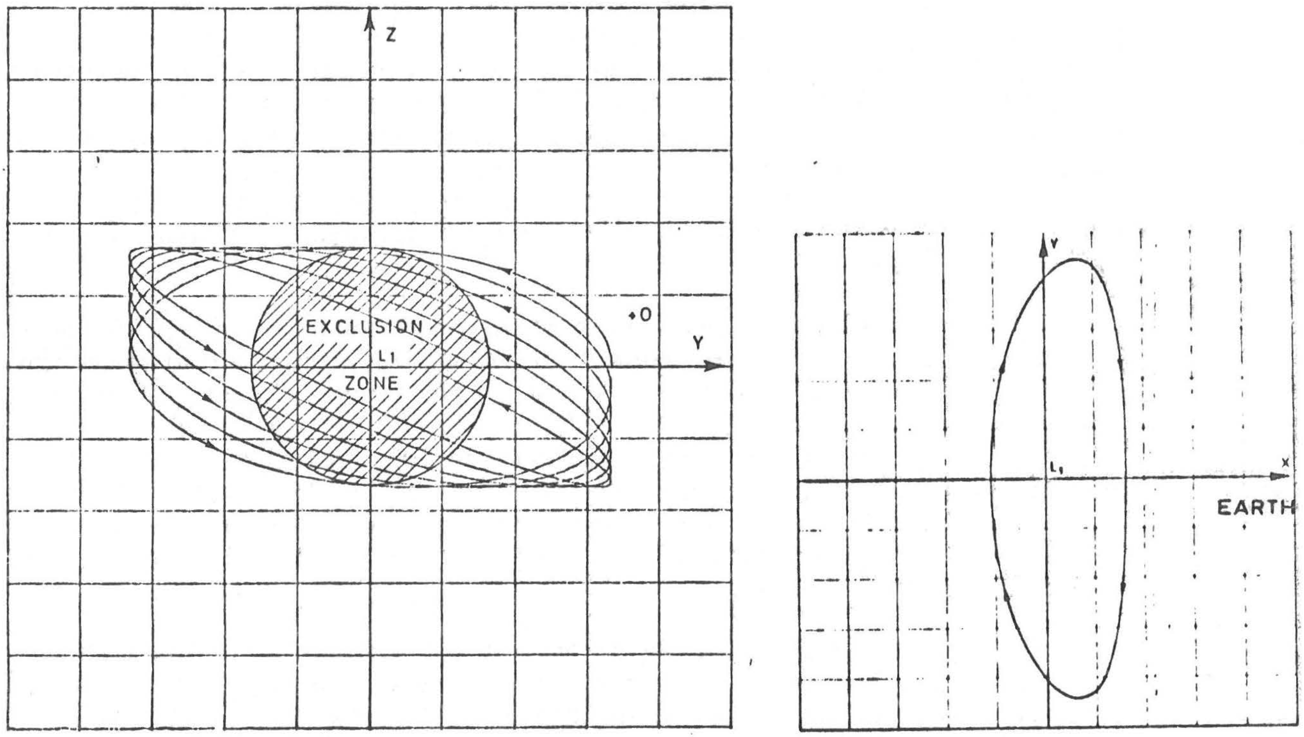


Figure 2.1.2: Typical lissajous trajectory in YZ-plan (normal to Earth-Sun line) and XY-plane (ecliptic plane).
(From R. Farquhar and D. Muhonen)

smaller amplitudes are required. However, the problem of straylight has to be investigated and depends mainly on the field of view of the instruments. This will define the required amplitudes.

2.1.3 Launch

DISCO can be launched by either Ariane 2 or Ariane 3 in a dual-launch configuration with a second passenger (see section 2.2.8). This will most probably be a geostationary (telecommunication) satellite. It is therefore assumed that both spacecraft will be injected into a geostationary transfer orbit (GTO).

2.1.4 Transfer Trajectories

Basically there are two types of transfer trajectories to the libration points L1 or L2 as shown in figure 2.1.3. A slow transfer requiring about 120 days and a fast transfer of about 35 days. Only the slow transfer will be considered, since it requires less ΔV for insertion in the final orbit. The launch energy C_3 is about -0.6 km^2/s^2 corresponding to an impulse at the perigee of the GTO lying in the ecliptic and properly oriented with respect to the Earth-Sun direction of about 750 m/s. Optimal alignment of the GTO line of apsides is obtained for a launch around midnight for a transfer to L1 and around noon for a transfer to L2. However, the GTO is in general inclined to the ecliptic by 15° to 31°, depending on the launch date. The exact values of the required velocity increments and the corresponding launch windows have not yet been determined, but it is estimated that 1000 m/s is sufficient to ensure reasonable launch windows. This 1000 m/s can be delivered by the GEOS Apogee Boost motor, assuming a total spacecraft mass before ABM firing of about 900 kg. If detailed computations during the Phase A study indicated that a velocity increment superior to 1000 m/s were necessary, a more powerful boost motor would have to be selected.

Mid-course manoeuvres to correct for injection errors and additional manoeuvres are estimated to require about 100 m/s. This will be delivered by the hydrazine system.

2.1.5 Operational Orbit - Injection and Maintenance

The velocity increment required to inject into the final operational orbit is a decreasing function of the amplitude of the desired orbit; a few m/s for amplitudes of about 10^6 km to 280 m/s for injection into the L_1 point itself. For an orbit with A_y = 100 000 km the insertion ΔV is only 100 m/s.

As the orbits are unstable they will eventually diverge from the specified nominal orbit and orbit maintenance manoeuvre will be required. The estimated velocity increment required for orbit maintenance is about 15 m/s per year.

The total estimated velocity increment required for a 6 year mission and for an amplitude of A_y = 200 000 km is about 400 m/s. This corresponds to about 90 kg of hydrazine for a total spacecraft mass of 570 kg.

2.1.6 Tracking

The tracking requirement, frequency and accuracy have to be evaluated. During Phase A-1, it is estimated that with S-band tracking the position error will be a few tenths of km and the velocity error a few mm/s.

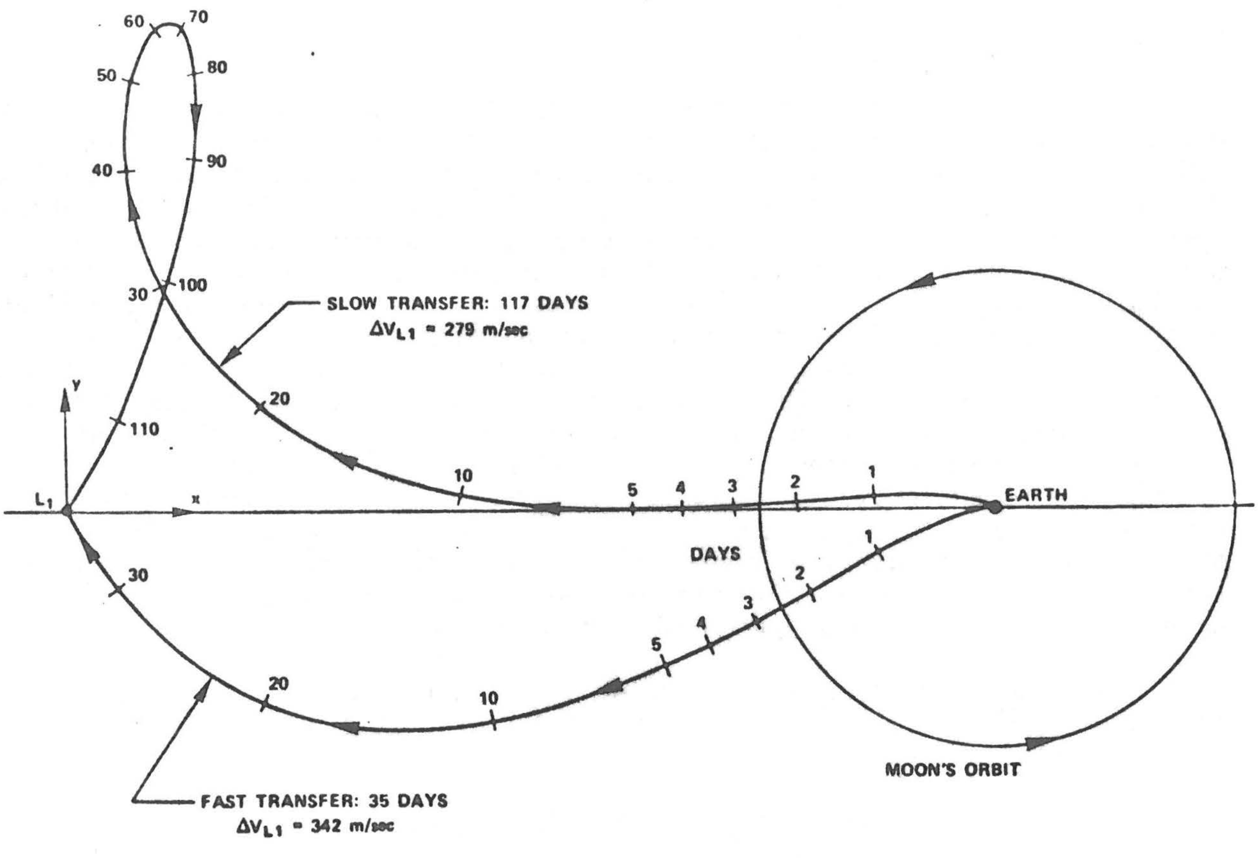


Figure 2.1.3: Typical transfer trajectories to the L_1 point in rotating system (From R. Farquhar and D. Muhonen)

2.2 System Description

2.2.1 Requirements

The main requirements which drive the technical design of the system and subsystems are as follows:

i) the baseline final orbit selected in this assessment study is close to the Lagrangian libration point L1 or L2;

ii) the spacecraft is to be launched by a vehicle of the Ariane family; the configuration and total initial mass shall be compatible with a dual SYLDA arrangement;

iii) the injection into the final orbit shall be compatible with a "standard" Ariane procedure; an intermediaire geostationary transfer orbit is therefore highly desirable, in order to ease the identification of a second passenger, e.g. an application satellite;

iv) the spacecraft is spinning and permanently pointing to the sun;

v) in order to minimise the operational cost, only one ground station of the ESA S- (or X)-band network shall be foreseen;

vi) the lifetime shall extend over 5 to 6 years; however, reduced operations may be agreed with the scientists during the last part of the life;

vii) an essential constraint is related with the need to ensure the required accuracy of the scientific instruments during the lifetime (see section 1.6). In particular:

- precautions shall be taken to minimise outgassing during design, integration and operations;
- a cold trap shall be provided on the spacecraft;
- the perigee boost motor shall be preferably ejectable.

