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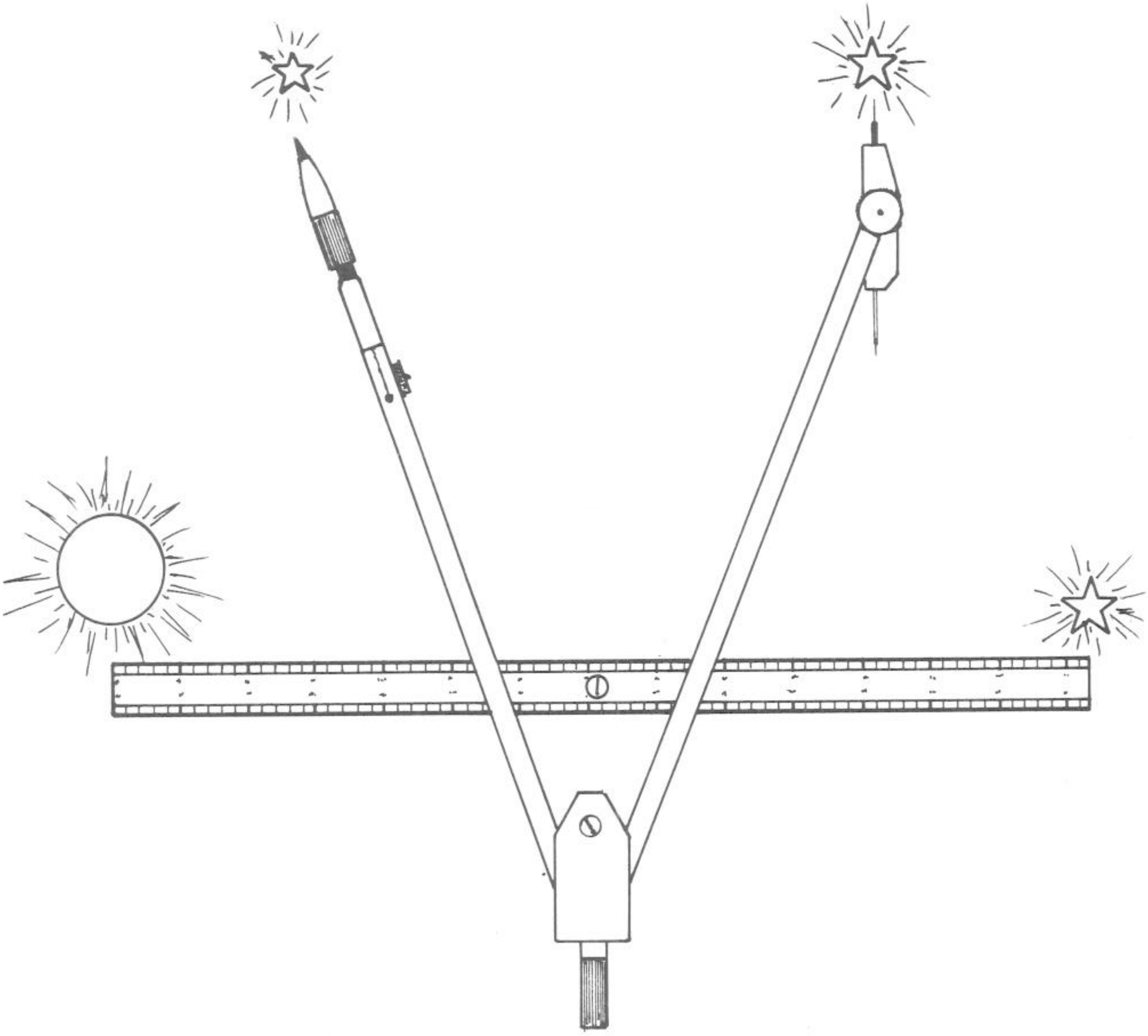
SPACE ASTROMETRY

HIPPARCOS

REPORT ON PHASE A STUDY



S P A C E   A S T R O M E T R Y

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Abstract

The scientific objective of the proposed mission is the accurate measurement of the five astrometric parameters of celestial bodies (i.e. position, proper motions and trignonometric parallaxes), leading to one or two orders of magnitude improvement over the present knowledge with respect to coordinate precision, number of observed objects, limiting brightness and execution time. Such improvement can only be reached by space techniques as the traditional methods are largely inadequate: they are slow, insufficiently accurate and subject to a variety of systematic errors and regional inhomogeneities.

The mission will yield the following direct results:

- a dense (2 stars per square degree) reference system, which can be related to an absolute frame of reference,
- five or six open clusters within the range of parallax determined distances,
- H-R diagram positions of many early type stars and red giants and the fine structure of the diagram for A-F-G stars,
- a catalogue of astrometric parameters for an enormous variety of kinematical, dynamical and astrophysical investigations,
- a list of ~~several~~ a few thousand presently unknown binaries.

The mission will yield significant indirect benefits such as:

- the redefinition of the basis of the cosmic distance scale, leading to a detailed kinematic and dynamical description of a sizeable part of the Galaxy,
- together with photometric and spectroscopic data, the study of the chemical and dynamical evolution of the Galaxy (ages of clusters and families of stars),
- the testing of present cosmological theories.

The satellite described in the present report can yield the following achievements:

average mean error

. accuracy

- position : 0.0015 arc sec (present 0.04 arc sec at best)
- proper motion : 0.002 arc sec (2.5 years observation) (present 0.002 arc sec/year after more than 50 years of observation) — 1.8
- parallax : 0.002 arc sec (present 0.013 arc sec at best) — 1.9

0.001 - 0.002 stars brighter than $m_v = 10$
0.002 - 0.005 for fainter stars

. negligible systematic errors, as compared to present errors of 0.005 arc sec or more

. large number of stars : 100 000, compared to a few thousand presently observed

. faint stars: up to magnitude 11

. homogeneous sky coverage   *complete and reasonably uniform*

The proposed satellite will be injected into transfer orbit by Ariane in a dual configuration, i.e. together with another spacecraft, which can be a geostationary one. The final orbit of the astrometric satellite is circular, ~~geosynchronous~~ (period 24 hours), ~~at an equatorial inclination of 20° or less~~. Thus, continuous telecommand and telemetry links will be maintained during the whole lifetime (nominally 2.5 years) using only one European ground station.

geostationary equatorial orbit

The principle applied for determining the astrometric parameters consists in measuring with high precision the angular distance between stars separated by a large angle, of the order of 70°. The measurements are obtained by a differential method, comparing in the focal plane of a single telescope the positions of stars imaged from two different fields of view, superimposed by means of a complex mirror with two reflecting surfaces. The attitude of the satellite is controlled in such a way that the telescope fields of view scan the whole celestial sphere in a smooth motion.

Simultaneously to the system study, a theoretical analysis has been performed, requiring the implementation on ESA's computer of a sophisticated model of the satellite, including an advanced mathematical filtering algorithm. First exploitation of this software has confirmed in a rigorous way the achievable accuracy of the astrometric parameters as listed above.

SPACE ASTROMETRY

(HIPPARCOS)

Foreword

Astrometry, the science of positions and motions of heavenly bodies, is the oldest branch of Astronomy. But, in spite of its continuous progress, it is the only discipline which has not yet experienced the scientific explosion that drastically changed the aspect of science in the past thirty years, although it must be recognized that astrometric data are at the very base of most astrophysical theories and of our conception of the Universe, in terms of distances, masses, absolute luminosities and motions of the stars.

The astrometric satellite is the only tool that has been conceived so far which is capable of advancing the science of astrometry through space research, as has already been achieved in other fields of astronomy, in planetology and in geophysics. The satellite will permit the improvement in accuracy of existing measurements by a factor of 10 or more and will allow a hundred times more objects of various kinds to be observed. There is no precedent in science where such a leap forward in precision obtainable or in increase in sampling has not produced a host of new discoveries and changes in physical concepts.

Should this mission be fulfilled, such discoveries and changes are likely to influence our basic understanding of stellar structure, of galactic dynamics, of stellar evolution, of galactic evolution and of cosmology. It is not too presumptive to state that all present concepts in these fields - and probably in others - will need to be completely revised as a result of the mission of the astrometric satellite.

NOTE: The proposed name of the mission (Hipparcos) refers to the famous Greek astronomer (190-120 BC) who, by measuring the position of the Moon against the stars, determined the Moon's parallax and derived the correct distance of 30 times the diameter of the Earth.

Also, he made the first accurate star map which led to an important discovery: comparing his observations with those of his predecessors, he found a uniform shift of the stellar positions from West to East. This effect could be accounted for by assuming that the North Celestial Pole rotates in the sky with a period of 26,700 years, giving rise to the "precession of the equinoxes".

HIPPARCOS is also an acronym for "HIgh Precision PARallax COllecting Satellite".

replaced by Murray and Høg contribution. + contrib. Lindegren. (Expected accuracy of astrometric data)

1. SCIENTIFIC SIGNIFICANCE AND OBJECTIVES

1.1 Introduction

At present, the need for a large and an accurate body of astrometric data is urgently needed in many fields of astronomical research-like studies of the structure and dynamics of our galaxy, its chemical evolution, of the mechanics of star formation and finally in the determination of the cosmic distance scale. At the same time however it becomes increasingly evident, that the traditional ways of obtaining these very fundamental quantities are largely inadequate to the purpose: the procedure is slow, insufficiently precise and subject to a variety of systematic errors and selection effects.

Of the many technical improvements and new techniques that have been imagined, only the proposed astrometric satellite indeed offers for the first time in history the possibility to build a uniform reference system over the whole celestial sphere that would have a better precision than the best existing system (FK4) and 50 times denser. It will be free from the regional disuniformities and north-south differences so adversely affecting the present situation. Centuries of painstaking work from the ground can be made obsolete by an entirely new body of precise data which by their very nature will stimulate a tremendous advance in every astronomical field of research.

This Phase A study has confirmed these great expectations; the satellite presented in the following pages is capable of satisfying the crucial requirements of one to two orders of magnitude improvement over the existing situation with respect to coordinate precision, number of observable objects, limiting brightness and execution time. For stars brighter than about 11 m the parameters to be obtained will be accurate to:

position	0."0015
parallax	0."002
proper motion	0."002/year

Two different philosophies of sky coverage have been investigated in detail in this study:

- the determination of a reference system, dense of stars and complete down to a certain limiting magnitude, with errors strictly dependent on the luminous flux, with no a-priori selection of the program stars.

- the observation of a sufficiently high number of stars (more than 1 per square degree) to insure in any case a good reference system, with in addition the possibility to select a-priori star groups for their particular astrophysical significance and to spend a greater portion of the time to reach fainter interesting objects.

We feel that a good solution has been found capable of satisfying the basic requirements of both philosophies, taking also into account the other foreseen developments in astrometric techniques in the next decade. The number of stars to be observed will be up to about 100 000 (depending on magnitudes and on integration times in the chosen program), distributed almost uniformly over the whole sky.

The mission outlined here will thus yield the following direct results:

- a dense (2 stars per square degree) reference system better than the FK4 and first epoch positions to yield proper motions ten times more precise (0".0002/year) with a second mission only after 10 years.

- five or six open clusters within the range of parallax-determined distances.

- H-R diagram positions of many early type stars and red giants and the fine structure of the diagram for A-F-G stars, on the basis of geometrical distances.

- parallaxes independent of kinematical biases.

- a catalogue of astrometric parameters for an enormous variety of kinematical, dynamical and astrophysical investigations, most of which presently require years of painstaking data-collection efforts or cannot be done at all (f.i. masses of nearby binaries at the 15% level).

- a list of several thousand presently unknown binaries with separations less than 0".5.

However, despite the large number of investigations already planned with the directly obtained data (the Science Team has already informally received more than 70 different proposals), the most important consequences of the mission may be indirect.

The main contribution is certainly the redefinition of the basis of the cosmic distance scale by measuring the parallax of new distance indicators, such as A and late B stars etc. This will affect all other distance indicators and have consequences on all galactic and extra-galactic astronomy (Hubble constant).

These new indicators will give accurate spectroscopic parallaxes up to 1000 parsecs. Combined with the new proper motions, this will lead to a detailed kinematic and dynamical description, of a sizeable part of the galaxy and permit to study:

- the reality of the axi-symetric steady state model of the galaxy.

- the reality of the "lacking mass" in our region of the galaxy.

- the dependence of kinematic properties with position (galactic dynamics) and populations, in particular for intermediate population II.

- the properties of stellar association, and the birth places of some stars.

- the detection of stream motions and of Stromberg drift for various galactic latitudes.

Furthermore, together with photometric and spectroscopic data, the problem of the chemical and dynamical evolution of the galaxy will benefit from crucial data. The ages of various clusters and other families of stars will be obtained. And, since the luminosity of stars depends partly upon the abundances of helium, the evolution of this abundance will be estimated and this will provide a test for the present cosmological theories.

These are some examples of what the satellite will bring to astronomy. These and some more are discussed in more details in Section 1.4, while Section 1.5 indicates the quite reasonable magnitude of the parallel effect that ground-based astronomy should provide in support to the mission. But all favourable consequences of the mission cannot be foreseen. It will most likely take two to three decades before the astronomical community will have completed the full exploitation of the impact of this fascinating new set of data. Indeed one may have great expectations of this mission; it is inconceivable that a factor of 100 in number of objects or a factor of 10 in accuracy will not generate an exciting new science.

1.2 Present and Future of Ground-Based Astrometry

Let us consider the present state and the foreseeable development of ground-based astrometry for each of the parameters that the astrometric satellite will determine: system of reference, parallaxes, and proper motions.

1.2.1 Fundamental System of Reference

An absolute or fundamental system of reference can be defined geometrically (using faint point-like galaxies) or dynamically (motion of the Moon or members of the solar system). In practice, however, the system has to be materialized by a catalogue of positions and proper motions of stars. At present the most accurate system is materialized by the Fourth Fundamental Catalogue FK4 containing 1535 fundamental stars. The internal accuracy of positions is 0".05 to 0".10, but depends considerably on the region in the sky. The systematic errors are of the same order except for the southern hemisphere where these are larger. The proper motions are given with a precision between 0.0007/y and 0".004/y with systematic errors of the same order. The most serious limitations of this catalogue are the following:

1) Limited number of fundamental stars

2) Limitation to stars brighter than $m_V = 7.5$

3) Inhomogeneities of distribution and quality of the observations (random and systematic errors)

4) Erroneous values of precession and the motion of the equinox.

These limitations affect almost all applications. Extension in number of stars and to fainter stars down to 9^m are provided by the catalogue AGK3R, SRS and FK4sup. But the accuracy is much lower than in FK4: a factor 5 in proper motions. Improvement and extension of the FK4 should be incorporated in the new FK5 and FK5 sup. The gain in accuracy, a consequence of the application of improved techniques, is expected to be relatively modest : a factor of 2 or maybe 3.

The extension to even fainter stars is possible by photographic methods. But until now, the results that were obtained are quite discordant and have an accuracy of less than 0",1.

1.2.2 Improvements in the Determination of Star Positions

In fact the accuracy of astronomical measurements has only very slightly improved since the last century. Consequently, the accuracy of the main applications of astrometry has also remained almost stationary. This applies in particular to the following fields:

- Rotation of the Earth (UTI) and polar motion
- Geodynamics
- Motion of the Moon and planets
- Kinematics and dynamics of the Galaxy
- Determination of stellar masses

etc.

So the progress of many fields of astronomy now requires very important advancement in the fundamental reference system.

From the ground, the most serious limitation is due to the atmosphere (refraction and scintillation). Some improvements are possible. For instance, the use of photoelectric transits instead of visual transits may decrease random errors of meridian circles (Hog, Requième) or of astrolabe (Billaud), and slightly extend their use to fainter stars. This will probably be useful in order to improve the fundamental reference system by the present classical methods. But it still seems really difficult to avoid the effects of refraction on the local systematic errors of the system.

The very long base-line interferometry (VLBI) on the extragalactic objects seems able to give a fundamental reference system coherent with random errors of 0".001 or less. The atmospheric refraction is less important by the use of large wave lengths. It will give a very high accuracy in the determination of geophysical parameters (polar motion, Earth rotation, plate motions, solid Earth tides) but the link of the frame with other stars with the same accuracy remains a difficult problem. The laser distances of the Moon will give information only on the Earth-Moon system. The dynamical reference frame that is obtained will not be linked to stars. The radar techniques to some nearby planets seem able to improve the ephemerides of planets, but at the present time, the improvements are limited by the errors caused by the planetary topography.

Proper Motions

Thanks to many years of patient observations, many proper motions are available but they are often not reliable.

Some of them are individually useful in spite of the random and the systematic errors. They are the large proper motions of the nearest stars; for instance the proper motions by Luyten and Gielas. But more often the proper motions are useful only for statistical use in order to extend the distance scale by calibration of spectral stellar type and to study the general motions in the Galaxy. For these goals the systematic uncertainties on the reference system and the systematic local errors are the most important limitations. It does not appear that any of the future ground-based improvements described above would in any way appreciably improve this situation.

1.2.3 Parallaxes

The determination or trigonometric parallaxes of stars is a fundamental activity in astrometry. All distance determination in the universe is based ultimately on parallaxes by the astrometric method.

Until 1974 trigonometric parallaxes of some 7000 stars have been measured, heavily concentrated in the northern hemisphere. The average standard error is 0".013, however only 5% of the parallaxes have a relative error of less than 10% (mostly for distances smaller than 20 parsecs). More than half of the parallaxes have an accuracy of less than 50%. The random and systematic errors can be fairly large (a considerable number of negative parallaxes have been obtained). Moreover there exists a systematic difference of 0".005 between the northern and southern hemisphere. This difference is still unexplained.

Since some of the observatories have stopped their activities in parallax measurements, the number of new parallaxes determined will only increase slowly by 500 to 1000 in the coming 10 years. New development of classical ground-based instruments will increase the accuracy only modestly to about 0".003, except for a very small number of selected stars that will be observed by optical interferometry - a very precise but cumbersome technique. In these cases, again, the objects will be limited mainly to the northern hemisphere. Moreover, the samples will not be representative for the whole population as a consequence of the strong selection effect (preference for large proper motion stars).

In spite of some trials not yet successful, the use of photoelectric receptor instead of photography, with an increased integration time in order to minimize the local effects of atmosphere will perhaps be able in the future to improve the precision. But in many ways it seems difficult to obtain results on a large number of stars.

Thus, the progress to be expected in the coming decade will be insufficient for most of the applications and restrict the application to the solar neighbourhood.

1.3 Improvements By Space Astrometry

1.3.1 General Conclusions

The astrometric satellite, as described in the present document, is essentially designed to obtain the relative positions of stars with an accuracy that is limited only by diffraction and photon statistics and is no more hampered by atmospheric turbulence or refraction, by instrumental deflexions and all other causes of errors present in all ground-based astrometric techniques.

Roughly speaking, a successful mission, lasting at least 1.5 yr, is expected to yield parallaxes and relative positions and proper motions for 50 000 - 100 000 stars down to magnitude m_{pg} = 13, each astrometric datum having an accuracy of a few milliarcsecs.

As a general statement, one may say that, a 2.5 year mission would, approximately give trigonometric parallaxes and each component of the position in ecliptic coordinates (λ, β) with an rms error of $\pm$ 0".002 for stars brighter than 11th photographic magnitude. The components of the proper motions (μ_λ, μ_β) will have an rms of $\pm$ 0".002 per year. The overall limitation which is that the total integration time per unit area of sky should be roughly uniform, implies that a maximum number of about 100 000 stars will be observable during the mission.

However, a more detailed description of expected results requires specification of instrument, mode of scanning, observing program, etc.

We give an example of a mission model in order to show what kind of discussion will have to be made when all parameters will be completely frozen.

1.3.2 Example of a Mission Model

replaced by Lindegren contrib.

Let us consider the following mission model (indications of scaling properties are given when possible).

instrument : (described elsewhere). If performance is limited by diffraction and photon statistics, the mean error of any astrometric quantity scales is ℓ^{-2}, where ℓ is the linear size of the aperture.

scanning mode : revolving scanning with Sun/spin axis angle ξ = 36°. The m.e. does not depend critically on the scanning mode as long as ξ is the same; they are however roughly inversely proportional to sin ξ for ϖ, λ and μ_λ, and almost independent of ξ for β and μ_β.

mission length : 2.5 yr. For positions and parallaxes the m.e. scales as $t^{-0.5}$, for proper motions as $t^{-1.5}$.

Then we expect the astrometric mean errors given in Table 1.1 for two alternative programs. The programs should be regarded as examples only, illustrating dependence on magnitude and accumulated observing time on a given object.

Table 1.1 Number of stars, distribution of observing time, and expected accuracy for two alternative observing programs.

PROGRAM I							
m_{pg}	Number of stars	% of all stars on sky	Obs. time per star	% of total obs. time	Mean errors (sky averages) pos.	p.m.	par.
		(%)	(s)	(%)	(10^{-3} arcsec)		
< 6	2 900	97	1010	5	0.9	1.2	1.2
6 - 7	4 700	87	1030	8	0.9	1.2	1.2
7 - 8	10 400	70	1070	19	0.9	1.2	1.3
8 - 9	16 400	40	1150	31	0.9	1.3	1.3
9 - 10	12 800	12	1290	27	1.1	1.5	1.5
10 - 11	3 600	1.2	1490	9	1.3	1.9	1.9
11 - 12	200	0.03	1740	1	1.9	2.7	2.7
12 - 13							
Total	51 000	-	6.10^7s	100 %			
Average			1180 s		1.0	1.4	1.4

PROGRAM II							
m_{pg}	Number of stars	% of all stars on sky	Obs. time per star	% of total obs. time	Mean errors (sky averages) pos.	p.m.	par.
		(%)	(s)	(%)	(10^{-3} arcsec)		
< 6	3 000	100	280	1	1.6	2.3	2.3
6 - 7	5 400	100	300	3	1.6	2.3	2.3
7 - 8	14 800	100	320	8	1.6	2.3	2.3
8 - 9	40 800	100	385	26	1.6	2.3	2.3
9 - 10	16 000	15	560	15	1.6	2.3	2.3
10 - 11	12 000	4	1030	21	1.6	2.3	2.3
11 - 12	6 000	0.8	1900	19	1.8	2.6	2.6
12 - 13	2 000	0.1	2100	7	3.1	4.3	4.4
Total	100 000		6.10^7s	100 %			
Average			600 s		1.7	2.3	2.4

Program 1 comprises more or less the minimum set of stars necessary to set up the celestial sphere. It is obtained by dividing the sky into 51 000 areas, each of the size of the FOV (54' x 54'), and selecting the brightest star in each area.

For Program II the ambition is to observe (1) all 64 000 stars down to m_{pg} = 9.0 and (2) an additional 36 000 stars down to m_{pg} = 13, selected as astrophysically interesting and/or as faint astrometric reference stars. Note that 62% of the time is spent on the 36% fainter stars. The absolute maximum observing time per star is about 2400^s (sky average), which is approached for the faintest stars in this program. Thus there is little room for improving their accuracy by extending their part of the total observing time even further.

