

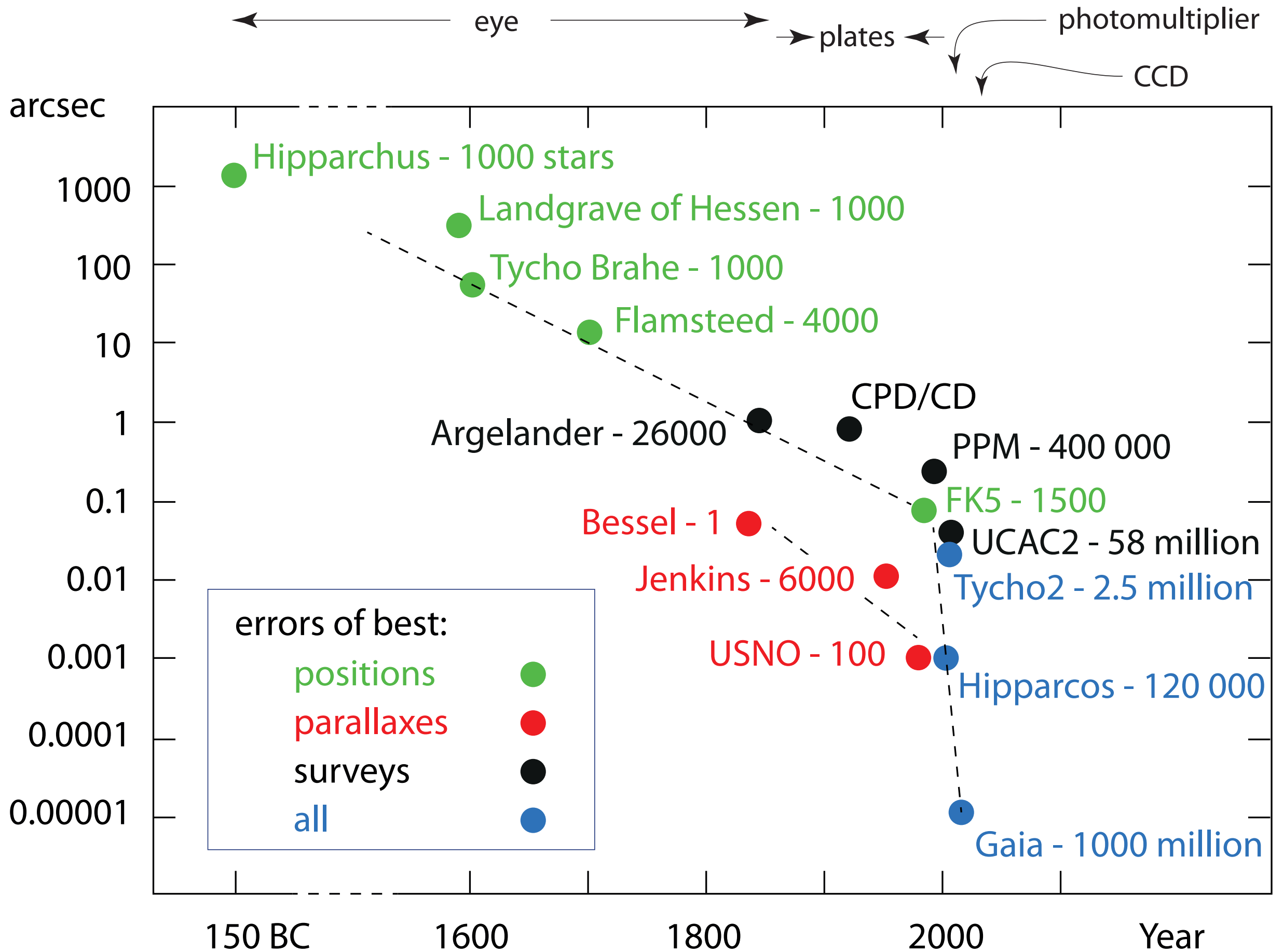
# The Science of Gaia and Future Challenges

A Science Meeting to mark the  
retirement of Lennart Lindegren

Lennart's Contribution to Science

*Michael Perryman, Lund  
30 August 2017*

# Astrometric accuracy over time



“Hipparcos is the first time since Sputnik in 1957 that a major new development in space science has come from outside the United States”

*Freeman Dyson, Princeton  
(Infinite In All Directions, 1988)*

“The bedrock of astronomy remains the compilation of what is out there... It is invidious to single out surveys which I find particularly impressive, but I make an exception for the Hipparcos astrometric satellite.”