The main characteristics of the model payload are indicated in section 1.5 and in Annex 2.

The DISCO spacecraft development, launching and operations proposed here is conceived as a pure European activity. During the course of the present study, it has been a constant concern to all involved to select the simplest possible technical options, to use essentially existing or proven technics and equipment with a view to minimise the total costs but still fully satisfying the scientific requirements.

2.2.2 Launch Configuration

The launch vehicle is to be selected in the Ariane family. In the time frame of interest, according to the current plans, Ariane 1 will no more be available, but Ariane 2, 3 and 4 will all be operational. As Ariane 4 is not yet an approved ESA project and has anyway much larger capabilities than required by DISCO, the selection is limited to Ariane 2 or 3. The alternative is further discussed in section 2.2.8.

In order to be compatible with a standard Ariane injection procedure in a SYLDA configuration (requirements ii) and iii) of section 2.2.1), the spacecraft will be first put into a geostationary transfer orbit. Insertion into the transfer orbit to the libration point will be obtained by delivering at perigee a velocity increment estimated to be smaller than 1000 ms^{-1}. Motors with solid or liquid propellant can be considered for that purpose.

A biliquid-motor of the SYMPHONIE/GALILEO type presents the interest of good flexibility for adjusting the velocity increment and high specific impulse. Also, due to its restartable capability, the same motor can be used for mid-course correction and insertion into the final orbit. Moreover, the attitude control subsystem can use the same propellants, provided low thrust nozzles are mounted. However, the difficult problem of possible dynamical instability due to motion of liquid in the tanks and, above all, the strong preference for an ejectable perigee boost motor (requirement vii) of section 2.2.1) lead the assessment team to select a solid motor.

The GEOS apogee boost motor appears to be quite satisfactory. Its main characteristics are as follows:

- diameter 684 mm
- overall length 1130 mm
- inert weight 36 kg
- maximum propellant weight 267 kg
- specific impulse 286 seconds

This motor fully loaded is able to deliver a velocity increment of some 1000 ms^{-1} to a total initial mass (including the motor) of about 900 Kg. The motor can be off-loaded if necessary. Its good reliability has been demonstrated in-flight.

2.2.3 Spacecraft Configuration and Structure

A preliminary lay-out of the DISCO spacecraft in the launching configuration is depicted on figure 2.2.1 (for the L2 libration point orbit).

The experimental payload and the various technical subsystems are accommodated inside a cylindrical structure of diameter 1.2 metre and height 0.8 metre. The scientific instruments will be installed in tight containers to improve the stability of the optics. The high gain S-band horn used for telecommunications during the operational phase is also mounted in this compartment. In the L1 libration point orbit, this horn will be mounted in a reverse position, looking towards the motor in the launching configuration.

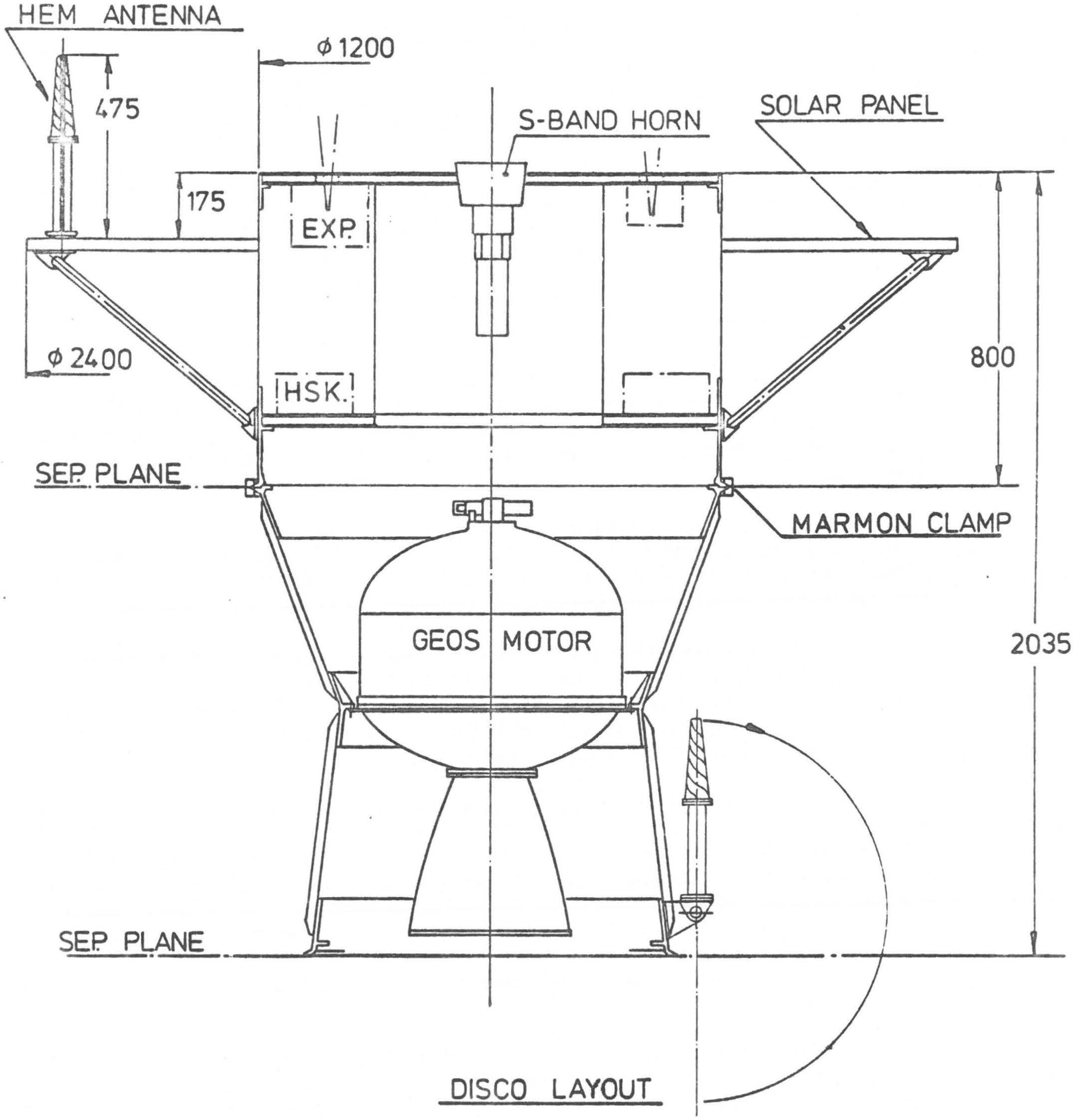

HEM ANTENNA
ϕ 1200
475
S-BAND HORN
SOLAR PANEL
175
EXP.
ϕ 2400
HSK.
800
SEP. PLANE
MARMON CLAMP
GEOS MOTOR
2035
SEP. PLANE
DISCO LAYOUT

FIG. 2.2.1.

The solar cell array is carried on a circular fixed platform of external diameter 2.4 m supported by struts. For reason of simplicity, deployable panels are avoided, the platform diameter being still compatible with a SYLDA arrangement. An hemispherical antenna is mounted at the edge of the solar array, and a second one, deployable, near the separation plane with Ariane. These antennae are used for the early mission phases.

The solid perigee boost motor is attached to the Ariane separation plane by a conical adaptor and a standard separation device; the motor holds the spacecraft by means of another conical adaptor. The separation of the motor from the spacecraft is obtained via a marmon clamp similar to the one used for EXOSAT.

2.2.4 Thermal Control

During the geostationary transfer orbit, the motor adaptors must be covered with thermal blankets to ensure minimum heat leak. A thermal shield must cover the nozzle; this shield will be blown off at ignition. Due to the unstable dynamical configuration, this phase will be anyway of very short duration.

During the operational phase, in the final orbit close to a libration point, the thermal environment will be very stable: no eclipse, fixed solar panels continuously normal to the sun direction. In the transfer orbit to the libration point, the thermal environment will be very similar.

The proposed thermal control design is purely passive, with the possible exception of some heaters for the attitude control thrusters, for which about 8 watts are provided. The upper and lower surfaces of the spacecraft will be covered with multilayer insulation material; the lateral cylindrical side will be used as radiator.

The average internally dissipated power is estimated as 215 watts. There is sufficient surface area for the lateral radiator to dissipate 317 watts. continuously at a radiator temperature of 15°C (equipment temperature 25°C). This leaves about 100 watts for absorption of solar flux through the experiment fields of view. The battery will be heated separately by insulating it from the spacecraft as is done for ECS or other communications satellites.

The maximum solar panel temperature is estimated as 80°C (back side panels black painted).

The thermal blanket at the bottom of the spacecraft is continuously exposed to deep space in the operational phase. The outside layer can be expected to reach a temperature of - 150°C and can therefore act as a thermal cold trap.

2.2.5 Power Subsystem

The DISCO mission has some areas which differ from previous scientific mission power subsystems. The most obvious area is the annular shape of the solar array which makes conventional stringing of the solar cells impossible.

As a total area of more than 3 square meters is available for placing the solar cells, it is considered that the present spacecraft power requirements of 265 watts (peak) can be met; however, further studies should be made to to optimise the cell lay-out and establish the actual available power.

The requirements for a five year operational life with peak power loads of 100 watts for approximately half an hour to one hour per week imposes Nickel-Caldium or Nickel-Hydrogen batteries. Thus the satellite should not have any magnetic cleanliness requirements. The Depth of Discharge for the batteries can be about 60% as the number of cycles is small. Recharging of the battery should not be a problem as power will be available during non-operational periods of the RF link or of some of the experiments. No excess solar array power is thus allocated for battery charging.

A preliminary weight breakdown for the mission is given in table 2.2.1.

TABLE 2.2.1

UNIT	MASS/UNIT	UNITS/S/C	TOTAL MASS
Solar Array	20 kg	1	20 kg
Batteries 10 AH (16 cells)	≃ 8 kg	2	16 kg
Power Control Unit	4 kg	1	4 kg
Battery Discharge Regulator	2 kg	2	4 kg
Battery Charge Regulator	1 kg	2	2 kg
Power Distribution Unit	7 kg	1	7 kg
Pyrotechnic Unit	3.3 kg	1	3.3 kg
Data Handling Converter	2.2 kg	1	2.2 kg
AOCS Converter	2 kg	1	2 kg
		TOTAL	60.5

The battery weight could be reduced by about 20% by using Nickel-Hydrogen cells

2.2.6 Attitude and Orbit Control

2.2.6.1 Requirements

i) Absolute pointing error of payload axis (this is also the spin axis) less than 0.5°. This is referred to the sun.

ii) During some periods, of the order of 30 minutes, the absolute pointing error should not exceed 1 arcminute. This is to permit some imaging of the solar surface.

iii) Relative pointing error is to be analyzed in detail, The latest statements indicated a desire for not more than a few arc-minutes over an interval of 1 hour.

iv) The spin rate should be rather low, e.g. 5 rpm.

v) Baseline orbits are controlled orbits around the libration points L1 (between sun-earth) or L2 (beyond earth as seen from sun).

vi) Lifetime of 5 to 6 years.