Homogeneity

The astrometric accuracy is in fact a function of position on the sky. There are fairly large systematic variations with ecliptical latitude (β) and smaller periodical variations with longitude (λ). Also, there is some anisotropy such that the latitude components of positions and proper motions are more accurate than the longitude components at low latitudes, whereas the reverse is true at the poles. The mean errors in Table 1.1 are sky averages; the variations with latitude are given in Table 1.2.

Table 1.2 Relative mean errors of astrometric parameters as functions of ecliptical latitude.

β	$\Delta\lambda \cos\beta$	$\Delta\beta$	$\mu_\lambda \cos\beta$	μ_β	$\tilde{\omega}$
0°	1.8	0.9	1.8	0.9	1.2
$\pm 30^\circ$	1.3	0.8	1.3	0.8	1.1
$\pm 60^\circ$	0.6	0.7	0.6	0.7	0.8
$\pm 85^\circ$	0.3	0.8	0.3	0.8	0.4
Mean sky	1.2	0.8	1.2	0.8	1.0

Improvement by Averaging

It is of considerable interest to know how much we can possibly improve the parallax and common proper motion of a cluster by averaging the measured quantities for individual stars. The mean error $\bar{\varepsilon}$ of the average of n quantities, each with m.e. ε, is given by

$$\bar{\varepsilon}^2 = \frac{\varepsilon^2}{n} \; (1 + (n-1)\rho),$$

where ρ is the average correlation between any two of the quantities. As $n \to \infty$, we obtain the asymptotic mean error $\varepsilon\sqrt{\rho}$. It is found that ρ = 0.2 for stars closer than $\cong 1^\circ$, decreasing to $\rho \lesssim 0.05$ for distances $\gtrsim 4^\circ$. Thus, for extended clusters such as the Hyades it should indeed be possible to reduce the mean errors by a factor 4, whereas it seems dificult to reach even a factor 2 for less extended clusters, taking also into account the necessary shorter observing time per star in this case.

Improvement by Dynamical Smoothing

The results given in this example are based exclusively on the measurements of the angles between stars observed simultaneously in the field. But it is possible to add supplementary information by linking stars that are observed in an interval of time of 200-400 seconds provided that during this interval the attitude of the satellite is a continuous function of time (no sizeable jitter). In this case, for the same integration time, mean errors indicated in Table 1.1 could be reduced by factors of 1.2 to 1.5 for fainter stars (m = 9 to 11).

1.4 Scientific Significance and Consequences of the Mission

1.4.1 Introduction

The new astrometric data which can be obtained from the Space Astrometry Satellite programme will be comparable in extent with, and far superior in accuracy to, most of the data on star positions, proper motions and parallaxes which have been accumulated during the past three centuries, and on which much of our present knowledge of stellar luminosities, distances and kinematics is based. The impact of these new observations will be manifested both in the direct benefit which will be derived from the improvement in data which has already been obtained for many stars, and also in the impetus which will be generated toward the further study of many astronomical problems. This will require the expertise of many individual astronomers and research groups for the following decade or more.

In this chapter we shall consider these two aspects of the exploitation of the data to be obtained in this project, using the general conclusions of Section 1.3 for precision.

1.4.2 Stellar Reference Frame

An immediate consequence of this mission will be a major improvement in the quality of the astrometric reference frame for ground based astrometry, geodynamics and studies of the solar system.

Absolute proper motions will be obtained for fifty times more stars and for a hundred times fainter stars than are currently available in existing catalogues of comparable accuracy (FK4) and will be 5 times more precise than those contained in catalogues of similar extent (AGK3, SAO). Fifty years of future ground-based observation will be required to obtain the equivalent of one satellite mission.

Absolute positions will be obtained 20 times more accurately than in the FK4 catalogue. This is impossible from the ground . But, perhaps the most significant improvement over current data will be the uniformity of precision over the whole sphere, and in particular the absence of any inhomogeneity between the northern and southern celestial hemispheres, which is inevitable in any ground based work.

The reference frame defined by the positions and proper motions observed by the satellite, although homogenous, will not in itself be inertial. However, provided that a sufficient number of stars can be linked to extra galactic radio sources whose positions have been measured by interferometric techniques, it can be related to an inertial frame. (See Walter, 1975). Alternatively, the observation of Earth rotation and polar motion by classical optical techniques relative to the satellite reference frame, and by radio interferometry, will give a comparison between the two frames. Therefore, the catalogue deduced from the astrometric satellite mission, will become the accessible representation of the best absolute reference system that will exist. The following consequences will occur:

1) Astronomy

Among the various kinematic and dynamical galactic studies, many would suffer a systematic error if the reference system is not absolute. In particular, it is necessary that the global motions which are investigated should be absolute in the following cases:

- Galactic rotation and differential rotation;
- Motion of star groups, spiral arms, etc ...
- Global kinematic properties of stars;
- Statistics in the motions perpendicular to the Galactic plane.

2) Geodynamics and Solar System

Furthermore, the present reference system will contribute:

- to establish the connection between the dynamical reference systems (planets-Moon) with the geometrically absolute system;
- to get the non gravitational effects in the motion of the Moon and relativity effects for all bodies;
- to set the reference for the measurement of the precession which is one of the most sensitive indicators of the internal structure of the Earth;
- to set the reference for the secular part of the polar motion as observed since 80 years and which is linked to crustal motions and the variations of Earth moments of inertia;
- to set the reference for secular effects in the motion of planets which are used to determine their masses (see details in Kovalevsky, 1975).

1.4.3 Direct Benefits to Astronomy

The great increase in good astrometric data, to be expected from the satellite, will have far reaching consequences in most branches of stellar astronomy. The most important advance will be the measurement of trigonometric parallaxes with high relative accuracy, for many more stars than are ever likely to be possible from ground based measurements; furthermore, these new parallax measurements may reasonably be expected to be free from the large systematic errors which have been known to be present in the existing data (e.g see Upgren, 1977, for a recent review of ground based parallax work). The parallaxes of known nearby stars will be considerably improved but, more significantly, the effective distance to which parallaxes will be measurable will be greatly increased, with the consequent enlargement of the total volume of space surveyed.

(a) Absolute luminosities

Up to the present time, even for stars as close to the Sun as 10 parsecs, the uncertainty in absolute magnitude due to error of parallax has been at least $\pm\, 0^{m}.2$. With the increased precision attainable with the satellite, absolute magnitudes with this uncertainty will be obtained for stars as far away as 50 parsecs; at 10 parsecs the error will be only $\pm\, 0^{m}.04$.

It will be possible to measure directly the trigonometric parallaxes of stars in the Hyades cluster, with a precision of about 10 percent, so that the average parallax of the cluster stars should be obtainable to 1 per cent if sufficient stars are observed. The direct trigonometric determination of the distance to this important cluster will thus be considerably more accurate than the classical determination from the convergent point of proper motions ($\sim \pm$ 5 per cent; Hanson 1977), and it may also be possible, for the first time, to measure the intrinsic dispersion in transverse velocities, which is the limit to the accuracy attainable by the convergent point method.

(b) Luminosity Calibration

The use of trigonometric parallaxes for luminosity calibration is a topic of some considerable interest at the present time (eg Turon Lacarrieu and Crézé, 1977; Lutz and Kelker, 1973; Lutz, 1978). Quite apart from difficulties associated with systematic differences between parallaxes measured at different observatories, there is an overriding limitation due to the cosmic spread of absolute magnitudes, which introduces bias into any sample selected to an apparent magnitude limit. Even adopting the conservative view of Lutz (1978) that only parallaxes which are known to be better than about 15 percent can be used for calibration, the effective "horizon" will be extended from about 15 parsecs, for ground-based parallaxes, to 75 parsecs for those measured with the satellite. The increase in the available volume, by a factor of more than a hundred, brings within range for the first time B type main sequence stars and some K and M type giants; this is illustrated in Fig 1.1 which shows the estimated distance modules (apparent magnitude, m, minus absolute magnitude, M, plotted against colour (B-V) for the 100 brightest stars (Allen 1973, p 239). The two dashed horizontal lines indicate respectively the distance module m-M = 1.0 corresponding to the ground based "horizon" and m-M = 4.4 which is the expected horizon for parallaxes measured with the satellite.

It is estimated (eg Allen, loc cit, p 249) that there should be some 15 000 stars with $m_{pg} \lesssim 11$, within 75 parsecs, two thirds of which will be F and G type main sequence stars. It will be quite impractical even with the satellite, to measure all stars brighter than $m_{pg} = 11$ but a complete survey to this limit in extended areas, for example in high galactic latitudes, would give for the first time a selection of many nearby stars which do not suffer from the well known kinematic bias in favour of high velocity stars which affect most ground-based parallax measurements.

These data will permit, in particular, a detailed analysis of the structure of the main sequence for G and F stars which might bring some new results on the evolution of these stars in connection, for instance, with their kinematic properties. Another problem is to see whether the zero age main sequence depends upon the abundance of heavy elements and of Helium. This last point will bring crucial observational evidence on the chemical evolution of the Galaxy. In conjunction with the kinematical properties of stars, there will be a possibility to test the dependence of Helium abundance as function of age, which has cosmological consequences.

In order to fully exploit the parallax capability of the satellite, further selection will be essential. For example, all the late type dwarfs in the lists of Vyssotsky and his collaborators (Vyssotsky 1943, 1956, 1958; Vyssotsky et al. 1946, 1952) and of Upgren et al. (1972) can be observed; many of these could be as far away as 50 parsecs.

(c) Stellar Masses

If the relative orbit and parallax of a binary system are known, then the total mass of the system can be calculated from Kepler's third law; since the parallax enters with the third power, an error of 5% in this parallax represents an error of 15 percent in the total mass. The mass ratio, and hence individual masses, can only be determined if the motion of each component relative to their centroid is known.

At the present time, out of about 500 binary systems with well determined orbits, only about 25 have parallaxes known to within 5 per cent; the masses of these particular systems will be better determined when their parallaxes have been measured from the satellite, and there should be an increase, by a factor between five and ten, in the number of stars for which masses can be determined to 15 per cent.

The satellite will provide the first ever systematic search for double and multiple stars. So far, about 70 000 such systems are known, and it is estimated that several thousands, with separations between 0''1 and 0''2 will be detected for the first time, during the course of the programme. Although it will not be possible to measure separation and position angle, the systematic measurement of parallax will indicate those nearby systems for which ground-based astrometric orbits, essentially by interferometric methods, are likely to yield values for the masses.

It is therefore not exaggerated to say that the astrometric satellite is a unique occasion to improve by about an order of magnitude the number and the precision of the knowledge of stellar masses, which are the most basic and the less well known parameters for stellar structure and evolution studies (Mayor, 1978)

(d) Galactic Studies

(i) General Kinematics and Dynamics

The determination of Oort's constants A, B from proper motions

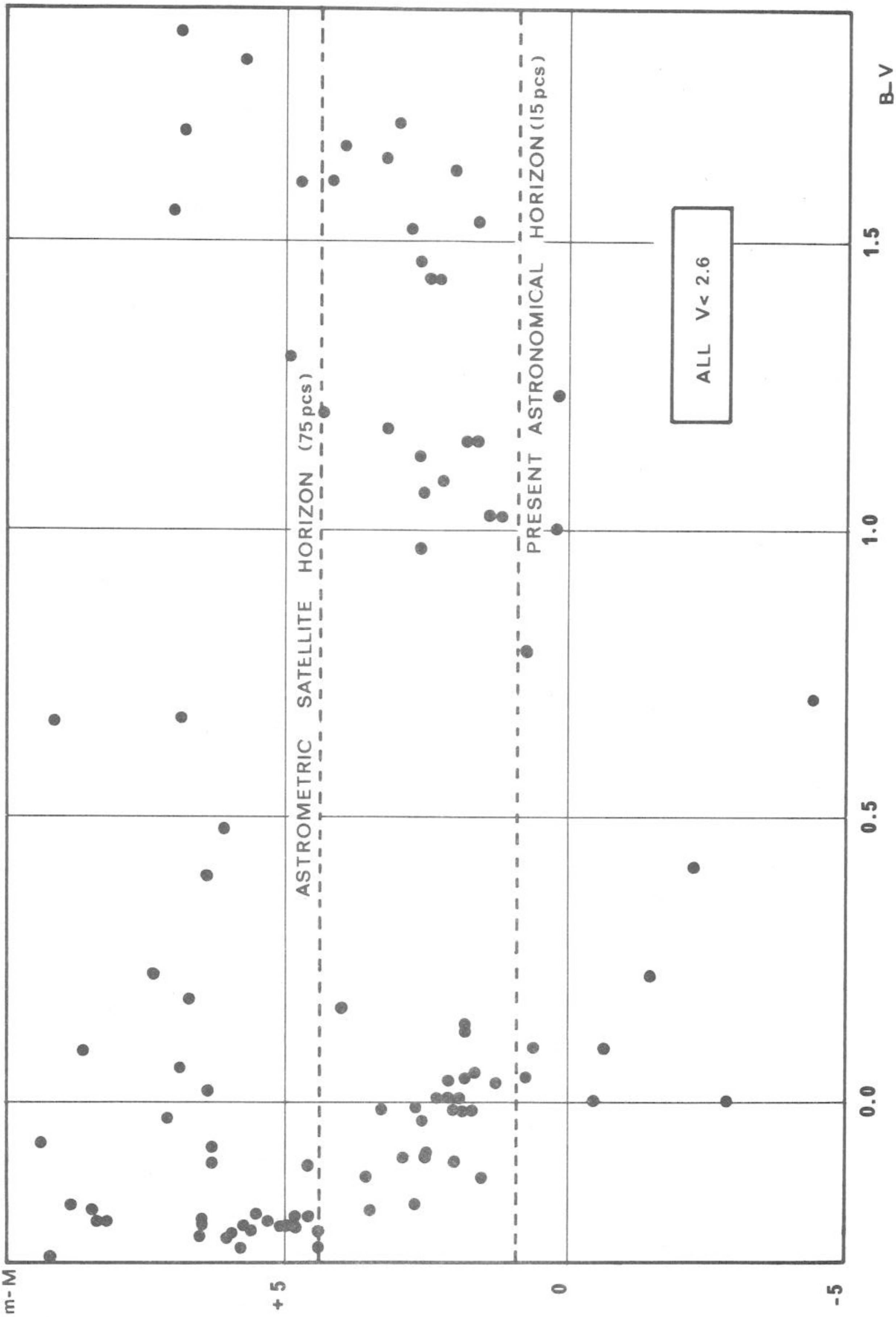
ASTROMETRIC SATELLITE HORIZON (75 pcs)
PRESENT ASTRONOMICAL HORIZON (15 pcs)
ALL V< 2.6
B–V
0.0
0.5
1.0
1.5
m-M
+5
0
-5

FIGURE 1.1

will be much improved by the availability of more precise distances and proper motions of distant early type stars. The constant B can only be determined directly from proper motions, and a serious limitation hitherto has been the lack of homogeneity in the proper motion system between the two celestial hemispheres; this will not affect the space astrometry system.

For the first time it will become feasible to verify some of the assumptions of symmetry in the velocity field, which are currently needed in order to interpret observational data. For instance are the components of motion perpendicular to the galactic plane in statistical equilibrium, and is the ratio of axes of the velocity ellipsoid for any population of stars consistent with the values of Oort's constants as required by the axi-symmetric steady state model of the Galaxy?

The large number of stars within 75 parsecs for which accurate transverse velocities, and ultimately space motion components, will become available, will provide answers to these questions.

The new data will also enable more detailed study of the problem of the reality and dynamical significance of star streaming and moving groups.

(ii) <u>Studies of Special Objects</u>

Space velocities will be obtained with precision whenever the transverse velocity is well known, that is only for close stars (1 km/s at 20 parsecs, 5 km/s at 100 parsecs). In any case, this will provide several thousands of well determined space velocities, so that statistical properties of such orbits might be obtained for the first time, giving a new approach to the dynamics of the Galaxy.

It will be possible to trace back the galactic orbits of many individual young (B and A type) stars in the general field, whose ages are presumed known, in order to locate possible areas of star formation as they existed some 500 million years ago.

Of a special importance will be the study of the Hyades cluster for which about 50 stars will be observable. It will permit to extend the calibration of the HR diagram and its comparison to the standard main sequence and to interpret it in terms of the age of the cluster. The dynamics of this cluster will also be an important subject of studies.

1.4.4 Indirect and Longer Term Benefits

In the previous two sections we have outlined some of the fields in which the new astrometric data can be used more or less immediately. The full impact of this new data will require supplementary observational material such as radial velocities, photometry and spectroscopy of the programme stars. Another important impact will come indirectly, via supplementary knowledge acquired directly, that is later applied to other more distant or fainter stars or other objects. In this section, we consider some of the fields of research which will benefit from this extended data.

(a) Cosmic Distance Scale

The calibration of absolute magnitudes of main sequence stars will be put on a much firmer basis than at present, when photometry of all the newly measured parallax stars has been obtained. With many more stars available, it should be possible to classify sufficient numbers of stars according to age and chemical composition, and hence to study the detailed structure of the main sequence as a function of these parameters.

The distances of clusters with differing ages and compositions can then be calibrated directly from the parallaxes of photometrically similar stars; in this way, the brighter distance indicators, such as cepheids, RR Lyrae variables and OB stars can be calibrated independently of the usual main sequence fitting procedure, thus extending the improved distance scale to extra galactic objects.

This new improved and extended cosmic distance scale will have an enormous impact on most of the fields of galactic and even extragalactic astronomy. It will also permit to extend to a much larger volume of the Galaxy, studies that are now made only in the strict neighbourhood of the Sun.

It will also permit to study with an improved accuracy most galactic features to 1 000 parsecs, like associations, clusters, spiral arms, structures perpendicular to the galactic plane, etc. We give, below, some examples:

(b) Galactic Evolution

The basic observational material required for a study of the chemical and kinematic evolution of the Galaxy consists of the distribution in space, the velocity vectors and luminosities, of stars with well-defined spectral or photometric characteristics, which enable age and composition to be estimated. Closely allied to this general problem is that of mapping the interstellar absorption in the extended solar neighbourhood. Narrow band photometric techniques such as that of Stromgren (1964, 1977) have proved to be powerful tools for this classification work, and great advances can be expected in our understanding of the rate of star formation, the luminosity function of the brighter stars, and the dynamical state of the Galaxy, at various epochs in its history, when radial velocities and photometric data become available for all the programme stars observed with the satellite.

Since the luminosity of the main sequence depends partly on the abundance of helium, it may well be possible to estimate how this has varied with time, and hence to provide a test of the "big bang" theory.

(c) Galactic Dynamics

Many of the stars on the program will be intrinsically bright main sequence stars and subgiants. The improved calibration of luminosities will enable the distances of these up to say a kiloparsec, to be determined photometrically with an accuracy of about ten per cent. Taken in conjunction with the new proper motions, transverse velocity components can then be computed; at one kiloparsec, the statistical mean error will be about ± 10 km/sec for low velocity objects, rising to ±30 km/sec for velocities of 100 km/sec. This new data will therefore be especially valuable for studying the velocity field of intermediate age and population II stars, particularly when radial velocities have also been obtained.

Of particular importance will be the detection of stream motions, and of Stromberg drift at various distances from the galactic plane.

At a distance of 500 parsecs, the rms error of a transverse velocity component will only be about ± 5 km/sec for normal stars; it should therefore be possible to measure variation of velocity dispersion, and the star density, up to this distance from the plane and hence to make a completely independent determination of the force law K_z and hence the local mass density.

(d) Kinematics of Special Objects

The study of stars in moving clusters and associations is important, both for the calibration of luminosities from the convergent point of proper motions, and for the investigation of age and evolution of such systems. About ten associations within 1 000 parsecs could be investigated using the newly determined distance indicators and precise proper motions. Also, about 10 galactic clusters will be investigated within 300 parsecs.

Up to the present time only a few such objects have been studied, notably the Hyades cluster. Work on extended objects such as the Scorpio-Centaurus association and the Ursa Major cluster has been hampered by errors and inhomgeneity in the proper motion system which will be absent from the space astrometry data.

Of particular importance will be further study of Gould's Belt, particularly its kinematic age and possible relationship with the Orion spiral arm.

1.4.5 Conclusion

The whole field of astrophysics is directly concerned by the results of the astrometric satellite. It is difficult to foresee what will be all the consequences. The examples given in the last two paragraphs only show that in many domains, the result of the mission will render obsolete all the present state of the art, and that a completely new era will start for stellar and galactic astronomy (structure, evolution, dynamics, etc.).

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1.5 Related Activities

This section is first concerned with the selection of stars for observation by the satellite and the required ground-based astrophysical observations. Then the expected developments of ground-based astrometric radio techniques are outlined. Finally the astrometric use of ST is presented.

1.5.1 Related Ground-Based Astrophysical Observations

Stars to be observed from the astrometry satellite can be pre-selected according to their interest for astrophysics and stellar astronomy. They may be of interest as individual stars or as members of a well defined sample of stars for which astrometric data is required.

In addition to these astrophysically selected stars others must be added so that the sky is uniformly covered with three nets of about 5000 stars each around the magnitudes 6,9 and 12. These nets shall serve as reference for meridian circles and for photographic astrometry. A higher density of reference stars is required in particular for photographic astrometry with long-focus telescopes of small angular fields, and this can be obtained by automatic meridian circles through interpolation in the highly accurate nets established by space astrometry.

An inquiry on proposed investigations based on space astrometry has shown that about 50 000 stars, most of them brighter than $m_B = 11$, would satisfy nearly all wishes of astrophysical nature and for basic reference nets. Another highly emphasized wish is to observe all stars down to a given limiting photographic magnitude (e.g. 9), so that there would be no selection bias introduced in the statistical studies.

The reference nets of the satellite itself require about 60 000 stars uniformly distributed. This follows from the size of the field of view of the telescope which is one square degree.

All these requirements are not conflicting, and it thus appears that the total available integration time of the mission can be concentrated on 100 000 stars, thereby obtaining a higher accuracy on each star than if the observing time were distributed on allstars down to a certain limiting magnitude. One of the possibilities mentioned in the Mission Definition Study was to observe all 250 000 stars to $m_B = 10.5$ but it has turned out that this satellite version was no more simple than the one with preselection now preferred.

A tentative distribution of the 100 000 stars is = 60 000 of $m_B < 9$, 30 000 of $9 < m_B < 11$ and 10 000 of $11 < m_B < 14$. (See also Section 1.3).

In order to select these stars spectroscopic and photometric sky surveys must be used, mostly relying on those already existing, since time will be too short to add new surveys.