*Malcolm Longair  
Cavendish Laboratory, Cambridge  
(Millennium Essay,  
Astronomical Society of the Pacific, 2001)*

# How do we recognise scientific contributions?

There are some standard metrics. For Lennart:

- Papers: 108, first author 23
- H-index: 15
- Doctoral students: 8
- Awards:
  - ESA Director of Science Medal, 1999
  - Fellow, Royal Swedish Academy, 2010
  - Honorary Doctorate, Paris Observatory, 2011
- Director of the Lund Observatory
- Committees and Coordinator... several for both projects



# ESA Director of Science Medal: Bern, May 1999



# Selection of Lennart's refereed papers

- **Atmospheric limits of narrow field optical astrometry** (A&A, 1980)
- **Estimating the external accuracy of the Hipparcos parallaxes by blind deconvolution** (1995)
- **Fundamental definition of radial velocity** (A&A, Lindegren & Dravins, 2003)
- **The astrometric core solution for the Gaia mission:** overview of models, algorithms, and software implementation (A&A, Lindegren et al., 2012)
- **Gaia Data Release 1. Astrometry:** one billion positions, two million proper motions and parallaxes (A&A, Lindegren et al., 2016)
- others more outside the scope of this meeting, including
  - **“Determination of stellar ages from isochrones: Bayesian estimation versus isochrone fitting”** (A&A, Jorgensen & Lindegren 2005)
  - **“*seminal work on the Cramer-Rao bound presented by Lindegren (1978)*”** quoted by Mendez et al 2013, in their “Analysis and Interpretation of the Cramér-Rao Lower-Bound in Astrometry”



# But there is one crucial way to visualise Lennart's excellence...

- Through his compilation of “Working Notes”, now online
- Although non-refereed, these are:
  - treatises on many key subjects for Hipparcos and Gaia
  - always: rigorous, accurate, timely, and often definitive
  - many with algorithms...
  - these have shaped, underpinned and optimised both missions
  - they demonstrate Lennart's remarkable ability to:
    - identify a problem
    - analyse, solve and summarise it
    - explain it in a way that others can understand



