# HIPPARCOS -an Assessment

Chairman & Editor: *C. Turon*

# THE HIPPARCOS ASTROMETRY SATELLITE - TWO YEARS AFTER LAUNCH

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ABSTRACT. Launched in August 1989 into a geostationary transfer orbit, the Hipparcos astrometry satellite failed to reach its intended geostationary orbit through the failure of its apogee boost motor. Present indications are that the possible operational lifetime should nevertheless extend beyond the end of 1992, with extremely high-quality scientific data being returned for some 65 per cent of the time. For an assumed 3-year operational lifetime, the original mission goals (positions, parallaxes, and annual proper motions with an accuracy of about 2 milli-arcsec) should be achievable (the pre-launch expectations of the planned 2.5-year mission would be achievable with a 3.5-year mission in the revised orbit). This paper describes the in-orbit performance of the satellite most relevant to the scientific goals.

## 1. INTRODUCTION

Overviews of the European Space Agency's Hipparcos astrometry mission, its history, scientific objectives and observing programme, payload design, satellite operations, and data reductions, have been given frequently before launch (e.g. Kovalevsky 1984, Høg 1984, Bouffard 1985, Perryman 1989). A comprehensive description of the satellite, observing programme, and methods foreseen for the data reduction, is contained in a 3-volume ESA publication (Perryman et al. 1989). Accepted within ESA's mandatory scientific programme in 1980, with a planned operational lifetime of 2.5 years, the mission goal is to measure the astrometric parameters of about 118 000 stars with a precision of some 2-4 milli-arcsec (depending on magnitude) for the main mission and, as subsequently incorporated during the design phase, the astrometric and two-colour photometric properties of a further 400 000 stars with somewhat lower precision for the Tycho experiment.

After launch by Ariane on 8 August 1989, the failure of the apogee boost motor to place the satellite in its intended geostationary orbit initially resulted in a significant lowering of the expected scientific results from the mission. The early stages of the implementation of the revised Hipparcos mission (including the perigee raising manoeuvre and final orbit selection, additional ground station implementation, solar array power monitoring, revision of the attitude control system, and payload and satellite commissioning) have been described elsewhere (Clausen & Perryman 1989, Hassan et al. 1990). After two years in orbit, following the inclusion of two further ground stations into the satellite tracking

*J. Bergeron (ed.), Highlights of Astronomy, Vol. 9,* 383–387.

network, and the successful implementation of a revised operational concept, the astrometric results from the data acquired so far will be substantial, and confidence is growing that the original mission goals may still be attained. This paper concentrates on a description of the present satellite system parameters and the spacecraft and payload performances, to the extent that they influence the achievable scientific goals. Accompanying papers in the present volume describe aspects of the Input Catalogue performance and the present status of the data processing tasks.

## 2. SPACECRAFT AND PAYLOAD PERFORMANCE

The ESOC (Darmstadt, FRG) control centre continuously uplinks the characteristics of the programme stars to be observed (including their position, selection index, field of view, minimum and target observing time, and whether they are to be used for real-time attitude reference). This information controls both the observing programme and the scanning motion of the satellite. Data telemetered from the satellite (principally the photon counts from the main and star mapper detectors, and real-time attitude information from the gyros and star mapper) are monitored, merged with auxiliary parameters such as satellite orbit information, and dispatched to the data reduction consortia (van der Ha 1989).

After launch, and after definition and implementation of the revised operational concept and the incorporation of the ESA Perth and CNES Kourou ground stations into the telemetry/telecommand network, the spacecraft and payload were commissioned, and the routine data acquisition phase commenced on 1 December 1989. However, the subsequent few weeks were characterised by non-optimised on-board calibration parameters, as well as somewhat limited ground station coverage. With the incorporation of the NASA Goldstone ground station in May 1990 (and the subsequent release of the Kourou station) the typical daily useful data acquisition rate has remained at some 60-70 per cent.