2.2.6.2 Preliminary Baseline

i) Principal attitude sensors:

- coarse sun sensor for sun acquisition
- fine sun sensor for operational sun pointing of the spin axis (a two-axis sensor)
- a star scanner to provide a phase reference pulse in each revolution. This can be a single slit scanner. If a V-slit scanner (or equivalent) is used redundant or improved attitude information can be obtained. This scanner can also be used in transfer orbits
- sun aspect sensor to be used in transfer orbits
- integrated accelerometer for orbit control
- after separation from the Ariane third stage, the assembly spacecraft-perigee boost motor is probably highly dynamically unstable. Therefore, an active nutation damper (fully redundant) based on an accelerometer is foreseen. This device has been successfully flight proven in Meteosat and is also implemented on Exosat.

ii) Actuation

The attitude and orbit will be controlled by hydrazine thrusters (8).

A total mass of 89 kg of hydrazine has been included; this will provide the following impulses:

- mid-course corrections in the transfer orbit to the libration point; estimated value: 100 ms^{-1}
- insertion into the orbit close to the libration point; estimated value 100 to 200 ms^{-1}
- orbit maintenance, estimated 15 ms^{-1} per year (i.e. 90 ms^{-1} for a lifetime of 6 years)
- attitude control; in particular, change of spin axis attitude by 1° per day to follow the sun

2.2.6.3 Budget estimates

i) <u>Mass</u>:

attitude measurement	3.7 kg
attitude control electronics	7 kg
reaction control (without fuel and tanks)	8.5 kg
passive dampers	1.5 kg
hydrazine fuel	89.0 kg
hydrazine container	12.5 kg
TOTAL	122.2 kg

ii) <u>Average power</u>

attitude measurement	3 W
attitude control electronics	4

These values are of regulated voltage, excluding the reaction control system. Possible tank heating is also excluded. For the thruster catalyst heating, unregulated power of 2W per thruster can be expected during long periods, typically for a set of 4 thrusters, i.e. 8 watts.

2.2.7 Telecommunications

2.2.7.1 Antennae

In the interest of economy to avoid conversion of a ground station to X-band, a pure S-band telecommunication subsystem has been selected.

The antennae set includes an omni-directional assembly used mainly during the transfer orbits and a high gain directional antenna used during the operational phase.

The omni-directional assembly comprises two hemispherical antennae, with a minimum gain of -6 dBi; each is essentially the same as in ISPM and EXOSAT; mass of each is about 200 g.

The high gain antenna is a 1.35 λ horn fed by a septum polarizer, of a mass of 1.5 kg. For the L1 orbit, this antenna is mounted on the back of the spacecraft (motor side) and gives a coverage of ± 25° with a gain of 6 dBi minimum. For the L2 orbit, it is mounted on the front of the spacecraft (figure 2.2.1) and gives a coverage of ± 5° with a gain of 9 dBi minimum.

2.2.7.2 RF link

Preliminary RF link computations have been carried out with the following assumptions. The ESA 15 m station parameters have been taken from figures supplied for GIOTTO, but the uplink power in the operational phase (i.e. through the horn) has been lowered to 500 watts, this being a known constraint for the use of the Odenwald station. A fairly high uplink bit rate of 120 Bps has been chosen together with a housekeeping telemetry rate of 150 Bps. Standard ESA ranging has been used in the budget. It has been assumed that ranging operations will be unfrequent in the operational phase and conducted only with housekeeping telemetry. By its nature, as seen from the centre of the Earth, the orbit is one of almost constant range and it is not clear whether Earth-based measurements will be very useful in reconstituting the trajectory in the operational phase. The main results of the computation can be summarized as follow:

In the preoperational phase, using the hemispherical antennae and Villafranca or Carnarvon as ground stations with a 78 dBW transmitter, there is no problem with telecommand, but the telemetry and ESA standard ranging show a negative budget.Several possibilities to improve the telemetry situation exist (add Reed Solomon coding, restrict the view angle, increase the transmitter power). For ranging, improved systems required by GIOTTO will have to be used for DISCO.

In the operational phase, using Odenwald as ground station, there are no problems even using the standard ESA ranging; 3 bKps can be transmitted with ample margin (3.8 dB).

2.2.7.3 Budgets

i) The total mass of the telecommunication subsystem is estimated as about 13 kg.

ii) The power from the main-bus during telemetry transmission in the operational phase is estimated as about 38 watts.

2.2.8 Data Handling

2.2.8.1 Requirements

The analysis assumes that a single ESA ground station will be used for data recovery and telecommands.

Apart from the normal functions of telemetry and telecommand management of the payload and spacecraft subsystems, the following mission specific requirements are identified:

i) Capability of a low bit rate (approximately 100 to 200 Bps) housekeeping telemetry transmission via the omni-antenna on-board. This is required during the transfer and the cruise phase of the mission.

ii) Capability to store data (payload and the spacecraft summary status, appropriately labelled) when ground link is not available, on the average 16 hours per day. Proposed buffer store size is 16 Mbits which will allow:

- up to 225 Bps continuous storage of payload data
- and up to 50 Bps of synchronization and spacecraft data.

iii) Capability to store command sequences up-linked during ground station pass to be executed during the blind phase of the orbit. This facility is required to pre-programme payload operations profile, switch redundant units, maintain required attitude, etc.

iv) Capability to transmit up to 3 kBits per second of data during the ground station pass. This will consist of approximately 500 Bps of stored data, time multiplexed with the real time payload and spacecraft telemetry.

2.2.8.2 Subsystem Configuration

The proposed data handling subsystem will be derived from the standard ESA OBDH (On-Board Data Handling) configuration, sized to the mission requirements. The estimated mass and power consumption are 15.5 kgs and 12.5 watts respectively which includes a 16 Mbit buffer store.

The buffer store estimate is based on 16 Kbit C-MOS chip technology.

2.2.9 Mass Budget

The preliminary mass budget of the spacecraft can be established as follows:

Experiments	150 kg
Structure	60 kg
Thermal	15 kg
AOCS	122.2 kg
Power	60.5 kg
RF subsystem	13 kg
Data Handling	15.5 kg
Harness	40
Sub-total	476.2 kg
Margin (20%)	95.2 kg
TOTAL MASS IN CRUISE ORBIT	571.4 kg
Motor inert mass	36 kg
Propellant	267 kg
Attachment structure	30 kg
Sub-total	333 kg
TOTAL MASS AT LAUNCH	904.4 kg

For a dual launch in the SYLDA configuration, the mass available in geostationary transfer orbit for a second passenger can be now evaluated for Ariane 2 and 3.

	Ariane 2	Ariane 3
Launcher capability	2065 kg	2470 kg
SYLDA (4400) mass	190 kg	190 kg
DISCO mass	904 kg	904 kg
Available for second passenger	971 kg	1276 kg

It is obviously premature to try to identify at the present time a possible second passenger to fly with DISCO. However, the preceding figures show that several types of application/telecommunications spacecraft can be found, either with Ariane 2 or Ariane 3.

2.3 Operations and Ground Support

2.3.1 Control centre and ground stations

The concept for controlling DISCO from launch until the end of the six years mission at libration point 1 or 2 is based upon the use of the ESA Control Centre at Darmstadt (ESOC/OCC) which is supported by selected ground stations meeting the requirements of the mission phases. The OCC has to fulfil two essential control functions.

a) ensure that data recovery requirements are met;

b) ensure that data quality requirements are met.

Both tasks necessitate control of satellite (i.e. spacecraft and payload) and ground facilities operations in a cost effective and reliable manner. For this purpose the OCC will be the central decision making element in the control loop for mission planning and real time control. Ground stations act under OCC direction as remote terminals for data acquisition, command uplink and tracking. The OCC has also to provide through direct interfaces to scientific institutes pre-processed payload data in accordance to their requirements.

During the Launch and EARLY ORBIT Phase (LEOP), the ESA LEOP network comprising the following stations will be used:

- KOUROU	(11m antenna)	Guyana (F)
- MALINDI	(10m antenna)	E. Africa (I)
- CARNARVON	(15m antenna)	Australia

These stations, assumed compatible with the S-Band frequencies of the satellite, will support Telemetry, Tracking and Command (TT&C). Their usage will be scheduled in order to ensure proper OCC to spacecraft contacts during all mission critical operations.

During Cruise and Mission Implementation Phase only one of the following stations will be selected for regular TT&C support during approx. 8 hrs/day:

- WEILHEIM	(30m antenna)	Germany
- ODENWALD	(15m antenna)	Germany
- VILLAFRANCA	(15m antenna)	Spain

For the purpose of this study the principal ground station will be either the ODENWALD or VILLAFRANCA. It is assumed that the satellites transmitters will use S-Band frequencies and will be designed in order to allow acquisition of a data rate of 3 kbps over a distance of 1.5×10^6 km with a 15m antenna.

2.3.2 Operations

The mission can be broken down into four phases:

a) Launch and Early Orbit Phase

During this phase the satellite will be launched from the CSG launch complex at KOUROU and injected into an elliptical transfer orbit from which it will finally be transferred into the cruise phase trajectory. The latter will be achieved by using a spacecraft on-board ejectable solid motor, acting as a fourth stage of the launch vehicle. Thus the operations comprise activities between first ground station contact after launch and completion of cruise phase injection. The overall objective is to implement all planned operations requiring ground intervention in a reliable manner (minimising risk) and to safeguard the satellite and the mission such that successful achievement of cruise phase trajectory is guaranteed. Tracking data will also be provided by stations of the ESA LEOP network.

The following activities will be undertaken from the OCC:

- satellite acquisition and determination of spacecraft status - initialisation of onboard subsystems;
- initial determination of achieved transfer orbit parameters;
- analysis of spacecraft subsystems performance;
- determination of achieved attitude;
- accurate orbit determination and optimisation of boost motor (BM) firing for cruise orbit injection;
- attitude manoeuvre to optimal BM firing direction;
- BM firing operations and injection into cruise phase orbit.

