DP/PS(76)11, Rev.1
Paris, 25 January 1977

european space agency

SPACE ASTROMETRY

Report on the Mission definition Study

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CONTENTS

SPACE ASTROMETRY

Abstract

The international symposium organised at Frascati in October 1974, on Space Astrometry, demonstrated the fundamental importance of improving astrometric data for a large scientific community, and highlighted the potential of space projects in the field. Therefore, a Mission Definition Group was set up by the Agency for a more thorough investigation.

The increase in accuracy from ground-based observations of astrometric results has been very limited in the last half century, and improvements by more than a factor of 5 are not envisaged for the next two decades; this is largely due to error sources connected with the Earth as an observing platform. Many of these errors disappear almost completely when carrying out the measurements from space.

The space projects described in the present report can yield the following achievements (with slight variations depending on the selected system) :

- accuracy
  - position : 0.001 to 0.003 arc sec (present 0.04 arc sec at best)
  - proper motion : 0.001 to 0.003 arc sec/year (3 years observation) (present 0.002 arc sec/year after more than 50 years of observation)
  - parallax : 0.001-0.004 arc sec (present 0.013 arc sec)
- negligible systematic errors, as compared to present errors of 0.005 arc sec on parallaxes and 0.05 arc sec on positions
- large number of stars: 100 000, compared to a few thousand presently observed
- faint stars: up to magnitude 11 (or more)
- homogeneous sky coverage

The considerable improvement thus reached - which cannot be reached without the use of space techniques - would mark an essential step forward in Astrometry and would have profound repercussions in Astrophysics and Celestial mechanics (see section 1.4).

The baseline mission proposed by the Study Group consists of a small satellite weighing about 125 kg. injected into a quasi-polar, low altitude orbit by a Scout-launch vehicle. It carries a telescope of about 20 cm diameter with two fields of view for differential measurements, and a dissector as a photon detector. In order to fully explore the range of capabilities, two versions are presented, which are intentionally quite different as far as attitude control and scanning of the sky are concerned :

Option A - characterised by the possibility of establishing a preselection programme of observed stars, including an active attitude control. The stars can be observed up to magnitude 14.

Option B - characterised by a systematic scan of the sky, and observations of all stars of magnitude smaller than 10.5 as they enter the fields of view. The attitude control can preferably be passive (gravity-gradient stabilisation), but if necessary, may also include active sub-systems.

In case the baseline could not be implemented, the Group also considered an improved design, with a larger telescope (40 cm diameter) accommodated in a heavier spacecraft (i.e. about 400 kg), delivering naturally better performances, which could be put into orbits by various vehicles (e.g. Delta, Ariane, Shuttle). In addition, an instrument to be flown on Spacelab has also been discussed. However, because of the short duration of each flight and the required number (six in two years) of such flights, this solution is not the preferred one.

The Group finally strongly recommend that a phase A (Feasibility) Study be initiated as soon as possible on the baseline mission, with a view to optimise the design and the operation, and to precisely estimate the necessary resources and the develoment cost, which, in the Group's view, should in any case be quite moderate.

SECTION 1 : SCIENTIFIC SIGNIFICANCE AND OBJECTIVES

1.1 Introduction

Observing the position of stars and planets as a function of time has been a corner-stone of astronomy throughout the centuries. From the predictions of eclipses and the cyclic nature of the seasons in prehistoric times, astrometry has given the observational evidence, and quite often the incentive, for fundamental changes in our picture of the universe. These changes range from the solar system architecture (about 1500 - Copernicus) via the distance to the stars (1837, Struve : parallax observations) to the detection of the nature of our galactic system (1926, Lindblad, Oort : proper motions) and the spiral arms as the place of birth of stars (1952, Blaauw : proper motions in associations). In this continuously increasing insight in the structure and dynamics of the Solar System and our Galaxy, the tedious and exacting work of measuring the position and velocity ("proper motion") of stars has been of central importance.

1.2 Present Status of Astrometry

1.2.1 Fundamental system of reference

A fundamental system of reference can be defined geometrically (using faint star-like galaxies) or dynamically (motion of members of the solar system). These two systems are conceptually the same : they define fixed axes in space. However, since a dynamic definition has to use models of the observations in describing the movements of the members of the solar system, a geometric definition is preferable.

In practice, however, a practical system has to be defined by a catalogue of positions and velocities ("proper motions") of stars. The current standard catalogue is the Fourth Fundamental Catalogue (FK4), containing 1535 stars brighter than $m_v = 7.5$. The internal accuracy is about .05"-.10" in the position (for the epoch of the catalogue) depending on the position in the sky, with relatively large systematic errors in the Southern Hemisphere. The error in proper motions is of the order of .002"/year; therefore, the accuracy just mentioned deteriorates rather quickly with time. In addition to these errors of the order of .10", an uncertainty exists in the rotation of the fundamental system (constant of precession) of about .20" per century. (see for more details the Proceedings of the Symposium on Space Astrometry held at Frascati in 1974; ESRO SP-108, March 1975.)

These errors, coupled with the limited number of stars (only one per about 25 square degrees) and the limitation to relatively bright stars (m_v less than 7.5) only, affect all applications of the fundamental system.

The inadequacy of this present fundamental system with its relative error of about 10^{-5}, is especially clear if one realises that new methods of observations (long baseline radio interferometry, laser-ranging of the distance Earth-Moon, stellar occultations by the Moon, radar observations of the Earth-planets distances, etc.) have relative precisions of 10^{-7}-10^{-9}, one to several orders of magnitude better than the actual definition of the system. New proposed ground-based methods (see Appendix 2) promise an increase in the precision of one, maybe two orders of magnitude. However, they will not be able to overcome the limitation set by the limited number of accessible objects.

More precise astrometrical measurements for many more objects would have far reaching consequences for the astrophysics based on the measurement of stellar positions.

In the following it will be shown that we envisage with an astrometric satellite an increase in the number of stars with accurate positions from 1500 to about 10^5, with a limiting magnitude of about 11 and a positional accuracy of better than ".002 (compared to ".10 now at m = 7.5) and proper motions accurate to .002"/year.

Under no circumstances can we expect ground-based methods to attain, or even approach, these precisions for so many stars. It is, furthermore, emphasized that these observations will serve as a first epoch set. Time will greatly improve the accuracies of the proper motions.

It should be emphasized that the motions are the main data for deriving distances, and all theories of evolution of our Universe depend, therefore, on these motions.

1.2.2 Parallax observations

All distances in the universe beyond the solar system are ultimately based on the determination of trigonometric parallaxes. In the last century the parallaxes of about 7000 stars have been measured with a precision of about ".013, with a systematic (and unexplained) difference of about ".005 between large Northern (Mc Cormick) and Southern (Yale Southern Station) hemisphere series of observations.

The expected increase in the number of ground-based parallaxes over the next decade, is estimated to be of the order of less than 1000, with a modest increase in precision to about ".004.

The error in the distance scale resulting from parallax observations is much more dramatically shown if one realises that the above stated errors are translated into distance errors of less than 10% for only about 400 stars, most of them closer than 20 pc. More than half of the parallaxes known, and hence derived distances, have accuracies less than 50%. Since a large part of the error is systematic, distance scales determined from many stars simultaneously have not a much higher accuracy.

Distances beyond 100 pc are all based on statistical properties of the group of bodies under consideration. The relation between these properties and distances are determined in the region of overlap where both direct parallaxes and statistical properties can be determined. The best way to study these connections is by observing star clusters. However, the nearest star cluster usuable for this type of work, the Hyades, has a distance of about 42 pc, and hence its stellar members have parallaxes of ".025 only. In the following it will be shown that an astrometric satellite will be able to determine parallaxes down to a limiting magnitude of about 11 for about 10^5 stars with a precision of ".003.

1.3 Improvements by Space Astrometry

The increase in accuracy of astrometric results has been very limited inthe last half century, and improvements of more than maximally about a factor of 3 for ground-based observations are not envisaged for the next two decades. This is largely due to some error-sources connected with the Earth as an observing platform.

By moving the observing equipment to a platform aboard an artificial satellite many of these errors disappear completely, or to a large extent :

(a) Atmospheric refraction : no model-dependent systematic corrections.

(b) Atmospheric turbulence : diffraction limit instead of 'seeing' limit.

(c) Telescope bending : weightlessness.

(d) Full hemisphere coverage : no systematic North-South differences.

Taking these, and other, improvements into account, space astrometry can obtain :

(a) Accuracy :

.001" - .003"	in position	compared to	.04"
.001" - .003"/yr	in proper motion	"	" .002"/yr
.001" - .004"	in parallax	"	" .013"

(b) Negligible systematic errors : compared to about .005" on parallaxes and .05" on positions.

(c) Large number of stars : 100,000 compared to several thousand.

(d) Faint stars : m less than 11

(e) Homogeneous sky coverage : No selection for North-Western-continent winter night time.

1.4 Astrophysical Significance

If a space astrometry mission would be able to determine the parallax of 30 or so stars in the Hyades cluster with the precision mentioned above, these observations alone would already warrant this mission.

By determining the distance to the Hyades with a relative precision of about 10^{-2}, we would be able to :

(1) Make a better age determination of open clusters possible.

(2) Better define an important basic step in the determination of the cosmic distance scale.

(3) Better calibrate the period - luminosity relation for Cepheids.

(4) Better determine intrinsic stellar luminosities (stellar physics).

(5) Better space velocities of subdwarfs.

In addition, precise parallaxes for a very large number of stars will also give, for the first time, reliable possibilities of directly observing the luminosity function, velocity dispersion and space distribution of different types of stars (in combination with other observations, of course), and, for stars at low galactic latitude, it seems possible to get direct evidence of interstellar reddening within the first 100 pc or so (see Symposium report).

The determination of a fundamental reference system free from systematicerrors, will also in itself already be a major contribution towards several problems :

(1) By providing an accurate reference system, new observations with relative precision of 10^{-7}-10^{-9} (see App. 2) can be referred to an initial system.

(2) Proper motions of a large number of stars will give the possibility of studying systematic motions in groups of stars, and make a better definition of the galactic structure and mass possible.

(3) Providing an initial reference frame ("first epoch") at the earliest possible moment, will make it possible to determine proper motions better, earlier : time is a great help in precise proper motion determinations.

(4) The reference system will provide an absolute reference frame for high precision ground-based relative proper motions over small angles.

(5) A fundamental reference system will provide a system of reference for the determination of time, the movement of the

Earth's axis in space, the influence of energy exchange between the Earth and Moon on the lunar-orbit, the polar motion, etc.

As has been stated before, time is of great importance in deriving precise proper motions : Launching a back-up satellite after a number of years will greatly improve the proper motion determinations.

1.5 Related Efforts

The space astrometry results, after they have been analyzed and catalogued, will have their greatest impact on astrophysics if related, ground-based observations are carried out for the astrometric observed objects.

The correlations of physical properties of stars with distance and velocity require :

(1) Radial velocity observations to determine the space motion of the star.

(2) Colour determination.

(3) Luminosity determination.

It seems worthwhile to advise the astronomical community to consider a coordinated effort to obtain these results. It is advisable to have this cooperation already at the pre-flight stage, so that, if a preselection of stars is possible aboard the spacecraft, this preselection may be done in an optimal way.

It goes without saying, of course, that high-precision, ground based relative astrometric observations which can be tied to the space reference frame are necessary also, if only to provide a higher density of stars (10^5 stars gives, after all, only 2 stars per square degree).

SECTION 2 : EXPERIMENTAL PACKAGES

2.1 Principles

2.1.1 Scientific objectives

The proposed space astrometry projects aim at locating with high accuracy a very large number of stars on the celestial sphere by determining their mean positions, their proper motions and their trignometric parallaxes.

Four main interrelated objectives are envisaged in the present projects : (1) to establish a fundamental system, a net of primary reference stars which can serve as basis for all other astrometric observations from space and from ground, (2) to improve the galactic distance scale by observations of trigonometric parallaxes and of proper motions of suitable cluster (Hyades), (3) to provide space velocities of stars for the study of stellar kinematics out to a few kiloparsecs from the sun, and (4) to detect and to measure visible and invisible companions of stars by observing deviations from linear motion.

Each of these objectives has significance for a number of scientific topics, since it appears feasible to increase by a factor of at least ten the accuracy of stellar positions, proper motions and parallaxes over present day's standard and for ten to hundred times as many stars. The topics of galactic structure, stellar evolution, stellar masses, extragalactic distance scale, identification of radio sources, the existence of other planetary systems and the dynamics of the Earth would greatly profit.

2.1.2 Optical design

In order to construct an accurate celestial sphere, it is necessary to measure with high precision the angular distance between stars separated by a large angle, of the order of 90°. Such accurate measurements are obtained in the proposed projects by a differential method, comparing at the focal plane of a single telescope the positions of two stars imaged from two different fields of view. The two fields of views are superposed by means of a mirror with two reflective plane surfaces, inclined at a constant angle. The mirror, as well as the telescope itself, should be thermally very stable, and the design should minimise thermal variations.

2.1.3 Scanning and image analysis

To determine the complete celestial sphere without gap, it is clearly required to measure angles between stars located in all directions of the sky. This result is achieved by selecting a circular low-altitude orbit for the spacecraft, approximately "sun-synchronous" (i.e. inclined with respect to the equator at an angle of about 97°); the plane of the orbit will then precess at a rate of about 360° per year (see section 3.2).

The attitude of the spacecraft can be controlled in various ways, leading to several options (as described later), but always producing a scanning of the celestial sphere along great circles.

Due to the scanning motions, the star images, originating from one or the other field of view, cross the focal plane of the telescope, where their position is determined as a function of time. The measurement is carried out by means of a system of grids, each composed of successive transparent and opaque bands. A photon counting device behind the grids measures the number of pulses produced by the star through the grids during equal periods of time. Analysis of the photon counts results in a highly accurate determination of star position as a function of time.

In order to decrease the influence of interfering stars and of stray light, it is proposed to use a dissector, whose sensitive area is controlled to follow the star under study. Although solid state imaging detectors, particularly if combined with intensification stages (ICCD) might offer advantages, it is felt that the present state of technology of these devices does not justify their serious consideration for this project. On the other hand, photo-multipliers or image dissector tubes (IDT) do exist and require no further development to satisfy the detection requirements of this project. Image dissector tubes in particular would allow a considerable reduction of the effect of parasitic light, star background and dark current on the measurement accuracy. These effects decrease with the size of the instantaneous field of view. On the other hand, however, the smaller the instantaneous field of view in relation to the total field of view covered by the slit pattern projected on the entire cathode area of the IDT, the higher are the accuracy requirements in the setting of the deflection coil currents, to encounter and follow the selected stars traversing the slit pattern. In the following sections, the instantaneous field of view in the scan direction is assumed to be about 0.5% of the total field of view. This requires a setting of the instantaneous field of view with an accuracy of about 0,5%. Taking into consideration distortions of the image dissector tube and their change under different environmental conditions, the open loop tracking of a star would require an accurate calibration and continuous transformation of coil coordinates in celestial coordinates during observation. This is possible and in a similar way is done in high accuracy star field sensors but entails operational complexity and necessitates careful control of environmental conditions. A larger instantaneous field of view together with a decreased total field would relax the accuracy and calibration requirements. However, it must be left to a more detailed feasibility study to perform a trade-off analysis taking into account design and operational consequences together with scientific objectives.