The spacecraft sub-system with the greatest direct relevance to the scientific data quality is the attitude control sub-system. Through a combination of the transits of reference stars across the star mapper grid, and the interpolation of the 3-axis attitude knowledge between star mapper transits, the satellite real-time attitude is estimated on-board (with the exception of short intervals around the gas-jet actuations required to maintain the nominal satellite orientation) with an accuracy of better than about 1 arcsec rms. This accuracy is required for pointing of the instantaneous field of view of the detector to the programme stars as they cross the field of view. The revised mission has introduced significant complications into the attitude estimation procedures (due primarily to the high background noise during crossing of the van Allen belts, larger data interruptions, and significant variations in the perturbing torques as a function of the earth-satellite distance). In general, the real-time and on-ground attitude requirements are reached, with the exception of intervals immediately following perigee transits, where more complex ground station interventions have been designed to ensure that the satellite attitude converges rapidly to an accurately-known state.

The optical quality of the payload meets the design specifications in all respects. This is indicated by the amplitudes of the first and second harmonics of the signal modulation (and their field dependence for both fields of view), as well as the near constancy of the phase difference between the two harmonics for single stars over the field of view, and the well-determined celestial sphere to grid transformation parameters derived as part of the great-circle reductions. Predicted chromatic image displacements, of the order of 2 milli-arcsec between stars of extreme colour indices, have been verified by in-orbit measurements using a 'chromaticity filter' which can be inserted into the optical path, and further confirmed by the great-circle solutions in NDAC and FAST, and in the preliminary sphere solution results.

The modulating grid, nominally uniform over the field of view, was in practice constructed, by electron-beam lithography techniques, as 46 × 168 discrete 'scan fields'. Laboratory calibration provided the coefficients of the 'medium-scale irregularities' associated with the main and star mapper grids. Application of these calibration quantities to the in-orbit data, and various tests designed to establish the correctness of the on-ground calibration, have verified the quality of the grid—the medium-scale correction terms are insignificant for all but the very brightest stars, and can be safely omitted in the data processing for the main grid.

The final elements of the detection chains, the image dissector tube detector for the main field, and the two photomultiplier tubes for the star mapper detectors function nominally, and the redundant detectors have not been brought into use after initial in-orbit calibrations. The uniformity, stability, and overall quantum efficiency are all within their respective specifications. The observed count rates are within the original error budget allocation, supporting the use of the established error analysis tools used for assessing the final expected mission accuracy.

The specifications for the detector background (including detector dark counts, sky background, stray light, and Cerenkov emission), some 100 counts $s^{-1}$ for the main detector, are met throughout the apogee region of the orbit, but are exceeded (marginally for the main detector due to its small instantaneous field of view, but significantly for the star mapper detectors) throughout the perigee region, due to Cerenkov emission, associated with the van Allen belts, arising in the dioptric elements of the relay optics. This enhanced detector background degrades the performance of the Tycho experiment near to perigee, and also complicates the attitude determination in these parts of the orbit. The effects on both are particularly severe during periods of high solar activity, where the enhanced background can be observed to persevere for several days. Thus far, it has nevertheless been possible to maintain the nominal scanning law throughout the mission, using the passage of bright stars across the star mapper slit system.

The main perturbations on the data reduction teams caused by the revised elliptical orbit are the higher signal background around the perigee regions, the larger number of data interruptions due to earth occultations, and the shorter lengths of the reference great circle sets available for the data reductions, which tends to weaken the rigidity of the great-circle solution. It should be stressed, however, that the elemental observations and the required payload performances (relative phase measurements, attitude reconstruction, and instrumental stability) follow very closely the predicted behaviour for the nominal orbit.

## 3. TEMPORAL EVOLUTION

### 3.1. Usage of Consumables

Of the original 11 kg of nitrogen, roughly 1 kg was used for the original attitude orientation manoeuvres, and normal operational usage has remained constant at approximately 5 g per day thereafter, with a predicted completed use by about the end of 1994. Control gas usage has been significantly higher than foreseen for the geostationary operation, with about 70 per cent being used to maintain the satellite attitude throughout the high perturbing torques of the perigee region, where earth gravity gradient, magnetic, and aerodynamic drag dominate the solar radiation torque environment experienced around the apogee region.