Additional operations may become necessary should contingencies arise. These contingencies will be identified before launch readiness and backup operations will be prepared accordingly. Throughout this phase the spacecraft will be controlled from the OCC Main Control Room (MCR).

b) Cruise Phase

The satellite will be monitored during station visibility each day throughout this period (i.e. for about 8 hours/day). Initial tasks controlled from the OCC are satellite commissioning activities. In addition some of the experiments may be checked out and activated to allow a certain level of cruise science to be undertaken during the three to four months the satellite will take to reach the Libration point. Mid course correction manoeuvres will be carried out to accurately set the satellite's trajectory for insertion into orbit around L1 or L2.

During this period the satellite will mainly be monitored and controlled from the DISCO Dedicated Control Room (DCR) at ESOC. Mission critical operations such as mid course correction and Libration insertion manoeuvres will however be controlled from the MCR at ESOC.

During the early part of the cruise phase a high density of tracking data will be required to compute the cruise trajectory. Range and Doppler data will be acquired by two ESA stations for this purpose (Carnarvon and one Northern hemisphere ESA station).

c) Libration Oribt Insertion

During this phase the satellite will be injected into orbit around either L1 or L2. For this purpose on-board hydrazine thrusters (activated by ground command) will be used. The operation will be initiated from the MCR at ESOC.

d) Mission Operations

The orbital operations of DISCO will start when all the payload sub-systems have been checked out subsequent to their initial activation. This will be followed by the mission proper which will last for 6 years. During this period the satellite operations will be controlled from the DISCO DCR at ESOC. Data will be acquired from the Villafranca or Odenwald ground station for about 8 hours each day. The ground stations (e.g. Villafranca and Carnarvon) will be available to provide range and Doppler data for orbit determination.

2.3.3 Data Processing

All data processing operations for spacecraft and payload control will be undertaken at ESOC using the Multi Satellite Support System (MSSS) computer complex and its associated software. This facility will provide real time and near real time analysis of spacecraft and payload data as well as all software for command control (scheduling, command, initiation and verification). The MSSS will provide possibilities for manual, scheduled and automatic commanding. Flight Dynamics computations such as orbit and attitude determination, manoeuvre support and the generation of some information for the selection of the DISCO observation programme will also be undertaken by the MSSS.

The Payload data required by the institutes will be processed at ESOC by an off-line computer to a level compatible with the 'institutes' ability to handle such data. No support for the scientific analysis of the data other than that required to operate the mission will be undertaken at ESOC. Auxiliary data such as orbit ephemeris, attitude data etc. will be provided to the institutes either on separate tapes or merged with the scientific data. The off-line computer will also be used for mission analysis tasks such as the computation of launch windows.

3. MANAGEMENT AND SCHEDULE

3.1 Science Management

Following mission approval, a Call for Experiment Proposals will be issued and instruments will be selected for flight by the usual competitive procedure. Each instrument will be funded nationally and will be developed under the responsibility of a Principal Investigator who will constitute the point of contact for the ESA project team. A project scientist appointed by ESA will coordinate the work of the Principal Investigators with regard to overall optimisation of the mission.

Annotated raw data from his/her instrument will be made available by ESA to each Principal Investigator. It is expected that the Principal Investigators will agree upon a scheme for exchange of data among themselves.

3.2 Technical Management

Subject to approval by the relevant Committees, it is proposed to conduct the future development phases by means of industrial contracts awarded after open competition.

During the Phase A study, the mission will be subjected to a rigorous analysis, leading to a full scientific and technical description of the overall system and to a detailed evaluation of the programmatic and financial elements.

It is proposed that procurement of the spacecraft be managed in the usual manner, with Phase B study and Phases C/D industrial procurement contracts funded and placed by ESA. The scientific instruments would then be nationally funded and delivered to ESA by specified dates. Responsibility for monitoring the industrial contract and provision of liaison between the contractor and instrument procurements groups would lie with the ESA project team.

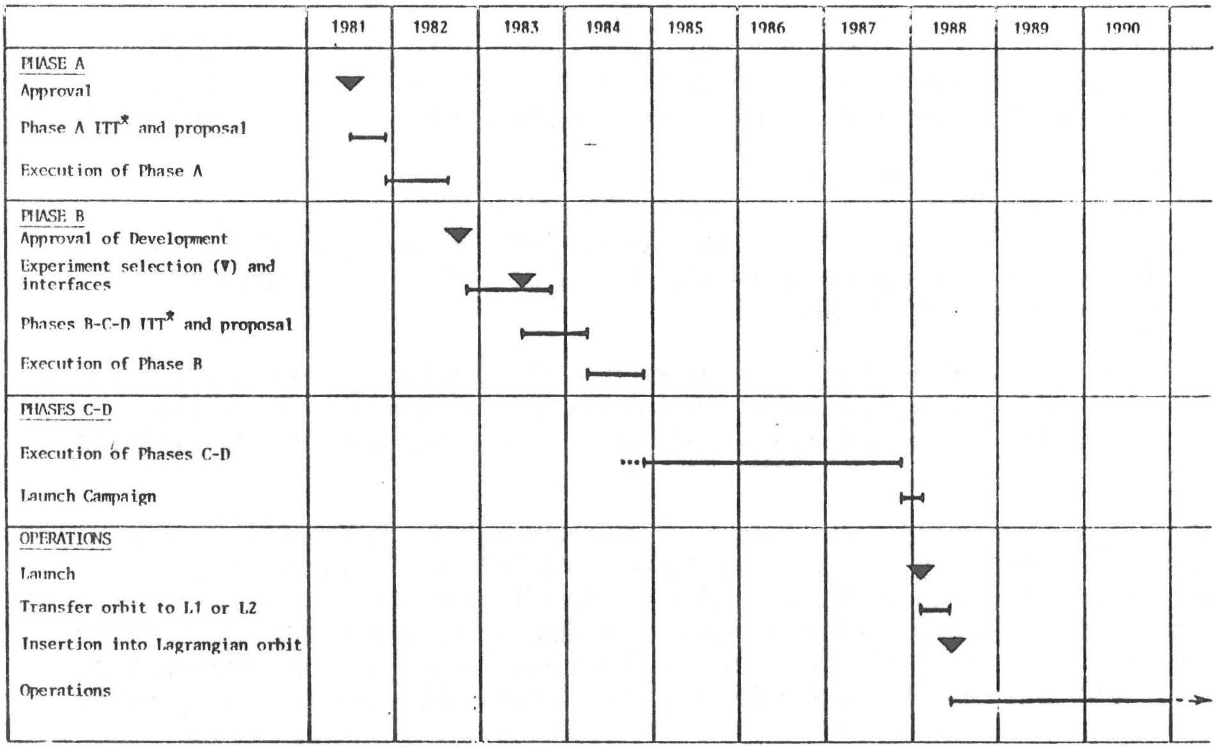
The contractor for Phases B-C-D will be responsible for the following activities:

- to assist ESA in mission analysis and system specification
- to develop and qualify the spacecraft system and subsystem
- to assist ESA in specification of experiment interfaces and acceptance of experiment hardware
- to integrate experiments in the spacecraft system and to perform system tests
- to deliver a fully tested spacecraft flight system
- to provide launch assistance and operations support.

3.3 Development Schedule

A preliminary development schedule is given in figure 3.1.

The selection of the real scientific instruments is made before the start of the Invitation to Tender for Phases B-C-D. The duration of the development Phases B-C-D is about 36 months. The spacecraft launching can occur at the beginning of 1988.



* ITT: Invitation to Tender

Figure 3.1: DISCO Programme Schedule

ANNEX 1

OTHER PROGRAMMES AND PROJECTS

The need for measurements of solar irradiance and its variability has been recognized by several groups in Europe and the United States. Related programmes and projects in this field are listed below.

I. SHORT MISSIONS

A. Solar Irradiance Module for Spacelab (SIMS)

This project was initiated by NASA and is based on the use of the Space Shuttle.

In response to the last Announcement of Opportunity made by NASA, several instruments to measure the solar irradiance were selected.

This mission has been defined as follows:

1. Four solar irradiance instruments are considered:

1.1 Solar ultraviolet spectral irradiance monitor

1.2 Solar spectrum from 180 to 3200 nm

1.3 Active cavity radiometers

1.4 Solar constant

Two types of instrument are devoted to the solar constant measurements (1.3 and 1.4), and two others cover the solar spectrum from 120 to 3200 nm, with an overlapping region.

2. The above instruments are accommodated in such a way that this payload will be as much as possible independent of the Shuttle and/or Spacelab systems, in order to be flown on various missions. In view of this, the payload is placed on a solar pointing platform.

3. The four instruments will be compared and calibrated against the same sources before and after flights, in particular with the NBS facilities.

4. Two flights per year during 10 years is the number retained for the mission.

5. The mission has to be considered as a calibration mission of solar instruments placed on board other orbiters.

The groups involved in the SIMS mission are: JPL (USA), NRL (USA), IRM (B), CNRS (F), IAS (B), Hamburg Observatory (D), Heidelberg University (D), PMOD (CH), SSD (ESA).

B. Solar Irradiance Monitor from Balloons (SIMBA)

The payload is carried by a stratospheric balloon at an altitude of 41 km and can be flown several times per year avoiding the specific problems of space vehicles. Due to the atmospheric absorption, the UV part is not correctly covered. Nevertheless, the mission appears as a significant complement to the SIMS mission and permits accurate calibration at wavelengths greater than 300 nm.

The payload is constituted as follows:

- Photometers } including in-flight calibration devices
- Spectrometer }
- absolute radiometer

This mission involves the following groups: Heidelberg University (D), Hamburg University (D), IAS (B), IRM (B), CNRS (F), PMOD (CH), Geneva Observatory (CH).

C. Tethered Balloon at South Pole

A resonance cell, similar to the one described in the present document, is being studied by CNES (F). It would be operated from a tethered balloon above the tropopause at the geographic South Pole (3 km above the ground). This would permit about two months of continuous observation. The status of this proposal is in the preliminary stage.

D. Solar Cycle and Dynamics Mission (SCADM)

We are aware of the existence of the SCADM programme (NASA Report SCADM No. 3). However, this programme does not appear in the list of future NASA programmes identified in the NASA "Report on Active and Planned Spacecraft and Experiments" (National Space Science Data Center (NSSDC), August 1980).