As regards the type of image detectors the best on record are those produced by ITT. In particular type F4012 with a cathode diameter of approximately 18mm is used for star sensing application. Versions with larger cathode diameters are also available but mass and volume limitations might prevent their use.

The angular distances between stars are obtained by comparing the measurements in position and time of different stars and by taking into account, in various ways, the continuity of the spacecraft attitude motion.

2.1.4 Practical implementations

The essential principles outlined in sections 211 to 213 can be implemented in a number of ways. With a view to demonstrate the feasibility and expected performances of practical realisation, the Mission Definition Group has selected, as possible examples, two configurations which intentionally are quite different; thus, the Group feels that the range of capabilities is well explored. These two configurations have been studied in sufficient depth to give a reasonable indication about the scientific quality and interest of the objectives achievable by the proposed space astrometry projects.

It will be a major task of further Phase A study, if approved, to optimise the spacecraft design from the scientific and technical viewpoints, and to select one or the other of these configurations, or a combination of them.

The main characteristics of the two investigated configurations, called hereafter "option A" and "option B" are as follows :

Option A

Option A is characterised by the possibility of establishing a preselection programme of observed stars.

The spacecraft attitude is controlled by an active system, thus allowing for some independance between the orbital motion and the attitude motion. The scanning of the celestial sphere can be organised in such a way that the intersection angles between the measured great circles are large enough for a good reconstruction of the sphere; in addition, each star can be observed more frequently during one year than with an automatic scanning.

A major technical advantage of option A is that only measurements along great circles - and not perpendicularly - are required.

Option B

Option B aims at a systematic search for the simplest observation procedure, as a means of improving reliability; consequently, programmed preselection of stars is given up when required for simplicity of the scanning.

Subject to confirmation by further technical study, the spacecraft attitude may preferably be controlled by a purely passive method (gravity gradient stabilisation); the very smooth motion thus obtained can be used for interpolation. However, if this stabilisation mode were not feasible, an active system could be designed.

The celestial sphere is scanned along great circles in the plane of the orbit. With the selected quasi-sun-synchronous orbit, the angles of intersection of the scanned circles at the equator plane between successive orbits are small, therefore it is necessary to measure along two directions, the plane of the orbit and the perpendicular to that plane.

The measured data are progressively improved in accuracy by using in auxiliary computation the precise determination of the spacecraft attitude.

2.1.5 Baseline and improved missions

According to the present findings of the Mission Definition Group, the astrometry mission can be carried out with a small telescope of diameter 20 centimetres accommodated in a spacecraft compatible with a Scout launch vehicle. Therefore, the baseline mission, either option A or option B, as described in sections 2.2 and 2.3, assumes the use of that launcher, and the expected performances(section 2.4) refer to the corresponding design.

The Group, however, in case these baseline missions could not be implemented, took also into consideration an improved design, with a larger telescope (e.g. 40 centimeters diameter) accommodated in a heavier spacecraft, leading to better performances. (section 2.5)

In addition, an instrument to be flown on Spacelab has also been discussed by the Group (section 2.6). However, its accommodation and operation on Spacelab have only been investigated in a preliminary way, because, due to the short duration of the flights, this solution was not recommended for an immediate Phase A study. The technical feasibility of the baseline mission will have to be finally confirmed during the Phase A study.

2.2 Option A

2.2.1 General

As explained in section 2.1.2, a basic technique common to the different space astrometry possibilities considered is to superpose two areas of the sky in one telescope by means of two plane mirrors forming a very constant angle with each other, (Fig. 1). The angle between the two axes of vision, the basic angle, was originally proposed (cf.MS(74)36) to be 90°, but it may be given nearly any value at least between 50° and 110° with little variation of accuracy.

Observations of stars are obtained from image dissectors behind a slit system in the focal plane of the telescope while the latter performs a quite smooth rotation around an axis perpendicular to the two axes of vision. This rotation gives the stars a smooth motion across the slits so that the angle between two or more stars may be derived from the few seconds of photoelectric recording obtained. It is a design goal for the attitude control that it shall provide a rotation so smooth that the jitter contributes less error to the observed angle than the statistics of photon counting.

The angle of the complex mirror must remain very constant whereas its absolute value is not critical. If the mirror angle is 45°, the basic angle is 90° and a direct connection of a quartet of 4 equidistant stars on a great circle can be obtained in 4 steps of observation. This will provide a calibration of the basic angle in addition to the angles between the stars along the great circle. This calibration is fundamental for space astrometry of large arcs, which is sometimes called absolute astrometry.

If the angle between a pair of stars differs from the basic angle, or a multiple of this, a method of interpolation must be used, which, in option A, is provided by means of a large field, (e.g. 90')
along the great circle.

2.2.2 Optics and the image analysis

The selected optical system is shown in Fig. 1. The two optical axes form an angle of 84° defined by a complex mirror of two components only. A Schmidt-Cassegrain telescope of 16 x 16 cm aperture can give diffraction limited performance in a ±1° field or more and in a large wave-length range, especially if the secondary mirror is nearly flat. Changing temperature gradients in the corrector plate can have the same effect as a changing basic angle, but study of the thermal stability has shown that this problem can be mastered. (see section 3.4.4)

The spacecraft shall rotate around the z axis so that the two axes scan near a great circle, thus the names : preceding and following axes, P-and F-axes. The rotation velocity must therefore be about v = 220 "/s, which is the geocentric angular velocity of a low Earth satellite. The possible directions of the rotation axis are discussed in sec. 2.2.4.

At the focal plane, the stars will cross a system of slits, Fig. 2, most of them perpendicular to the motion. Inclined slits at each end of the field serve to monitor the three-axes attitude to about ±1" by means of stars with known positions. An image dissector with a cathode spot of 30" x 30" must be controlled to follow approximately (±10") a selected star for about 0.2 s at a time, then the cathode spot is switched to the next selected star and then usually back to the first star again. This scheme shall minimize the influence of attitude jitter around the z-axis on the measured angle between the two stars - an error which must be ± 0.025" when averaged over 0.2s. Attitude changes around the x- and y-axes will only move the stars parallel to the slits and is therefore not critical (±1" jitter).

A photon counting at the image dissector must be performed in basic intervals of 1 ms corresponding to 0"22 of motion. After storage in the computer the values are Fourier transformed and only the few significant Fourier components need to be transmitted to the ground. A stable quarz frequency must time the photon counting.

On-board evaluation of the transit times must be performed for a bright star about every 30 s for monitoring the three-axis attitude as mentioned above. The counting of the photomultiplier behind the two-slit star mapper before the main field, (Fig. 2) is used for the initial coarse acquisition of stars or if exact attitude knowledge has been lost.

The transit time of a star across the slits should at best be derived from the Fourier transform components. Nearly equivalent is, however, in case of a grid with a period s_s equal to two times the slit width, s_w, to assume a sinusoidal modulation of the light. Lacroûte (ESRO PS-108, p. 11) has given a formula for the mean error obtained at one period as $\varepsilon = 0.26\ s_s\ N^{-0.5}\gamma$, where N is the number of photons counted on the modulated light component and γ is a factor depending on the background counts. Another method is to define the transit as the median (Høg ESRO SP-108, p. 62) and in addition to use a grid with a relatively larger period $s_s = 4s_w$. This median method is less sensitive to variations of the image profile but is most probably too pessimistic in view of the nearly perfect diffraction limited optics. Table 1 gives the mean errors σ_{sn} and σ_{md} for 1 s integration time for these two methods and assuming a sky background of 22 mag/sq. arc sec, 30" x 30" cathode spot and 3 Hz dark counts from the image dissector F4052(S20) from ITT at -20°C, giving a total of B Hz. i_{star} is the counting rate of a GO star assuming a total transmission T = 0.37 of the optics at each 8 x 16 cm^2 aperture. The slit has a width to let 90% of the star light pass. Only the estimate σ_{sn} shall be used in the following. A linear magnification of the telescope aperture gives higher angular resolution and therefore allows a proportional decrease of slit dimensions, the net result being that the σ's decrease with the second power of the magnification.

Table 1

Mean errors for 1 s integration, $s_w = 1.25''$

method		sine		median
grid period		$s_s = 2.5''$		$s_s = 5.0''$
dark counts		B = 24 + 3 Hz		B = 12 + 3 Hz
m	i_{star}	γ	$\sigma_{sn}('')$	$\sigma_{md}('')$
9	4215 hz	1	.016	.022
10	1678	1	.025	.035
11	668	1	.040	.056
12	266	1	.064	.094
13	106	1	.10	.17
14	42	1.2	.19	.33
15	17	1.7	.42	.72

2.2.3 Selection of Stars

In option A, the stars to be observed can be selected on the basis of their astrophysical relevance and of their role in the planned fundamental system, in which they should be well distributed on the sky and in magnitude. Preferably, of course, a star may serve both purposes.

An astrophysically relevant selection should cover as well as possible the different spectral types, luminosity classes, magnitudes, galactic longitudes and latitudes, and the different peculiar types of stars. This requirement can only partly be fulfilled due to the limited astrophysical knowledge about the majority of faint (m = 11) stars.

During observation, a list of stars near the scanned great circle with their positions ($\pm 1''$) must be available in the on-board computer. By means of the real time attitude knowledge, the stars are picked from the list, which contains about 3000 stars for a period of 12 hours, and the dissector cathode spot is moved accordingly. With this preselection method, an integration time between 4 s and 10 s may be spent on a star each time it enters the field of 54' x 76' (Fig. 2).

For this method, a uniformly distributed fundamental reference system (RS) of bright stars, m = 9, with one star per square degree is required. A further equally dense and bright auxiliary system (AS) is set up. Finally, a program system (PS) shall contain all other stars (e.g. 100 000) to be observed. The cathode spot is either switched between two RS stars or between a RS and a PS star letting the RS star serve as reference. With a field of one square degree there are on average two RS stars in the field simultaneously, taking P and F-axes together. Sometimes, about once per minute, it will, however, occur that no RS-star is in the field, but before this happens an AS star will be selected during the scanning itself to fill the gap. Thus, relatively little observing time is spent on AS stars, while all RS stars receive about equal observing times. On average, the following distribution of the 20 seconds observing time in the field on the categories of stars and on inclined 45° slits seems optimal.

RS : AS : PS : 45° = 8 / 2 / 8 / 2 (in s)

Thus, each RS star is observed 4 s of its time in the field, and during 2 s of this it is being connected to another RS star. It can be shown by means of an analogy to the general symmetric method for determination of division corrections, (Høg, AN 286 (1960) p. 65) that the about 360 RS stars encountered on a scanned great circle obtain a mean error equal to the mean error from 2 s integration time, to be taken from Table 1 if the attitude jitter can be neglected. In this way the coordinates along a great circle are obtained for the RS stars together with a calibration of the basic angle between the axes, and the observed PS stars are tied to the RS stars. A calibration of the slit system must also be obtained and the corrections must be applied.

2.2.4 Mode of scanning

For each star, five astrometric unknowns must be separated and measured ; two ecliptic coordinates at a mean epoch, the two proper motion components and the trigonometric parallax.

The preferred scheme in option A is to measure the projections of stars on a great circle, and not the coordinate perpendicular to it. How can these measurements along great circles best be arranged and combined to give two-coordinate measurements of the whole sphere?

Two makes of scanning likely to solve this problem have been investigated :

- inclined scanning, where the direction of the axis of spacecraft rotation perpendicular to the two fields of view (Fig. 1), is always maintained at an ecliptic latitude of 30°. This mode of scanning (Fig. 3) covers the part of the sky whose ecliptic latitudes are comprised of between + and -60°, and loses only 14% of the sky around the poles. It gives a nearly orthogonal two-coordinate coverage in one year,

- <u>revolving scanning</u>; where the z rotation axis moves at a constant angle, e.g. 60°, from the sun, making one revolution in about two months (Fig. 4). From a scientific point of view, this mode is the most desirable, since it covers the sky with two-coordinate measurements at least three times in one year. A total observing period of 2 years will give a separation of the five astrometric unknowns.

Further study during Phase A will be required to select the optimum scanning mode in option A. In both cases, the z rotation axis moves slowly in the inertial space, so that active stabilisation seems feasible. In the data on expected performances presented later, inclined scanning has been assumed.

The resulting accuracy after three years of inclined scanning with an ecliptic latitude of 30° on the five astrometric parameters, is given in Table 2 for a mean error of 0.002 arc sec at each epoch. The mean error is derived from table 1 (section 2.2.2), which has been established for 1 second of integration time. The accuracy on the astrometric parameter is proportional to the mean error. A star will be observed for instance 2 seconds each time, twice on each orbit and during 16 orbits at each epoch, accumulating therefore, to 64 seconds per epoch, so that for a star of magnitude 9, the mean errors will be (see Table 1) $0.016 \times 64^{-0.5} = 0.002$ arc sec.

<u>Table 2</u>

<u>Accuracy of inclined scanning</u> (for 0.002 arc sec mean error)

ecliptic longitude	0.00 20	arc sec
ecliptic latitude	0.00 14	"
parallax	0.00 32	"
proper motion (longitude)	0.00 20	arc sec/year
" (latitude)	0.00 12	"

These accuracies have been computed for a star near the ecliptic plane, but are in fact valid for most of the sky.

2.3 <u>Option B</u>

2.3.1 <u>Orbit and sky scanning</u>

The orbit and stabilisation of the spacecraft are similar to those successfully experienced with the ESRO TD-IA satellite.

The orbit, circular and of low altitude is approximately "sun-synchronous" (i.e. inclined with respect to the equator at an angle of about 97°); however, the exact inclination will be selected in such a way that the precession rate of the orbital plane is slightly more than 360° per year, e.g. 2.5 rotations in 2.33 years (see section 3.2).

The directions of the observed stars always lie in the orbital plane; therefore the spacecraft x axis, bisectrix of the two fields of view, will be pointed near the zenith (Fig. 5) and the normal to these fields, axis z, will remain approximately perpendicular to the orbital plane. The requirements on attitude accuracy with respect to the nominal pointing directions are as follows :

- x axis : along the vertical, within ∓2°,
- y axis : along the velocity vector, within ∓2°,
- z axis : perpendicular to the orbital plane, within ∓5°

There is no particular need for the correlation in attitude between one orbit and the next one; this is due to the fact that with a mean precession of 4 arc minutes, each star will be observed on an average of 12.5 orbits at the equator.

The requirements on angular velocity of the spacecraft axes are not very constraining; however, angular acceleration should be kept preferably below 0,3 arc sec/sec^2 along all three axes.