1.5 Related Activities

(short introduction? see conclusions of Murray & Høg's paper.

keep ? modifying

1.5.1 (Related groundbased observations

After the selection it is highly desirable to obtain more detailed and accurate astrophysical data for these stars. The basic astrophysical information required to make full use of the astrometric data obtained from space may be briefly summarized as follows:

1: accurate classification of the objects as to type (spectral class, population type, peculiarities);

2: ~~distance~~ distance modulus (if no trigonometric parallax);

3: effects of interstellar medium;

4: radial velocity.

Among existing observing techniques, it seems fairly clear that intermediate - band photometry (points 1-3) and the Griffin photo-electric scanning method (point 4) would be the most efficient ways to obtain this information for large numbers of stars. The maximum effort involved can be estimated by considering, as a concrete example, a programme of 100 000 stars of average magnitude around 10^m.

A telescope size of 1.5 m seems a reasonable compromise between size and availability. Experience with existing multichannel photometers and radial velocity scanners indicates that integration times with a 1.5 m telescope would be of the order of 30-60 sec. 500 observations in an average night should thus be possible, assuming an efficient method of moving from star to star. If three observations of each type are needed for the detection of most of the variable objects, one finds in each hemisphere about 600 clear nights, or some full two years on a first-rate site, would be required to complete such a programme of astrophysical observations.

This obviously represents a major effort, but is not at all impossible if carried out over a decade or so, even if one contemplates to use existing telescopes. It does not follow however that it would remain a realistic proposition if its extent were doubled or tripled. It therefore seems imperative to select very judiciously the number and kinds of stars on the observing programme in order to obtain the maximum useful information from the effort invested. The decision whether or not to follow up systematically all stars which are variable in light or velocity has a profound influence on the possible size of programme, since that alone implies about a doubling of the total number of observations estimated above.

Necessary preparatory work for the astrophysical programme includes:

a: a well thought-out policy for selecting the programme stars;

b: perfection of methods for rapidly setting and centering on a star.

c: extension of photo-electric radial velocity methods to all spectral types;

d: development of optimum photometric systems with regard to both astrophysical information and efficiency in observing. In this connection, it should be recalled that the number of stars with good trigonometric parallaxes available for the basic calibration of such systems would be dramatically increased by the astrometric space program.

It appears from above that a good deal of collaboration and coordination is required between on the one side space astrometry, and on the other side ground-based astrometry and astrophysically ground based observations if full benefit and quick results are to be drawn from the satellite.

1.5.2 Radio 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 and the absolute dynamical frame to the reference system defined by the stars.

Radar

The radar technique can be applied to the bodies near the Earth (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 already achieves 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 objects of 15th to 19th magnitude so that the problem of the link to the reference stars remains. It might be solved by new visual interferometric techniques (Connes, Labeyrie, etc ..) provided that the astrometric mission includes several stars of magnitude 9-12 within a degree of the extragalactic reference point. There are also about 10-15 radio-stars that can and must be part of the program of the astrometric satellite and that will contribute to this link.

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

1.5.3 Astrometric Use of the 2.4m Space Telescope (ST)

It is intended to utilize the Fine Guidance System for relative astrometry. It will be able to connect a star to two others within a distance of 0°.5. A mean error of ±0".002 is expected after averaging and calibration of scale value using calibration fields. The magnitudes are presently restricted to fainter than m_V=10 but it is expected to extend this range to m_V=3 by suitable neutral-density filters. Larger arcs than 0.°5 shall be measured by "chaining" so that connection to bright fundamental stars with known absolute position and proper motion will be possible.

~~Other instrumentation studied in the course of planning the ST is no longer foreseen for astrometry.~~

Thus, accurate relative parallaxes and proper motions may be determined for selected faint stars in a number limited by the competition on observing time with the many other tasks of ST. Determination of absolute proper motions requires longer observing time due to the chaining method and will be restricted to very few objects. The proposed ESA project, however, aims at absolute astrometry of very many 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.

1.5.4 Optical Interferometry

Optical interferometry is an old technique that has just become operational for studying double stars and it is expected that from the ground and also if embarked upon a Spacelab, the direct interferometric techniques will permit the measurement of angular distances of stars with magnitude 17 or smaller to an accuracy of 0".001 or better, provided that they are within 1° of separation. This technique, like the use of the Space Telescope, will complement the astrometric satellite mission by linking the reference frame to quasars. It will also permit to increase the number of stars observed in open clusters whose distances will be determined by the mission. It will also be used to determine the orbits of close binaries whose distances will be measured by the astrometric satellite and therefore contribute to the determination of new precise stellar masses.

2. PAYLOAD

2.1 Principles

The methods used for the execution of the astrometric mission and the preliminary description of possible technical solutions were defined by the Mission Definition Group during their study in 1975/1976.

The basic principle is to measure with great precision the angular distance of pairs of stars separated by a large angle, close to 70°. The measurement is made by a differential method, by comparing in the focal plane of a single telescope the positions of the images given by two observed stars, separated by approximately that angle; the two images are superimposed by means of a complex mirror with two reflecting surfaces. The attitude of the spacecraft about its centre of gravity is controlled in such a way as to scan the whole celestial sphere in a regular movement; as a result of this motion, the images of the stars, whether they come from one field or the other, move across the focal plane of the telescope, where their position is determined as a function of time. To this end, use is made of a system of grids composed of alternately opaque and transparent bands which modulate the incoming light; behind these grids, a photon counter (image-dissector tube) determines the number of pulses produced by the star images when they cross the grid system. The data thus collected is transmitted to the ground by telemetry in suitable form as a function of time. They are processed on the ground and yield the desired astrometric parameters.

The present Phase A study has shown that a spacecraft configuration comprising two sub-assemblies with minimum interfaces was to be preferred: these sub-assemblies are the payload and the satellite (or bus). The payload includes the optical subsystem (telescope, complex mirror), the modulation subsystem (grids and star mapper) and the detection subsystem (image dissector); the bus carries all the usual technical sub-systems, such as power supply, attitude control, telecommunications. Each sub-assembly can be separately developed and integrated in its specific structure and carries its own thermal control. All critical accuracy aspects are concentrated on the rigid payload sub-assembly, which is attached to the bus with very moderate alignment specifications; the satellite bus is therefore composed of quite conventional equipment.

The following sections summarize the results of the payload study. (Sections 2.2 to 2.7)

2.2 Selection of Preferred Optical Concept

The first step of the study was the determination of optical parameters, (first-order or gaussian elements, such as focal lengths, distances, etc.) which would make the telescope comply with a number of basic requirements, such as:

i) a scale factor (arcseconds per mm) large enough to permit the use of a grid which could be fabricated with the required accuracy, (but also requiring a reasonable dimension of the linear field);

ii) a limited overall length of the system, considering that the scheme calling for combining two fields of view into one telescope already asks for a considerable free space in front of the telescope system;

iii) assessment of the performance requirements of the single optical components (such as numerical apertures, field angles, etc.), consistent with the accuracy to be achieved. This first investigation lead to the conclusion that, for a linear aperture of the entrance pupil of 25 cm, the gaussian solution suggested in the Mission Definition Study, that is a cassegrain system of two mirrors with an equivalent focal length of about 12 microns per arcsec, could be considered optimal, and was thereafter adopted, with small variations, for all solutions further investigated. With this configuration, the length of the telescope can be kept well under one meter, and the total overall length from pupil splitting device to focal plane can be kept within a total 1.5 meter length, which was considered acceptable.

Within this gaussian frame, two systems have been investigated in detail from the geometric optics point of view:

- a Ritchey-Chretien telescope corrected for a field of about 36 arc minutes;

- a Baker-Schmidt telescope corrected for a field of 1^{o} or more.

At the mid-term review, the scientists selected the larger field option, i.e. the Baker-Schmidt solution. Four configurations of this type were studied, combining two different focal lengths with two different apertures (namely circular, 25 cm in diameter and rectangular, 32 x 16 cm). The study of residual aberrations, after optimisation of the four configurations, showed that the one with 25 cm aperture and 2460 mm focal length was by far preferable. It then became apparent that the real obstacle was the presence of chromatic aberrations introduced by the presence of a dispersive medium, the correction plate. All attempts to reduce the shift in photometric gravity center of the image due to difference in star-spectral composition were unsuccessful, and errors of several tenths of a micron, corresponding to several hundredths arcsec could be expected. These errors have been considered incompatible with the mission goals, because they are unpredictable unless one introduces the knowledge of the colour class-type for each star entering the field, a requirement which has been estimated as unfeasible.

An alternative concept to the reflecting complex mirror had been proposed, in an attempt to remedy the possible drawback of that device: a different entrance pupil for each of the two fields of view. This alternative solution would have consisted replacing the complex mirror by a semi-transparent system, thus ensuring that the two beams are really superposed. However, this attractive solution had to be abandoned because it introduced aberrations or chromatic effects due to prismaticity.

Finally, it was decided to adopt an all-catoptric Baker-Schmidt design, in which the dioptric correction plate is omitted, but the faces of the complex mirror are suitably deformed. This solution has been extensively examined and it has then shown that it leads to excellent theoretical results as far as correction of the aberrations is concerned. It constitutes the best trade-off proposed at the end of Phase A and is described in the following sections.

2.3 Optical Design

The selected optical design is based on an all reflective Baker-Schmidt telescope, in which the correcting plate is obtained by deformation of the beam-splitting complex mirrors. The solution is very promising for a number of reasons, i.e:

- no colour error,
- deformation by reflection is about four times less than by transmission,
- the correcting surface coincides, as it should, with the entrance pupil,
- the correcting surface is at the largest possible distance from the primary mirror.

It is of interest to reduce as much as possible the angle between the normal to the beam-splitting mirrors and the telescope axis, however, the smaller the angle, the longer the minimum distance between the complex mirror and the primary mirror. As a trade-off, this last distance has been chosen as 1300 mm, which allows an inclination of about 18°, leading to a basic angle of (between the two fields of view) about 70°.

Assuming for the deformed mirror profile a simple fourth order curve, a third order solution has been found and subsequently optimised by ray-tracing. The main parameters are given in Table 2.1. Figure 2.1 represents the light path and Figure 2.2 is a drawing of the optical assembly.

The semi-field is 47 arc minutes, corresponding to a linear distance of 33.6 mm at the focal plane, or 12.2 μm per arcsecond.

Computations of the aberrations have shown that the marginal rays are corrected beyond any practical significant limit, the wave retardations being of the order of 5 to 8.10^{-3} μm or 50 to 80 Å. The system is almost theoretically perfect or can be made perfect with minor refinements. But the manufacturing tolerances are so stringent that it does not seem possible to match them in the present state of the art, unless a special technological study is performed. However, a perfect instrument, although obviously desirable, is by no means necessary for meeting the accuracy objectives of the mission, as indicated in Section 1. Indeed, what is generally required is stability of the parameters during some tens of minutes, as has been demonstrated by the theoretical study summarized in Section 3.

TABLE 2.1

Optics Main Parameters

COMPLEX MIRRORS		
Diameter	250	mm
Basic Angle	72°	
TELESCOPE		
Primary Radius of Curvature	2044	mm
Primary Diameter	286	mm
Secondary Radius of Curvature	1102	mm
Secondary Diameter	110	mm
Primary-Secondary Mirror Distance	700	mm
Primary-Focal Surface Distance	74,77	mm
Equivalent Focal Length	2459	mm
F/Number	9,84	
Linear Obscuration Factor	44%	
COMPLEX MIRROR - TELESCOPE PRIMARY DISTANCE	1300	mm

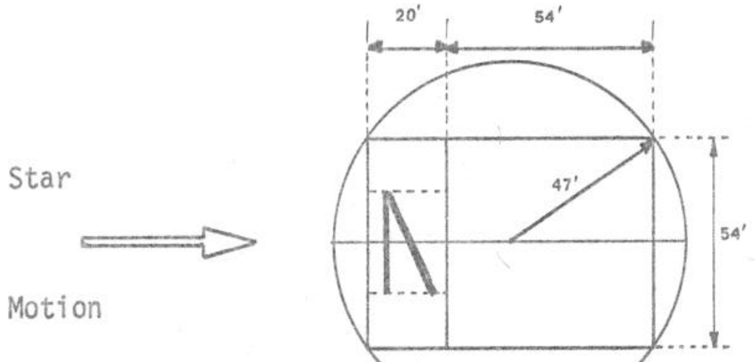
2.4 Grid System

The grid system at the focal plan fulfills two functions:

- a first part, operating when a selected number of bright stars enter into the field of view, which is used to determine accurately the telescope axis attitude, constitutes a star mapper

- following it, the modulating grid, transmits the light signal coming from all observable stars to the image dissector tube via the relay optics.

This grid system has been the subject of extensive studies, but their final optimisation will need further investigations, in particular through exploitation of the software elaborated during the theoretical study. The present baseline consistent with the telescope design outlined in Section 2.3, is the following:



The star mapper, covering a surface of about 20 x 18 arc minutes, include two grid systems at an angle of the order 45^{o}. The accuracy analysis, assuming that the positions of the selected stars are known a-priori from previous astrometric determination with an accuracy of the order of 0.1 arc second, has shown that the telescope axis attitude can be measured onboard continuously with an error of about 1 arc second. The operation of the star mapper requires that stars to be observed are selected on the ground, that their parameters are periodically loaded in the spacecraft memory, and that an onboard computation is executed; implementation of these functions has been defined in a preliminary way during the Phase A study and the necessary software has been established. The onboard attitude information derived from the star mapper will be used for controlling the position and motion of the instantaneous field of view of the image dissector when stars identified from the ground will cross one or the other telescope fields of view.

Various shapes for the modulating grid have been considered, yielding information in one or two dimensions. The grid will be constituted by a periodic pattern of alternatively transparent and opaque bands. The optimum grid period is equal to a few times the resolution limit, which is equal to about 0.4 arc second or 5μm on the focal plane.

As an example, the following specifications have been discussed with a manufacturer (J. HEIDENHAIN) and found feasible.

- dimensions	: 40 x 55 mm,
- support	: curved (on focal surface),
- pattern	: linear with 15 micron width bands, or alternatively at 45^{o} in short steps,
- opacity	: 5 as a design goal

Detail specifications on tolerance (for parallelism, regularity) remain to be defined.

It is to be noted that the association of the star mapper and the modulating grid in close proximity on the same surface at the focal plane eliminates stringent alignment problems.

2.5 Relay Optics and Detectors

2.5.1 Relay Optics

The relay optics transfer the star image modulated by the grid system from the telescope focal surface onto the sensitive photocathode plane. The following conditions apply:

- conjugate the curved and negative surface of the telescope focal surface (R = -1189 mm) with the photocathode ~~surface~~ with a ratio of about 4,

- the entrance pupil position shall be the Baker-Schmidt telescope output pupil position,

- the object aperture shall be the telescope's one i.e. F/10 which yields an image aperture of F/2,5,

- the entrance field of Ø = 56 mm (54' x $\sqrt{2}$) shall be reduced down to the photocathode useful diameter of Ø = 14 mm,

- the overall optical length shall be limited to about 350 mm.

The useful signal is contained in the modulated light from the grid output. Therefore, the relay optics aberrations and alignment tolerances are only defined by the requirement that the star images shall remain within the instantaneous field of view of 30 x 30 arc seconds. A typical design has been worked out to include seven lenses, the first one being very close to the grid, demonstrating the feasibility of the optical and mechanical configuration.

A similar relay optics can be implemented between the star mapper and the photo multiplier with some relaxation as the surface to be illuminated is not restricted as for the image dissector tube.

2.5.2 Image Dissector Tube

In order to decrease the influence of interfering stars and of straylight, it is proposed as a baseline to use an image dissector tube. This type of tube is actually the only one currently available off the shelf and of course to be preferred in view of the recommended cost effectiveness approach. It allows 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 (IFOV). On the other hand, the smaller the IFOV and the higher are the accuracy requirements in the setting of the deflection coil currents to encounter and follow the selected stars crossing the slit patterns.

An overview of all the possible detectors should mention the solid state imaging detectors combined with intensification stages ICCD and the new family type most commonly called photicon with various position determination, concepts such as crossed-wire systems, multilayer thin film circuit or target array of diffused planar diodes. These types of tubes detect photon events with very high spatial and time resolution simultaneously while maintaining sensitivity over a large area. This is an advantage over the image dissector which is sensitive only in one resolution element of its field at one time. On the other hand its use has to be carefully weighted in view of its utilization in a spacecraft as the required electronics amount rapidly to prohibitive implementation not to mention data rate and costs aspects. This is why the image dissector tube has been preferred in the present Phase A study.

The proposed tube is 4012 RP manufactured by ITT Electron Tube Division, which has been used on several space programmes and has a proven reliability. A highly linearized version is being developed as a detector for the Spacelab Instrument Pointing System. It includes a S-20 type photocathode surface.

The instantaneous field of view of the Baker-Schmidt telescope of 30 x 30 arc seconds corresponds to an area of 90 x 90 microns on the photocathode; a usable area of 50 x 50 microns has been selected in fact. The various error causes have been assessed as follows:

- tube piloting : with 12 digit words, about 3 microns at the photocathode;
- deflection and focus coils current precision and stability : very small;
- mechanical and thermal drift : practically negligible;
- voltage stability : a 10^{-3} stability of the image section potential leads to a deflection deviation at the edge of the field of 3.5 microns;
- influence of outer magnetic field : cancelled through adequate shielding.

To these errors should naturally be added the errors originating from the incorrect determination of the motion of the observed star within the field of view, deduced from attitude data of the star mapper; these have been estimated to be smaller than a few microns at the photocathode.

The control of the tube implies that a window can follow very precisely an a-priori path with a given constant speed. As the window is only about 0.5% of the tube screen dimension, and the non linearity of the tube deflection can attain 10%, it is necessary to correct the tube deflection characteristics. Practical solutions have been worked out, and it has been shown that the associated electronics are by no means a critical aspect.

2.6 Baffles

As the spacecraft will most of the time observe stars during the day and as the telescope fields of view can look at the Earth due to the scanning motion, straylight shall be eliminated by means of baffles.

The minimum signal to background ratio to obtain a good extraction of the information has been fixed at 5, limited by the data processing electronics. The sky background level has been specified to be equivalent to 20 stars of magnitude 15 for an instantaneous field of view of 10^{-4} square degrees.

(max. revolving angle of 45° is envisaged)

The main straylight sources are the Sun and the Earth. The Sun influence is eliminated by canting the baffles at the maximum elevation angle (revolving angle) above the exit plane. The Earth influence has been carefully computed and it has been concluded that baffles with a ratio length over a diameter of 5 are adequate, reducing the straylight below the specified level when the Earth centre is seen at an angle superior to about 25^{0} from a telescope field axis (at a geosynchronous altitude).

to be reviewed by Matra

2.7 Mechanical Design and Thermal Control

2.7.1 Structural Concept

The complete payload is structurally independent from the spacecraft to which it is rigidly connected by a single plane base interface, perpendicular to the main axis and located right under the complex mirror. Figure 2.2 represents the general configuration.

The telescope itself is structurally and thermally decoupled from the main envelope through a cyndrical invar shell holding together but autonomously the primary and secondary mirrors. This part is limited at both ends by the spiders which are fixing both mirrors. It is held in a structural frame, also in invar which is used as a reference and located at the primary level. The link between the complex mirror assembly and the telescope is realized through a parallelepipedic structure made of honeycomb and carbon fibre also underpinned on the reference frame.

Relay optics and folding prisms and/or mirrors prior to detectors are located on a honeycomb and carbon fibre plate also fixed to the reference frame. As for the grid device itself and its associated prisms, its fixation is realized to the hub which is the holding system of the primary mirror.

A thermal protective shield is disposed behind the primary, decoupling the telescope from heat dissipation in the detector's compartment.

Detectors themselves are located sideways parallel to the optics main axis.

The primary mirror is made of a Zerodur block 290 mm in diameter and 60 mm thickness. Secondary mirror dimensions are respectively 103 x 40 mm.

The fixation of the primary is realized through a central annular fitting through which the light reaches the grid. The back face of the mirror is limited at its centre to the invar hub of a cartwheel the arms of which are fixed on a circular invar ring itself hooked to the structural reference frame.

A hood closes up the whole volume behind the grid and is coveniently shielded with a 5 mm Aluminium plate as a protection against radiations.

Optical centering is achieved with an external mean, the final fixation being insured with a pin. No more adjustment is further necessary.

The secondary mirror is fixed to a spider through a central screw-bolt system taking advantage of the obscuration. The spider made of three thin mirror arms holds the secondary with respect to the telescope structure and all the adjustments are made at this interface level. The coincidence of optical axis of both mirrors is set with spherical wedges and chocks. When the accurate position is found the holding is tightened and maintained through fixing pins.

The mass breakdown has been evaluated as follows (in kg):

Telescope-	Primary mirror	7.7	
	Secondary mirror	1.0	
	Mirror Supports	6.9	
	Tube	12.0	
	Miscellaneous structure	3.2	
			30.8
Other items-	Complex mirror	10.5	
	Support base	14.0	
	Structural parts	23.5	
	Relay optics	0.8	
	Image dissector tube	2.0	
	Photo multiplier	0.4	
			51.2
Electronics-	Within payload		4.0
		TOTAL	86.0 kg.

2.7.2 Manufacture of the Complex Mirror

The baseline complex mirror is a triple split symmetrical device with a correction figuring implemented on the reflecting surfaces; it is constituted by a central mirror and two parallel lateral ones; the angle between the optical axis of the central mirror and the common axis of the lateral ones defines the basic angle. The absolute value of that angle is not very critical (as it will be evaluated by the data processing algorithm), but it must remain constant within a fraction of a thousandth arc second during a period of time of about 20 minutes.

Two manufacturing approaches have been analyzed: either three separate blocks or two blocks only, one with a shape. The main problem is related with the parallelism of the two sided mirror which is closely dependent on the necessary minimum spacing which can be accepted between two adjacent blocks. However it appears that this spacing can be made large enough to relax considerably the blocks' assembly process, thereby largely increasing the confidence in the feasibility of a suitable complex mirror. In addition, it must be pointed out that a two-mirror configuration may be acceptable, thus eliminating the parallelism problem.

The baseline solution implies that the mirror surfaces are deformed in order to act as correcting plates. The curves of equal deformation are ellipses of small eccentricities. It has been shown that a vacuum deposition technique developed for a similar application can give satisfactory results.

2.7.3 Thermal Control (see Section 4.3)

The temperature gradient requirements have been determined as follows:

- across complex mirror	$\mp 0.2^{o}$
- between primary and secondary mirrors	$\mp 0.5^{o}$
- between secondary and complex mirrors	$\mp 0.5^{o}$
- between entire optical system	$\mp 1.5^{o}$

These requirements impose a sophisticated active thermal control design. In addition to the use of well proven techniques (thermal blankets, coatings, controlled conductive paths, etc.), the subsystem includes a thermal control logic (performed by the onboard computer) that processes the outputs of temperature sensors properly set on optical components and drive heaters as required. The system is fully redundant. In addition, several heat pipes isothermalise the temperature on the mirrors mounting cylinder.

The thermal behaviour of the complex mirror have been extensively investigated. It has been concluded that the variation of the basic angle stays well below the specified values of 0.001 arc second during 20 minutes.