II. LONG MISSIONS

A. Upper Atmosphere Research Satellite (UARS)

This mission is mainly devoted to the study of the atmosphere from 8 km to 120 km and requires temperature, composition and wind measurements. These quantities are to be used in selfconsistent atmospheric models. As photodissociation and absorption are two significant processes acting in the Sun-Atmosphere system, the solar output as a function of wavelength is required. Consequently, two instruments are foreseen on board UARS-1 and UARS-2, having the following characteristics:

- wavelength range 120 - 400 nm
- band-passes 0.15 and 5 nm
- accuracy 6% - 10%,

and using different methods of inflight calibration: Deuterium lamp or stars.

The two instruments will be calibrated against the NBS facilities.

The groups involved in the solar measurements are: NRL (USA) and Colorado University (USA).

B. Solar Mesosphere Explorer (SME)

This mission is to be launched at the end of 1981.

The wavelength range is 160 to 310 nm and Lyman-alpha; the resolution is 1.5 nm.

The experiment is conducted by Colorado University (USA).

C. San Marco

The mission is to be launched at the end of 1981.

The wavelength range is 20 to 700 nm; the resolution is 0.7 to 4 nm.

The group involved is the Institute for Space Physics (D).

D. NOAA-F and NOAA-G

These two missions will be launched, respectively, in April 1983 and April 1985.

They will conduct total irradiance and UV (160-400 nm) measurements.

The groups involved are NASA/LARC (USA) and NOAA (USA).

E. Venera Halley Probe

Interferometric measurements of the global solar oscillations are planned on board this Soviet mission to Halley's comet. No contemporary measurements of irradiance are at present planned on this mission.

F. Solar Internal Dynamics Mission

This is a NASA mission whose broad lines as described in the current NASA documentation are, indeed, in the spirit of the DISCO proposal, with some emphasis on the dynamo problems.

The mission is proposed for the late 1980s; the NASA working group will be set up only in 1982. The status of the mission definition is at the moment in a very preliminary stage.

ANNEX 2

INSTRUMENT DESCRIPTIONS

This Annex contains descriptions of the instruments included in the DISCO model payload.

The information was supplied by the scientists named at the head of each section.

ANNEX 2A

Solar Irradiance Monitors

C. Fröhlich (PMO)
World Radiation Center - Physikalisch-Meteorologisches Observatorium
Davos (CH)

and

D. Crommelynck (CROM)
Institut Royal Météorologique de Belgique
Brussels (B)

For the sake of data quality confidence, it is important that the total solar irradiance be monitored by at least two independently designed absolute pyrheliometers. These should be characterized by direct laboratory measurements. Their design should also be such that, in flight, some performance tests can be made. Two types of instruments responding to these objectives are:

a) the PMO-6 type radiometer developped by the World Radiation Center Davos (CH) used on stratospheric balloon flights, on sounding rockets and in the future on the US "Solar Package".

b) the CROM type radiometer developped by the Royal Meteorological Institute of Belgium which will be flown on Spacelab-1 and latter on the US "Solar Package".

Both radiometers operate in the so called active mode which means that an automatic control system matches the energy received from the sun in the cavity by controlled electrical power dissipation.

In the PMO radiometer (figure 2A) the cavity has an inverted cone shaped bottom, painted with specular black paint (absorptance 0.998). The servo system maintains the temperature difference between the cavity and a heat sink constant with an electrically calibrated heat flux transducer using resistance thermometers as sensors. To control the degradation of the absorptance, the light reflected by the cavity is measured by a silicon cell.

In the CROM radiometers there are two parallel identical cavities. The cavities are cylindrical with flat bottom, painted with diffusing black paint (absorptance 0.99880 ± 0.00005). The servo-system maintains in equilibrium the heat flux measured by two thermoelectric heat flux sensors located between the cavities and the heat sink. Each of the two cavities can be operated as measuring radiometer by opening and closing the shutter in front of it. While one cavity is operated actively the other acts as reference.

In both instuments, the solar irradiance is calculated by substracting the electrical power supplied to a cavity illuminated by the Sun from that supplied to the same cavity when it is in the shade (shutter in front of the cavity open and closed, respectively). The solar radiation flux can be calculated as:

PMO 6 ABSOLUTE RADIOMETER

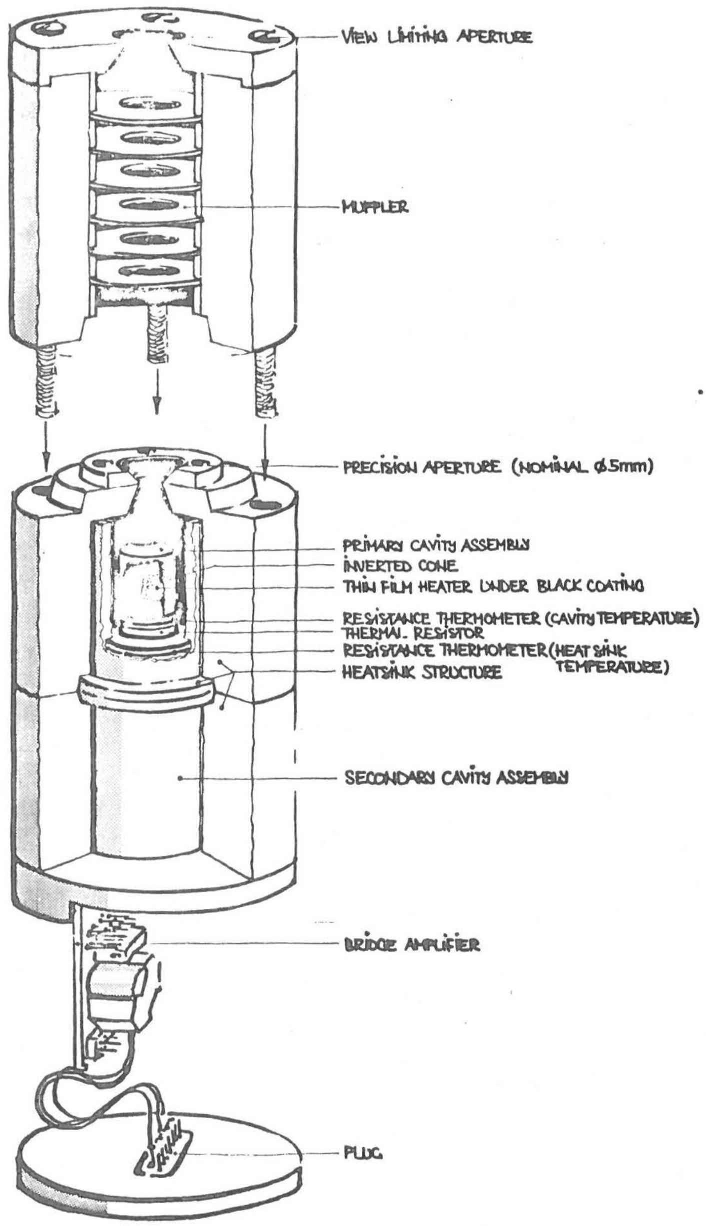


Figure 2A

ANNEX 2B

Sunphotometer (visible)

R.W. Brusa and C. Fröhlich
World Radiation Center - Physikalisch-Meteorologisches Observatorium
Davos (CH)

Sunphotometers measuring the solar spectral irradiance at several fixed wavelengths with moderate resolution in a range from 250 to 1000 nm are used for the long term continuous monitoring of the solar variability and its spectral dependence.

The design of the sunphotometer is based on the instruments developed for the PMOD (Physikalisch Meteorologisches Observatorium Davos) Solar constant experiment successfully flown on balloons and rockets.

The basic design is very simple: a silicon photodiode is used as detector and views the sun through an interference filter (3-4 period dielectric filter) and a view limiting tube (figure 2B). Three such detector-filter combinations are comprised in one sensor head, which is temperature stabilized at about 40°C with an electrical heater. As this heater is on during the whole degassing phase of the satellite, the filter and detector surfaces will be kept clean. The three sunphotometers in one head are basically identical. One is used continuously and the two spare ones are exposed to the sun only about once a month and are used to detect eventual degradation of the continuously exposed one. Further to this check by redundancy, the sunphotometers at 820 nm are periodically calibrated during the mission at a single wavelength with a cw-laser diode, which can be positioned either in front of one of the sunphotometers or of one of the PMO-6 absolute radiometers, in order to determine the radiance from the diode.

The ground calibration of the sunphotometers is done by one of the following methods, depending on wavelength:

- synchrotron radiation
- dye laser radiation, which is calibrated with absolute radiometers
- black body radiation

The absolute accuracy, which will be achieved, ranges from 1 to 5% and is individually given in the following table, together with the precision.