2.3.2 Telescope and image analysis device

The two fields of view of the telescope, separated by an angular distance of 79°, are superposed by means of a mirror, 250 mm diameter, composed of two reflecting surfaces shaped on a block. An alternative solution, with three reflecting surfaces, appears to present a number of advantages that would require additional investigations, particularly as far as the diffraction pattern is concerned.

Due to the limited useful field, the telescope is of the Ritchey-Chrétien type with the following characteristics :

- large mirror diameter 250 mm, radius 2 044 mm
- small mirror " 98 mm, " 1 102 mm

The distance between the mirrors is 700 mm; the focal plane is situated 75 mm behind the large mirror. The equivalent focal length is 2 460 mm, which corresponds to 11.9 micrometer for 1 arc sec.

All optical devices will be manufactured in Zerodur, and the distance between the various optical pieces will be determined by that material. Only the connection between the complex mirror and the telescope can possibly be made in invar. To avoid systematic errors larger than 0.000 5 arc sec, it is sufficient that the variations of the temperature differences between the various optical components be smaller than 0.05°, a slow temperature drift is acceptable.

Super insulation of the complete optical device will be required; the heat loss of radiation to space of the complex mirror will be balanced by a small heater located in the baffles.

As the solar panels prevent the sunlight from shining inside the baffles, it is possible to eliminate spurious light with short baffles.

The useful area of the focal plane covers 25' x 25'; the star image is analysed by grids with a step of 2 arc seconds, inclined at 45° alternately in one direction and the other (Fig. 6). A dissector behind the grid system restricts the field to 25" x 25" following the star image motion in the focal plane.

Before entering into the measurement fields, the star image crosses a few clear bands of 1 arc sec width, which provides the necessary information for controlling the dissector. If the motion were very smooth (∓1"/sec), transit of the image on two clear bands will be sufficient. It will, however, probably be necessary to use four bands. Each clear band is a grid comprising three stars.

The compression of photon counts during passage on the grids will depend on the motion steadiness. It may be possible to measure the speeds at entrance into the field, however, the speed can also be considered as an unknown. The photon counts are integrated during a transit of 1 arc minute, and their counts are transmitted to the ground.

2.3.3 Data processing

The ultimate accuracy is reached by successive improvements of the measured data.

All stars brighter than m = 10.5 are selected. For all these stars, the measured data are the transit times on the bands at the field entrance, and several groups of photon counts at known times given by integration over 1 arc minute.

Using the transit times at the field entrance and the known stars coordinates, the law of spacecraft motion along the direction of the mirror's intersection will be obtained. Using the same information and the approximate value of the complex mirror's basic angles, the law of motion of the mirror's bisectrix will then be obtained; the mean difference will provide a refinement on the value of that basic angle. All these data will be smoothed in order to obtain a complete description of the spacecraft attitude motion.

Using this known attitude, the position of the star's images will then be determined with an error smaller than one grid step. Taking into account, if necessary, the forms of images in different parts of the field, each group of photon counts will be processed to deliver the position of the stars at known mean time; the statistical mean square errors at this stage are, for each coordinate, for 1 arc minute, as follows:

m	10.5	10	9	8	7
error (0.001 arc sec)	43	34	22	13.5	8.5

The data processing proceeds by iterative steps, improving the attitude law by smoothing the data obtained; during each orbit about 1100 star transits occur, and for each transit several integrations over 1 arc minute. The star positions are improved at each epoch by considering the measurement of each star on one orbit and on the neighbouring orbits.

The next iteration consists of grouping neighbouring orbits in sets of about 20 orbits. The analysis shows that by comparing the values obtained with the two mirrors for the same stars, it is possible to detect and eliminate systematic periodic errors.

At the end of the mission (about 2.5 years), the results for various epochs will be compared in order to get the five astrometric parameters (two coordinates, two proper motion components, trigonometric parallax).

The final mean square error on the positions and the parallaxes at the equator are approximately as follows :

m	10.5	10	9	8	7	6
error (0.001 arc sec)	3.5	2.8	1.75	1.10	0.70	0.44

2.4 Scientific Results

2.4.1 Expected results

The expected results for options A and B are summarised in Table 3. They are compared with FK4, the most accurate ground based catalogue of positions and proper motions available today. Included also in the table are the results anticipated from the proposed automatic Horizontal Meridian Circle. (HMC)

The ground based parallaxes mentioned are the 6000 given in the Jenkins Catalogue. Presently, trigonometric parallaxes of about 50 stars per year of magnitude about 16 with an accuracy of ∓ 0.004

arc sec, are obtained with the best existing astrometric reflector, that of the US Naval Observatory.

The minor planets can be used for dynamical determination of absolute rotation.

Table 3

Optical Astrometry Projects

Project		FK4		HMC		Option A		Option B	
Instrument		Visual Meridian Circle		Automatic Meridian Circle		Spacecraft		Spacecraft	
Observing time		70 years		2 years		3 years		2.4 years	
Position	Mag. m	N	σ arc sec	N	σ arc sec	N	σ arc sec	N	σ arc sec
	6	$1.5\ 10^3$	0.04						
	9					$3.5\ 10^4$	0.002	6.10^4	0.002
	10			10^4	0.015			10^5	0.003
	10.5							5.10^4	0.004
	11			4.10^4	0.05	6.10^4	0.005		
	14			10^4	0.05	10^4	0.012		
Proper motions (arcsec/year)		$1.5\ 10^3$	0.0016	-	-	10^5	σ	2.10^5	1.4 σ
Parallaxes		6.10^3	0.013	-	-	10^5	1.6 σ	2.10^5	1.2 σ
Minor planets		-		yes		(yes)		(yes)	
Double stars		-		no		(yes)		(yes)	
Present status		Existing		Proposed		Proposed		Proposed	
Astrometric index		1		10^2		more than 10^4		more than 10^4	

The astrometric index, giving comparative evaluation of the various projects, is approximately equal to the number of observed stars N time the inverse squares of the mean error σ^{-2} (σ in units of 0.001 arc sec).

Although both options A and B clearly would lead to essential and comparable improvements in astrometric data, some comments on specific objectives of each of them are given in the following sections, 2.4.2 and 2.4.3.

2.4.2 Option A

The tentative selection of stars to observe includes 34 000 RS stars, (section 2.2.3) 60 000 PS stars of m = 11, and 10 000 PS stars of m = 14, which should obtain respectively 128s, 64s and 256s observing time per epoch. This requires nominally $11 \cdot 10^6$s of the 16.10^6 available in one half year and conforms roughly with the distribution ratio derived in section 2.2.3. The resulting mean errors are derived from Tables 1 and 2, taking the least accurate coordinate.

In a brief summary, option A can give positions with 20 times smaller errors than FK4, and for 100 times as many stars all being 100 times fainter than those in FK4. The proper motions are about as accurate as FK4. The trigonometric parallaxes will often have errors four times less than the best ones now being obtained on the ground, and for the majority of stars the error will be equal to the best obtained from the ground, but for 20 times as many stars as were observed during the past 70 years, and with higher accuracy.

The proper choice of PS stars and of their observing time must of course emerge from thorough studies and may differ from the present proposal, but not enough to affect this tentative comparison. The astrometric index at the bottom of Table 3 illustrates the order of magnitude of the statistical weights of the positions, but not the distribution on different magnitudes which is, however, shown higher up in the Table.

Thus far, observation only of stars can tie these into a rigid coordinate system, but must leave four free parameters : two zero points which have no astrophysical significance, and which may be defined to conform with ground based catalogues, e.g. FK5 and two rotations, i.e. zero points of the proper motions which must be determined to conform with an inertial system, sometimes called an absolute system or rotation free system. This is possible with the geometric method when a number of the faint stars, m = 14, are selected near to quasars to which they are then connected by photography. Reaching m = 14 allows only to observe a few quasars directly, but not compact galaxies. The dynamical method to determine the absolute rotations may be applied on observations of minor planets, but with only three years of observation and only near 90° elongation from the Sun, it will probably be difficult to separate the rotations from the orbital elements of planets and Earth. This question should be studied. Inherently better in this respect, would be the revolving scanning because it covers different elongations several times a year.

2.4.3 Option B

In this option in which a preselection of stars is not possible, all the stars of magnitude below a given value will be observed. It is proposed to observe all stars brighter than magnitude 10.5. Thus, astrometric measurements can be made on about 250 000 stars with the accuracy indicated in Table 3.

The main scientific results obtained can be summarised as follows :

(a) a sphere of reference, very coherent and accurate with many stars, covering all the surface except a small fraction of 1/400 near the poles, will be determined and will constitute an excellent reference system.

(b) the absolute rotation of the reference system cannot be measured by the observations during two years. However, a first determination with an uncertainty of 0.15 arc sec/century will be derived from a comparison with FK5.

Using the absolute photographic proper motion relative to the galaxies, with only the presently published plates of Lick, it will soon be possible to reach 0.019 arc sec/century. This precision will be improved when taking account of the results obtained by Poulkovo and of future publications by Lick after 1976.

Improvement by a factor 5 on the knowledge of the absolute rotation free of systematic error, will allow much better studies on the motions in the galaxy at larger distances.

Knowledge of the proper motions of stars, with a mean density of 6 stars per squared degree, and a precision of about 0.2 arc sec/century, as reached after two years of space observation, without systematic errors, will make it possible to correct all systematic errors in our catalogues. It will then be possible to better extrapolate the scale of distance deduced from the trigonometric parallaxes using statistical parallaxes. However, the improvements will be much more important after a new mission, ten years later.

(c) Good trigonometric parallaxes will be measured for the giant stars ($M < 0$) :

parallaxes	magnitude	accuracy	numbers of stars
0.010 arc sec	less than 5	5%	150
0.010 - 0.007 arc sec	less than 6	10%	600
0.007 - 0.005 arc sec	less than 8	20%	2100

This information will be very useful for checking theories on the evolution and the scale of distance.

(d) The number of R.R. Lyrae stars for which good trigonometric parallaxes will be measured, will be small. However, data on about 40 of them will provide parallaxes useful for statistical studies.

(e) Parallaxes of about 10 Cepheids with an accuracy of 30% and of 20 at 50%, will be measured.

(f) Diagram H.R.

From the 250 000 observable stars, about 30 000 will have their trigonometric parallaxes measured within 10%, especially for M between 0 and 8. This quite large sample will give matter for many studies on the structure of the diagram in relation to spectral characteristics, chemical composition, velocities in galaxy, age of the stars, etc.

(g) Faint stars

The small optical telescope proposed is not well adapted for measurements on faint stars. Only long integration times could deliver parallaxes measurements more accurately than from ground based stations.

(h) Double stars

Good parallaxes measurements will be obtained for the center of light, when the image projection perpendicular to the grids is not too large. Very good parallaxes for about 250 double stars, which are generally very near, will be obtained leading as a consequence to accurate mass determination.

(i) Solar system

Positions for small planets and planet satellites will be measured, however, the number of different epochs for each of these objects is too small for really useful information. In an indirect way, the elimination of the systematic errors (namely absolute rotation) in the stellar catalogues,(past, present and future) is likely to improve the orbits considered in celestial mechanics.

2.5 Improved Spacecraft Missions

2.5.1 Multiple launches

It has already been pointed out at the end of section 1.4, that launching a second spacecraft after several years would greatly improve the proper motion determinations.

The first mission covering two to three years can mainly establish a fundamental system, improve the galactic distance scale, and provide first epoch positions. A repetition after five or ten years would provide greatly improved proper motions and therefore constitute a long-term experiment of essential value for stellar kinematics and for detection of invisible companions, in addition to the further improvement of the fundamental system and the distance scale.

As has always been the case for ground based astrometry, long term aspects must be the main scientific concern of space astrometry. Such a statement does not weaken, even slightly, the importance attached to performing only a single space mission. It merely emphasises the scientific significance of two almost trivial facts :

- proper motions determinations improve linearly with increasing epoch difference

- measurement of perturbations in the motion of stars due to unseen companions, improves with the square of the time base.

Therefore, the Mission Definition Group strongly recommends, as the most significant scientific improvements, that a Space Astrometry programme should be established, calling for the launching of a second spacecraft, identical or similar to the first one, after a time of some ten years.

2.5.2 Delta launched spacecraft

As discussed in section 2.1.5, the baseline mission proposed by the Group,(options A or B) is carried out by a small spacecraft launched by a Scout vehicle delivering the scientific results discussed in section 2.4.

It is however, clearly possible to greatly improve the performances for a higher cost, when designing a spacecraft using the same general principles of larger size and mass, to be launched by a Delta (or Ariane) vehicle. The dimensions of the mirror could then be increased by a factor of about 3.

As an example, some performances expected for that larger spacecraft are presented in this section, only for option B.

The limiting magnitude will then become 13, which means that about 2 500 000 stars could be observed with a mean square error smaller than 0.001 arc sec. However, the precision on stars brighter than m = 10.5, will probably not be better than 0.0003 arc sec, due to spacecraft attitude stabilisation. The following scientific consequences can be underlined.:

(a) The extension towards faint stars and the increase in the number of stars will be quite useful for the establishment of the reference system. It will be possible to connect directly to that reference system, all measurements taken with small fields instruments, e.g. with the (L)ST.

(b) Parallaxes of giant stars

For this class of stars, the improvements will be moderate because the measurement accuracy for the apparent bright stars will be modest and the apparent faint stars are too remote.

Anticipated results are as follows :

Accuracy on parallax	5%	5 to 10%	10 to 20%	statistically useful
Giant (M negative)	500	4000	30 000	
R. R. Lyrae			20	300
Cepheids		10	30	200

(c) H.R. Diagram and dwarf stars

The expected results are :

Accuracy on parallax	5%	5 to 10%
M between 1 and 10	20 000	100 000
M " 10 and 12	500	
M more than 12	50	
White dwarfs	10	

(d) The large number and high accuracy of measured proper motions will be essential for a number of problems in stellar dynamics in the galaxy.

2.6 Spacelab-borne Instrumentation

2.6.1 Description

The design of the instrument to be flown on Spacelab follows the same general principles described in sections 2.1.2 to 2.1.4. It is, however, mounted on the Instrument Pointing Sub-system (IPS), which performs the telescope pointing towards selected pairs of stars and the scanning motion along the great circle connecting the stars.

The complex mirror, 570 mm in diameter, is formed by two reflecting surfaces at an angle of about 45°; hence the two fields of view of the telescope are separated by about 90°. The telescope, with a large mirror of the same diameter, is of the Ritchey-Chrétien type, with an equivalent focal length of about 4.3 meters and a useful field of 10' x 2'.

Special care would be required for the thermal design (super-isolation, use of cerrodur) and for protection against stray light (baffles 1.5 to 2 meters long).