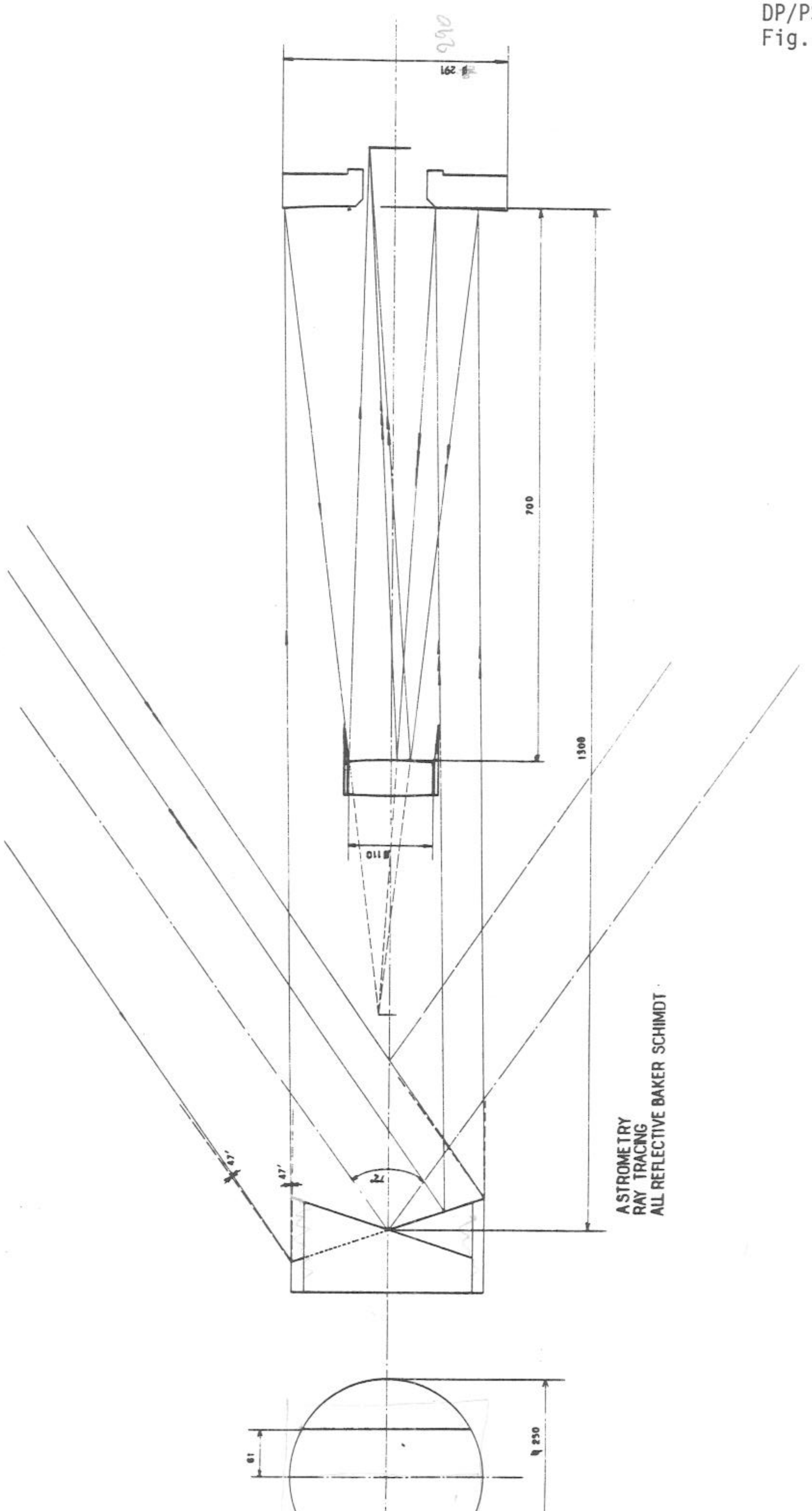

ASTROMETRY
RAY TRACING
ALL REFLECTIVE BAKER SCHIMDT
700
1300

FIGURE 2.1

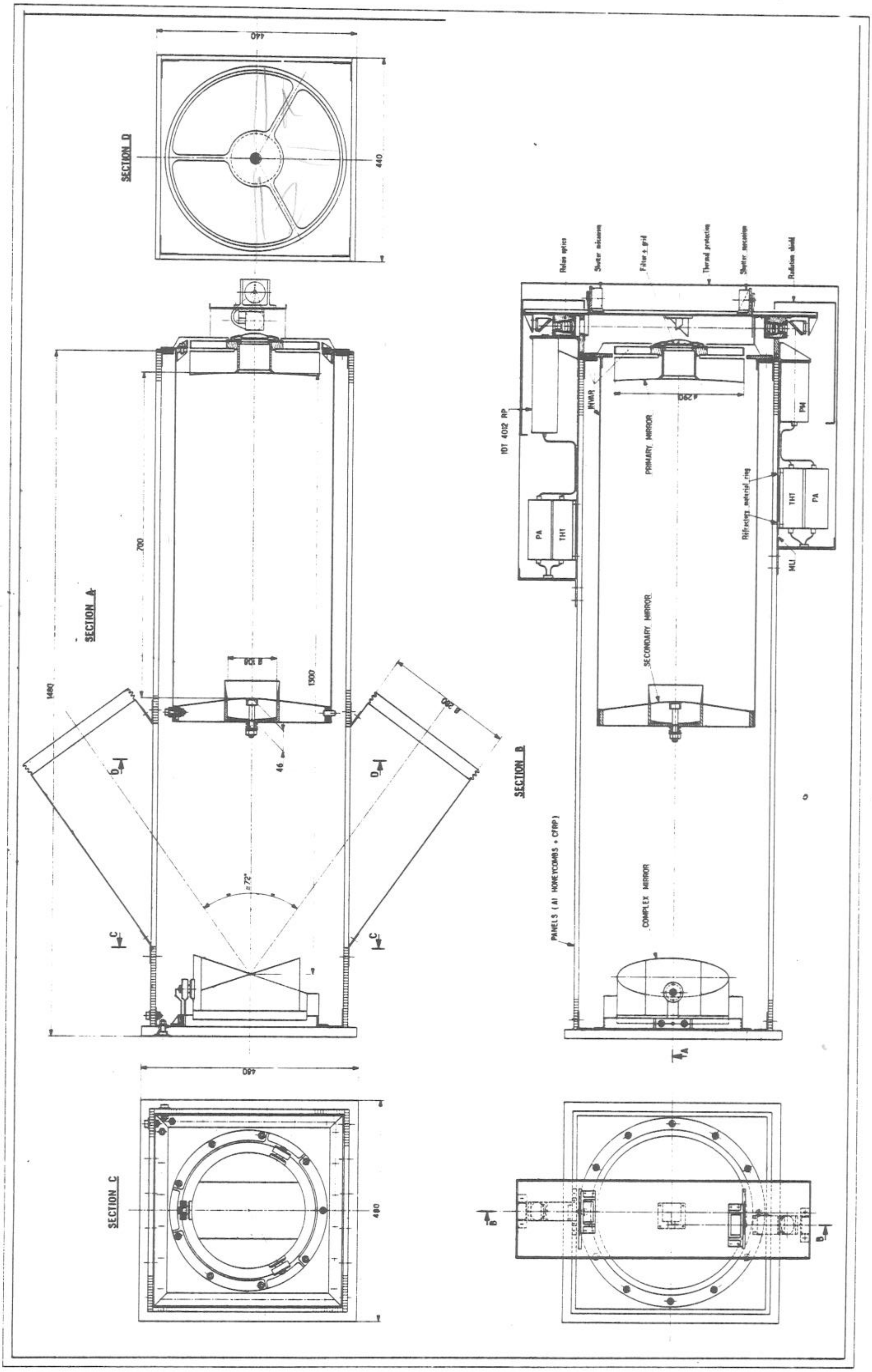

SECTION D
440
SECTION A
1480
700
1500
≈ 72°
SECTION C
480
SECTION B
IDT 4012 RP
PRIMARY MIRROR
SECONDARY MIRROR
COMPLEX MIRROR
PANELS (Al HONEYCOMBS + CFRP)
PA
THT
PM
MLI

FIGURE 2.2

3. MISSION ANALYSIS AND ACCURACY EVALUATION

3.1 Mission Analysis

3.1.1 Launch Vehicle and Orbit

The specified launch vehicle is the Ariane launcher currently developed by ESA.

The astrometric spacecraft can be designed for a large variety of Earth orbits; in the Mission Definition Study, a quasi polar sun synchronous orbit at low altitude (circular at 500 km) was selected; this orbit, together with variants at higher altitude (1400 km) was studied during the first part of the present Phase A. However, Ariane's basic mission is injection of a total mass of about 1700 kg. into a geostationary transfer orbit (perigee 300 km, apogee 36 000 km, low inclination), which is required for a large number of application satellites (telecommunications, navigation, meteorology). It is therefore highly desirable that the orbit of the astrometry satellite is compatible with this geostationary transfer orbit making it possible to consider a dual launch with another application satellite. The structural device for carrying inside the fairing two different spacecrafts is being studied in ESA under the name of SYLDA (Système de Lancement Double Ariane) and is planned to be built soon.

It has then been decided to fly the astrometric spacecraft into a geosynchronous orbit. In fact, this solution presents the following advantages:

- it is effective from a cost point of view, since the launching costs will be shared with the companion satellite;
- it is scientifically satisfactory;
- it allows the use of only one ground station situated in Europe, continuously in communication with the spacecraft; thus, the cost of the links with the Control Centre are considerably reduced and, in addition, the onboard communication subsystem is simplified (e.g. no bulky memory is required).

The selected orbit is inclined at about 20^{o} on the equatorial plane, such that it is close to the ecliptic plane. Eclipses occur each day with a duration varying from about 40 minutes to about 70 minutes. It is clear however, that the orbital parameters can be modified with a large flexibility, in order to take account of the presently unknown constraints of the companion satellite (in particular for opening the launch window, see following section).

3.1.2 Launch Window and Spacecraft Deployment

The optimum launch window has been chosen, in the absence of constraints due to the second satellite, in order to ensure:

- minimum inclination to the ecliptic plane (3.4^{o}),
- maximum exposure to Sun of the solar panels during the transfer orbit.

It has been concluded that the optimum launch date occurred around the Spring equinox (see Figure 3.1).

The spacecraft deployment sequence is illustrated in Figure 3.2. The first manoeuvre before apogee motor firing (AMF) consists in spinning up the spacecraft to 60 revolutions per minute; the configuration being dynamically unstable, an active nutation damper is used. At the fourth apogee, the apogee motor is fired, providing a velocity increment of 1530 m/s; sufficient to circularise the orbit and change the inclination by 10.^{o}5. After circularization, the spacecraft is oriented, located in the right longitudinal position, despun, deployed and the acquisition sequence then takes place.

3.1.3 Scanning of the Sky

partly L.L.

The motion of the spacecraft around its centre of gravity results in the scanning of the sky by the telescope fields of view. The two fields of view must regularly scan the whole sky along the same great circles in such a way that the coverage is complete with minimum gaps. In addition, in order to reconstitute the celestial sphere with best accuracy, the crossing angles of the scanned great circles must be as large as possible. Moreover, as the stray light originating from the Earth prevents observations (see Section 2.6), the periods of time when the Earth approaches any field of view by an angle less than about 30^{o} must be minimised.

A number of scanning modes have been extensively studied. The preferred solution is the following one, being understood that variations are possible and that final optimisation is left for further trade-off.

Let x be the telescope axis (bissector of the two fields of view, see Figure 3.3) and z the perpendicular to the plane containing the axes of these two fields of view. The z axis is maintained at a constant angle C to the Sun direction. The spacecraft scanning motion results from the combination of two rotations:

- a spinning motion around the z axis, characterized by the number R or revolutions per day (i.e. per orbital periods),

- a slow revolution of the z axis around the spacecraft-Sun line, characterized by the number K of revolutions per year.

The z axis then follows on the sky a curve of epicycloidal shape.

X A good compromise appears to be R=10; computations have shown that in this case, with a suitable phasing of the motion, a succession of 5.2 scans (each of 2.4 hours) can be executed without Earth occultation followed by an occultation period of about 40 minutes and then again by 4.2 unocculted scans. The sky scanning velocity is about 150 arc seconds per second, which means that the image of a star remains about 20 seconds at each passage on the modulating grid. The angle C is equal to about 30^{o}.

The number K can be selected between 6 and 12.
Symmetrical scanning is defined as a scanning on which at any two instants of time half a year apart the rotation axis z will point in exactly opposite directions. Symmetrical scanning can be obtained for the following combinations of K and C: (K,C) = ($8,45^{o}$),($10,36^{o}$), ($12,30^{o}$).

Further optimisation of these three parameters K, R and C will have to be carried out using the software developed during the theoretical study.

3.2 Accuracy Evaluation

L. Lindegren.

3.2.1 Derivation of the Mathematical Models

Very sophisticated and modular models have been set up to simulate in detail the functioning of the system. The models can be used to feed the filtering or optimization algorithms, and to support sensitivity studies against deviations or perturbations.

Basically, the output signal obtained on board is the intensity of a Poisson process which depends on a number of parameters related to each of the logical items in the breakdown (and even which involve a stochastic process for the residual attitude): telescope mounting and pupil shape, basic pattern of the modulating grid and distorsions/misalignments, location and shape of the instantaneous field of view (IFOV), sensitivity and misalignment of the cathode, spectral characteristics of the star, background and stray light ; and on the other hand, for the model of the direction of the object, complex entrance mirror, residual attitude, nominal scanning law and model of astrometric positions.

The telescope is defined by its modulation transfer function (MTF);

- the real grid is represented by the Fourier transfer (FT) of the characteristic transparency function.

- the image dissector tube (IDT) cathode efficiency is described by its FT representation;

- the IFOV is described by means of the FT of the characteristic function of mask shape.

The model of the star direction in the focal plane is obtained by means of a sequence of transformations:

- from the Ecliptic Satellitocentric frame to the Nominal Scan frame.

- from the nominal scan frame to a frame bound to the spacecraft.

For the residual attitude angles, a very realistic model has been set up for this critical item, which closely follows the hardware design and uses stochastic differential equations:

. the Euler equations for the rigid body, with perturbing torques on each axis, modeled as white noises that might present correlations between axes;

. control angular momentum, produced by reaction wheels, where the time derivative is assumed to follow a feedback law which is normally a linear function of the stimated angular positions and rates, with given gain matrices;

. to account for the gyro noise and estimation error, a 3-dimensional white noise and a 3-dimensional colored noise is superimposed on the feed-back law

3.2.2 Basic Decomposition of Data Reduction

When considering the particular features of the present problem, it is immediately seen that the astrometricunknowns for the stars which will be observed might represent a set of up to 1 400 000 parameters to be determined.

For such a huge size, an attempt to solve the problem with any direct method, even a crude one like least squares, would be totally irrealistic because of the implied prohibitive computing time and storage requirements. In addition, the unavoidable accumulation of round off errors would make the validity of the solution questionable.

In this study, we have finally selected as the most promising one a decomposition method in three steps, which might further be reiterated, and which can be seen in an illustrative description as follows:

i) Step 1 : the observations made during several consecutive scans are grouped together for convenience in a set. Considering the short duration of the performance of this group of scans, the star motion is totally negligible during this period; the star positions can thus be depicted for instance by the abscissae of projections and the heights with respect to a reference great circle.

The analysis demonstrates that for the later determination of the astrometric unknown practically all information is contained in the measurements along the scanning direction (reference great-circle), and that measurements made in the perpendicular direction are not of large use because of their inaccuracy.

Secondly, since only angular distances between stars are measured, the abscissae of projections can be determined only up to an additive constant. This is also equivalent to considering the projection of a particular star as the origin of abscissae.

Together with star projections, inaccurately known instrumental parameters will be determined in this step.

ii) Step 2 : we introduce then as final astrometric unknowns the deviations with respect to nominal latitude and longitude, proper motion components and parallaxes (i.e. all small quantities), we can obtain a linearized condition equation for each observed star which involves as unknown quantities only the astrometric parameters of the stars and the abscissa of the star of the scan which defines the local origin of measurements (in a system consistent over the whole celestial sphere). The equivalent observation data is the innovation of the measurement, i.e. the difference between the measured distance of projection of the star with respect to the scan reference star, as obtained from Step 1, and the prediction of this quantity, based on a-priori known positions.

The number of condition equations is given by the number of angular observations, which will amount to 20 to 30 millions, depending on the particular missing profile.

The resulting set can be written in decomposed form, as :

- one linear system whose order is equal to the number of groups of scans considered, the unknowns being the abscissae of origin stars (or more generally the zero-points),
- and for each star, an independent system of order 5 whose unknowns are precisely the astrometric parameters of that star but in addition also the abscissae of zero-points of reference great-circles on which the star was projected during the mission.

Step 2 consists in solving the system for the zero-points. This is a numerically heavy task, because this large system does not seem to be amenable to further decomposition.

Moreover, since only measurements of angular distances between stars are made, there remains basically 6 degrees of freedom in the determination of the zero-points (3 Euler angles and their time derivatives arbitrary in the orientation of the celestial sphere).

iii) Step 3 : once the system is solved, with the restriction mentioned, Step 3 consists in substituting the zero-point values and solves the astrometric parameters, which is straightforward.

iv) further improvements : in addition to the usual screening of the results obtained, to detect for instance abnormal values caused by undetected parasitic stars, an improvement of the result can be attempted by iteration on the previous steps. In particular, using an improved knowledge of the star position perpendicular to the line of scan will contribute in some cases to reduce the equivalent measurement error obtained at the end of Step

3.2.3 Filtering Algorithms L.L.

For the operational data reduction, the solution of linear systems of equations in steps 2 and 3 will be handled by techniques which, although difficult, are nevertheless classical in the field of large systems of equations (e.g. in geodesy). Therefore, this aspect was not considered.

In contrast, most of the effort to set-up algorithmic tools was concentrated on the solution of Step 1 : a rigorous data processing scheme was required to take into account the exact stochastic character of the output signal and the satellite attitude motion, as a reference for later simplifications. Only filtering methods are able to meet these requirements.

The present study is in this respect an original contribution : to our knowledge, the application and the decomposition of a filtering algorithm to a Poisson-Gauss process of this size had not yet been considered.

The observation is the record of counts of a Poisson process whose intensity is modified as function of the unknown star positions with respect to the scan, the inaccurately known instrument parameters, and the residual attitude vector which received a stochastic model. We have introduced a state vector A governed by a stochastic equation.

The optimum estimate of this state vector together with the covariance matrix measuring the accuracy are obtained from the posterior probability of A, given the record of counts, as conditional expectations. To obtain a tractable filter, we simplify by introducing Taylor expansions around the optimum estimate.

In the present study, we are only interested in the covariance matrix. The operation of the filter is then practically reduced to the integration of a matrix Riccati equation along the scan.

At first glance, this seems to be an insurmountable task, because, in addition to the well-known numerical problems with Riccati equations:

- the order of the covariance matrix will usually be over 1 000 for a scan (storage problem)

- with a consistent system of units, the coefficients involved have very large differences in magnitude (round-off errors problems)

- the covariance matrix is badly conditioned because accurate measurements are made on strongly correlated parameters (usually, this results in a quick loss of symmetry and positivity due to rounding and truncation errors).

- a complete scan corresponds to some $2.5.10^5$ periods of the intensity signal in the right-hand member of equations; this is a prohibitive amount for the number of steps in the numerical integration.

After extensive investigations, efficient remedies have been found and tested:

i) decomposition of the state vector : the parameters corresponding to stars to be observed are grouped into batches comprising stars observed during the same period.

ii) introduction of scaling factors : in addition to the differences in order of magnitude, the covariance matrix is numerically ill-conditioned, because some parameters remain correlated for a long time. On the other hand, it appears not feasible to introduce the square-root filtering, (Choleski decomposition of the covariances matrix). Scaling is to be seen as equivalent to an automatically adapted system of units, and rescaling can be made in the course of the computation whenever needed.

iii) stabilization of integration : numerical integration of the Riccati decomposed equations proved to be extremely unstable. Astep length as small as 10^{-3}s was necessary to avoid divergence with usual integration schemes. Since this was unacceptable, we have devised a special procedure.

The relations are a slight modification of a numerical integration scheme of the first order. However these modifications are essential, because they will ensure that the generated covariance matrix is positive even if truncation errors are large. This algorithm is consistent and convergent, and thus is stable. It could be refined to produce an algorithm of higher order, but the complexity of the derivation would drastically increase, and we prefer to consider if it is necessary for a smaller step size.

iv) averaging : The covariance is nearly constant on a grid step and we can approximate this covariance by time averaging. However, this is very advantageous only if the average can be obtained in analytical form. For the time being, this evaluation has been made only on a simplified model (assuming a signal is calibrated on board for heterogeneities of cathode, negligible chromatic effects, and the cut-off of second harmonic), and should be extended.

3.2.4 Software Developed and Numerical Results

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The software specifically developed for this study amounts to about 5 000 statements of standard FORTRAN H, in addition to edition and plot utilities interfacing with the package UGP on the ESOC ICL 4/72 computer. A major effort has been devoted to this task, since the Agency anticipates to extensively use this software, if future studies are approved, in particular to further optimize the mission configuration and derive accuracy estimates under a wide range of assumptions.

Except for the solution of large systems of linear equations involved in Step 2, all types of methods and models needed for the study of the mission and processing of data have been implemented :

i) evaluation of MTF telescope and derivatives : the software enables a complete study of any instrument of interest for the mission : design of the optimally corrected instrument from gaussian characteristics, exact evaluation of the MTF by ray-tracing, computation of derivatives if needed.

With this tool, effects of thermal and structural perturbations on the module and the phase of the MTF, as well as chromatic perturbations can be rigorously assessed.

ii) model of signal output : for sophisticated sensitivity studies, a general model of the signal has been implemented as a module. (However, the IFOV boundness is ignored). Although possible in principle, the use of this model in the filter is not recommended nor needed.

iii) observation generation and filtering algorithm : in addition to implementing the sophisticated algorithm in detail, this software includes a module able to prepare, from a simulated or a real star catalogue, the ordered list of stars to be seen during the scan, with a partition in batches for processing. It also contains a driver module which simulates an onboard strategy for optimum observation interlacing for visible stars.

iv) evaluation of scanning laws : this program estimates the final accuracy which is to be expected when performing Step 3 of the previous reduction scheme, for a given accuracy obtained from Step 1, when a sufficient redundancy is achieved in the measurements of angles between reference stars such that the contributions of errors due to zero-points determination is negligible.