The solar arrays responsible for the satellite power supply (and battery charging for eclipse operations) are subject to significant radiation damage as the satellite passes twice per day through the high radiation environment of the van Allen belts. The major degradation mechanism, the trapping of minority carriers in the silicon due to the effects of the proton background, resulted in an initial sharp decrease in the open-circuit array voltage. Comparisons between the in-orbit measurements (corrected for variations in the earth-sun distance, spin phase, and temperature variations) and theoretical performance (based on radiation environment model AP8 max, Sawyer & Vette 1976) are in good agreement, and illustrate the flattening of the degradation with time. Further complicating the on-board power management, in the present orbit, both the frequency and the duration of the eclipses significantly exceed the geostationary case for which the batteries were designed. However, maximum eclipse periods of more than 100 min have been passed so far without power-saving contingency measures. The voltage and current extrapolations are consistent with satellite operations until end 1994.

### 3.2. Payload Structural and Response Stability

The active payload thermal control, designed to maintain the entire payload area (including mirrors and detection systems) at a constant temperature to within ±0.05°C, functions nominally. The associated specification on the allowable evolution of the basic angle (between the two fields of view) was 1 milli-arcsec over 12 hr. The long-term evolution is presently about 1 milli-arcsec over 30 days. Information on the payload stability over shorter timescales is not available directly, although star abscissae measurements based on two reference great-circles with opposite poles and the early sphere solution results indicate that this specification is comfortably met.

The extremely high tolerances on the payload stability necessary to guarantee the astrometric mission goals extend to all other terms in the geometrical transformation between the celestial sphere and the instrumental focal surface. The relevant terms are well-estimable in the great-circle processing, and their temporal evolution (typically at the level of 1 milli-arcsec over several weeks) is monitored through the first-look processing and through the main FAST and NDAC data processing chains. The evolution of these transformation coefficients is attributed principally to moisture release from the carbon-fibre structure, and a physical model of the structural changes necessary to explain these effects has now been established. The structural changes, while extremely small, lead to the (foreseen) requirement to refocus the instrument, using diagnostic measurements of the depth of signal modulation from the two fields of view. Presently the evolution is of the order of two refocussing 'steps' of 1.4 $\mu$m every 30 days.

Initial values of the photon counts as a function of magnitude for both the image dissector tube and the star mapper detectors were within a few per cent of the predictions. A decrease of the counts with time was predicted due to radiation darkening of the glasses in the relay lens systems of both detector chains. In-orbit results, derived from the ESOC payload monitoring, demonstrate that the pre-launch degradation estimates were somewhat pessimistic (neither for the solar array degradation nor for the optical darkening are the effects of anomalously large solar events prominently discernable). The effects of the changing response with time are taken into account in the photometric processing and calibration where the evolution can be fully characterised at the 0.001 mag level.

## 4. MISSION PROSPECTS

Present accuracy assessments indicate that operations extending to the end of 1992, representing a three-year operational life, will yield positions, parallaxes, and annual proper motions of the 118 000 stars to an accuracy corresponding the original nominal mission goals of about 2 milli-arcsec. This promising situation is essentially due to the fact that, with the elemental observations following the pre-launch expectations, the final achievable accuracies depend, to first-order, on the square root of the available observing time (some 70 per cent of 'real-time', as opposed to some 90 per cent of real time expected for the nominal mission).

## ACKNOWLEDGEMENTS

The Hipparcos project is a collaborative programme between the European Space Agency and the European scientific community, represented by the four scientific consortia NDAC, FAST, INCA and TDAC. The involvement of these teams, of industry, and of the ESA Project Team and Operations Team at ESOC, in all aspects of the mission, is underlined and acknowledged.

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