The grid system is located in the focal plane, with a step of 0.8 arc sec, covering a field of 10' x 1'. Control of the dissector limits the instantaneous field to 10 x 10 arc sec; the scanning velocity is about 5 arc sec/sec and the photon counting period of some 0.01 secs. Two dissectors are used, one for each star. Stray light of zodiacal origin is reduced to the equivalent of 0.5 star of magnitude 16. The integration time can be as high as 400 seconds for faint objects (limiting magnitude about 17).

2.6.2 Instrument capabilities

The potential capabilities of the Spacelab-borne instrument can best be illustrated by the following examples :

(a) Quasars.

To be used for the determination of the reference system absolute rotation. They are 20 of magnitude less than 16, and 40 at magnitude between 16 and 17.

(b) R.R. Lyrae.

For an absolute magnitude assumed to be + 0.5, parallax measurements individually meaningful, with an uncertainty smaller than 30%, could be obtained up to magnitude 9.5 on about 20 objects. In order to get statistically significant results, the measurements would have to be extended to 300 near R.R. Lyrae up to magnitude 11.5.

(c) Cepheids.

With absolute magnitudes of about -3, only the brightest are near enough for their individual parallaxes to be meaningful. For about 10 of them, the parallaxes would be obtained within 25%, and for 40 (magnitude smaller than 7), within 50%. For the others, the determinations would be only statistically useful.

(d) White dwarfs -

Their number amounts to :

m less than 13	10	uncertainty	5%
m between 13 and 16	90		5%
"	100		5 to 10%
"	300		10 to 20%

In fact those which are companions of a double solar would not be well observed; however, they would be well determined by the companion.

(e) Red dwarfs -

The potentialities are enormous; considering only uncertainties of 10% :

M more than	14	about	150
	12		1000
	10		5000

(f) Giant -

For those with M negative :

parallax (arc sec)		uncertainty	number	magnitude m
less than	0.010	5%	150	less than 5
"	0.005	10%	1000	" 6
"	0.003	20%	4000	" 8

In particular, the Hyads would be easily observed.

(g) Double stars -

The last catalogue of double stars included 559 binaries. By a careful selection of the directions of measured arcs, their parallaxes could be determined for most of them within 5%, as they are generally near.

(h) H.R. Diagramme -

There is a very large choice on the various parts of the diagramme, with respect to age, velocity and chemical composition of the stars.

(i) Various problems -

It would be possible to check the calibration of absolute magnitude, as a function of lines H and K intensities, to obtain absolute magnitudes for W.W. Ursae major, to measure parallaxes on eclipsing binaries.

2.6.3 Observation programmes

Taking account of the Spacelab availability and of the limited duration (7 days) of the flights, programmes of observation would have to be defined for the optimum use of the instrument. It appears in any case, that 6 flights during a period of at least 2 years, would be required in order to distinguish between proper motions and parallaxes.

Various observation programmes can be elaborated. As an example, a possible choice would be :

- about 60 quasars,
- about 400 R.R. Lyrae (m less than 11.5) and 200 Cepheids (m less than 8) for the distance scale,
- about 500 white dwarfs,
- about 1000 red dwarfs
- about 3000 giant nearer than 300 parsecs
- all double stars with known or predicted orbits (about 600)
- selected stars in the HR diagramme
- special stars (eclipsing binaries, W.W. Ursae, etc.)

It is expected that about 20 000 stars would be thus observed.

SECTION 3 : SYSTEM DESIGN

3.1 Introduction

As explained in section 2.1.5, the Mission Definition Group proposed to further investigate a baseline mission carried out by means of a small spacecraft compatible with the Scout launch vehicle.

The Group also considered an improved but larger spacecraft with increased astrometric performances, to be launched by a more powerful launch vehicle, namely Delta (or possibly Ariane or Shuttle).

Finally, the Group discussed the possibilities of accommodating an Astrometry device on Spacelab, and recognised the vast potentialities of that option. However, due to the short duration of Spacelab flights, and consequently to the large number of required flights, (about 6 in 2 years) the Group did not recommend the study of this alternative as a first priority.

The following sections 3.2 to 3.7 deal with the spacecraft design; section 3.8 discusses some engineering aspects of the Spacelab device.

3.2 Orbit Selection.

For a regular scanning along great circles, the orbit should be circular. Moreover, in order to avoid radiation damage in the inner radiation belt, the orbit should be as low as is compatible with the required lifetime of at least 2.5 years. This leads to an altitude of about 550 km. (depending on the solar activity during the operational lifetime).

For reasons of power generation and in order to minimise the thermal problems, a "sun-synchronous" orbit appears to be the first choice. However, this implies that the scanning of a given region of the sky occurs at similar positions of the Earth, which may render the determination of the parallax difficult. It is therefore suggested to select the inclination in such a way that the initial node is at :

$$\Omega = \alpha_{\odot} + 270° - \Delta\alpha$$

and becomes after five scans $\alpha_{\odot} + 270° + \Delta\alpha$

such that the orbit is only in the mean "sun-synchronous". This, however, increases the eclipse time. The optimum launch period is around the spring equinox, which minimises the total eclipse time.

The following table shows the minimum eclipse time for 3 different values of $\Delta\alpha$:

$\Delta\alpha$ (degrees)	inclination (degrees)	time for 5 scans (years)	minimum total eclipse time (percentage)	maximum duration of an eclipse (minutes)
0	97.79	2.5	3.8	22
20	98.15	2.4	4.9	23
40	98.35	2.3	11.9	26

3.3 Launch vehicle and performance

3.3.1 General

Two categories of launch vehicles were considered for the spacecraft options :

- Delta 2310
- Scout D

3.3.2 Delta 2310

This is presently the launch vehicle in its category with the smallest available payload mass. For sun-synchronous orbits, launches from Western Test Range will provide the following capabilities (including 27 kg. attach fitting) :

- 500 km. altitude .... 900 kg.
- 1500 km. altitude .... 550 kg.

In order to launch a 40 cm. telescope, a Delta-class vehicle is the minimum to be considered. However, its excessive mass capability rules it out, except if it is considered to launch a complex, multiexperiment spacecraft. The alternative seems to be a Shuttle launch of a 250-300 kg.-class spacecraft, where the Space Transportation costs could be shared with a number of other payload elements. Such a launch, in a nearby polar orbit, cannot take place before 1984.

3.3.3 Scout D

The preferred solution will be a Scout-launched spacecraft, for which a design similar to the Astronomy Netherlands Satellite (ANS) seems adequate. Scout-launch vehicle will remain available in the early 1980's.

With a spacecraft ballistic coefficient estimated to be 0.007 m2/kg, and assuming a stagnation temperature of the molecular flow of about 1000° C, the following circular orbit altitude requirements are derived :

2 years lifetime .... 492 km.

3 years lifetime .... 550 km.

These values are probably very conservative, so that we can plan for a launch into a circular orbit with 550 km. altitude, although perigee deviation (at 95% probability level) could be as large as -240 km. By admitting a loss in payload of about 3 kg., planning for a 550 x 650 km. elliptical orbit, the perigee deviation (at 95%) would not exceed -160 km., for 0 km. apogee deviation. Using the Scout D launch vehicle, we then obtain a spacecraft mass of 125 kg., including a substantial margin at this stage of the study.

Residual orbit eccentricities (at 95%) will remain in the 0.01 - 0.02 range.

3.4 System Requirements

3.4.1 General

Besides those dictated by the scientific experiment package, the spacecraft system requirements are conventional, and pertinent to attitude-scanned spacecraft placed on sun-synchronous orbits. It is thus of interest to briefly recall the essential characteristics of the experiment package (see sections 2.2 and 2.3 for detailed analyses), which are drivers to spacecraft system design.

Let us recall that the mission will be flown with a single experiment, i.e. the astrometric telescope, for which system two basically different options exist, according to different scientific objectives.

Option A is an experiment where absolute positions of individual stars are necessary, as well as relative positions of two stars falling simultaneously in the field of the instrument. Preprogramming of stars to be observed is considered there as an advantage.

Option B relies entirely on a sequence of two or three stars falling simultaneously in the instrument field of view. Selection of observed stars is according to spacecraft instantaneous attitude.

3.4.2 Mission duration

Option A calls for more than 2.5 years of observation. Orbital altitude (assumed circular) must be at least 500 km.
Option B accepts a 2.3 years lifetime. The orbital requirement must be considered same as above.

3.4.3 Instrument accommodation

Considering launch vehicle limitations, the baseline instrument to be accommodated will have a length of about 1600 mm., with a 230-250 mm. diameter of the primary, and a complex mirror consisting of a set of plane mirrors. Baffles will be required along the directions of observations.

Option A has 2 directions of observation, symmetric about the main optical axis, and separated by 84 degrees.

Option B also has 2 directions of observation, separated by 79 degrees.

Both types of instrument are considered to use image dissectors as sensing elements, thus having the capability of tracking a target across the whole detector field of view. Size of the instantaneous field of view is somewhat different for both options.

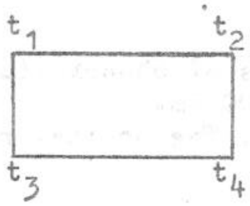
Option A has a grid system perpendicular to the scanning direction, whereas Option B uses a network of mutually parallel polygonal lines with segments inclined by ±45° to the scanning direction, successively across the detector's field of view.

3.4.4 Thermal requirements

Internal alignment must be kept constant over a certain period of time, typically 20 minutes, corresponding to a quarter of the total orbital scan.

The following table summarises the time variations of temperature gradients across the instrument which must not be exceeded. (over e.g. 20 min.)

	Option A	Option B
Across complex mirror	0.05°	0.05°
Across corrector	$\Delta <$ 0.01°	Not applicable
Secondary-primary mirrors	0.1°	0.1°
Secondary-complex mirror	0.5°	0.5°



$$\Delta = (t_1 - t_2) - (t_3 - t_4)$$

<u>Option A</u> - The effective angle between the two optical axes must be kept constant within 0.001 arc sec over a time of about 20 mins. A complete calibration of the angle is obtained on each scan so that longer term changes are less critical. A cause for a change of angle would be a change of temperature gradient across the complex mirror; another would be a change of the difference between the temperature gradients across the corrector plate in the two beams. The table allows a contribution of 0.0005 arc sec for each cause.

<u>Option B</u> - No corrector plate is foreseen.

<u>General</u>

The scale value across the slit system should not change more than 0.0003 arc sec during 20 minutes due to a change of temperature of the invar tube between the secondary and primary mirrors. The connexion between the secondary and complex mirrors is less critical and the requirement is only tentative.

The table implicitly assumes mirrors in zerodur (thermal expansion coefficient $5.10^{-8}/°C$), a corrector of 8 mm BK7 at -20°C for option A, tubes of invar (coefficient $0.6\ 10^{-6}/°C$) between the optical parts, a field of 90 arc min in option A, and of 30 arc min in option B. A Zerodur support of the primary mirror could be used to relax the temperature requirements if necessary.

3.4.5 Pointing requirements

Pointing, or - more correctly - attitude scan requirements are different for both options. The following table summarises those values. (at 3-sigma levels)

	Option A			Option B		
Experiment characteristics	30°-inclined scan Field 80' x 50'			Sun-synchronous scan Field 25' x 25'		
Spacecraft axis	X	Y	Z (rotation axis)	X	Y	Z (rotation axis)
Nominal attitude	ZX contains vertical	normal to zx	22° from orbit normal	vertical	velocity	normal to orbit
Absolute pointing error	± 2°	± 2°	± 5°	± 2°	± 2°	± 5°
Attitude reproducibility between consecutive orbits	± 10'	± 10'	± 5°	Not applicable		
Rate	0	0	220"/sec	0	0	220"/sec
Rate error	± 10"/sec	± 10"/sec	± 10"/sec			
Accelerations	Not applicable			± 0.3"/sec^2	± 0.3"/sec^2	± 0.3"/sec^2
Jitter (error on time average of angle)	± 1"	± 1" (for T = .2 sec)	± .025"	± .003"	± .003" (for T = 0.1 sec)	± 0.003"
Onboard attitude determination	± 5"	± 5" (after 30" elapsed)	± 5"	Not applicable		

In option A, the attitude should be determined on board the spacecraft by other means than use of the instrument signals.(e.g. gyroscopy, sensors)

3.4.6 Data acquisition, storage and processing

For both options, the basic process is to acquire photoelectron counts from stars imaged on the screen of the image dissector, then to average them on a time corresponding to the scan of a fraction of the detector field of view (typically, 1 sec.). Due to the impracticality of ensuring ground coverage by more than 1 or 2 ground stations, storage of the 'compressed' data is essential. Processing will also be requested, in addition to "photoelectron count compression", to elaborate very accurate attitude scan rates (and parasitic motions) from star sensor data and from the counts themselves.

Due to its more complex grid pattern, and to its dependence on external fine attitude reconstitution, Option B requires more processing than Option A.

Assuming the availability of only 1 ground station, and depending on rate stability and onboard processing capability, both options could require data storage capacities as high as 10-20 Mbits, in order to accommodate compressed data between instants of ground transmission (this could be doubled for a 40cm telescope accommodated in a larger, heavier and more performant spacecraft).

3.4.7 Power requirements

The experiment will have to operate continuously at a maximum rate of 7 watts. This will possibly pose problems at the epochs where eclipses will occur. High voltage supply (2kv) is required for the image dissectors.

3.5 Spacecraft Configuration

The configuration will be typical of an orbital scanning spacecraft (like TDIA, ANS), placed on a sun-synchronous orbit, with the sun grossly normal to the orbit plane. A box-type architecture will be adequate, possibly with solar panels folded over the telescope apertures, in stowed position for launch (see Fig. 7), and extended in the plane of the telescope's optical axes in the operational conditions (see Fig. 8).

In this configuration, the telescope baffles could not protrude outside the spacecraft skin panels. Alternatively, both solar panels may be stowed against the spacecraft back panel in the launch configuration, thus imposing no constraint on baffle length. The suppression of parasitic light originating from the sun and the earth albedo by appropriate baffling generally constitutes a serious problem. In the context of this project, however, it is eased considerably by the fact that the position of sun and earth with respect to spacecraft coordinates varies only over a limited range. This allows the use of structural elements of the spacecraft itself to serve as shields against parasitic light leading probably to a significant reduction in the size of the baffle proper. Moreover, the telescopes are always pointing away from the earth; with respect to the sun, canted baffle apertures can be envisaged allowing space itself to act as a sink for unwanted radiation.

Equipment (electronics, computer, etc.) will be fixed on the structural panels which also hold the telescope. This at least is mandatory for a small Scout-launched spacecraft (for mass reasons). For a bigger spacecraft, which would accommodate the 40 cm-telescope, a modular type of arrangement is obviously achievable, as the weight constraint then disappears.

Spacecraft antenna will have to be mounted at the end of a boom, in order to ensure little spacecraft interference, if S-band (2200MH) is used. In the case of gravity gradient stabilization, a long boom (10 m) will have to protrude from the spacecraft body, parallel to the main optical axis of the telescope.