Because of the limited time, emphasis was put on the development and tuning of software tools to remain available; at present, they have not yet been extensively exploited, and only preliminary numerical results are given here:

a) evaluation of MTF : they have been evaluated for the baseline instrument (Baker-Schmidt all-catoptric), with symmetrically split circular and rectangular pupils, for various wavelengths and position of the object : the major result is that the instrument corrected so far is close to perfection : the residual phase in the MTF would cause only a displacement of the order of 5.10^{-4} arc second for the photocentre. The rectangular pupil is more efficient than the circular one and further, the phase for residual aberrations, if any, is more linear. (See examples on figures 3.4, 3.5).

b) grid optimisation : the computations have been restricted to monodimensional grids, since it is now recognized that although they are theoretically interesting, bidimensional grids would generate a too complicated signal in view of onboard handling and calibration. The optimum selection of grid parameters (step and darkness ratio) can first be based on photon statistics, but consideration must also be given to detectabilitv of parasitic stars (by means of higher harmonics present with a larger grid step). To this end, angular accuracy per unit of time and photon flux have been evaluated (ignoring jitter), for various grid steps (normalized) and darkness ratios (fig. 3.6). The optimum value of darkness ratio is between 0.3 and 0.4 and not very peaked. The pattern as a function of grid step is very different for the central and the external part of the pupil. The combined curve however maintains a secondary minimum at about 0.4 of the resolution limit, which is the best trade-off.

c) <u>filtering</u> : a number of experiments have been performed with the filtering algorithms in order to investigate the effects of many parameters. However, this represents only a preliminary set of experiments. In particular, due to time constraints, it was not possible to obtain a run with a large number of stars to cover a complete scan.

After tuning runs to fix the time-step, we checked that on a perfectly calibrated instrument and without jitter, the present baseline gives an accuracy of about 5.10^{-3} arc second for one second of observation, and that the nominal jitter (0.025 arc second in 1 second) does not significantly degrade the result. Also, it is verified that switching more often to other stars reduces the effect of the jitter. Figures 3.7 and 3.8 give evolution of parameters estimated under both conditions.

Based on these results, it can be extrapolated that, for an average mission profile (e.g. 80% of mission time for the observation of about 50'000 reference stars), the available equivalent accuracy of abscissa <u>after one scan</u> will certainly be better than 5.10^{-3} arc second.

d) <u>improvement by step 3</u> : the efficiency of different scanning laws has been compared by means of a procedure which evaluates the coefficients of improvements of step 3 : this is defined as the ratio of the final standard deviation of an astrometric parameter to the standard deviation instar projection abscissa after one scan (assumed to be uniform). Many different laws have been considered. The theoretical dependence as function of mission duration has been verified ; the influence of the revolving angle is plotted on figure 3.9 and for the baseline value (30^0), figure 3.10 displays the improvement as a function of star ecliptic latitude. The previous results were obtained with a symmetrical revolving scanning.

Considering the conservative value of about 5.10^{-3} arc second for the accuracy on one scan, it is seen that for the baseline value of 30^0 for the revolving angle, the accuracy on astrometric parameters is likely to range from 0.7 to $1.6.10^{-3}$ arc second, (as seen in figure 3.9) and will be improved from 0.75 to $1.35.10^{-3}$ arc second for an angle of 36^0.

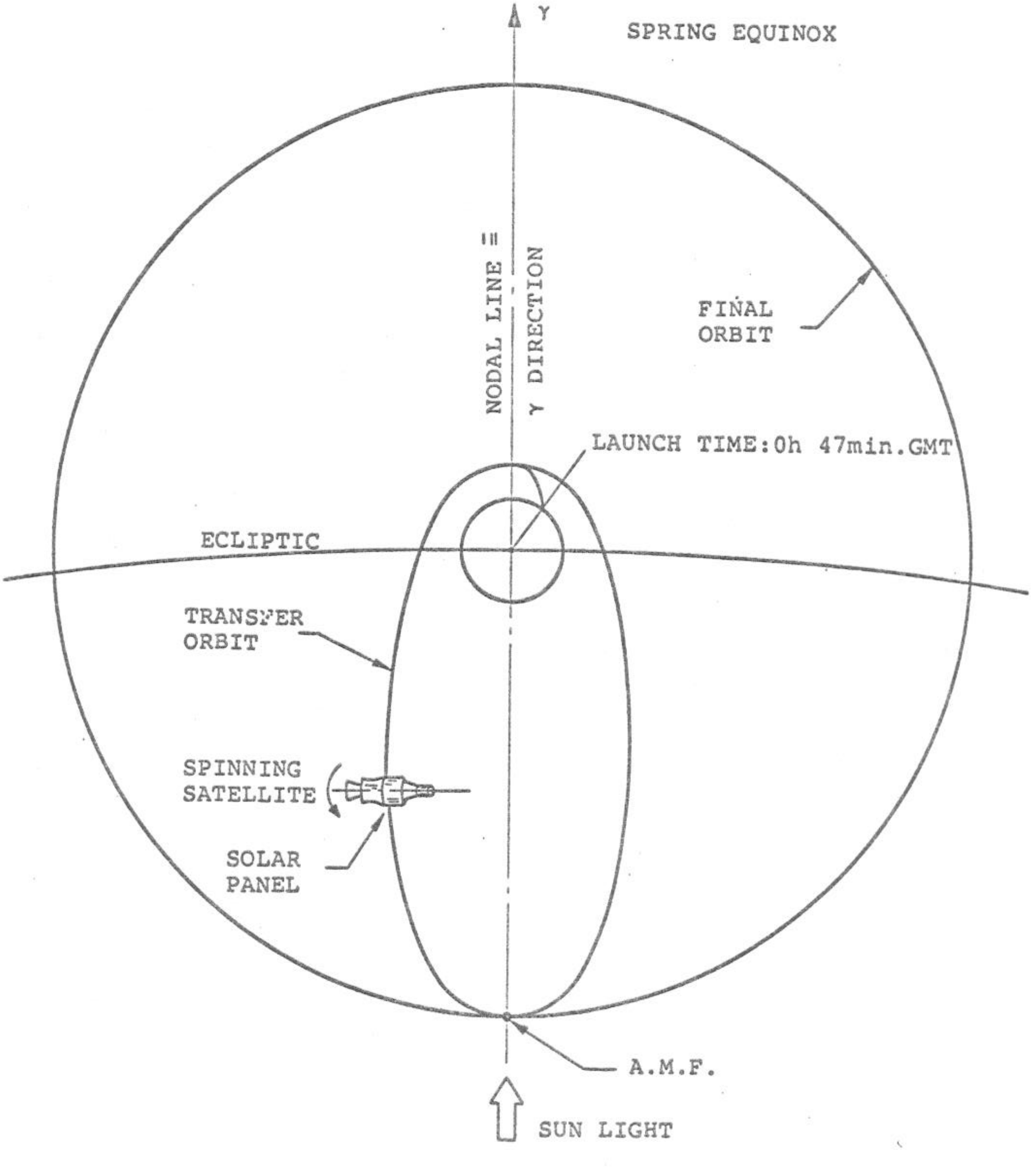

Y
SPRING EQUINOX
NODAL LINE ≡
Y DIRECTION
FINAL
ORBIT
LAUNCH TIME:0h 47min.GMT
ECLIPTIC
TRANSFER
ORBIT
SPINNING
SATELLITE
SOLAR
PANEL
A.M.F.
SUN LIGHT

FIGURE 3.1

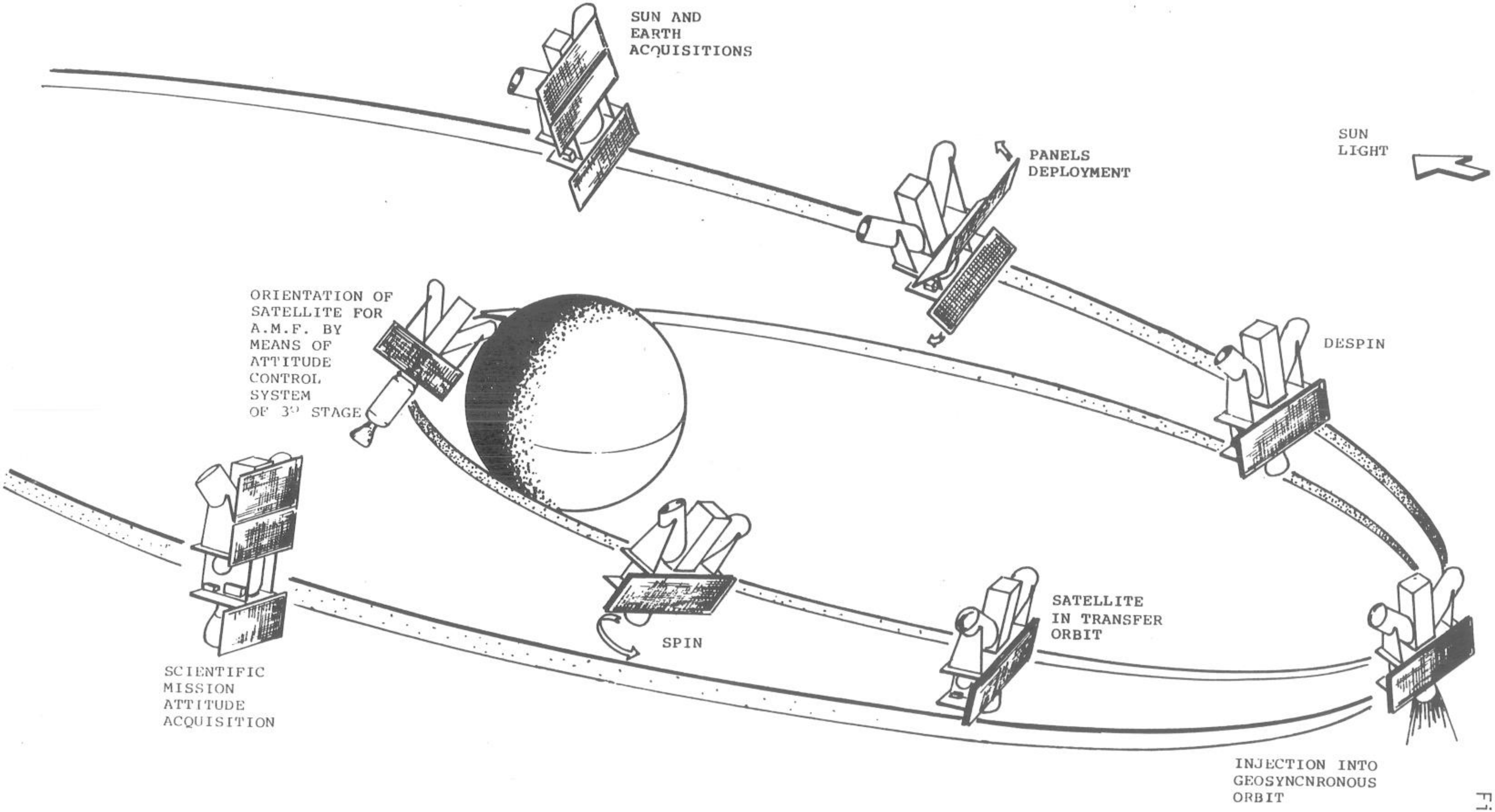
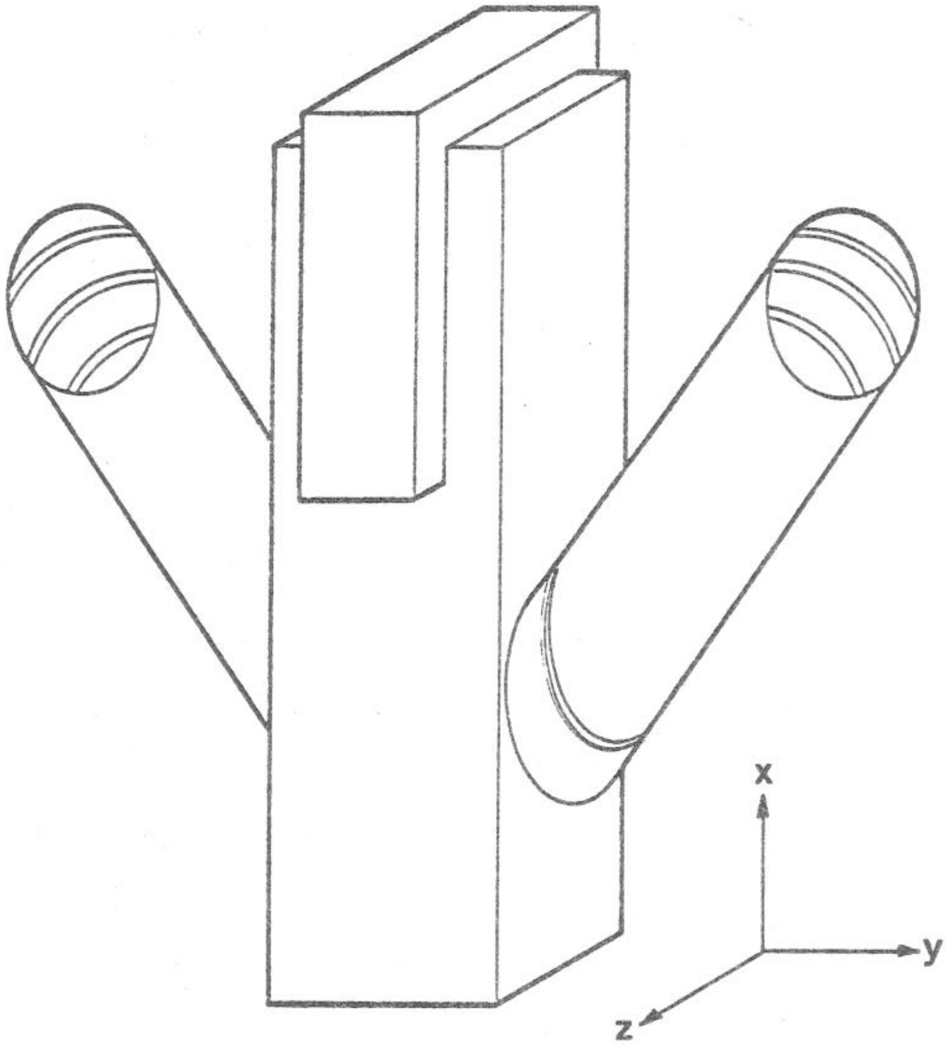


FIGURE 3.2 - SATELLITE DEPLOYMENT



ASTROMETRY PAYLOAD

FIGURE 3.3

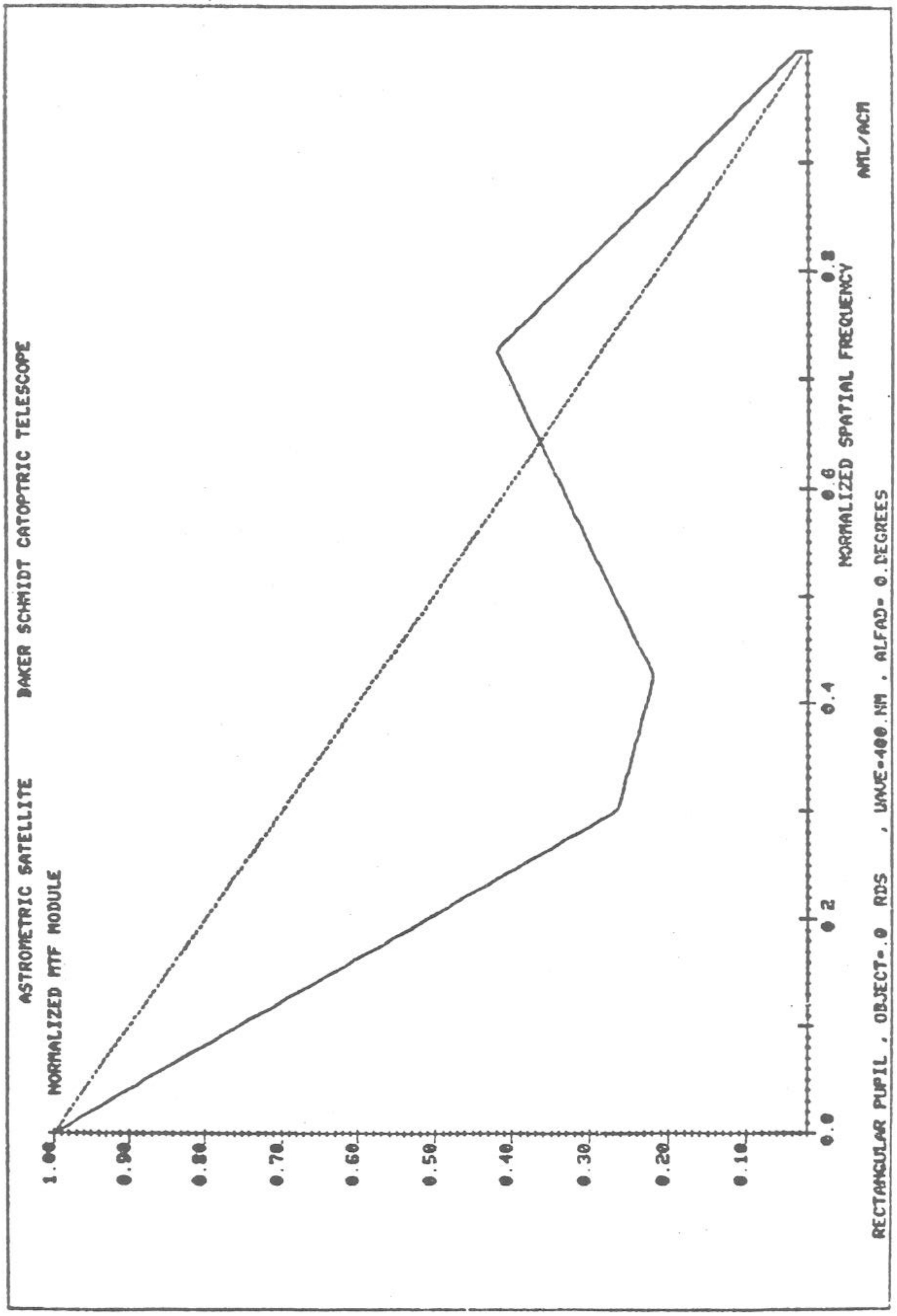

ASTROMETRIC SATELLITE
BAKER SCHMIDT CATOPTRIC TELESCOPE
NORMALIZED MTF MODULE
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.0
0.2
0.4
0.6
0.8
NORMALIZED SPATIAL FREQUENCY
RECTANGULAR PUPIL , OBJECT= 0 RDS , WAVE=400 NM , ALFAD= 0 DEGREES

FIGURE 3.4

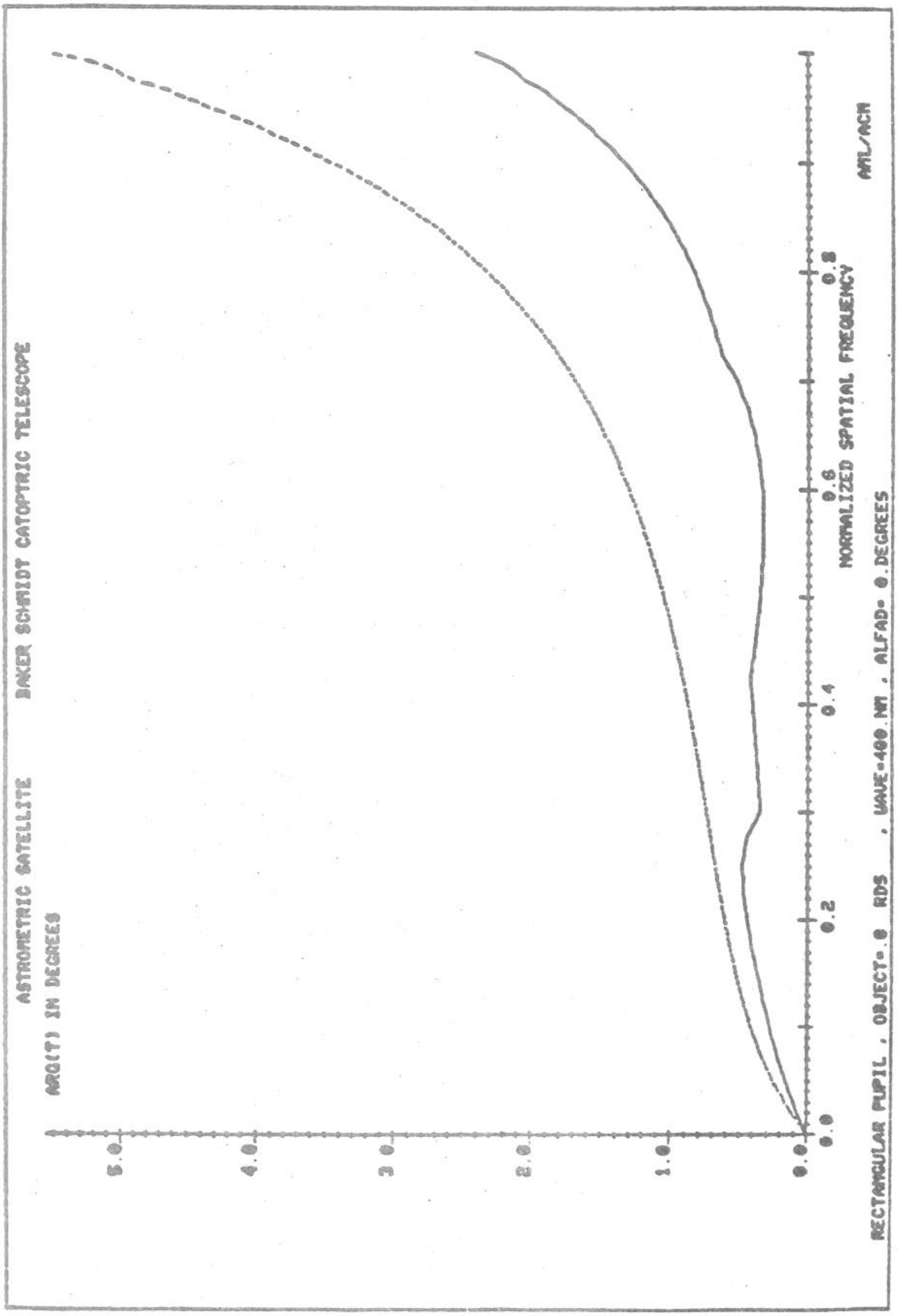

ASTROMETRIC SATELLITE BAKER SCHMIDT CATOPTRIC TELESCOPE
ARG(T) IN DEGREES
5.0
4.0
3.0
2.0
1.0
0.0
0.0
0.2
0.4
0.6
0.8
NORMALIZED SPATIAL FREQUENCY
AML/ACM
RECTANGULAR PUPIL , OBJECT= 0 RDS , WAVE=400 NM , ALFAD= 0 DEGREES