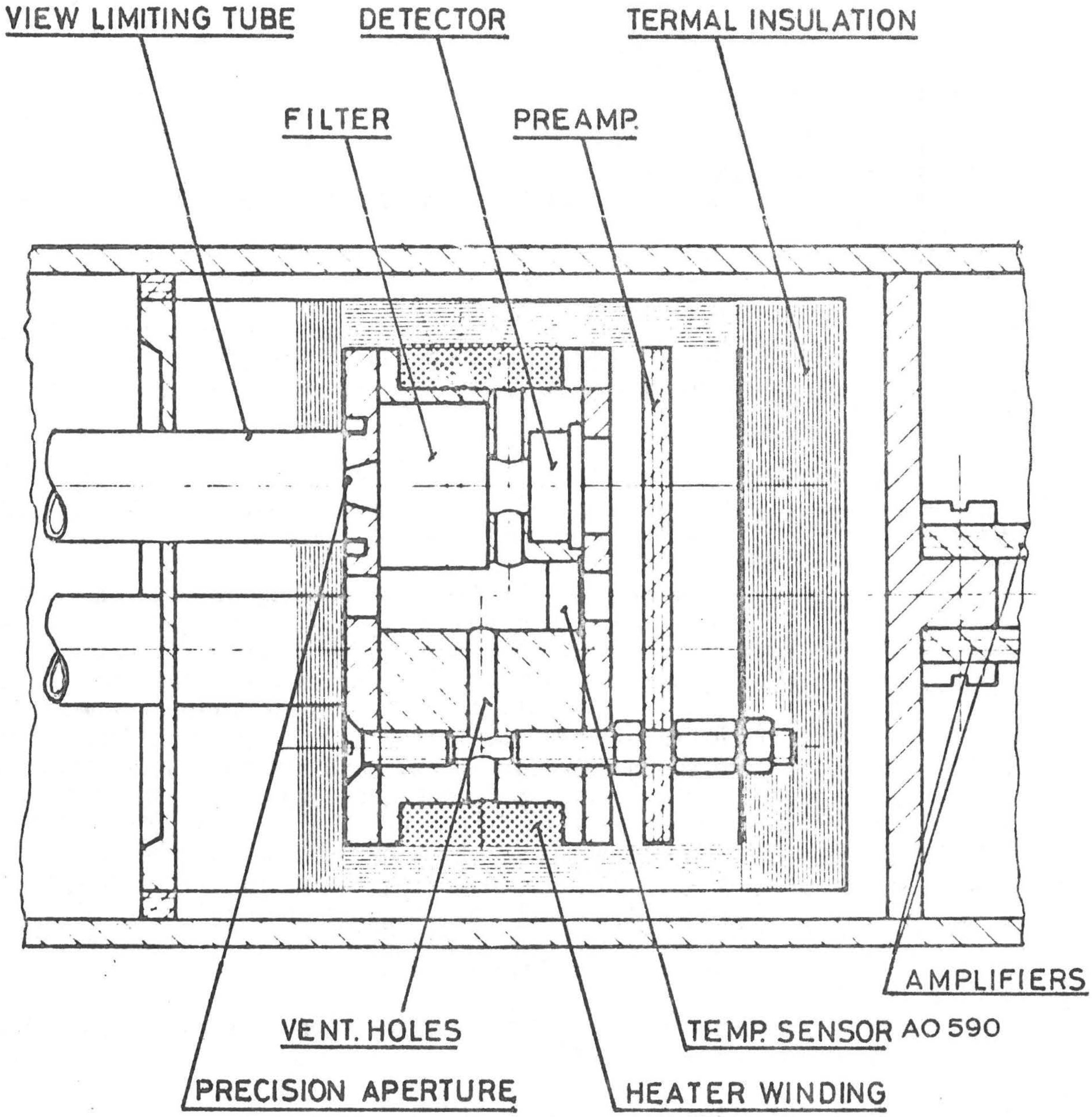


Figure 2B: Schematic drawing of the detector assembly of a triple-PMOD-Sunphotometer

Center Wavelength (nm)	Bandwidth (nm)	Calibration accuracy (% of signal)	Precision (resolution, stability) (ppm of signal) (1)	(2)
250	10	5	500	25
320	10	3	200	10
500	5	1	50	3
675	5	1	50	3
820	5	1	50	3
1000	10	2	100	5

Specifications of the PMOD-sunphotometers

(1) single measurement
(2) DC are AC signal sensitivity with a 3 hour integration time

For a rough imaging of the sun using the spin of the satellite lenses can be put in front of the sunphotometers, so that the total field of view is reduced to about 15 arcmin and the view axes is offset by about 8 arcmin. In this way the centre of the field of view will perform a circle around the centre of the sun, as the spin axis hits the centre of the sun during these phases.

ANNEX 2C

The 160-210 nm Photometers

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The concept of the instruments is shown on figure 2C. It is kept purposely simple with the main concern of avoiding contamination and, in case this occurs, to be able to measure it. This imposes some design constraints that we now describe.

Each photometer is made of two channels. The first channel is used to continuously monitor the solar flux, and the second one is used for calibration only. Both channels are equipped with a light baffle which allows the same condition of solar illumination as the entrance window of the photometer. A temperature difference of 30°C is maintained between this light baffle and the entrance window of the photometer by cooling the baffle to an average temperature of 10°C and heating the window to approximately 40°C. This, in principle will strongly limit the damage of contamination on the window which might be caused by organic volatiles emitted either by the electronics of the instrument or by the satellite itself. In addition the need for a cold trap in the satellite itself appears necessary. The satellite should be integrated and manipulated in conditions of extreme cleanliness to avoid potential contamination. Furthermore, the instruments electronics should be sealed and separated from the body of the photometer.

The photometer itself is composed of an ultra-violet interference filter of the type manufactured by Acton Research Company or by MATRA-SEAVOM, which has a bandpass of about 10 nm and a peak transmission of about 10%. Two such filters mounted in series might be necessary if the rejection in the wings is not sufficient to eliminate the long wavelength. The filter or the set of two filters is sealed to the detector, airtight so that the front face only of the filter is in direct contact with the external environment.

The detector can be either a silicon diode or a photodiode of the type EMR 543. These diodes are accurately calibrated at the NBS and can be manufactured with various combinations of photocathodes and window materials. For example, the 543 P-09-00 Model is a solar blind, end-on, magnesium fluoride window tube with a 28 mm diameter, semi-transparent rubidium telluride photocathode. The spectral sensitivity of this rugged detector extends from 115 nm to the photocathode threshold at 320 nm, with excellent longer wavelength rejection. The tube is capable of withstanding 50g shocks of 11 ms duration and operating at temperatures as high as 100°C. The tube which is primarily designed as a calibration standard in the U.V. region ensures also good stability. It is normally potted with three wires brought out of the fiberglass housing.

We assume that the main source of degradation is the contamination of the entrance of the photometer (i.e. the interference filter) by outgassing material. The second channel comprises a filter or set of two filters identical to those of the photometer, with the back face kept free of contamination by a tight cover which is freed only at the time of calibration.

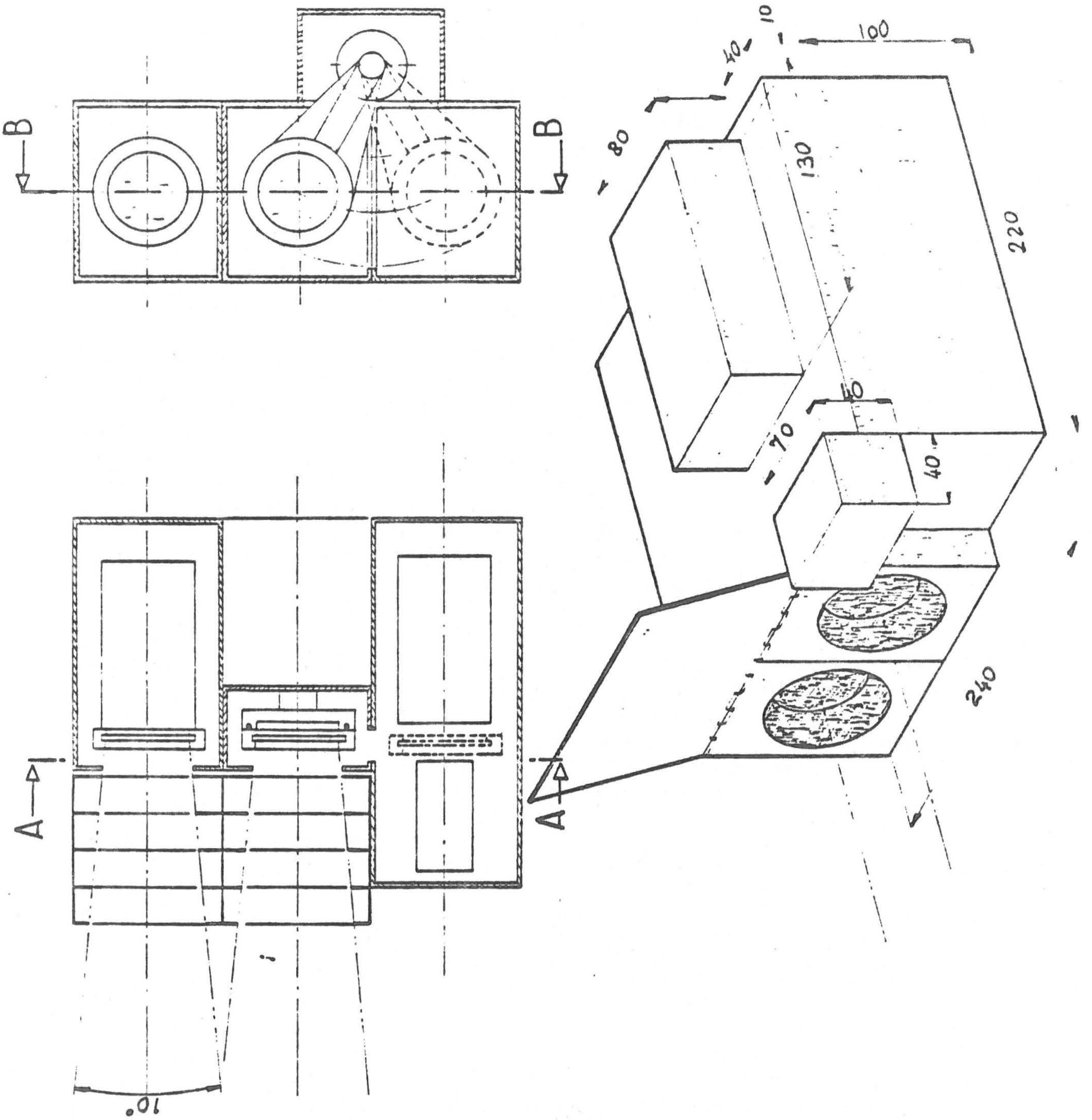

Figure 2C: The 160-210m photometers

The calibration consists only in measuring the degradation in the transmission of the filter. This implicitely assumes that we do not expect major changes in the efficiency of the detector of the photometer. These will be measured by means of calibration balloon or rocket or Space Shuttle borne instruments.

The calibration sequence starts by first uncovering the back face of the filter of the second channel and by means of a two position mechanism to insert the filter in the calibration set. This set consists of a small pen-ray or deuterium lamp and of a detector which can be identical (but this is not a necessity) to the detector of the main photometer. The lamp and the detector are fixed with respect to each other to insure maximum photometric stability during the 2 calibration phases. The first one consists in measuring the signal from the lamp with the filter in. In the second one the measurement is made without the filter. The ratio between the two measurements yields the transmission of the filter. The absolute value of each measurement is of no interest since we make a direct comparison between the two phases. The duration of the phases is of one or two minutes which is short enough to avoid contamination of the uncovered face of the filter. Calibration sequences should be repeated once every week or so. For this measurement to be of any significance, the solar illumination, temperature and working conditions of the two filters (the one in the photometer and the calibration one) should be as nearly identical as possible.

ANNEX 2D

Instrument to Measure the Solar Spectrum from 170 to 3200 NM

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An instrument, already built for flight in the First Spacelab that consists of 3 spectrometers and their detectors, and 5 in-flight calibration lamps, is proposed.

The spectrometers are double monochromators of 10 cm focal length using concave holographic gratings with the following characteristics:

- the six gratings are mounted on the same mechanical shaft rotating with a screw and nuts system giving a precision of 2 arc-second at any position. The spectral precision is 10^{-2} nm.
- the UV monochromator range of measurement overlaps with the one of the visible monochromator. Same as for visible and IR monochromators.
- transmitting diffusors (grinds) are placed in front of the three spectrometers.
- filters wheels are placed at the exit slits to remove the second order signal.
- two photomultiplier tubes (PM) and a PbS cell, chopped at 512 Hz, are used as detectors.