3.6 Spacecraft Sub-systems

3.6.1 Structure and thermal

Considering again the baseline telescope to be accommodated in a Scout-launched spacecraft, a good example of a convenient structure is a double-H, similar to ANS (see Fig. 9). The primary mirror square mount will be fixed to the inner panels of the structure. Structural reinforcement will be necessary, due to the presence of lateral holes for instrument viewing. The base of the structure will be carrying a ring to match the Scout launch vehicle adaptor top section. Conservation of telescope alignment under launch constraints is one of the major problems to be studied during phase A; it is also a critical area for the design of the spacecraft, although in view of the set of requirements of section 3.4.4, proper design does not seem difficult to achieve.

Simulation results for a 40 cm. aperture telescope show that, over 15 minutes, thermal exchange between instrument and spacecraft should not vary by more than 0.6 watts, in order to ensure thermal gradient along the telescope not to exceed 0.04°C. This is well within the possibilities of passive thermal control (insulating blanket around the instrument).

Thermal exchange from the surface of the complex mirror towards cold space at 2.8°K for the 40 cm. telescope, will be of the order of 10 watts/beam. Thus, as a maximum, 1 watt from controllable electrical heaters would be required to obviate dissymetries, if any, of thermal flux across the complex mirror.

The situation is even better for the approximately 20 cm. aperture telescope associated with the Scout-launched spacecraft.

3.6.2 Attitude measurement and control

i) Stabilization modes

From the requirements as explained in section 3.4.5, the baseline spacecraft will have to point an inertially fixed direction, either normal to the plane of the orbit (option B), or inclined at a fixed angle from the Sun's direction, in a plane containing this direction and perpendicular to the orbit (option A). For both options, the spacecraft shall rotate about the pointing axis at the orbital rate. It is recalled that emphasis is put on the regularity of attitude motion. An improvement to the baseline option A will require the pointing axis to revolve in a conical motion about the direction of the Sun, with a period of 2 months.

ii) Attitude control

The use of reaction jets is discarded, in order to avoid contamination on the optics. In view of the requirement of motion regularity, the suitability of momentum wheels and more generally of gyroscopic devices, will have to be carefully checked in the course of the feasibility (phase A) study.

For a momentum wheel of 25 Nm (HSA-FMW-25), torque noise is estimated to be 4×10^{-5} Nm, which would just provide acceptable performance of the experiment in option A. However, fixed axis momentum wheels with magnetic bearings are already under development, and it is expected that their torque noise be reduced by at least an order of magnitude with respect to those using conventional bearings.

Altogether, option A definitely rules out passive (gravity gradient) stabilization, because of the requirement of pointing away from the normal to the orbit (30° from Sun line); thus, stabilization by a wheel is mandatory. For both options, the axis of the momentum wheel would be fixed in the spacecraft, normal to the telescope main optical axis, and directed along the axis of spacecraft rotation. This type of stabilization has been successfully employed in the U.S. Small Astronomical Satellites (SAS).

Passive stabilisation would be suited to option B, although the feasibility study may conclude that torque noise from momentum wheels is also not critical.

A deployable boom will be extended in the direction of the telescope's main optical axis. A mass of 5 kg at the tip of a 10 m boom will give pitch and roll moments of inertia of about 500 m^2kg, to be compared with the spacecraft alone moments of inertia of the order of 5 - 15 m^2kg. With an orbital rate of about 10^{-3} rad./sec (period approx. 100 min.), and external torques of the order of 10^{-5} Nm, amplitudes of motion of a few degrees will be achieved, about pitch and roll axes (spacecraft rotation is about the pitch axis). A residual spacecraft magnetic moment of the order of 10^{-1} Am^2 would not enable the Earth's magnetic field to generate torques exceeding 10^{-5} Nm (e.g. ANS Specification : .5 Am^2 - ANS actual : 1.2 Am^2 maximum). Suitable damping must be of course provided, because of the low natural damping of the system; magnetic torquers may be used to this purpose.

Among other problems to be investigated during the phase A study, are for instance, that of stability, related to thermal bending of the boom. But the main problem is yaw motion (about local vertical, thus affecting the rotation axis) which may be at least 10 times larger. It may be compensated by periodic magnetic torquing, or by use of an auxiliary momentum wheel along pitch axis.

iii) Attitude measurement

Suitable attitude and rate information is required (see section 3.4.5) in order to :

- if a momentum wheel is used, provide wheel rate control
- orient the rotation (pointing) axis
- generate information on attitude to assist in experiment data processing

In option B, if the spacecraft is gravity-gradient stabilized, rate information from a sensor external to the experiment is not required.

Conversely, wheel stabilization (mandatory for option A), must be controlled from rate information, generated by a gyro of the 'inertial guidance' class of accuracy (random drift of the order of 10^{-2} deg/hr.).

IR Earth sensors are foreseen for gyro update, and Sun sensors for attitude measurement, in order to maintain the attitude bias in its specified limits and to ensure adequate sky coverage for all 5 epochs. Accuracy requirements appear moderate and resemble those obtained in the TD project. Therefore the astrometry project does not require major new technological development in the field of Earth and Sun sensors.

As regards Earth sensors, the use of conical scan sensors of the type employed in TD or ANS is envisaged for intermittant gyro update. Within the research and development activities of ESA, the development of a high accuracy pitch and roll sensor will be particularly attractive in the case of orbital scanning,(option B) provided the sensor development schedule can be made compliant with the project schedule envisaged.

Sun sensors are unlikely to present any technological and development problems in case of the orbital scanning mode. In these modes the ANS sun sensor can be employed directly, most probably with a minimum of modifications required. In the inclined and revolving scanning modes, however, a development effort may be required to cope with varying offset requirements becoming necessary.

An onboard computer required by experiment data processing, will assist in elaborating real time attitude and rate from sensor signals.

3.6.3 Data storage and processing; telecommunications

Requirements have been defined in section 3.4.6. To perform onboard reduction of the raw data (individual counts of photoelectrons, grid locations, time), a computer will be advantageous. Such a computer, with a memory of 500 kbits, has been flown on ANS. An alternative is the onboard computer developed and qualified under ESA's Applied Research Programme. The latter is probably more advisable in view of its short operating time (a few micro-seconds for addition), with respect to the high input rate (about 500 bps) continuously involved during experiment operation. Experiment data rate may be reduced by a factor of 2 or more, if sufficient regularity of spacecraft motions is ensured.

Depending on the number of ground stations foreseen in the system, a certain amount of onboard storage of reduced data will be necessary. Coverage with one single ground station results in an interval of 12 hours between times of visibility. Thus, about 10 - 20 Mbit storage is required. With present state-of-the-art technology, tape recording is mandatory. However, for a launch in the early 1980's, the tape recorder may be replaced by solid state storage devices, e.g. 'magnetic bubble' memories, presently under development. Data from the memory will be dumped to the ground station at each passage. Accounting for a 10 minute visibility period, a maximum of about 35 kbps will be required. The maximum slant range in a passage being of the order of 2000 km (for 600 km flight altitude), and ground reception assumed to be in S-band (about 2290 MHz) by a 9 m diameter dish antenna, about 200 kbps could be transmitted with a very good error rate (10^{-6}) with a 1 watt-RF transmitter, via an own S-band antenna. Quasi-omnidirectional antennae in S-band have already been flown, e.g. on Pioneer-Jupiter spacecraft.

VHF (137 MHz) carrier may be considered, if the telemetry rate does not exceed about 20 kbps, due to bandwidth limitation (with 1 watt RF power, 64 kbps are theoretically possible, with 10^{-5} bit error rate).

For the case of the larger satellite - 40 cm. telescope - there would be no mass/power problems (due to the available margins) in storing 42 Mbits during 12 hours, and transmitting these at a rate of about 70 kbps during 600 seconds of visibility. For this version, the use of NASA's Tracking and Data Relay Satellite System (TDRSS) may also be envisaged, to minimize data storage requirements. The penalty is in requiring larger spacecraft power (several watts) and a medium gain antenna (e.g. toroidal pattern). Ground processing of the data will, no doubt, be an important part of the system, to be assessed during phase A studies. Although not critical, the amount of investment and operations to be involved may be important.

3.6.4 Power

The maximum spacecraft power budget may be estimated as follows (values in watts) :

Experiment detectors	2	(continuous operation)
Experiment electronics	5	(" ")
Mirror heaters	2	
Att. measurement (optical)	5	(continuous operation)
Mag. torquers	13	
Tracking, telemetry, telecommand	3.5	
Computer	8	(continuous operation)
Tape recorder	5	(continuous); 10 watts during ground station visibility
RF	8	
	51.5	

If, in addition, a fly wheel and gyro system is required, the maximum increase in power consumption is :

Momentum wheel	17	
Gyro system	6	(including temperature conditioning)
	23	

The maximum power requirement is thus 74.5 watts (or 79.5 watts during ground passes, 10 min./ 12 hrs.).

This can be satisfied with a solar generator (two deployable rigid panels), providing about 95 watts at the end of life after 3.5 years of operation, supplemented by a conventional Ni-Cd battery. The size of the ANS panels (2 x 0.41 x 1.23 m^2) is of course suitable, assuming cells with an efficiency at the beginning of life of about 10%.

3.6.5 Mass budget

The following preliminary mass budget may be derived :

	Option A	Option B
Experiment, including detector and electronics	14.3	16.8
Structure and thermal	42	43
Power	12	12
Attitude control	20	12
Onboard computer	6	6
Data storage (tape)	7	7
T, T & C	8	8
Margin	15.7	20.2
Total	125	125

For attitude control, a gyro system similar to SAS-C is included in option A. Option B is assumed to be passively stabilised, with a mass of 5 kg. at the tip of a 20 m. telescopic boom, without reaction wheel nor gyro system.

The mass budgets have been established in assuming the use of existing hardware, or short-term development. They show that at this stage of the study, sufficient margin is available for a spacecraft to be launched by Scout D in a circular orbit at 550 km. altitude.

3.7 Trade-offs for the Feasibility Study

The study on the experiment having concluded in an acceptable performance with an approximately 16 cm. telescope, and this solution appearing to be best accommodated in a 'Scout-class' spacecraft, will have to be considered as the baseline option. A step further in scientific return could be gained by the original 40 cm. telescope, accommodated in a larger spacecraft, although launch vehicle selection becomes less obvious.

Besides configuration, the main trade-off investigations shall bear on attitude measurement and control, but selection of spacecraft rotation axis (on scientific grounds) will have a major impact. However, detailed studies may reveal that simulation results in insufficient performance of gravity gradient stabilization (large yaw motions).

Attitude trade-offs will impact requirements on data processing (onboard) and data transmission. Ground command capability will also have to be carefully evaluated. Finally, it is expected that, due to uncertainty on future available ground stations, the option between VHF or S-band carrier frequencies remains open (the possibility of removing bandwidth limitation in VHF is also to be looked upon).

Spacecraft operation timelines will have to be studied in order to improve the evaluation of the power budget and sizing of power generation subsystem.

Eventually, it is recalled that ground data processing of the experiment (and attitude reconstitution) shall be part of the study.

3.8 Spacelab-borne Instrumentation

3.8.1 Accuracy

Simulation results of the Spacelab Instrument Pointing System (IPS) (Ref. 3), based on a '3-axis' mathematical model, show accuracies (under disturbed conditions) which are well within the specified performance.

Goals from the specification are recalled hereafter (unit: arc/secs).

	Line of sight	'Roll'
Bias Error	.8	15
Quiescent stability	.33	1.6
Man motion	1	4

From 3-axis simulation, we get line of sight motions bound by :

Amplitude	.2"
Rate	.1"/sec
Acceleration	.2"/sec^2

Roll amplitude should not exceed 4"

Line of sight manoeuvres could be done at a rate of 2.5 deg/sec.

3.8.2 Physical accommodation

The simplest way to accommodate the instrument is to align its main optical axis along the 'line of sight' of the IPS. By proper software implementation, the IPS is then certainly capable of :

- orienting one of the 2 viewing directions, selected as the reference direction (45° from main optical axis)
- once the reference direction is pointed to its target star, rotate the instrument about it so that the other viewing direction points the other selected star

This scheme calls for a combined motion of the IPS line of sight and roll.

The difficulty lies with accuracy of roll motions, the impact of which should be assessed in the course of a phase A study.

An alternative accommodation would be to mount the instrument canted on the IPS, so that the 'reference' viewing direction would be aligned with the IPS line of sight, but this is not preferred for the following reasons :

- difficult instrument clamping for launch and landing, its body being inclined with respect to IPS line-of-sight
- restriction of IPS motion due to instrument orientation with respect to IPS
- incompatibility of astrometric telescope with other instruments on IPS
- more impact of IPS roll inaccuracy

The primary mirror of the telescope, weighing about 10 kg., will be located near the remote end of the instrument from the IPS base plate, as well as the detector package and electronics will be. Thus, mass will be concentrated at the extremity of the telescope. The dynamics of the motion during IPS manoeuvres, as well as the problems of clamping for launch and landing, and of launch environment, require investigation.

3.8.3 Use of Spacelab energy resources

During manoeuvres, assuming that they will use the maximum IPS velocity of 2.5°/sec, the maximum power consumption of IPS is assumed to be 1100 watts.

During exposures (pointing) or small amplitude scans at a rate of 5 arc sec/sec, the power consumption is assumed to be 350 watts.

In addition, the instrument detector and signal electronics are assumed to consume a maximum of 20 watts in permanence.

Accounting for 20 hours per Spacelab mission, with average exposure time of 10 sec. (minimum : 4 sec. maximum : 400 sec.), and about 2400 exposures, the total energy consumption amounts to about 17 kwxhrs per mission. The average power thus corresponds to approximately 0.85 kwatts.

These figures are to be compared with Spacelab energy available to payloads. For a typical short module/three-pallet configuration, Spacelab Payload Accommodations Handbook (May 1975 edition) indicates the following capability :

- average power 3.8 kw max.
- energy 391 kwxhrs max.

It is thus observed that operations of IPS associated with the astrometry mission are compatible with Spacelab resources. However, the average power consumption of 0.85 kw means that - during these operations - a substantial amount of total payload power will be consumed.

3.8.4 Use of command and data management system (CDMS)

The software of IPS, to perform the orientation and scanning programme, is operated through CDMS. It is presently difficult to assess how much of CDMS resources will be utilized in this respect, in view of the very frequent manoeuvres required from IPS, but it is probably not critical.

The experiment data, basically photon counts, will be processed by CDMS. Photon events will be accumulated every counting interval (0.1 second) in the experiment counter. Data output will be processed at a rate of approximately 320 bps (10 counting intervals/sec, motion parameters, etc.) through one of the 3 RAU's (remote acquisition units) available from the IPS. For 2400 exposures with an average exposure time of 4 seconds, the total information return amounts to 3 Mbit/mission. Real time transmission to the ground through CDMS will be utilized.