FIGURE 3.5

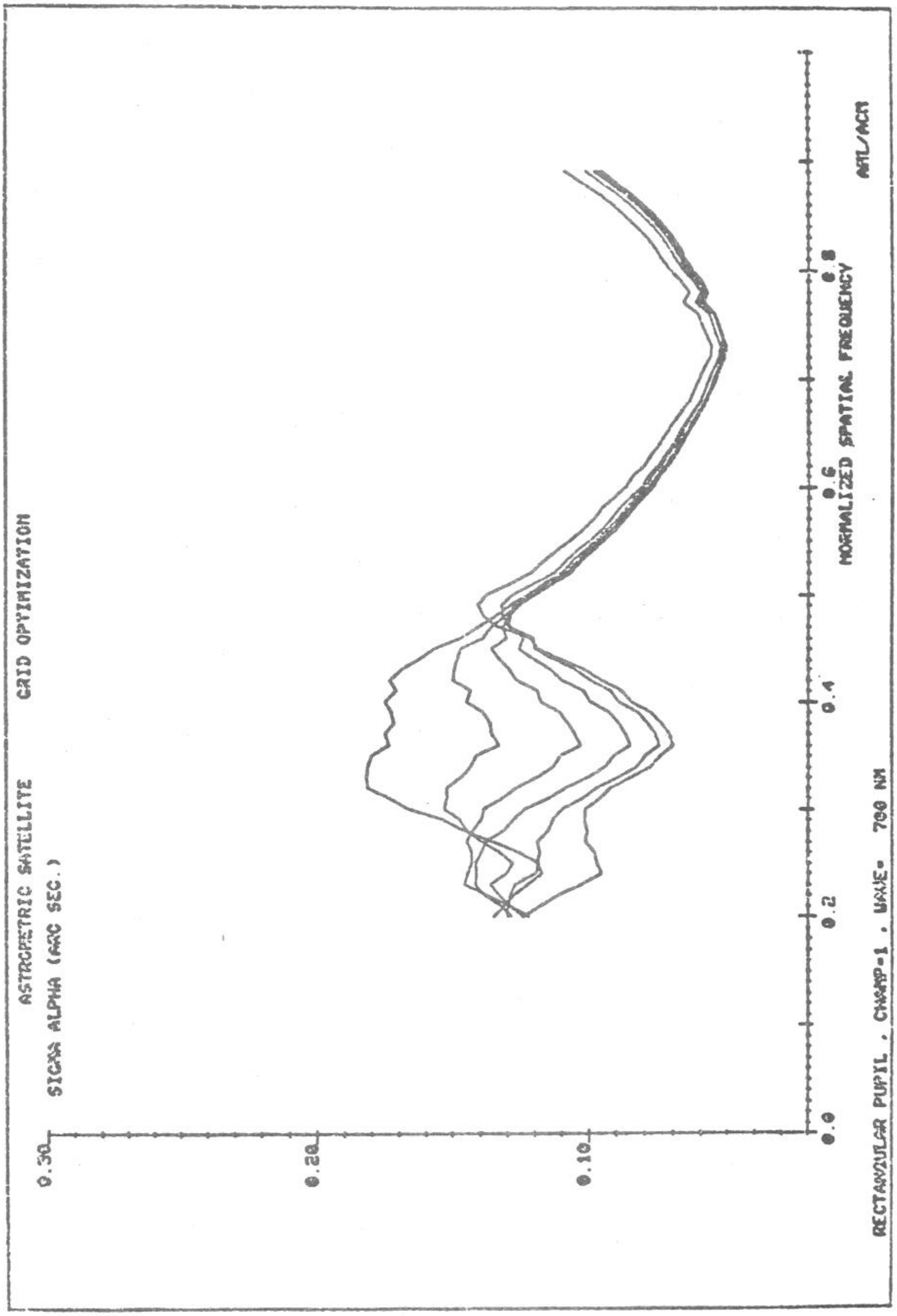

ASTROMETRIC SATELLITE
GRID OPTIMIZATION
SIGMA ALPHA (ARC SEC.)
0.30
0.20
0.10
0.0
0.2
0.4
0.6
0.8
NORMALIZED SPATIAL FREQUENCY
RECTANGULAR PUPIL . CHAMP-1 . WAVE= 700 NM

FIGURE 3.6

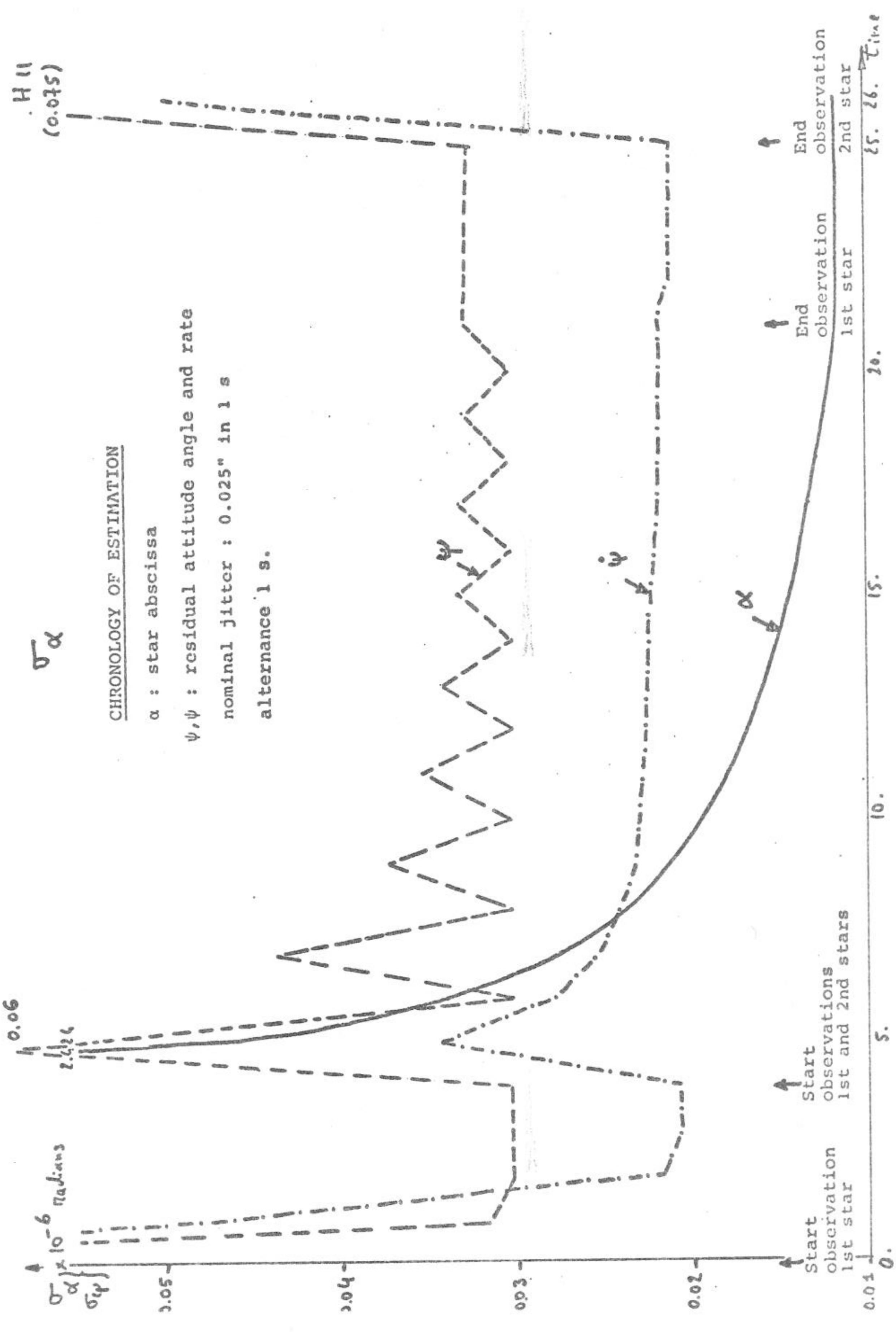

CHRONOLOGY OF ESTIMATION
α : star abscissa
ψ,ψ̇ : residual attitude angle and rate
nominal jitter : 0.025" in 1 s
alternance 1 s.
Start observation 1st star
Start observations 1st and 2nd stars
End observation 1st star
End observation 2nd star

FIGURE 3.7

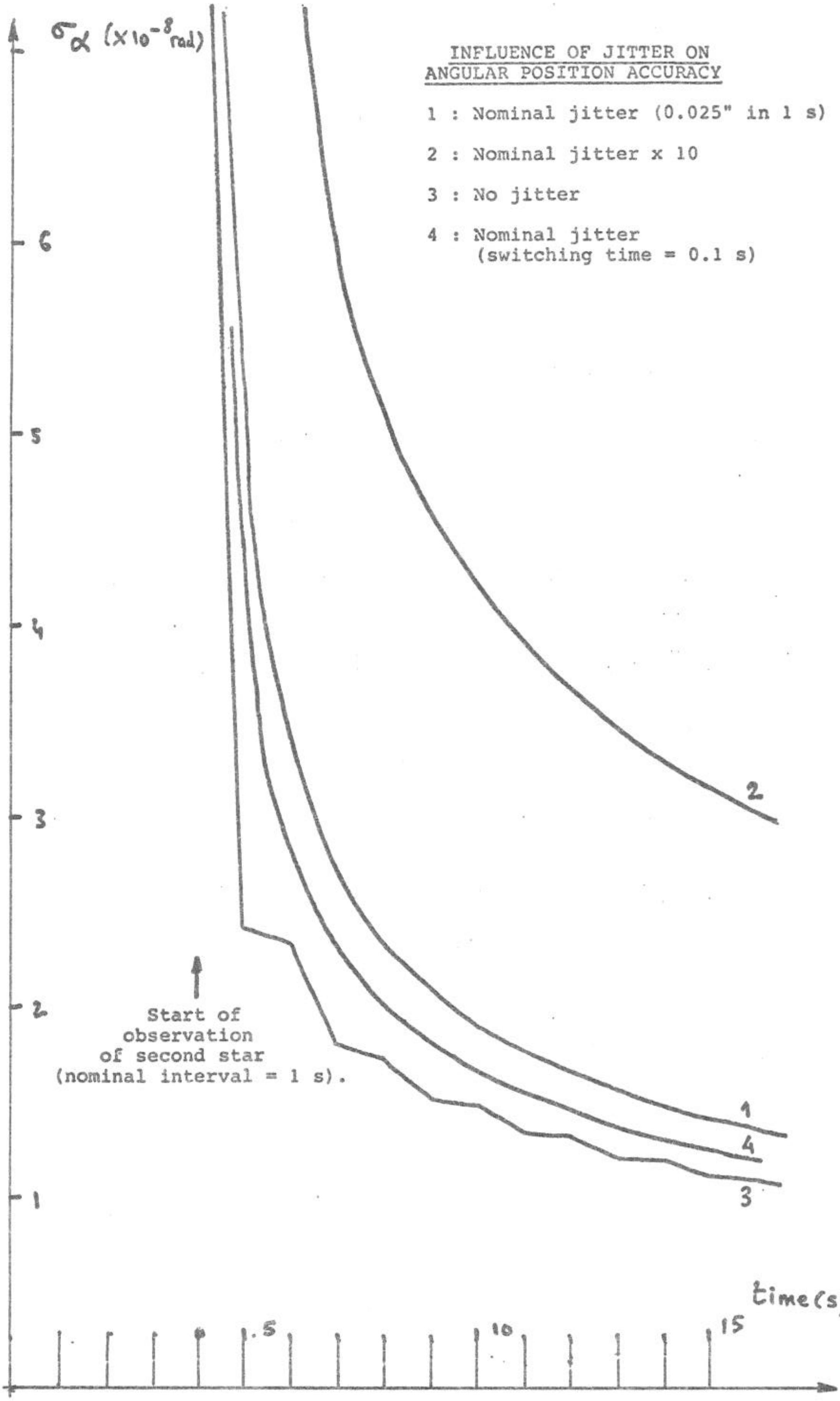

σα (×10⁻⁸ rad)
INFLUENCE OF JITTER ON ANGULAR POSITION ACCURACY
1 : Nominal jitter (0.025" in 1 s)
2 : Nominal jitter x 10
3 : No jitter
4 : Nominal jitter (switching time = 0.1 s)
6
5
4
3
2
1
Start of observation of second star (nominal interval = 1 s).
2
1
4
3
5
10
15
time(s)

FIGURE 3.8

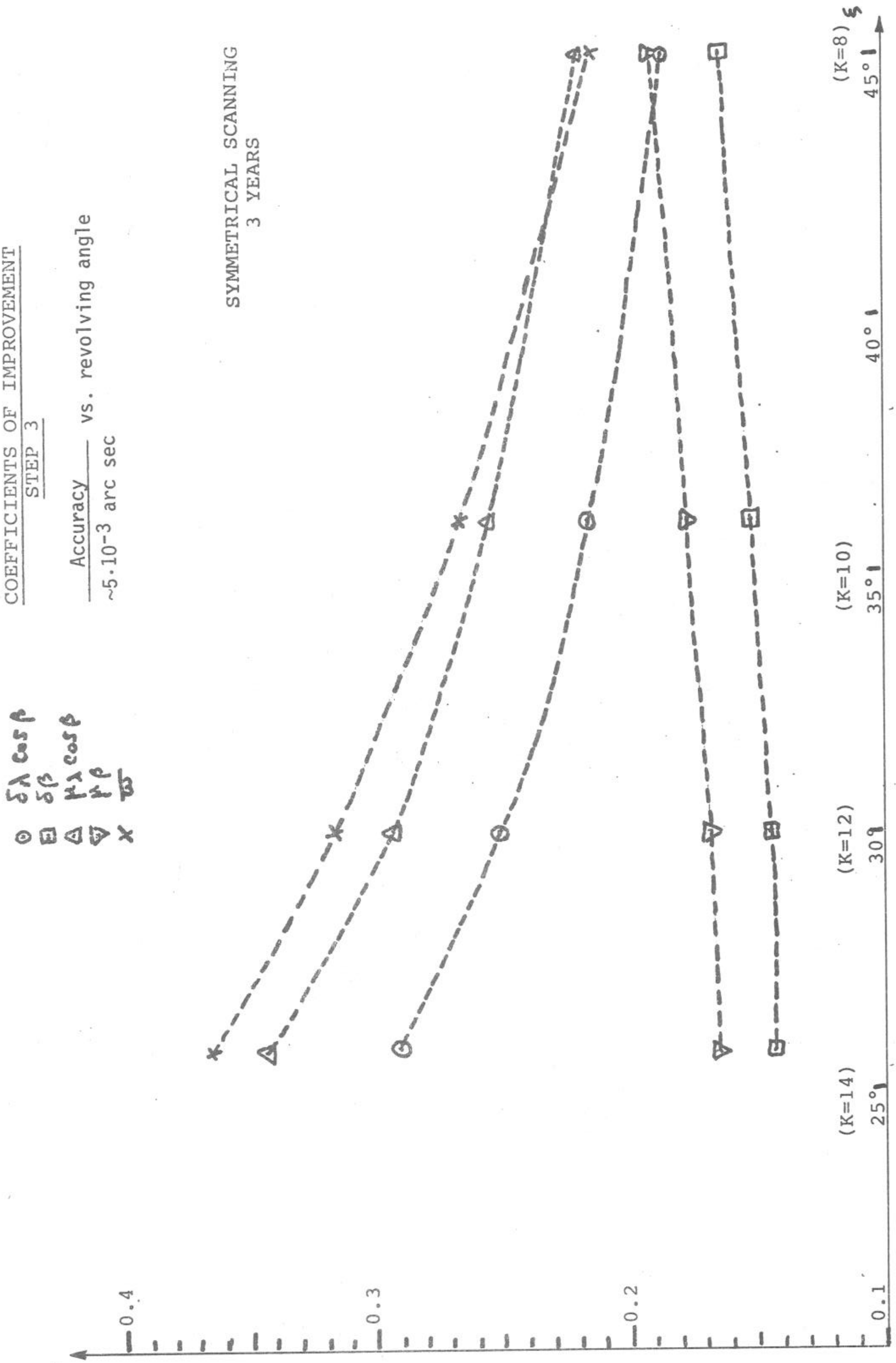

COEFFICIENTS OF IMPROVEMENT
STEP 3
Accuracy
~5.10-3 arc sec
vs. revolving angle
SYMMETRICAL SCANNING
3 YEARS
(K=8)
45°
40°
(K=10)
35°
(K=12)
30°
(K=14)
25°
0.1
0.2
0.3
0.4

FIGURE 3.9

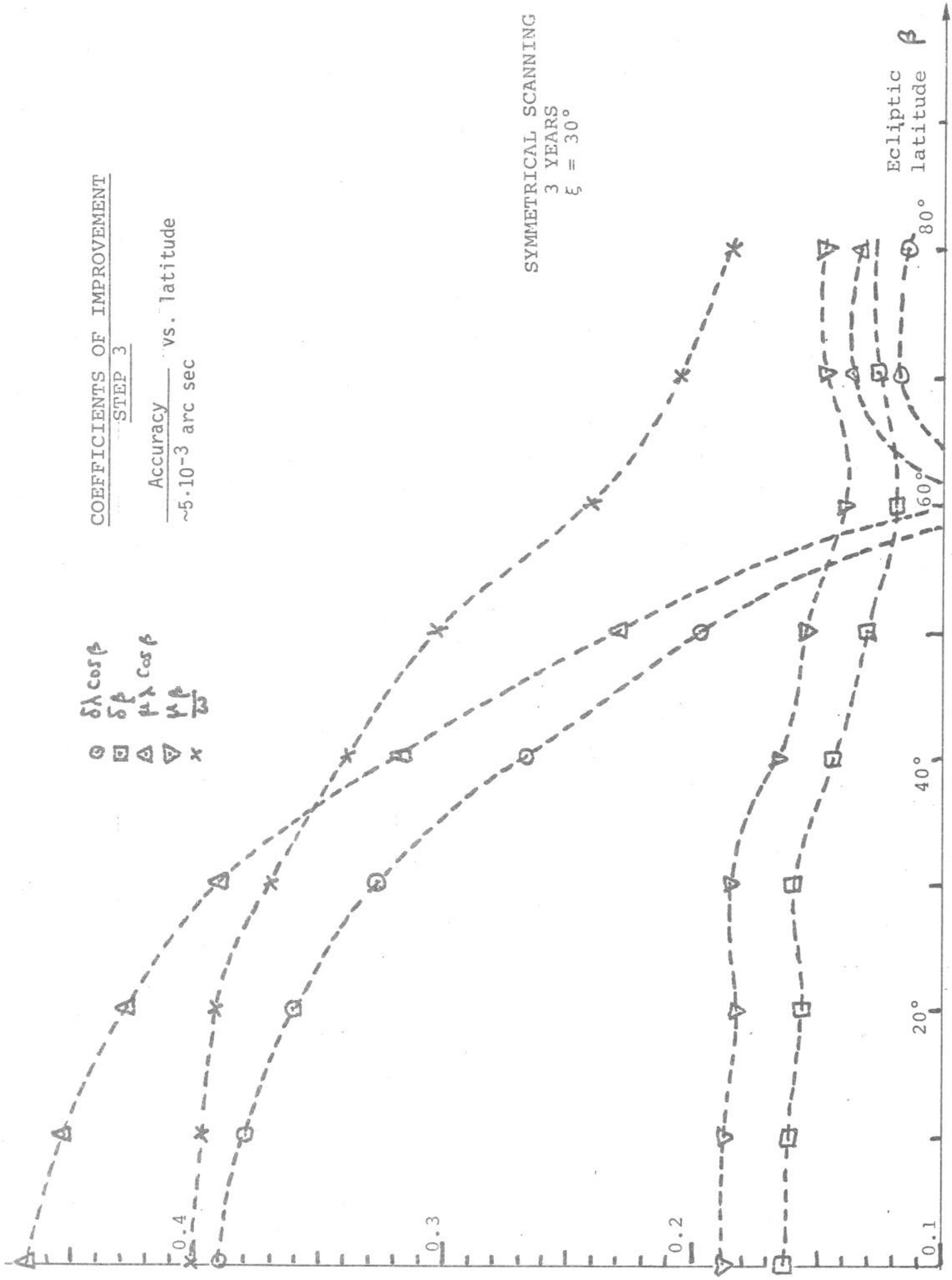

COEFFICIENTS OF IMPROVEMENT
STEP 3
Accuracy
~5.10-3 arc sec
vs. latitude
δλ cos β
δβ
μλ cos β
μβ
ϖ
SYMMETRICAL SCANNING
3 YEARS
ξ = 30°
Ecliptic latitude β
20°
40°
60°
80°
0.1
0.2
0.3
0.4

FIGURE 3.10

4. System Design

4.1 Requirements and Configuration

The astrometric spacecraft must be compatible with the Ariane launcher, in its present configuration defined in the User's Manual AR (75)01 of August 1976. It will be placed in orbit at the same time as yet another unidentified spacecraft, by a single launch vehicle. Therefore, it will be accommodated in the dual launch system currently being developed under the name of SYLDA (Système de Lancement double Ariane). It can be located either in the upper position or inside SYLDA.

According to the study specifications, the telecommunication links will use European facilities and ground stations, operating in the S band. The lifetime shall be 2.5 years at least.

It was a strong study requirement to make every effort in order to reduce the spacecraft development costs and, in particular, to use as much as possible of existing equipment and proven technologies.

These constraints, together with the mission requirements, led to the general configuration drawn in Figure 4.1 and described in the following sections.

4.2 Structure

4.2.1 Description

The fundamental consideration for the configuration is the criterium of decoupling, as far as possible, the telescope assembly from the bus, so that the stresses and strains of structure do not involvethe telescope structure. For that reason, the baffles are fully decoupled from the telescope.

The spacecraft consists of the following basic assemblies:

- Main structure
- Telescope
- Baffles and supports
- Apogee boost motor
- Solar array
- Antennas

i) Main Structure

The main structure is composed of:

- two honeycomb platforms (upper and lower platform)
- four honeycomb panels (north, south, east, west panel) and one cone.

The cone is a thin wall structure riveted at its lower end to a marmon ring and at its upper end to a ring which supports the lower platform.

This upper ring supports the Apogee boost motor.

The four panels are mounted on the lower platform and support the upper platform. The loads are transferred to the cone through the four panels and through four struts which connect the lower platform to the lower ring of the cone. The junctions among the panels are obtained by means of brackets currently developed for the ECS program.

ii) Telescope

The telescope assembly (Section 2) is fixed on the centre of the upper platform through its base which constitutes the only structural interface with the bus. The connections of the telescope assembly with the baffles are not rigid.

iii) Baffles and Supports

Each baffle is supported by a structure formed by three honeycomb panels with special fittings for accommodating the baffles. This support structure is fixed by means of junctions on the upper platform.

iv) Apogee Boost Motor (ABM)

The ABM is fixed to the upper ring of the cone. It can be installed at a late stage of the integration process.

v) Solar Array

The two solar arrays are fixed, at four latching points, (two on upper platform and two on lower platform), all on the southern side of the spacecraft. The deployment mechanisms do not seem to present any particular problem.