The wavelength range, spectral data and detectors are listed in table 2D1.

Monochromators	Range	Band-pass	Lines/mm	Detector
UV	160 - 365 nm	1 nm	3600	PM (EMR 641F)
VIS	277 - 889 nm	1 nm	1281	PM (EMR641E) (+5° C)
IR	805 -3160 nm	20 nm	354	PbS cell (-10° C)

Table 2 D1

The principle of one spectrometer is given on figure 2D. A complete solar spectrum from 170 to 3200 nm is recorded in 15 minutes.

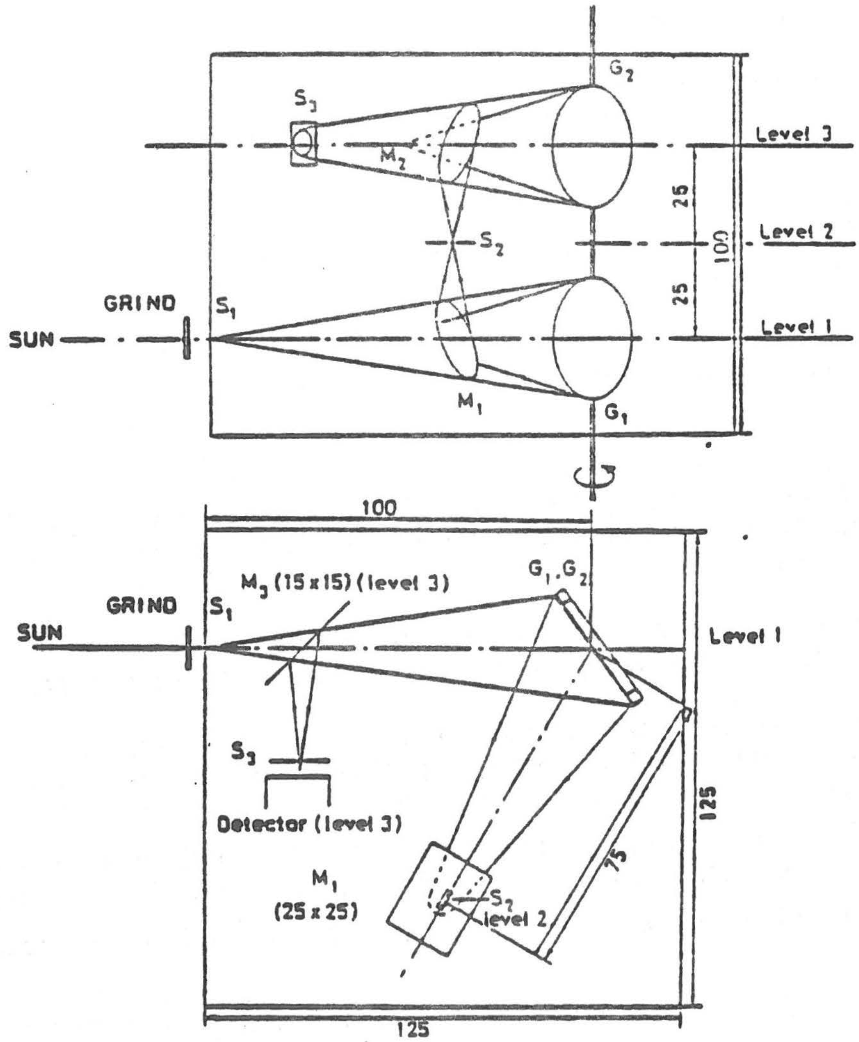

Figure 2D: Schematic of one double monochrometer. Three same units are mounted on the same mechanical shaft.

Lamp Type	Spectrometer	Purpose	Power	Number
Tungsten ribbon	VIS and IR	Instrument sensitivity	5 W	2
Deuterium	UV		15 W	2
Hollow cathod (filled with He)	UV and VIS	Wavelength scale and band-pass	2 W	1

Table 2 D2

The instrument is calibrated in flight by a set of lamps (table 2 D2) such that

- the radiating region (ribbon and anode) is imaged by lenses on the input grinds limited by preslits.
- the diameter and magnification of the lenses are chosen so that the signal due to the lamps is of the order of the one due to the sun.
- lamps and lenses are mechanically stable with respect to the entrance slits.
- the lamp currents are regulated at 10^{-4} to provide 0.1% stability.
- the lamp currents, voltage and temperature are telemetred.

Moreover, the instrument is subject to absolute calibration with a black body at 3000° K stabilised to 0.1° K. The obtained accuracy is estimated to be

5% for $\lambda < 250$ nm

3% for $250 < \lambda < 300$ nm

2% for $300 < \lambda < 400$ nm

and 1% for $\lambda > 400$ nm

For the measurement of the instrument band-passes and the calibration on the wavelength scale, hollow cathod lamps filled with Argon or Neon are used, as well as other elements that permit to cover the range from 170 to 3200 nm.

To overcome the unavoidable ageing of the detectors and the calibration lamps, comparisons with an identical calibrated instrument, flown in Spacelab and/or balloons will be performed at regular periods (about 6 months) during the spacecraft life-time.

ANNEX 2E

Far UV Spectrometer

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The aim of this instrument is to measure the spectral irradiance between 15 and 180 nm with photometric precision of 5 to 1%.

The wavelength range is covered by two grazing incidence monochromators geometrically identical. The grating spacing and blaze are adjusted for operation from 15 to 62.5 and 30 to 180 nm respectively.

Solar radiation is admitted directly through a fixed entrance slit. A stigmatic image of the entrance slit is formed by a grating which is holographically constructed to reduce aberrations. Wavelengths are scanned by a simple rotation of the grating; the fixed exit slit selects radiation diffracted at a constant deviation angle of 142°. The detector is a channeltron. The only mechanical motion is the rotation of the grating.

The field of view of the instrument is 3° by 1°.

Broad band filters will separate the different grating orders. With entrance slit dimensions of 0.1 mm x 3 mm the overall sensitivity will be better than 1 count/sec for 10^6 incident photons per cm^2.

Distinctive characteristics of the two channels are listed below.

Wavelength range	Grating constant	Band pass FW HM	$\Delta\lambda$/Step
Channel A 15 - 62.5 nm	1100/mm	0.15 nm	0.1 nm
Channel B 30 - 180 nm	550/mm	0.3 nm	0.2 nm

A rare gas ionization chamber is used in flight to detect possible drifts in the sensitivity of the instruments. The same filters which serve to separate orders in the monochromators are used to define, in conjunction with the appropriate rare gas, fairly narrow sensitivity bands. At first approximation each absorbed photon produces an electron-ion pair which is collected.

The resulting conduction current is a measure of the flux within the sensitivity band. Departures from the one to one correspondance between the number of absorbed photons and collected ions are small and do not depend on environmental conditions since only elementary physical processes are involved.

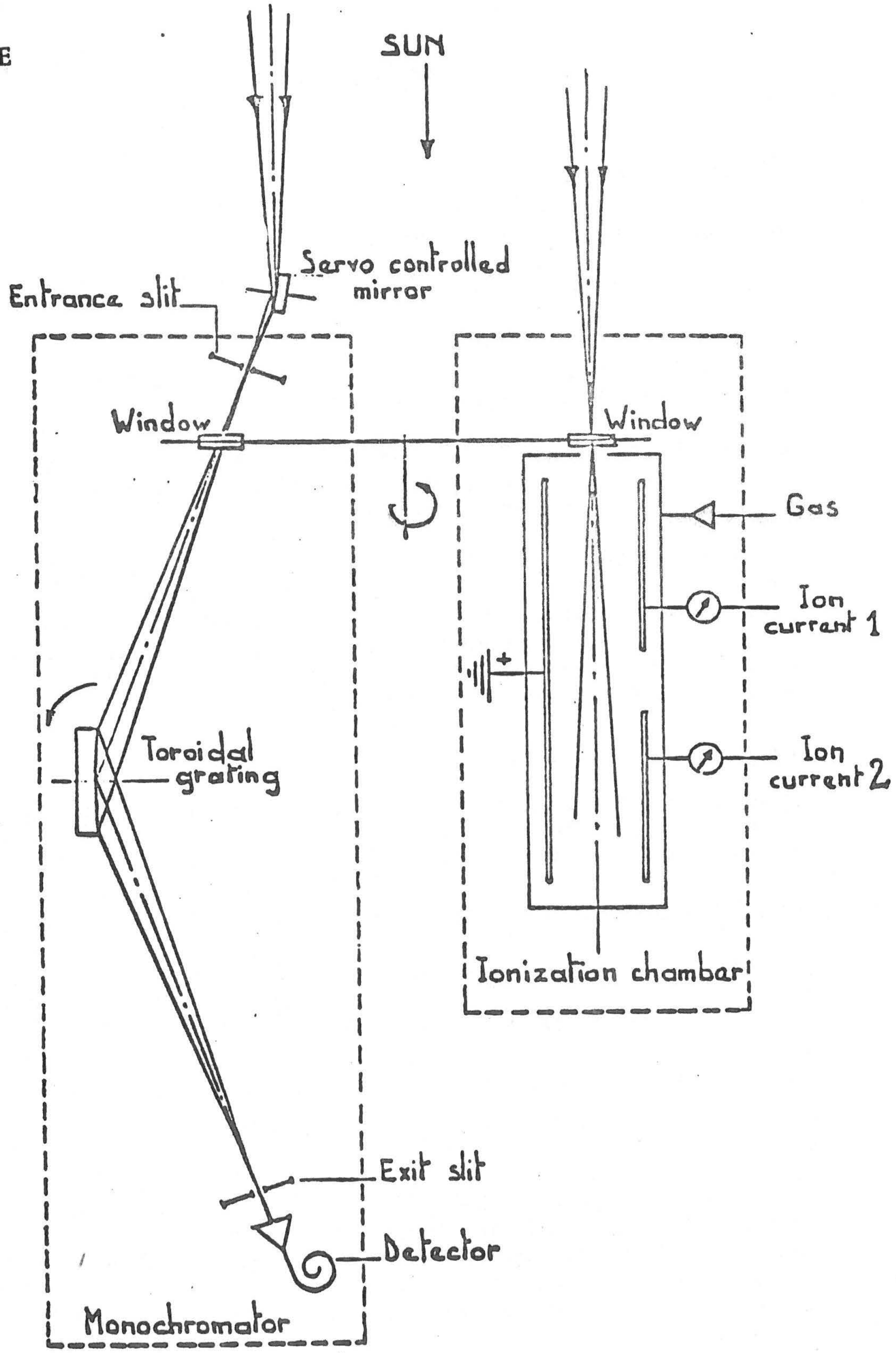

Figure 2E: Schematic diagram of the far-UV spectrometer showing the monochromator and the absolute ionization detector

Inside the chamber a positively biased electrode sweeps the ions from two consecutive regions 10 cm long toward two separate collecting electrodes. The second chamber is a detector with the appropriate sensitivity band to evaluate which proportion of the active flux is absorbed in the first chamber.