3.8.5 Crew time

Due to the fast rate of IPS manoeuvres for the astrometry operations, the programme of observation shall be of a high degree of automation, using the experiment computer to generate the sequence of manoeuvres. It is thus expected that crew intervention will be required only for such operations as periodic checks, calibrations, etc. This experiment will probably not be very demanding in terms of crew occupation.

3.8.6 Conclusion

Implementation of the astrometry experiment as proposed is certainly feasible on Spacelab. The experiment package would probably be mounted on the IPS together with another telescope, the diameter of which could probably attain 1 m if so wished (subject to total package mass, and Center of gravity offset, constraints with respect to IPS). The configuration of Spacelab could even be "long module and one-two pallet", or any other pallet combination. Use of CDMS, orientation programme of IPS, and crew occupation will be acceptable.

Problem areas to be investigated during a feasibility study include, among others :

- clamping of IPS payload if two telescopes are mounted (astrometry and another experiment).
- compatibility of IPS power consumption during astrometry operations (but total energy should not be a problem).
- software problems,(orientation and scanning laws from CDMS computer, etc.) especially in view of the combined line of sight roll motions required by the nature of the experiment, i.e. two separate simultaneous viewing directions.
- Spacelab mission analysis (optimal orbit, attitudes, etc.) and operations.

SECTION 4 : MANAGEMENT, TIME SCHEDULE AND FUTURE ACTIONS

4.1 Management Scheme

Three different possible Space Astrometry projects have been identified by the Mission Definition Group; their design and their expected scientific performances are described in the preceding sections 2 and 3.

The three possible projects are :

- a baseline mission, preferred and recommended by the Group, consisting of a small spacecraft (mass of about 125 kg) to be launched by a Scout vehicle.
- a larger spacecraft, of about 400 kg mass, with improved performances, which can be placed into orbit by several space transportation systems (Delta, Ariane, Shuttle).
- a Spacelab-borne instrumentation, to be mounted on the Instrument Pointing System (IPS), requiring at least six flights during a period of two years.

The management methods to be applied for the project development have not been discussed by the Group, as these are beyond their terms of reference. However, for the spacecraft versions, and particularly for the baseline, it appears that due to :

- the "one-experiment only" nature of the projects,
- the closely interrelated design requirements of the scientific package (telescope and image analysis) and of the technical sub-systems (e.g. attitude control, thermal control),
- the large amount of the scientific community interested in the data processing and in the exploitation of the results,

the project should preferably be carried out as a facility. This means that the spacecraft, including the experimental payload, would be developed under the responsibility of a main contractor under ESA's supervision. The total cost therefore, would be charged to the scientific budget. This conclusion is only tentative and subject to the usual approval procedure.

4.2 Involvement of European scientists

Astrometry Space projects are potentially of interest to a large number of scientific groups and experts in Europe. The community of astrometrists is very active in Europe, but has not yet entered the space age; the Frascati symposium in October 1974, has demonstrated their interest in this new promising method. In addition, as explained in section 1, the expected results and improvements to present knowledge are of fundamental importance to astrophysicists, celestial mechanic specialists, geodynamicists, etc.

The successful accomplishment of Space Astrometry will require a concerted effort of ESA and of a number of astronomical institutions during the development and operation of the satellite (or Spacelab payload). But in addition, it must be realised that a simultaneous effort to obtain other accurate basic observational data from the ground for some 100 000 stars, would be highly desirable. The determination of space velocities of the stars would strengthen the kinematic information which is required for the study of galactic structure. Therefore, radial velocities and distances should be determined together with spectral types, for example by multi-colour photometry.

The development and launching of the spacecraft as well as data acquisition and transmission to the ground would be ESA's responsibility. Supporting work which would be expected from astronomical institutions may be listed as follows, in intervals of years corresponding to an assumed space mission during 1981 to 1983 :

1.	Selection of stars for observation	1977-1980
2.	Development of data reduction procedure	1977-1980
3.	Data reduction (positions, proper motion, parallaxes)	1981-1985
4.	Application of astrometric data	1985-
5.	Measurement of radial velocities	1980-
6.	Measurement of photometric data	1980-

4.3 Time Schedule and Future Actions

The time schedule for the development of the baseline mission is estimated as follows, accounting for decision-making and approvals as required :

- execution of phase A (Feasibility)	: 8 months	October 76-June 77
- execution of phase B (Detail Design)	: 8 months	October 77-June 78
- development	: 3 years	August 78-August 81
- launch	:	August 81
- operations	: 3 years	August 81-August 84

A similar schedule, with mirror modifications, would apply to the development of a larger spacecraft.

For the Spacelab-borne instrumentation, it is estimated that flight operations could take place from mid-81 on.

The content of the phase A (Feasibility) study, if approved, should include two parallel main activites :

- a theoretical optimisation analysis, by which the final performances could be accurately determined. This study, to be carried out with a sophisticated software to be implemented, should aim at evaluating, by variations of the main parameters, the influence of the various parts of the system, at defining the optimum trade-offs and finally at investigating the data processing methods. Clearly, a statistical approach will be required for a number of characteristics. The main elements to be simulated include in particular :
  - the telescope and the complex mirror (e.g. diffraction patterns, aberrations, etc.),
  - the grid systems and the dissector control and response (homogeneity, sensitivity, photon counting output, etc.),
  - star characteristics and stray light (limiting magnitude, colour, baffling, etc.),
  - attitude control (accuracy, stability, rates, noise, etc.),
  - thermal variations,
  - onboard data compression, storage and transmission
  - data processing (filtering, iterations, construction of the celestial sphere, etc.).
- a usual technical system and sub-systems study, based on the findings of the preceding analysis, aiming at defining the spacecraft design down to the level of sub-systems. This study would include a precise evaluation of the management scheme, of the development schedule and an estimate of the required resources and of the project total cost.

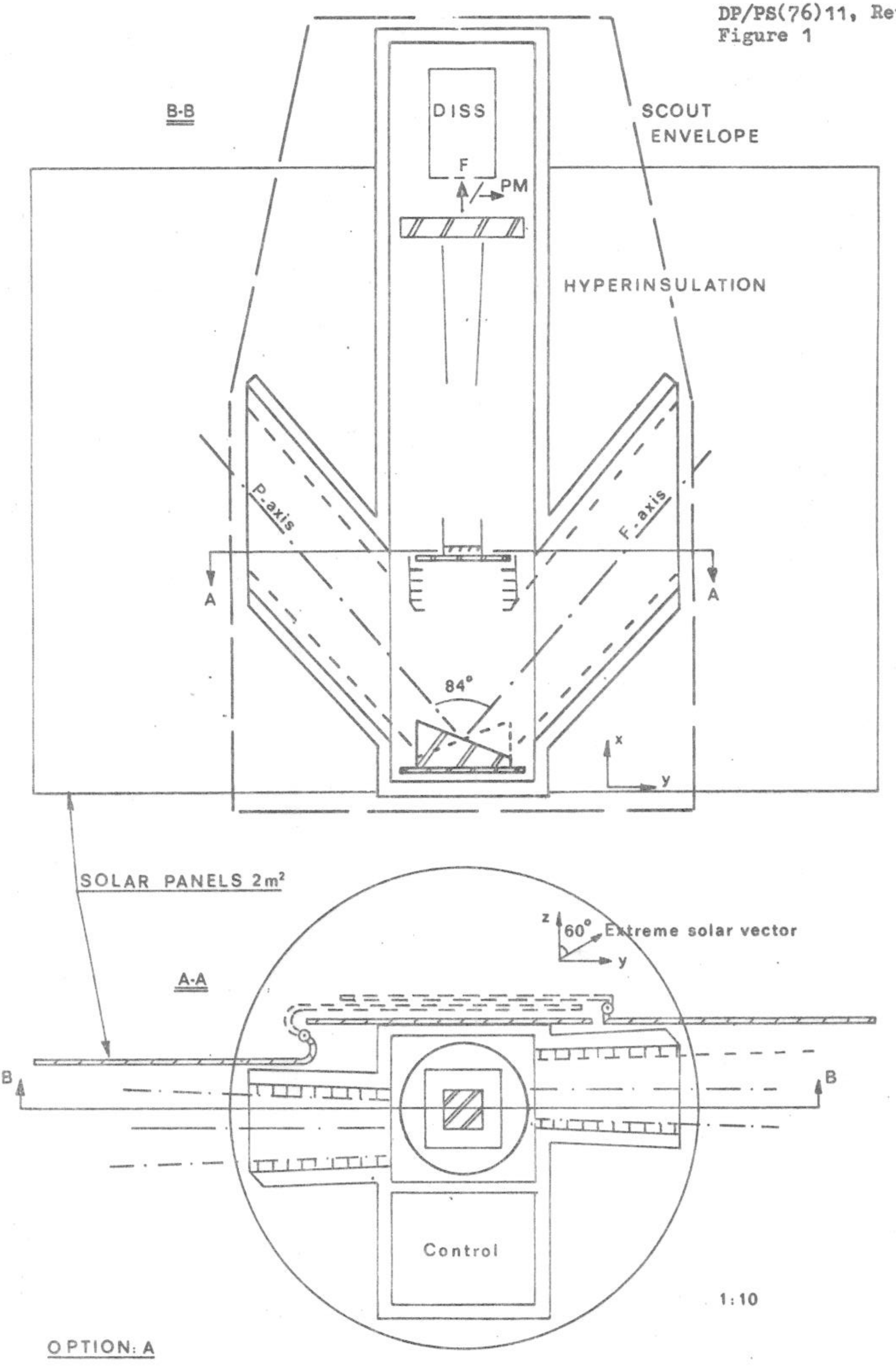
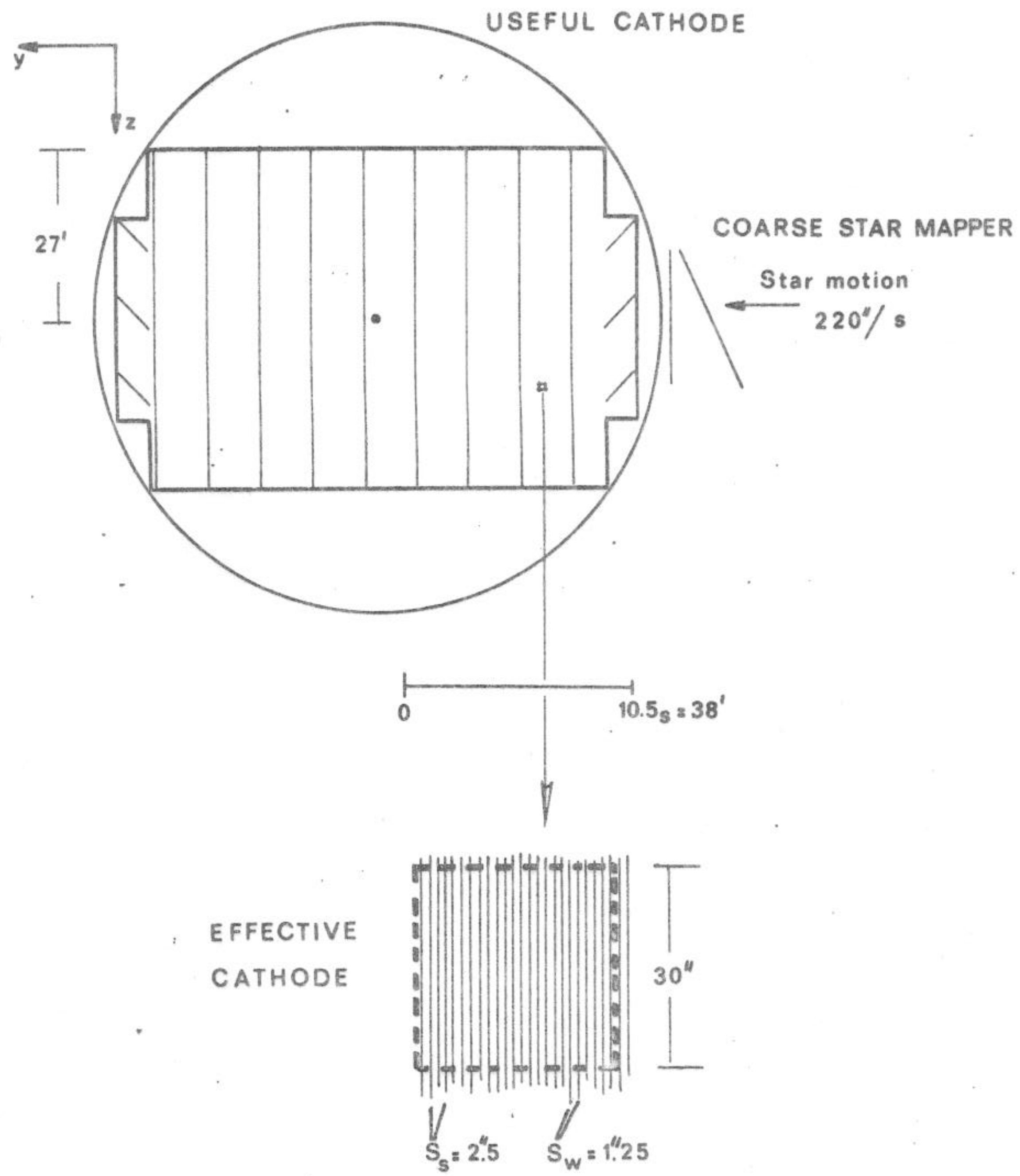
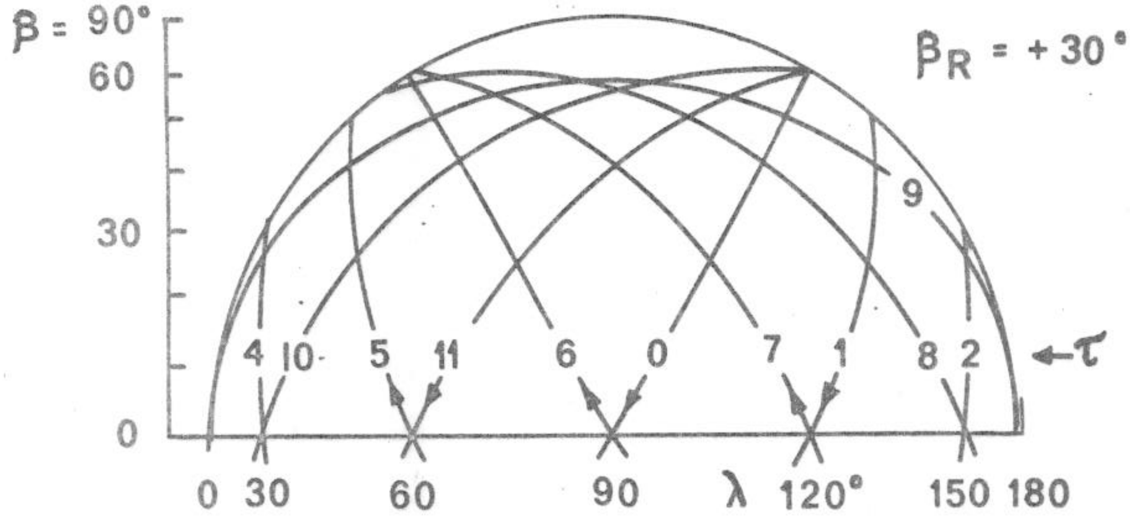