4.2.2 Characteristics

A simplified mathematical model with 188 nodes has been analysed, by means of a NASTRAN programme, with the following objectives:

- stress-strain analysis on a static model,
- eigenvalues and eigenvectors analysis on a dynamic model.

The first fundamental frequencies are:

- 22 Hz lateral
- 73 Hz longitudinal

4.3 Thermal Control

4.3.1 Description

i) Telescope

The thermal control design criteria for the telescope are based on the following general ground rules:

- decouple the telescope from external environment,
- decouple the telescope from the bus heat dissipation,
- use of controlled heaters and heat pipes to avoid thermal variation and to minimize thermal gradients.

The first condition is passively achieved by covering all the external surfaces with an appropriate multilayer insulation blanket to minimize the effect of external variable heat fluxes and to avoid a temperature decrease during the eclipse time.

The thermal resistance between the telescope baseplate and the bus mounting platform is minimized through the use of titanium washers and a thermal blanket.

Concerning the thermal control of optical systems the selected concept uses heaters located on the optical components mirrors and secondary structure, and heat pipes mounted on the mirror mounting cylinder (see Section 2.7.3).

ii) Bus

The main assumption in order to define a basic thermal design concept is to ensure an acceptable temperature environment for the equipment mounting panels (upper, south, north, east and west).

The bus's central body enclosing the electronics and equipment is thermally controlled by passive means. This compartment is fully insulated on all surfaces (except radiating areas on the lower parts of the east and west panels) by thermal blankets.

Fifteen single Aluminized Mylar layers are used to protect the equipment from the external variable thermal environment while single Aluminized Kapton blankets (15 layers) are used in the apogee boost motor areas where high temperature resistance is required.

The radiating areas, covered by an appropriate use of second surface mirrors, are sized to reject the maximum heat load at maximum power dissipation.

The internal compartments are painted black to enhance internal radiation exchange.

Solar arrays are conductively decoupled from the bus and their temperature is thermally controlled using appropriate emissivity of their rear surfaces.

4.3.2 Results

The mathematical model developed for the thermal analysis includes 220 modes. The telescope design complexity and stringent temperature specifications required a detailed model, taking into account an active thermal control logic, which establishes the relation between heaters and temperature measurements.

The thermal analysis has included computation in the operational case, i.e. a revolving angle c (Section 3.1.3) of 30^{o}, ten revolutions per day around the z axis (R=10) and 72 minutes of eclipse time per orbit. The Earth's albedo and infrared fluxes have been considered.

Table 4.1 summarises the results of computations giving the temperatures of equipment during two revolutions of the revolving axis z, starting from steady state conditions, as a function of time. The analysis shows that the optical system temperature gradients are within the required limits and that the control logic provides stable temperature gradients. The optical system consumes about 25 watts of heater power. The temperature of the mounting panels for the bus varies between 15^{o} and 21^{o} in sunlight and decreases to 13^{o} - 19^{o} after eclipses.

Finally, it is concluded that the thermal control is feasible, matching the stringent specifications for the telescope assembly, but that it is fairly sophisticated and would require further optimisation.

4.4 Power Supply

The design of the power supply subsystem appears to be conventional and therefore has not been studied in depth, its feasibility being established.

The power supply subsystem is comprised of the following elements:

- Solar array (Figures 4.2 and 4.3)

The solar array is carried on two deployable wings, one with two panels and the other with only one panel. The total surface amounts to about $5m^2$, covered with 9150 solar cells, each 2 x 2 cm, which provide the required power, taking into account a factor 0.92 for sunlight efficiency, a permanent Sun inclination of 30^{o}, particle degradation and a margin of 10%. During the transfer orbit, the power, about 40 W, is provided by the folded panels and the batteries.

- Batteries

The subsystem includes two Nickel-Cadmium batteries (for redundancy), delivering 415 Watt-hours during 1.2 hours of eclipse with a depth of 70% discharge.

TABLE 4.1

			REVOLVING ANGLE POSITION (DEGREE)										
			$\theta = 0^\circ$	$\theta = 90^\circ$	$\theta = 180^\circ$	$\theta = 270^\circ$	BEGIN OF ECL.	$\theta = 0^\circ$	END OF ECL.	$\theta = 90^\circ$	$\theta = 180^\circ$	$\theta = 270^\circ$	$\theta = 0^\circ$
			REVOLVING SIMULATION TIME (SEC)										
			34600	36800	38900	41100	41200	43200	45400	45500	47600	49800	52000
TELESCOPE	MIRRORS	PRIMARY	15.46	15.46	15.44	15.3	15.31	15.12	14.76	14.74	14.46	14.6	14.54
		SECONDARY	14.2	15.07	15.04	14.98	14.98	14.95	14.91	14.91	14.87	14.81	14.75
		COMPLEX	14.15	14.41	14.63	14.6	14.6	14.54	14.51	14.51	14.45	14.41	14.34
	MOUNTING CYLINDER	UPPER PART	14.44	15.02	15.3	15.16	15.16	14.96	14.75	14.74	14.7	14.65	14.6
		INTERM. PART	14.67	15.44	15.59	15.47	15.4	15.29	15.1	15.11	15.1	15.1	14.96
		LOWER PART	14.18	14.74	15.04	14.91	14.91	14.72	14.51	14.51	14.46	14.41	14.35
BUS	EQUIPMENT MOUNTING PANELS	UPPER	20.2	20.6	21.1	21.2	21.3	20.1	18.7	18.6	19.4	19.9	20.5
		SOUTH	20.2	20.6	21.1	21.2	21.3	18.2	16.7	17.1	19.2	19.9	20.5
		NORD	17.4	17.8	18.3	18.5	18.5	17.5	16.2	16.1	16.5	17.1	17.8
		WEST	14.5	15.9	15.7	15.5	15.5	14.4	12.9	13	13.8	14.1	14.8
		EAST	18.9	19.2	19.7	20.9	21.1	18.7	17.3	17.2	17.9	19.6	19.5
		SOLAR ARRAY	56	56	56	56	49	-118	-144	-81	56	56	56

- Electronics

Comprise the following items:

- shunt drive,
- battery charge regulator,
- battery discharge regulator,
- junction box and shunt radiator,
- control unit.

4.5 Attitude and Orbit Control

4.5.1 Perturbing Torques

The various perturbing torques acting on the deployed spacecraft in geosynchronous orbit, due to gravitational imbalance, magnetic effect and solar radiation pressure have been carefully simulated. The dominant perturbation is due to the radiation pressure, estimated with the assumption that the distance between the centre of pressure and the centre of gravity is 15 cm.

The total perturbing torque amounts to about 3.10^{-7} Nm around the x axis, $3.5.10^{-6}$ Nm around the y axis and $2.5.10^{-6}$ Nm around the z axis.

4.5.2 Constitution of the Subsystem

The attitude and orbit control subsystem mainly incorporates the following equipment:

- two analog coarse sun sensors (field of view 180°, accuracy 2°),
- one analog fine sun sensor (field of view 30°, accuracy 2 arc minutes),
- two infrared Earth sensors (field of view 20° x 9°, accuracy about 2 arc minutes),
- one Earth and Sun elevation sensor
- a rate integrated gyro package, including four gyros, with a random drift of 0.006°/hr.,
- four reaction wheels, of 2 Nms angular momentum,
- two single axis accelerometers with a measurement range of ∓ 100g.
- a reaction control assembly, using hydrazine as propellant with two tanks (each containing 5 kg. of hydrazine), 12 thrusters of 0.5 Newtons and 4 thrusters of 2 newtons.

In the present study, the electronics, mainly of analog type, are considered as specially designed for the subsystem; possibility of interfacing with the on-board computer has not been examined and should be the subject of future study.

The subsystem operation is based on a continuous control which derives information from the low noise gyro inertial reference in strap-down configuration updated by the star matter of the payload. In the acquisition phase, the gyros are updated by optical sensors. The attitude control is obtained by the four reaction wheels, desaturated by a hydrazine jet device.

4.5.3 Modes of Operation (See Figure 4.4)

Three phases can be distinguished:

i) Transfer Phase

During this phase, the spacecraft is spinning and the active rotation damper is in operation; attitude measurement is carried out by the Earth and Sun sensors and the attitude and position in orbit are controlled by the reaction jet system via telecommand,

ii) Acquisition Phase

This phase begins when the spacecraft is placed on the final geosynchronous orbit and consists of a sequence of modes executed automatically or by telecommand:

- despin,
- deployment of solar panels and of booms,
- sun pointing,
- acquisition of the Earth,
- setting up of the gyros,
- spinning-up of the reaction wheels.

iii) Operational Phase

The spacecraft is stabilised on three axes; after acquisition of the normal scanning rate, the control is executed in the normal mode. In this mode, the information is derived from the gyro reference unit, updated by the star mapper and signals are sent to the wheel drive electronics which provide the required control torque along the three axes.

4.5.4 Performance

The performances of the attitude control subsystem are summarised in Table 4.2 and compared with the specifications. It can be seen that the subsystem meets all specified requirements.

TABLE 4.2

ERROR SUMMARY

	Allowed		Obtained			Note
	X & Y	Z	X	Y	Z	
Absolute pointing 1	± 2°	± 5°	± 9'.6			not applicable because 2 is more stringent than 1
Attitude reproducibility after 1 orbit 2	± 10'	± 5°	± 9'.6			
Rate error	± 30"/sec	± 30"/sec	± 28.44" /sec			
Jitter	± 3" averaged time 1 sec	± 0.025" averaged time 1 sec	±0.0849	±0.0232	±0.0211	worst case

However, the filter produced by the gyros and the wheels on the star images motion is difficult to evaluate accurately and its influence has not yet been fully investigated. It is therefore proposed to carry on further studies and in particular, to consider the feasibility of an intermittent control subsystem without reaction wheels which has been strongly advocated by the scientists.

4.5.5 Apogee Boost Motor

The apogee boost motor selected in the present study is a solid propellant motor already used for GEOS, with the following main characteristics:

- total mass: 304 kg.
- propellant mass: 269 kg
- combustion time : 49.5 s.
- specific impulse : 286 s.
- total impulse : 76 648 kg. s.

The total impulse may be reduced, if required, by decreasing the propellant mass.

4.6 Telecommunications and Onboard Data Handling

4.6.1 General Description

In order to minimize the cost of the spacecraft, the communication subsystems defined during the study use "off-the-shelf equipment" as far as possible and are therefore mainly based on units developed for other projects. A general diagram is given in Figure 4.5.

During the on-station phase, spherical antenna coverage is required, while during the transfer orbit a cardioidal or toroidal antenna pattern should be sufficient. A full omnidirectional antenna pattern cannot be obtained with a single antenna, but two half spherical antennas in combination with a switch can be used. Three different antennas are proposed. The transfer orbit antenna is a single dual mode (different polarisations) antenna with a cardioidal or toroidal antenna pattern, while two half spherical antennas provide the spherical coverage during the on-station phase. Both of the S-band receivers but only one of the transmitters are energized at any time.

During the transfer orbit each of the two transponders are connected to one of the two antenna ports. Each receiver drives only one of the demodulators in the decoder. For redundancy purposes a cross-strapping between the two command execute units is implemented.

During the on-station phase each of the two transponders are connected to one of the two antennas by a change-over switch. By this arrangement a full spherical coverage is obtained at any time for telecommand and with the switch any of the transmitters can be connected to the earth pointing antenna. The normal procedure will be to have one of the transponders always connected to the earth pointing antenna and the other transponder serving as a back-up unit.. To avoid interruption of TM reception at ground when switching the antennas some overlap between the two half spherical antenna patterns is required.

4.6.2 Link Budgets

The telecommunication links operate on the S-band (2.2 to 2.3 GHz).

For telemetry, the spacecraft-power transmitter output is 5.3 watts and the antenna gain worst value - 3 db; assuming a ground station with a 9 m diameter antenna (gain 43 db), a data bit rate of 27.3 kilobits per second (corresponding to a bit rate of 54.6 k b/s after convolutional encoding) with a bit error rate of 10^{-5} which can be continuously transmitted from the geosynchronous orbit.

For telecommand, the capability of the link with the ground station amounts to at least 750 bits/s continuously.

4.6.3 Onboard Computer

The onboard computer performs the following tasks:

i) attitude reconstitution (synchronous attitude reconstitution, star mapper processing and gyro drift rate evaluation, data acquisition of selected stars).

ii) experimental data processing (acquisition of programme stars, transmission of experimental data).

iii) attitude control.

iv) thermal control.

The data processing has only been investigated in a preliminary way; a general purpose onboard computer is incorporated; a redundant CMOS memory bank of 8 kilowords has been included.

4.7 Mass Breakdown

The total mass of the spacecraft at launch amounts to 639 kg, with the following breakdown:

- attitude control		50.8
- power, pyrotechnics, harness		79.6
- communication and data handling		32.2
- structure		46.0
- thermal control		12.0
- payload		86.0
- margin (9%)		28.4
	Subtotal:	335.0
apogee boost motor		304
	TOTAL	639.0 kg.

The moments of inertia, with respect to the centre of mass, are equal to:

along the x axis : 60 kg m^2
along the y axis : 145 kg m^2
along the z axis : 170 kg m^2

in the operational configuration.

ASTROMETRY - CONFIGURATION

BASIC ASSEMBLIES:

- MAIN STRUCTURE
- TELESCOPE
- BAFFLES AND SUPPORTS
- ABM
- SOLAR ARRAY
- ANTENNAS

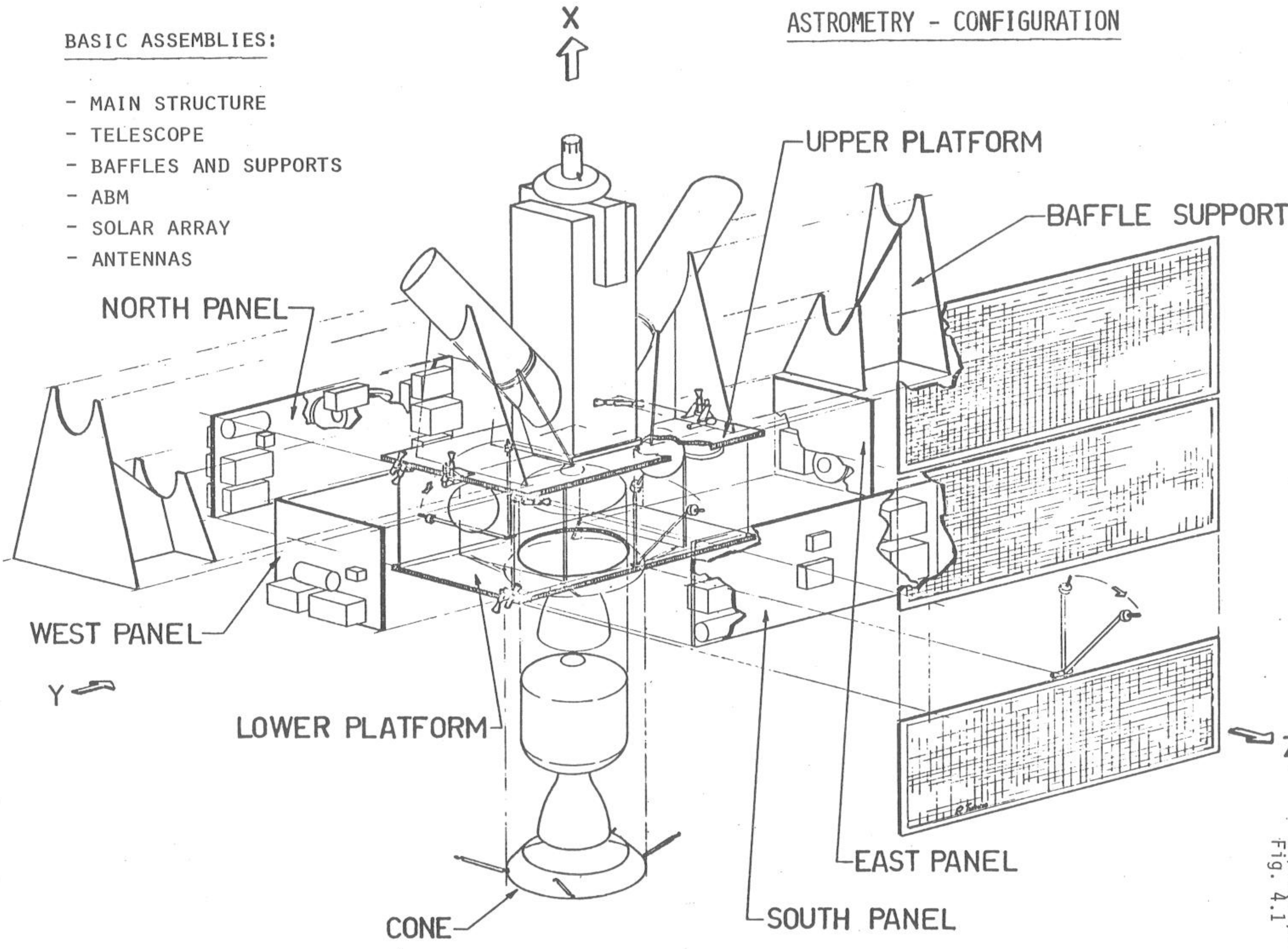


FIGURE 4.1

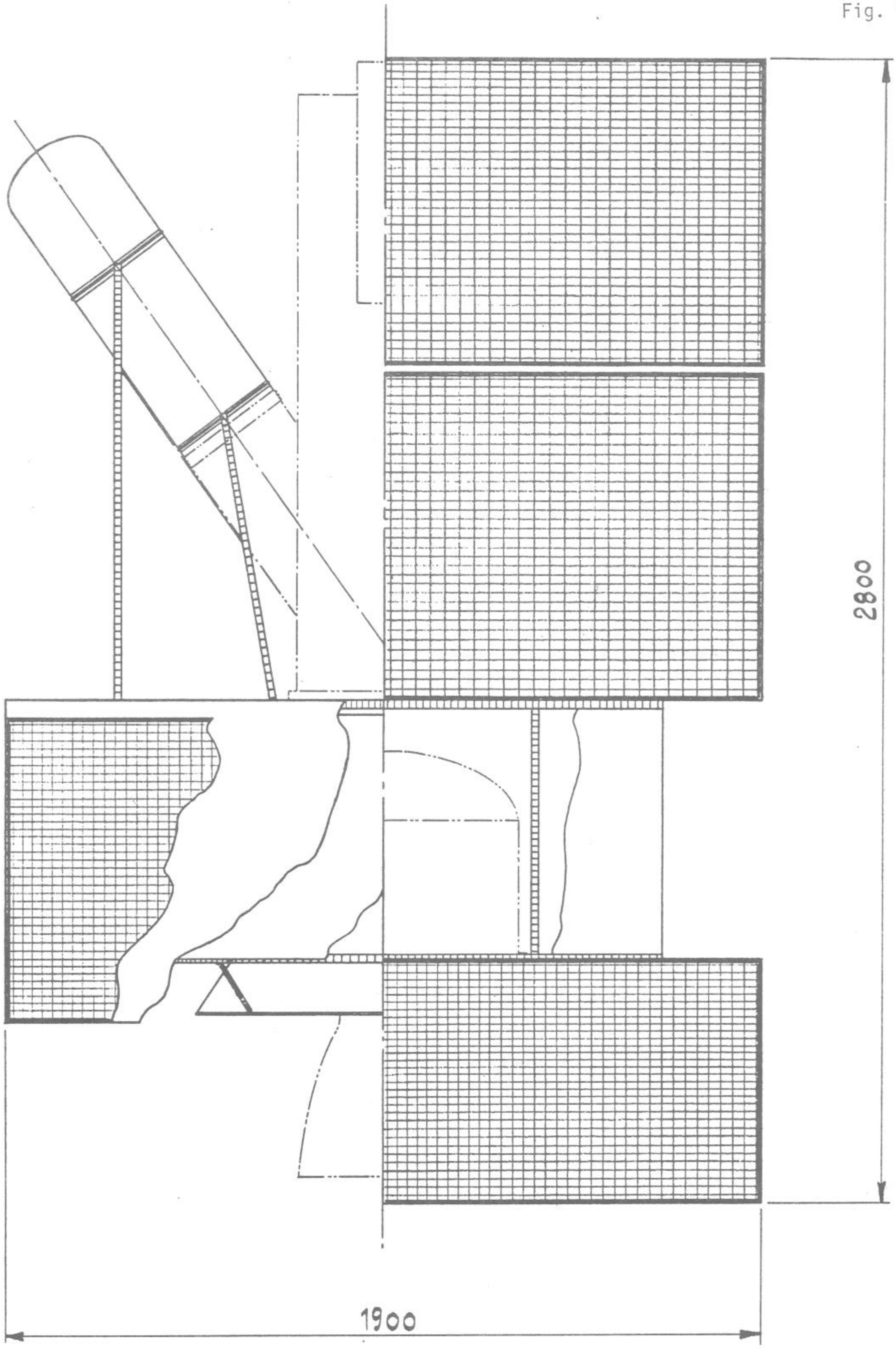


FIGURE 4.2

SOLAR ARRAY

- AREA : 4.5 M^2
- WEIGHT : 15 KG
- DEPLOY SEQUENCE : A - B - C

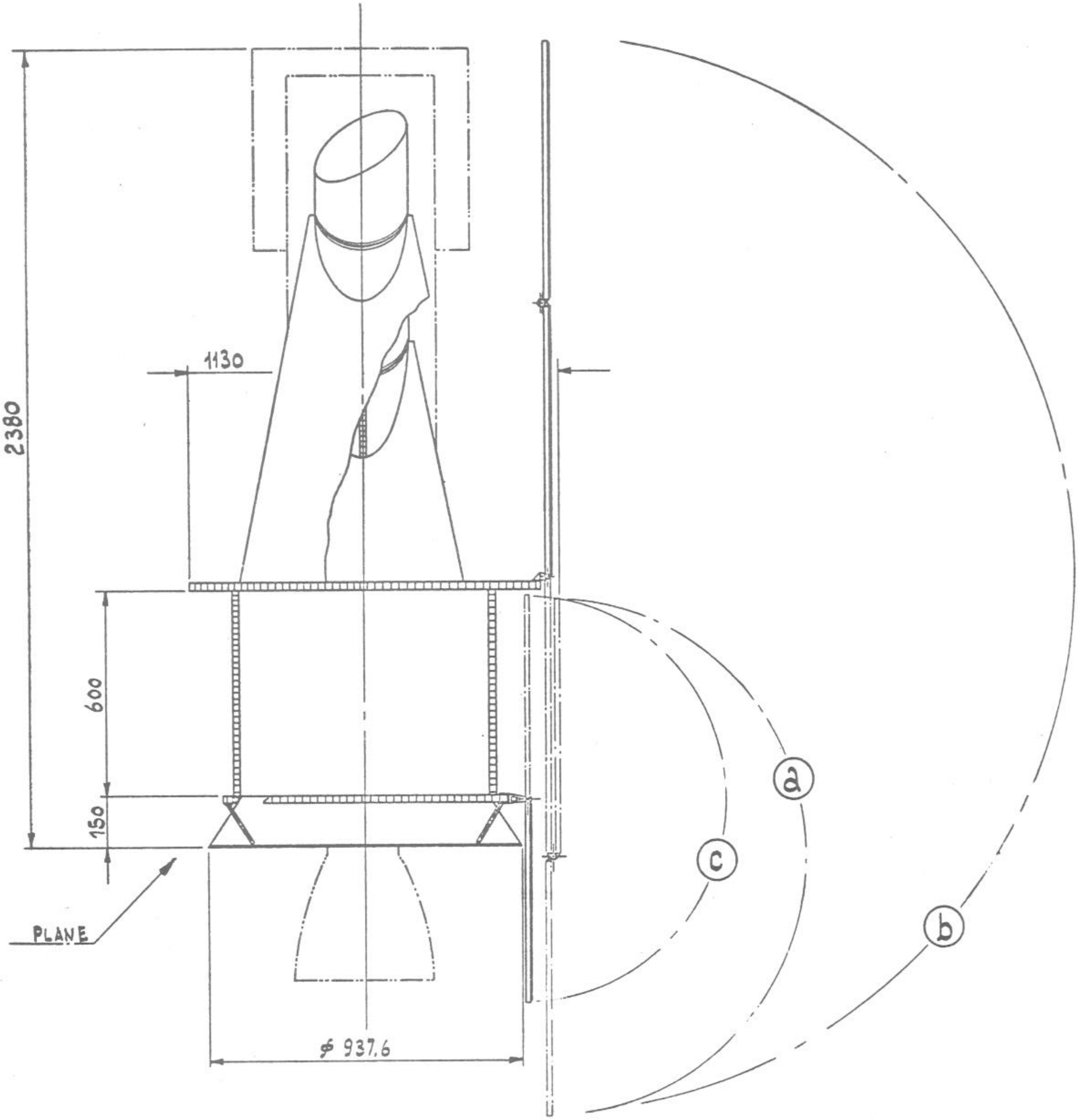


FIGURE 4.3

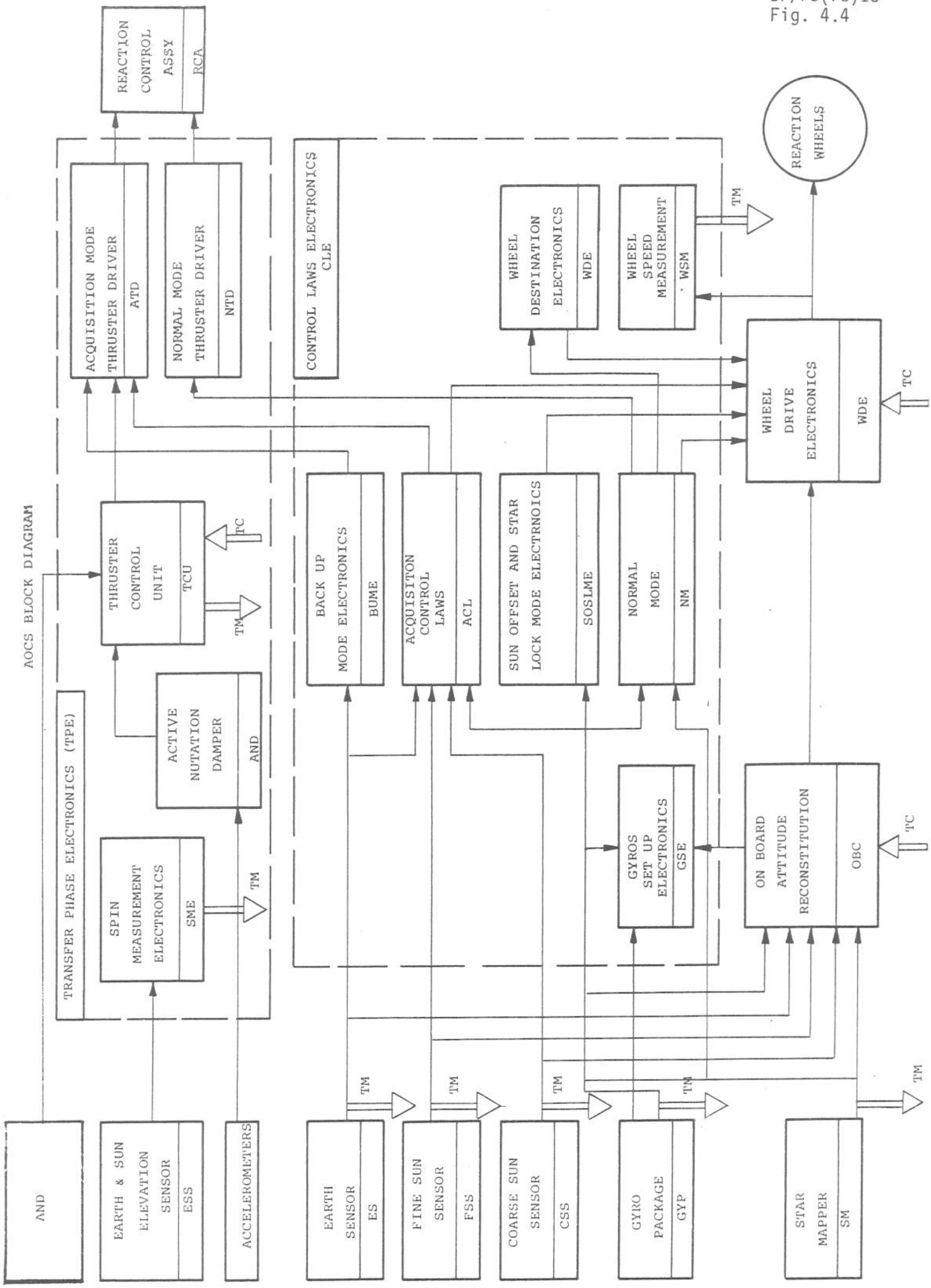

AOCS BLOCK DIAGRAM
REACTION CONTROL ASSY
RCA
ACQUISITION MODE THRUSTER DRIVER
ATD
NORMAL MODE THRUSTER DRIVER
NTD
CONTROL LAWS ELECTRONICS
CLE
REACTION WHEELS
WHEEL DESTINATION ELECTRONICS
WDE
WHEEL SPEED MEASUREMENT
WSM
TM
WHEEL DRIVE ELECTRONICS
WDE
TC
THRUSTER CONTROL UNIT
TCU
TC
TM
BACK UP MODE ELECTRONICS
BUME
ACQUISITON CONTROL LAWS
ACL
SUN OFFSET AND STAR LOCK MODE ELECTRNOICS
SOSLME
NORMAL MODE
NM
TRANSFER PHASE ELECTRONICS (TPE)
ACTIVE NUTATION DAMPER
AND
SPIN MEASUREMENT ELECTRONICS
SME
TM
GYROS SET UP ELECTRONICS
GSE
ON BOARD ATTITUDE RECONSTITUTION
OBC
TC
TM
TM
TM
TM
TM
AND
EARTH & SUN ELEVATION SENSOR
ESS
ACCELEROMETERS
EARTH SENSOR
ES
FINE SUN SENSOR
FSS
COARSE SUN SENSOR
CSS
GYRO PACKAGE
GYP
STAR MAPPER
SM

FIGURE 4.4

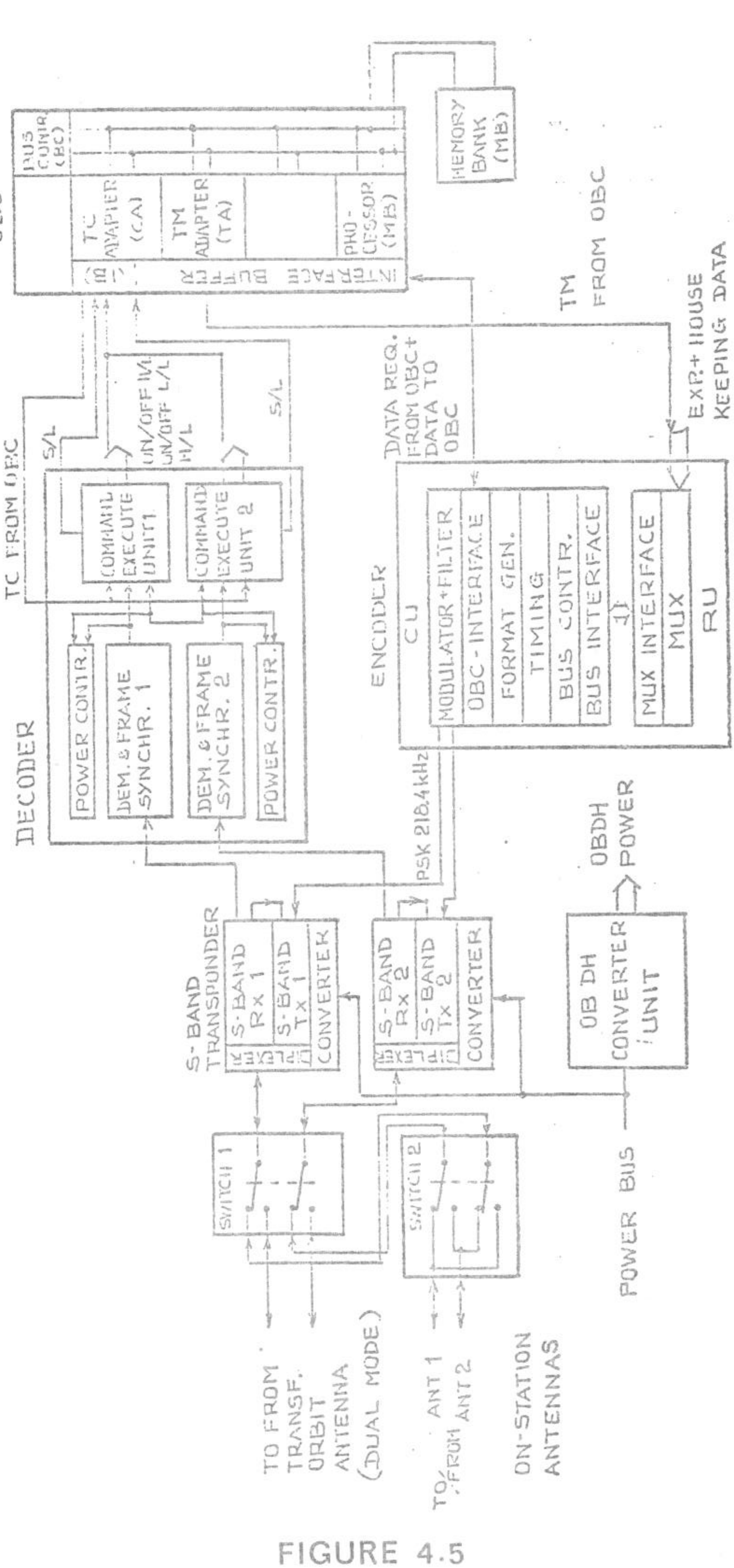

OBC
BUS CONTR (BC)
TC ADAPTER (CA)
TM ADAPTER (TA)
PRO-CESSOR (MB)
INTERFACE BUFFER
MEMORY BANK (MB)
TC FROM OBC
S/L
ON/OFF M/L
ON/OFF L/L
H/L
COMMAND EXECUTE UNIT 1
COMMAND EXECUTE UNIT 2
DECODER
POWER CONTR.
DEM. & FRAME SYNCHR. 1
DEM. & FRAME SYNCHR. 2
TM FROM OBC
DATA REQ. FROM OBC + DATA TO OBC
EXP.+ HOUSE KEEPING DATA
ENCODER
CU
MODULATOR + FILTER
OBC - INTERFACE
FORMAT GEN.
TIMING
BUS CONTR.
BUS INTERFACE
MUX INTERFACE
MUX
RU
PSK 218,4 kHz
S-BAND TRANSPONDER
S-BAND Rx 1
S-BAND Tx 1
CONVERTER
DIPLEXER
S-BAND Rx 2
S-BAND Tx 2
OBDH POWER
OBDH CONVERTER UNIT
SWITCH 1
SWITCH 2
POWER BUS
TO/FROM TRANSF. ORBIT ANTENNA (DUAL MODE)
TO/FROM ANT 1
ANT 2
ON-STATION ANTENNAS

FIGURE 4.5

5. MANAGEMENT, TIME SCHEDULE AND FUTURE ACTIONS

5.1 Managerial Arrangements for the Spacecraft Development

Although the design requirements of the scientific payload (optics and detection) and of the technical subsystems (e.g., attitude control, thermal control, on-board data handling) are closely interrelated, the present Phase A study has clearly demonstrated that the interfaces between them are such that the payload and the spacecraft can be developed simultaneously in relative independence by two different organizations.

It is thus proposed that the spacecraft be designed and developed by the Agency, whereas the payload be designed and developed by one or several scientific institutes. This latter aspect is dealt with in Section 5.2. In addition to the spacecraft, the Agency would also provide the experiment integration, the launch and the operations.

Subject to approval by the Agency's committees, it is assumed that the spacecraft development will be carried out by an industrial prime contractor responsible for the following activities:

- to assist ESA with the specifications and acceptance of hardware, components and scientific experiments supplied to the contractor by ESA;
- to study, develop and supply all hardware needed by ESA; to define the mission and operations of the spacecraft;
- to carry out the integration and testing required for the development of the spacecraft, and to provide the necessary general or specialized test facilities;
- to provide launch assistance.

The development philosophy would have to:

- give a high confidence in the technical integrity of the system, to reduce technical failures in the mission to a minimum;
- be cost-effective, to keep programme costs as low as possible; and
- allow for sufficient time margins in order to introduce imposed modifications in the next model programme.

At present, the development scheme for the spacecraft is not yet defined sufficiently well; however, taking into account the above principles, it could be similar to the ISEE-B one, or to the one proposed for the SEOCS spacecraft (ref. DP/PS(78)10). Further definition work is required on this aspect of the study, as outlined in Section 5.4.

5.2 Involvement of Scientists in the Mission

The opportunity to perform astrometric measurements from space will attract a large number of astronomers from various fields. Active involvement of scientists in this mission could be achieved principally through the setting up of a consortium (hereinafter referred to as Class I involvement) which would have the following responsibilities:

1) Design and development of the payload, including tests, calibration and on-board scientific software development.

2) Astronomical management (observation programme and data reduction).

The funding for the related activities should be provided by the sponsoring authorities of the scientists or institutes involved.

The following scheme is envisaged.

After an open invitation to the European astronomical community, an Astrometry Science Team (AST) should be set up, according to the ESA procedure described below. This AST should consist of two sub-groups, entrusted, respectively, with the two categories of responsibilities outlined above, viz.:

1) An Instrument Group, whose tasks would include:

   a) to design, develop, test and calibrate the payload, as well as develop the on-board scientific software;

   b) to assist ESA in the definition of the optimum spacecraft configuration; and

   c) to advise ESA on the detailed characteristics of the mission (attitude control, scanning mode, operational software, etc.).

2) A Scientific Data Retrieval Group, which would be responsible for :

   a) the production of the observing programme, after consultation of the astronomical community;

   b) the organization and coordination of the related ground-based activities;

   c) the organization of the data reduction, including the software production for real time evaluation of the satellite performance and the software for the reconstitution of the celestial sphere and the extraction of the astrometric data; and

d) the data evaluation process.

Members of the AST could be members of both sub-groups.

A further class of European scientist involvement in the mission (Class II) could consist of those scientists who successfully responded to an open invitation for observation programmes (i.e., groups of stars to be measured, a selection being necessary due to the limited on-board computer capacity). These programmes would be selected by a Programme Selection Committee (PSC) which would draw half its membership from among the members of the AST and the other half from the astronomers selected in accordance with ESA procedures.

The selection procedure for both the AST and the PSC will be similar to that normally used to select instruments for flight in free-flying spacecraft. The selection will be made, as far as possible, by the interested scientific community itself, organized and supported by ESA. Recommendations will be made by the Director General's scientific advisory bodies, assisted, if necessary, by specialized panels appointed by them. Proposers will be invited to discuss their proposals in person with the panels or committees. On the basis of these recommendations, the Director General will submit a proposal to the Science Programme Committee.

Finally, the world-wide community (Class III) will have access to the results after publication of the final catalogue.

5.3 Data Recovery and Distribution

The Space Astrometry mission can neither be seen as a normal observatory type mission nor as a "Principal Investigator (PI)" mission. Although inputs from several astronomers in various fields are necessary to constitute an observing programme, the results of this mission should be considered as a large homogeneous body of data to be reduced as a complete set. It is for this reason that it is realistic to consider the data reduction as an integral part of the mission. The AST should, thus, be responsible for the preparation and publication of the catalogue resulting from this mission.

The members of the AST (Class I, defined in Section 5.2) will be responsible for the complete treatment of the data, in order to derive the relevant astrometric parameters and to publish a final catalogue. The final data would, however, not be published until some time (but not more than two years) after the end of the mission. In the meantime, the members of the AST would have some pre-determined rights regarding selection of stars to be observed and the subsequent use of the derived astrometric parameters. These could be of the order of 50%.

The rest of these stars and related data would be allocated to the Class II users, defined in the preceding section. The selection of Class II programmes would not need to take place until about one year before launch. In this Class II selection, priority would be given to astronomers willing to commit themselves to determine, by means of ground-based observations, various parameters complementary to the mission's observations, in particular radial velocities.

After the period reserved for exclusive data use by scientists of Classes I and II, a master catalogue and/or improved catalogues will be published and made available to the world-wide scientific community (Class III). At that time, the raw data will also be made available to anyone upon request.

5.4 Time Schedule and Future Actions

5.4.1 Present status

The present Phase A study has shown that the mission is generally feasible, with some critical areas remaining in the payload part:

- The scientific payload has been defined and the analysis of its performances has shown that it can satisfactorily meet the required specifications; the optical design finally selected can be qualified as almost perfect, and the detection subsystem uses flight-proven equipment; the stringent thermal requirements lead to a sophisticated control which is well understood and technically feasible. The most critical item has been identified as the complex mirror, but solutions have been proposed to relax some constraints and then simplify its realisation.

- The spacecraft itself and its subsystems (telecommunications, power supply, attitude control) are of conventional design; however, the on-board data handling, whose feasibility is not questioned, has only been analysed in a preliminary way, and the subsystems remain to be optimized, the development scheme to be completely reviewed and the costs to be, consequently, re-evaluated.

- The theoretical study on the achievable accuracy of the astrometric parameters has resulted in the implementation of a modular software, allowing simulation of operation of the whole system and including an advanced filtering algorithm for the estimation of the parameters. The complete software has only been run for a limited number of cases, as was originally planned. The computation results are quite satisfactory and give increased confidence in the fulfilment of the mission objectives. It is now implemented on the ESA computers where it can be fully exploited at relatively low cost, thus constituting a powerful tool for further optimization of the mission.

5.4.2 Time schedule

Pending a redetermination of the development scheme, and taking into account a number of pre-Phase B activities proposed in the next section, the following time schedule can be envisaged in a preliminary way:

Pre-Phase B activities and preparation of Phase B	:	8 months
Phase B	:	10 months
Phase C/D	:	40 months

5.4.3 Recommendations for future actions

The main activities to be carried out as soon as possible have been identified as follows by the ESA study team and the scientific consultant group:

i) scientific payload

- study of the manufacture of various solutions for the complex mirrors (2 or 3 surfaces); development of a model.
- study of the baffles, in particular of rectangular ones; trade-off between scattered light and revolving angle.
- reassessment of tolerances of the thermal control and consequences on the design.
- homogeneity of the detector cathode; study of the instantaneous field of view control; preliminary investigation of advanced detector types (photicon).
- study of optics calibration.

ii) spacecraft subsystems

- feasibility on an intermittent attitude control with reduced jitter.
- definition of the on-board data management.

iii) theoretical studies, using the implemented software

- full exploitation of the computer programme for sensitivity studies and optimization of the main technical parameters.
- study of the effect of jitter.

- influence of Earth occultations.

- accuracies obtained for faint and multiple stars.

- reconstitution of the celestial sphere (rigidity).

- preliminary definition of operational data processing.

iv) Optimization of spacecraft subsystems and redefinition of development philosophy and schedule, with the aim of minimizing the costs still further, it being understood that the scientific objectives must be satisfied.

APPENDIX : Background and History

The idea to realise a satellite exclusively devoted to space astrometry, has been brought forward by Professor Lacroute who submitted a detailed proposal to CNES at the end of 1967. The essential principles envisaged at that time are still the basis of the present work: measurements of large angles by means of a telescope in which two fields of view are superposed by a complex mirror, image modulation by means of a grid and photoelectric detection. Between 1968 and 1970 CNES executed a feasibility study. At the end of 1970 CNES informed Professor Lacroute that the development could not take place within the French national program. It was not until the end of 1973 when within the long term planning activities of the Solar System Working Group (SSWG) that Professor Kovalesky made the group aware of this project.

At the beginning of 1974 the LPAC (the predecessor of the Science Advisory Committee), recognised the originality of the mission but because of the novelty of the discipline within ESRO, requested the assurance of sufficient scientific interest and an evaluation of the benefit of this mission for the scientific community.

As a consequence, the first international symposium on Space Astrometry was organized in Frascati on 22 and 23 October 1974. The considerable improvements to be expected in the determination of the astrometrical parameters as well as the importance of the astrophysical consequences were clearly evident. In fact the two questions posed by the LPAC obtained a positive response.

In early 1975 the SSWG, seconded by the Astronomy Working Group (AWG) and followed by the LPAC recommended that a mission definition study be carried out. This recommendation was endorsed by the Science Programme Committee (SPC). This mission definition study was then carried out between October 1975 and May 1976 by scientific consultants with support by ESA staff and the conclusions are reported in ESA document DP/PS(76), rev. 1.

After a review by ESA's scientific advisory committees in mid 1976 which included a public presentation and discussion in June, followed by a consultation of the Science Programme Committee in October 1976, the study proceeded into Phase A.

A new consultant group was set up to advise on the execution of the Phase A study. Consultants were selected from among those who responded to a further open solicitation of the scientific community. This team was entrusted with the task of precisely defining the scientific specifications of the mission as an imput to the industrial Phase A studies.

It had been proposed at the end of the Mission Definition Study that the Phase A activities should be carried out in two distinct parts:

a) a theoretical numerical study to determine the expected accuracy

b) a usual system study

After the normal tender actions, the contracts for these two studies were awarded to ACM and to Aeritalia respectively (the latter with the support of MATRA and CNR). Overall, these two study contracts were carried out during the period between May 1977 and March 1978. During the course of these studies, the scientifc consultant team advised ESA, refining and revising the payload and mission requirements where necessary as the system concept evolved. The two study contracts were managed by ESA staff and the involvement of ESA technical specialists was arranged as required. Progress reports were made of the Astronomy Working Group which had previously included this mission in its long-term planning report, (ESA document ASTRO (76) 13)).

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