The current to be measured range from 10^{-12} A to 10^{-9} A with an expected accuracy of 10^{-14} A.

The pressure in the double chamber will be accurately measured in flight for use with the known absorptions cross sections to carry out additional control computations. Gas can be introduced in the chamber at preselected filling rates to generate linear pressure scans. The broad band filters also act as vacuum tight windows.

The maximum pressure will be about 1 torr, to be reduced below 10^{-4} torr when the gas is dumped through an exhaust valve. Different filters will be flown.

ANNEX 2F

High-Resolution Spectrometer

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To study the global oscillations of the sun an instrument that has been highly successful in observations from the ground is proposed. The principle of the experiment can be summarized as follows. An interference filter isolates a 4Å bandwidth centered on the NaI 5896 resonance line.

The Doppler shift of the sodium D1 Fraunhofer line is deduced from differential monochromatic intensity measures in both wings of the line (figure 2F1). The two monochromatic filters are provided by the absorption of the solar light by a sodium vapour in a small optical cell. With adequate polarizer and the cell being in a magnetic field of about 5000 gauss (provided by a permanent magnet as well shielded as possible), the sodium vapour absorbs the spectral windows corresponding to the σ^+ and σ^- Zeeman components. Observation of the scattered light in the direction of the magnetic field through an electro-optic modulator allows a photomultiplier to measure alternatively intensities I_r and I_V proportional to monochromatic intensities in the red and violet wing of the solar line (figure 2F2). The bandwidth of these spectral windows ($\sim$ 0.050 Å) is determined by the temperature of the sodium vapour (165°C), the hyperfine Zeeman structure and the inhomogeneity of the magnetic field.

The high photometric and spectral stabilities required by the needed sensitivity is provided by an accurate control of the temperatures of the sodium cell and of the prefilter, as well as by the stability of the permanent magnet. Operating in integrated sunlight with a telescope diameter of about 6 cm, this apparatus gives, at the photomultiplier output, a mean current of 10^8 Electrons/s. The statistical noise is then 10^{-4}, which corresponds to $1 ms^{-1}$, with a time constant of 1 second, and it can therefore be reduced below 10^{-3} ms^{-1} by integrating over two weeks or more.

All electronic circuitries and thermal control, as well as the rate of A-D conversions and data acquisition are designed to insure that instrumental noise will always be significantly below statistical photon noise.

Altogether, the apparatus weighs presently about 40 kilos and requires an average power that could most certainly be reduced to about 20 watts by suitable thermal insulation of the cell.

The lifetimes of the various parts of the experiment (electronics, photomultiplier, permanent magnet) poses no particular problem. However the alcaline cell, if it were to be operated continuously for more than a few months would need further studies of the optical material.

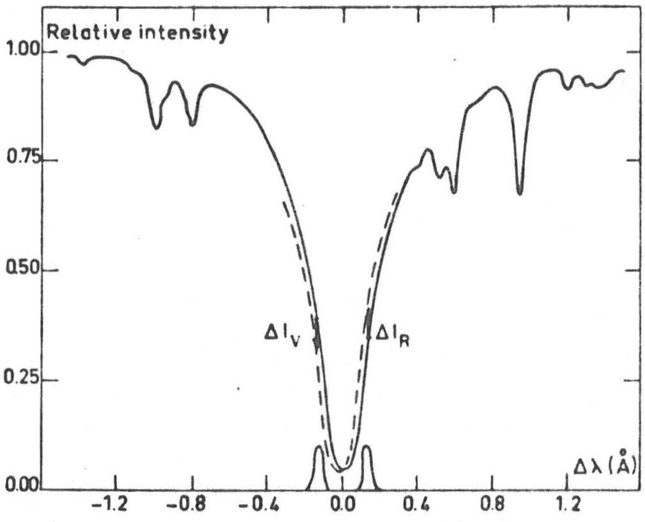

Figure 2F1: Principle of the Doppler shift measurement

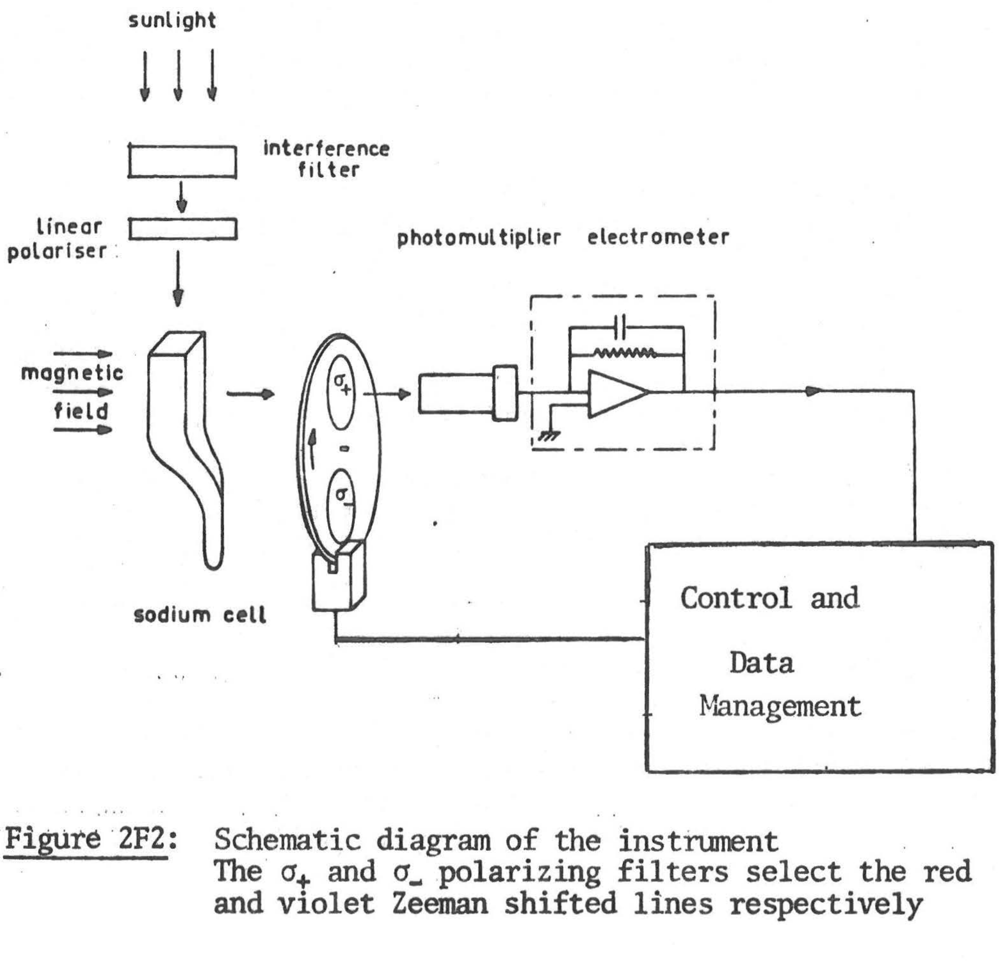

Figure 2F2: Schematic diagram of the instrument
The σ_+ and σ_- polarizing filters select the red and violet Zeeman shifted lines respectively

ANNEX 2G

Interferometer

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Technical Description

The instrument is made of 3 modules : a solar pointer, an optical package, a detector package. They are linked by optical fibers.

1.- Solar pointing device and associated electronics

It is a biaxial pointer actuated by 2 orthogonal torque motors. On the pointed platform are placed the detectors for pointing and a telescope of 2 cm diameter, 6 cm focal length. The entrance of the exit fiber is placed in the focal plane. Weight is 1.1 kg, dimensions 20.0 x 11.8 x 16.8 cm. Accuracy is ± 1 arc minute in a ± 10 degrees angle, along the 2 axes. Only constraint is that it has to have a clear view of the Sun. Thermal control is passive and needs 200 cm2 for radiation in the antisolar direction. If the satellite is already oriented towards the Sun with an accuracy of ± 1 arc minute, the pointing device can be disposed of, and replaced by the telescope alone.

2.- Interferometer module

This module contains the exit of the fiber, a lens, a filter, the interferometer itself, a Iodine absorption cell, a second lens and the entrance of the exit fiber. All components are made of glass (zerodur) inserted in a rectangular zerodur frame and maintained together by molecular adherence. This assembly is maintained at 50°C ± 1° by a heating system and covered with superinsulating material. Weight is 1.500 kg, dimensions 25.0 x 23.0 x 8.0 cm. It can be placed anywhere on the spacecraft. The length of the optical fibres can be chosen at will, provided the radius of curvature is kept above 2.0 cm.

3.- Detector module and associated electronics

At the exit of the fiber, the light is focused on a RETICON RL 128 L photodiode linear array (128 diodes on 2.5 mil centers) cooled by a Peltier element. Both detectors and cooling equipment are assembled inside a sealed box.

The array is self-scanned by two 64 stage MOS shift registers integrated onto the same silicon chip. One shift register scans the odd numbered photodiodes while the other scans the even numbered ones. Separate output video lines are provided for the odd and even elements. Each shift register is driven by a two phase clock and a start pulse to initiate each scan. Since a new photodiode is accessed on each clock transition, the two shift registers can be run 1/4 cycle out of phase and the two video lines tied together to give 128 elements of continuous video.

Signal is sent to TM through a microprocessor RCA 1802 and a memory for the summation of successive spectra (one spectrum is obtained every second and contains 3,072 bits). Spectra are accumulated for 1 minute in a 192 k memory.

Weight is 1.900 kg, dimensions 28.0 x 17.0 x 8.5 cm.

Active thermal control is provided by the equipment.

Electrical Specifications

	Voltage (Volts)	Peak power (Watts)	Average power (Watts)	Commands
Pointer	27	25	1.5	on/off
Interferometer	27	2.1	2	1. on/off 2. heat on/off
Detector	27	6	6	1. on/off 2. computer mode 1/mode 2 3. integration time 1/time 2

Telemetry

Slow analog : 1.- Temperature of the Iodine cell
2.- Saturation of the detector

Discrete : control of GC orders (5)

Numerical : 3,072 bits per measurement
memory : 60 measurements