B-B
DISS
SCOUT ENVELOPE
F
PM
HYPERINSULATION
P. axis
F. axis
A
A
84°
x
y
SOLAR PANELS 2m²
z
60°
Extreme solar vector
y
A-A
B
B
Control
1:10
OPTION: A

FIG.1



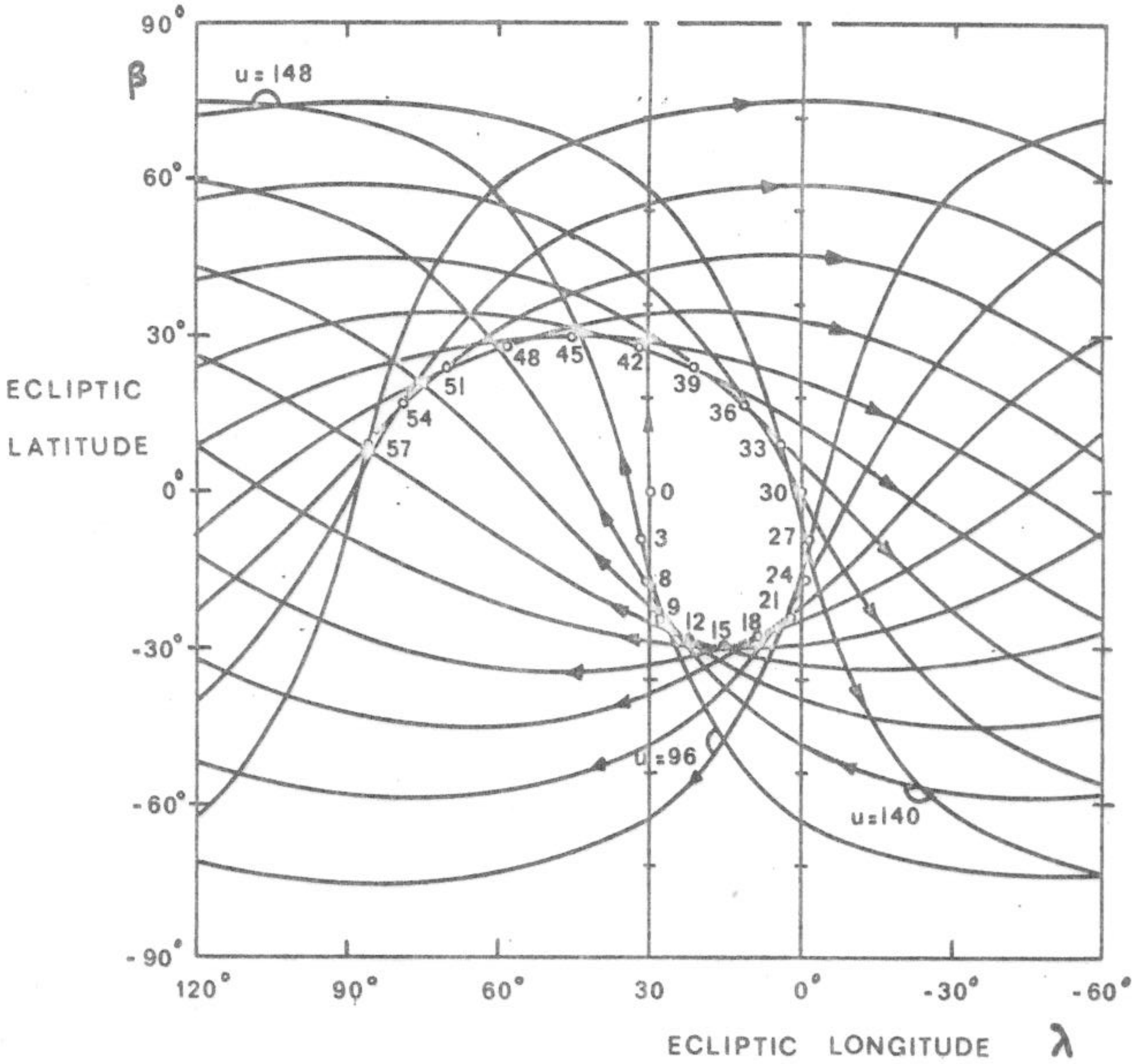
SLIT SYSTEM - OPTION A

FIG. : 2



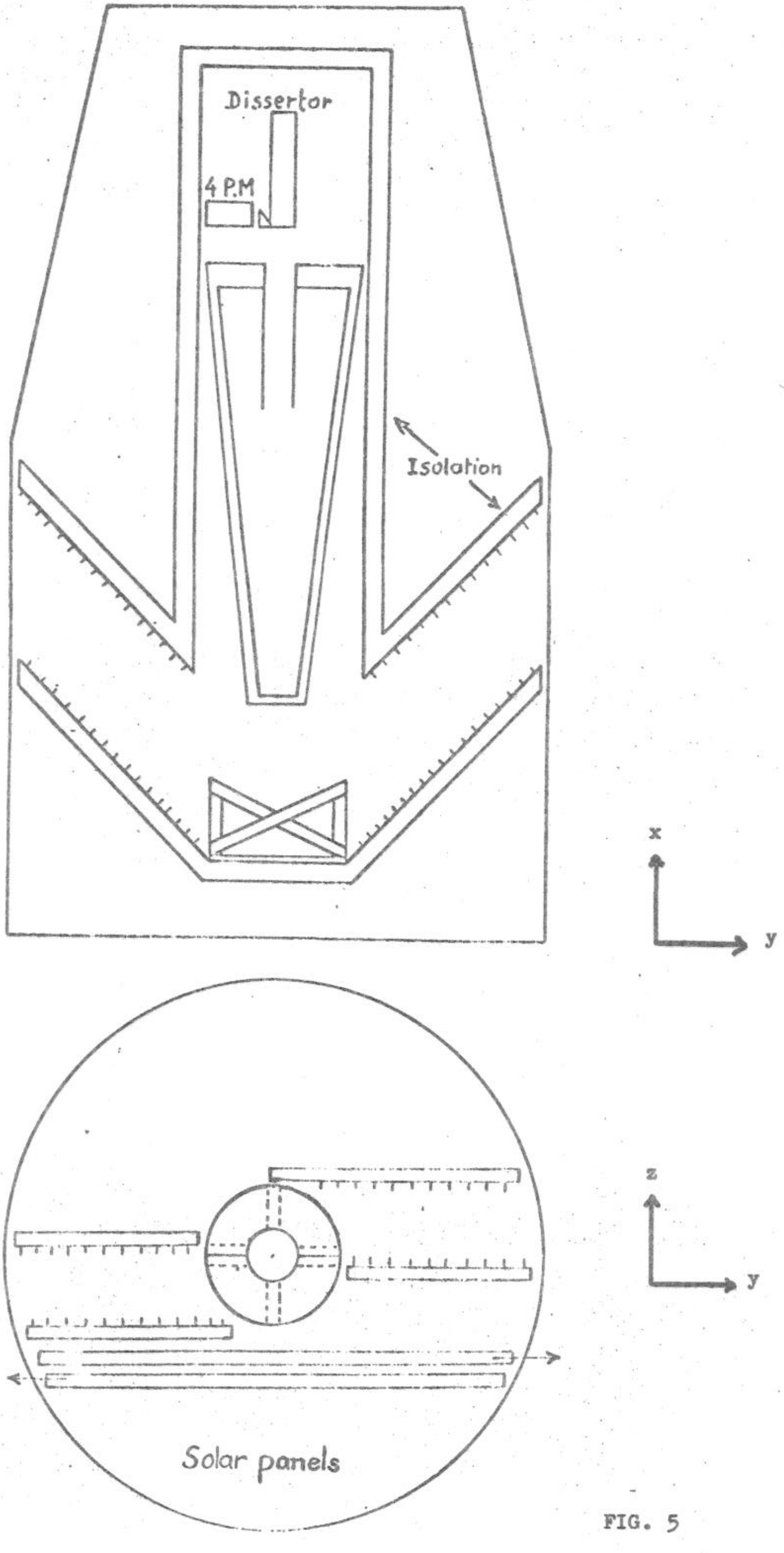
INCLINED SCANNING - OPTION A

Fig. 3



REVOLVING SCANNING - OPTION A

Fig.4



OPTION B

FIG. 5

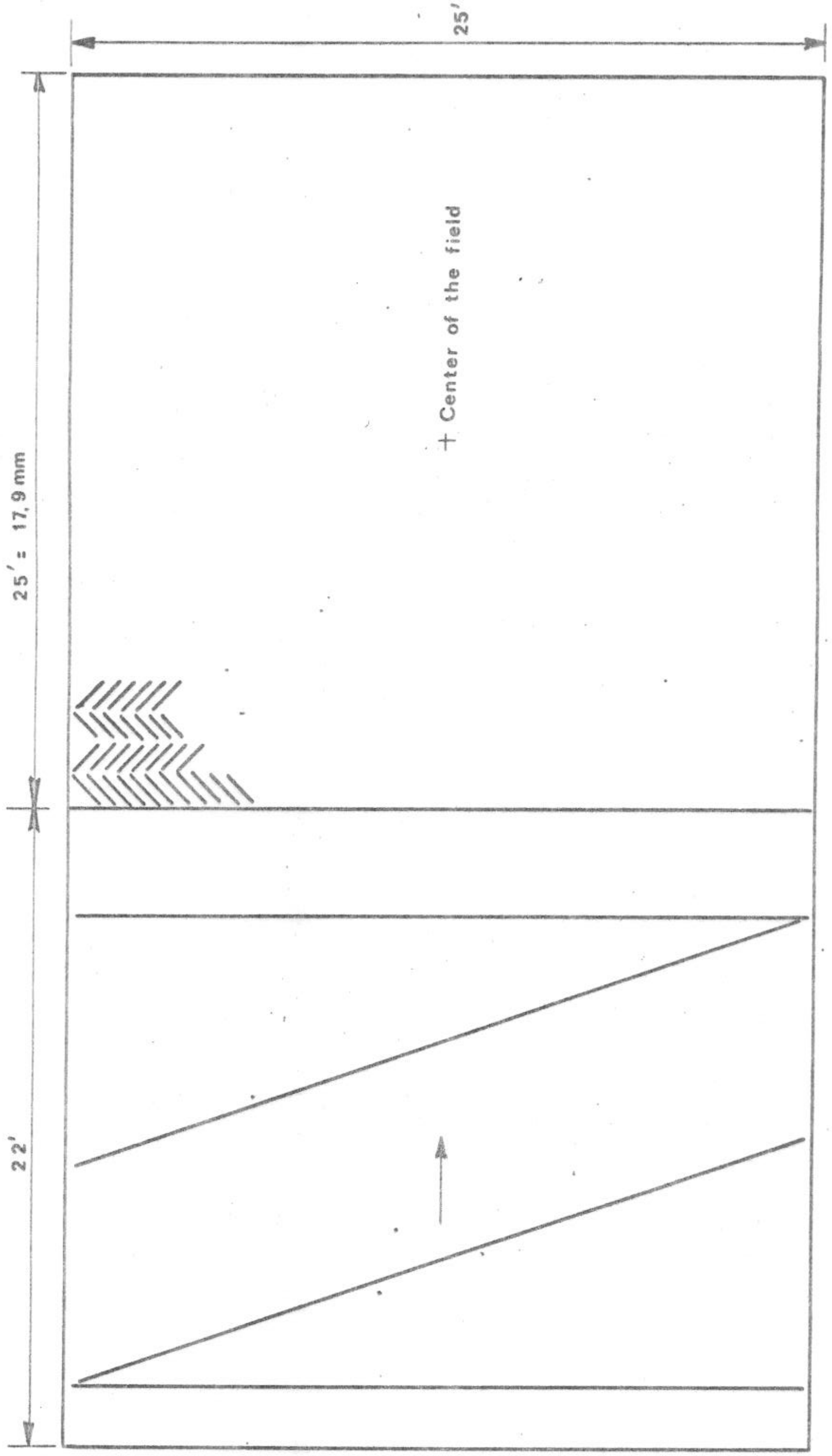


FIGURE 6 GRID SYSTEM - OPTION B

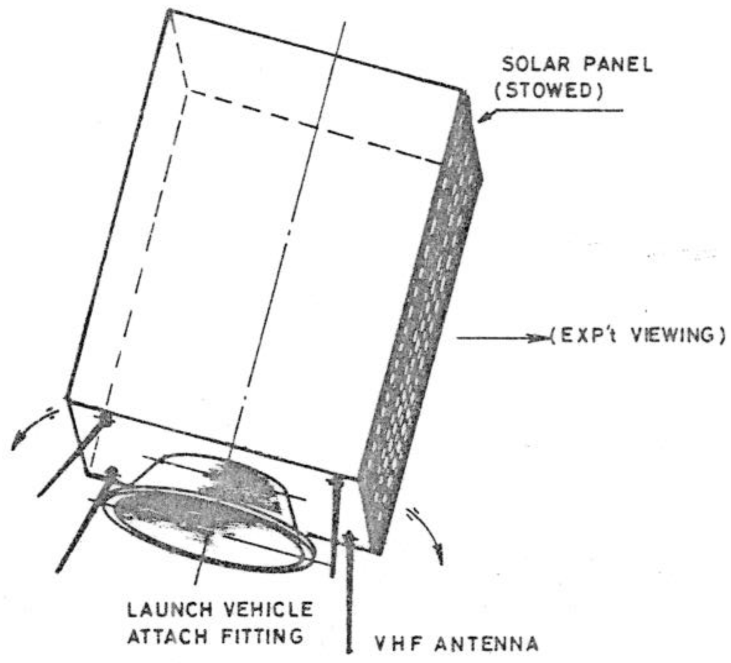


FIG. 7 ASTROMETRIC SPACECRAFT
(LAUNCH CONFIGURATION)

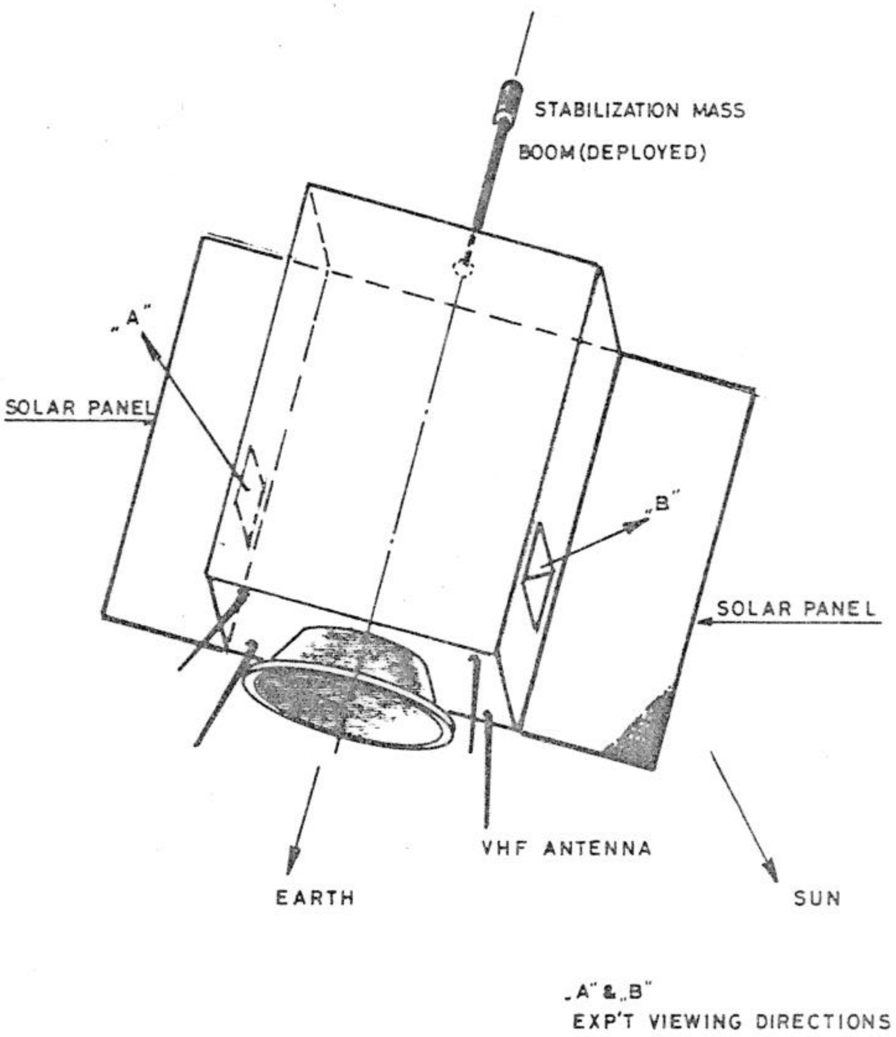


FIG. 8 ASTROMETRIC SPACECRAFT, GRAVITY GRADIENT STABILIZED (DEPLOYED)

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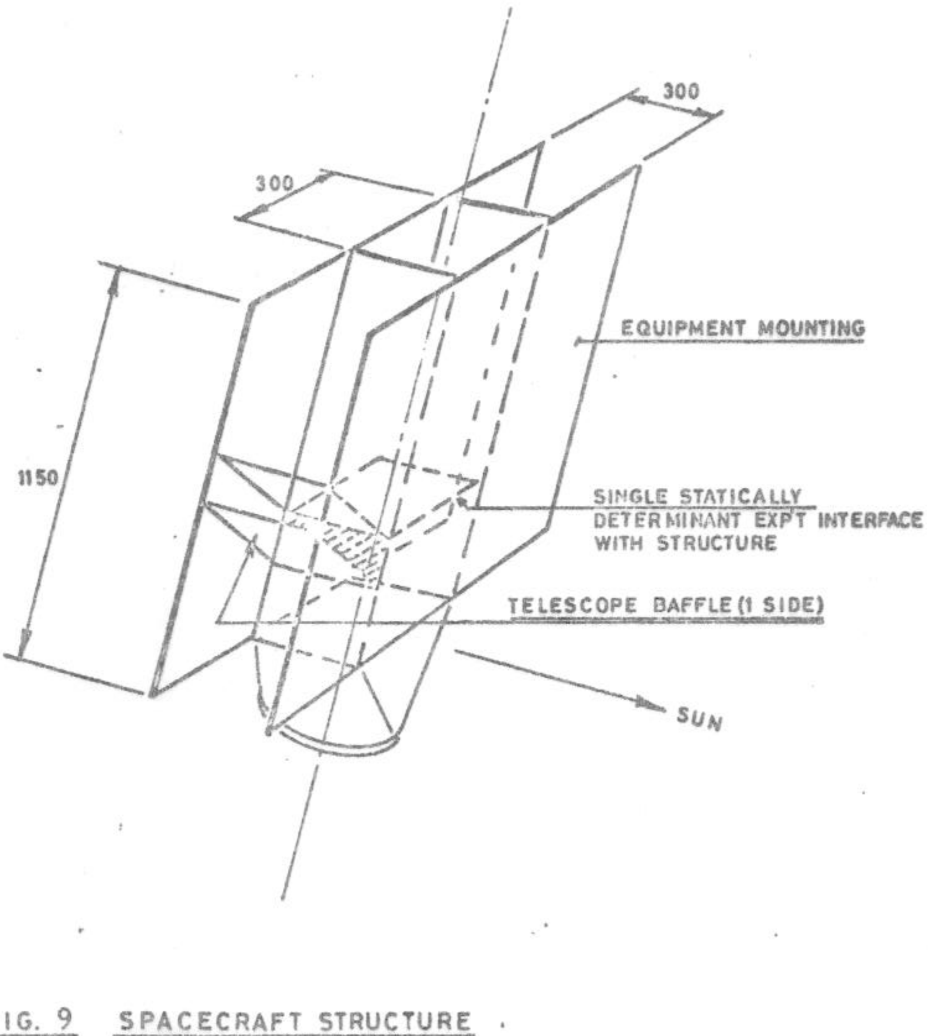

FIG. 9 SPACECRAFT STRUCTURE

APPENDIX 1 : BACKGROUND AND HISTORY

1. BACKGROUND

In 1974, following a suggestion from the Launching Programme Advisory Committee, (LPAC) the Agency organised an international symposium on Space Astrometry, with a view to answering two questions :

i) what would be the scientific significance and objectives of a space astrometry mission?

ii) what would be the support in the scientific community of such a mission?

The proceedings of the symposium, held at Frascati on 22-23 October 1974, are contained in document ESRO SP-108, dated March 1975. Three projects were presented :

- two proposals from Professor Lacroûte (Strasbourg) : an automatic satellite and a Spacelab payload
- a proposal from Professor Fredrick (Virginia) for an astrometry instrument to be mounted at the focal plane of the Large Space Telescope (LST).

Some conclusions reached at this symposium are that :

- improvements in astrometric data have a fundamental scientific significance and would provide decisive progress in astronomy, astrophysics, and geodynamics
- space astrometry can yield an accuracy unobtainable from ground-based observations and considerably increase the number of observed objects
- further studies should be carried out by a study team composed of scientists and engineers.

Taking into account the importance and activity of the Astrometry community in Europe, as well as the enormous scientific significance of the improvements to be expected from space techniques, borne out by the Symposium speakers, it was finally felt that the two questions raised by the LPAC could undoubtedly be answered in a very affirmative way.

Therefore, after consultation of the Agency's Advisory bodies and of the Science Programme Committee, it was decided to carry out a Mission Definition Study.

2. MISSION DEFINITION STUDY

The Mission Definition Group set up for this task was composed of five scientists : W. Brouw (Dwingeloo, Netherlands), M.G. Fracastoro (Torino, Italy), E. Høg (Copenhagen, Denmark), P. Lacroûte (Strasbourg, France), and R. Wilson (ESO, Geneva), and of four ESA engineers : K.H. David (ESTEC), R. Pacault (Headquarters, Chairman), E.A. Roth (ESOC), M. Schuyer (ESTEC). Contributions were received from P. Bacchus (Lille, France), V. Manno (ESA Headquarters) and from ESTEC engineers (B. Morgenstern, J.F. Redor, D.N. Soo, P.J. Underwood).

The Group met four times at ESA Headquarters, on : 75-10-01, 75-11-21, 76-02-19 and 20, 76-04-8 and 9.

At the Frascati symposium in October 1974, a two-axes telescope of 40 cm. diameter appeared as the preferred solution. However, at the beginning of the Mission Definition study, it became clear, following a suggestion by E. Høg, that the light economy of a spacecraft, as originally proposed by P. Lacroûte, could be improved by a factor of about one hundred if an image dissector was introduced as a detector instead of photomultipliers. Therefore, a small telescope with a diameter of about 20 cm, to be possibly launched by a Scout vehicle, was selected as the baseline solution. Different possibilities of passive and active attitude control suited for scanning of great circles were investigated; as discussed in section 2.1.4, two configurations, intentionally very different, were studied by the Group in order to fully explore the range of capabilities of the system : option A (preselection of stars) under E. Høg's leadership and option B (systematic scanning) under P. Lacroûte's leadership.

APPENDIX 2 : OTHER METHODS IN ASTROMETRY

1. GROUND BASED OBSERVATIONS

1.1 Meridian Circles

The accuracy of visual meridian observations has improved very slowly. In 1890 the mean error of a single visual observation was about 0".45, whereas 0".30 has now been achieved. The systematic error however, could hardly be improved below 0".1 or 0".2.

A number of instrumental improvements have been made in the past years and more is in progress (Høg p. 243 in: W. Gliese et al. 1974, ref. 4). A photographic meridian circle (Laustsen) gives ± 0".22 in each coordinate and reaches magnitude 11. A photoelectric slit micrometer (Høg) obtains ± 0".18 in right ascension and a photoelectric tracking micrometer (Requième) obtains even 0".10 in right ascension. Also the systematic errors have improved. The internal systematic error of right ascension ± 0".02 obtained with a slit micrometer (Høg) should be compared with the usual 0".1 or more of visual observations.

Now photoelectric micrometers should reach nearly the limit imposed by the atmospheric disturbances. This limiting mean error due to image motion is, according to Høg,

$$\sigma_T = 0''.33\ (T + 0.65)^{-0.25}$$

for integration times T : $0.25s \leqslant T \leqslant 14000s$, at the zenith and at a site near sea level.

An estimate of the future possibilities for ground based meridian work under the most favourable assumptions and observing conditions is of particular interest in connection with the planned space astrometry. According to the above formula for σ_T, an integration time of 2s is optimal (instead of the usual 40s), assuming a setting time of 3s. This can be achieved with a horizontal meridian circle and a slit micrometer. Furthermore, we assume optimistically that a privileged site is found with an image motion one half of the value at sea level. This would give a mean error of σ_T = 0".13.

Under these favourable conditions it should be possible to observe in 2 years about 10 000 stars brighter than 11^m with a mean error of ∓0".013 (for 50 observations per year, and assuming that the mean error decreases as $N^{-0.5}$) and at the same time 50 000 stars, some down to m = 14, with less accuracy ∓0".05. This less accuracy is adequate to derive proper motions in connection with older epoch observations since these have larger errors.

These predictions are about one order of magnitude lower (in total weight) than the predictions for Space Astrometry given by Bacchus and Lacroûte (1974), but since then the design of Space Astrometry has improved by one order of magnitude in spite of a reduction of telescope aperture from 40 cm. to 16 cm.

1.2 New Techniques

Laser - The laser technique with a high internal accuracy of at least 15 cm. can at present only be applied to the moon where a number of corner reflectors have been placed. The reduction and interpretation of the observations is considerably complicated by the large number of parameters occuring in the solution. The problem remains to tie the motion of the moon to the reference system defined by the stars.

Radar - The radar technique can be applied to the bodies near the Earth (Moon, Venus, Mercury, Mars, ...). The accuracy achievable allows a considerable improvement of the ephemerides of these planets. The method is hampered by the errors due to the planetary topography. A good definition of a reference system by the dynamical method is obtained, but the system is based on a very limited number of accessible objects.

VLBI - Extragalactic objects, with no measurable proper motion, are ideal for defining an inertial system, if they appear as point sources, as is the case for compact radio sources with an angular size of less than 0".001. VLBI achieves already the same accuracy as the best optical instruments and has the potential to decrease the error to 0".001 and less, if the overall system stability can be increased and calibration procedures refined. The interferometric measurements give the absolute declination and absolute right ascension differences free of regional, systematic errors. This allows the definition of a fundamental reference system, which, however, is restricted to faint object of 15th to 19th magnitude so that the problem of the link to the reference stars remains.

The new techniques Laser, Radar and VLBI allow to improve considerably the accuracy of the position of a limited number of selected objects. This leaves open the problem of connecting these objects to easily accessible reference stars providing a sufficiently dense distribution over the whole celestial sphere.

2. ASTROMETRIC USE OF THE 2.4m SPACE TELESCOPE (ST, ex LST)

2.1 Instrumentation

Some focal plane instruments of the 2.4m Space Telescope planned by NASA, as foreseen for the early flights, will be able to perform relative (very short arcs) astrometry; these are :

- the area photometer
- the high resolution camera.

However, dedicated astrometry instrumentation has been studied in the course of ST planning, including possibly :

- area mutliplexing astrometric sensor (AMAS) for wide field (5 arc min) work

- modified fine guidance interferometer for narrow field astrometry.

Use of the fine guidance system of ST with a high performance reticle was also considered, or the scanning of the star image with this system.

It is noted that wide angle absolute astrometry cannot be done without very high precision gyros, but these gyros are not planned for ST.

2.2 Historical Brief about High Precision Gyros

These gyros were considered for ST guidance, arranged in a 3-unit package strapped down in the Sub-systems and Service Module (SSM) of ST. All these gyros used gas bearings.

i) Third generation gyro

The most accurate model has been proposed by MIT, Ch. S. Draper Laboratory in 1974, and is labelled "third generation gyro". Its performance is as follows :

- drift-rate uncertainty		0.004"/hr
- RMS noise :	0.002"	0.001 to 2Hz
	0.0015"	0.1 to 5Hz

ii) Three-axis laser gyro

Performance was degraded by a factor 2 from the former.

Lifetime is estimated at about 20,000 hours

iii) Honeywell GG-337

The Honeywell gas bearing has the following performance :

drift 5"/hr

RMS noise : 0.0009" 0.1 to $5H_3$

0.0017" 0.01 to $5K_3$

This is not a gyro of the small class of precision as the former two. However, it is estimated sufficiently accurate for pointing acquisition of ST, but is not convenient for absolute astrometry, as shown by the following requirements :

arc length (o)	required accuracy (")
1	0.005
10	0.04
60	0.15

2.3 Conclusion

It is seen that, high precision gyros having presently been given up in the ST programme, the Space Telescope will only be able to perform 'relative' astrometry; wide angle astrometry, if desired from space in the early 1980's, will have to be carried out by space projects distinct from ST.

With the ST, relative astrometry can be performed in a small field of faint stars down to m = 17 and with an accuracy of about ± 0.002". Thus, accurate relative parallaxes and proper motions may be determined for selected stars in a number limited by the competition on observing time with the many other tasks of ST. The proposed ESA projects, however, aim at absolute astrometry of very many but not so faint stars. An interesting collaboration would be to observe with the proposed ESA satellite, some faint selected reference stars in fields where ST would observe fainter objects. This would in turn serve two purposes, (1) to determine the rotation-free system by means of quasars, and (2) to convert the relative proper motions and parallaxes obtained with ST in other fields to absolute ones.

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