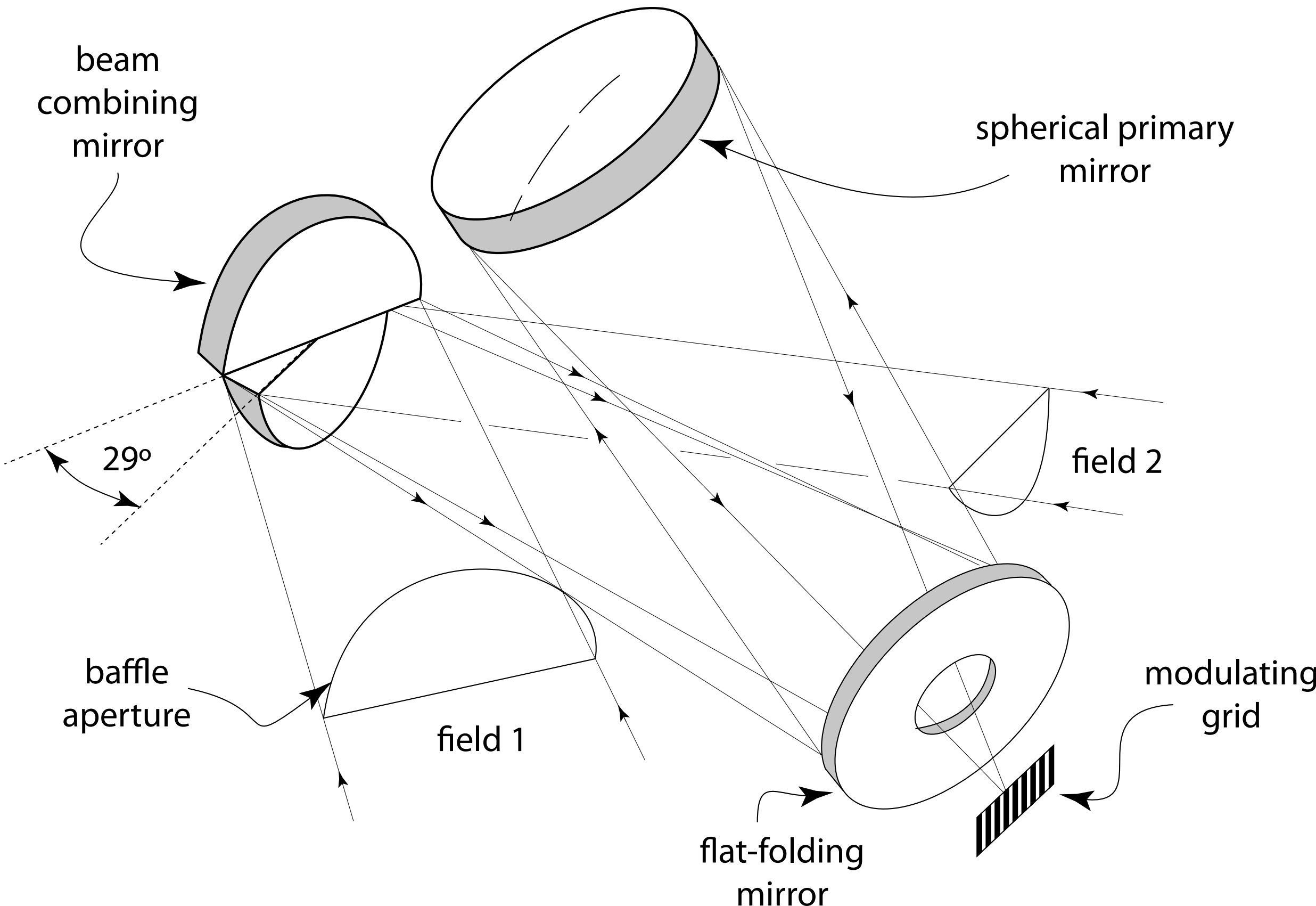
- [19840029 040 Calibration of Star Mapper distortion](#)
- [19840630 041 NDAC Process Diagram](#)
- [19840703 042 Light-time effects and the modelling of stellar proper motion](#)
- [19840717 043 Review of the Attitude Reconstitution and SMS Update](#)
- [19840727 044 Subroutines for calculating proper direction](#)
- [19841001 045 Ninth NDAC Report from Lund Observatory](#)
- [19841105 046 Step 2-3 Formation and Solution of Normal Equations \(WP6240, 6260, 6270\)](#)
- [19841212 047 Tenth NDAC Report from Lund Observatory](#)
- [19850131 048 SIP23 - Programs to simulate input data for Step 2-3 \(Soderhjelm\)](#)
- [19850207 049 SOR23 - A program to sort the input data for Step 2-3](#)
- [19850214 050 Attitude Reconstitution by Least Squares Data Analysis Consortium \(NDAC\) \(Lindegren and Soderhjelm\)](#)
- [19850215 Least-squares estimation of attitude for IDT](#)
- [19850222 051 Ground-based Data Analysis Consortium \(NDAC\) \(Lindegren and Soderhjelm\)](#)
- [19850225 052 Attitude Reconstitution by Least Squares Data Analysis Consortium \(NDAC\) \(Lindegren and Soderhjelm\)](#)
- [19850311 053 TYCHO Astrometry - Mathematical Formulation](#)
- [19850311 054 TYCHO Astrometry - Mathematical Formulation](#)
- [19850419 055 TYCHO Astrometry - Mathematical Formulation](#)
- [19850502 056 TYCHO Astrometry - Mathematical Formulation \(Soderhjelm\)](#)
- [19850508 057 Step 2-3 \(Lindegren and Soderhjelm\)](#)
- [19850524 057 Step 2-3, erratum \(continued\) \(Soderhjelm\)](#)
- [19850608 058 Error analysis of phase bunching for the IDT preprocessing](#)
- [19850611 059 Twelfth NDAC Report from Lund Observatory](#)
- [19850617 060 Notes on the IDT Preprocessing and RGO-DSRI interface](#)
- [19850619 061 Results of IDT Preprocessing simulations](#)
- [19850830 062 Preprocessing of ESTEC IDT photon count runs \(3\)](#)
- [19850903 TYCHO Astrometry - Mathematical Formulation](#)
- [19850905 063 Derivation of the StarMapper geometry in field coordinates](#)
- [19850913 064 13th NDAC Report from Lund Observatory](#)
- [19851029 Phase shifts due to IFOV depointing](#)
- [19851209 065 14th NDAC Report from Lund Observatory](#)
- [19851210 066 HIPPARCOS reductions for multiple stars, I \(Soderhjelm\)](#)
- [19850204 067 HIPPARCOS reductions for multiple stars, Ib \(Soderhjelm\)](#)
- [19850219 068 Preprocessing of ESTEC photon counts simulations. Run](#)

130/160 NDAC-LO  
230/280 TN on  
Hipparcos

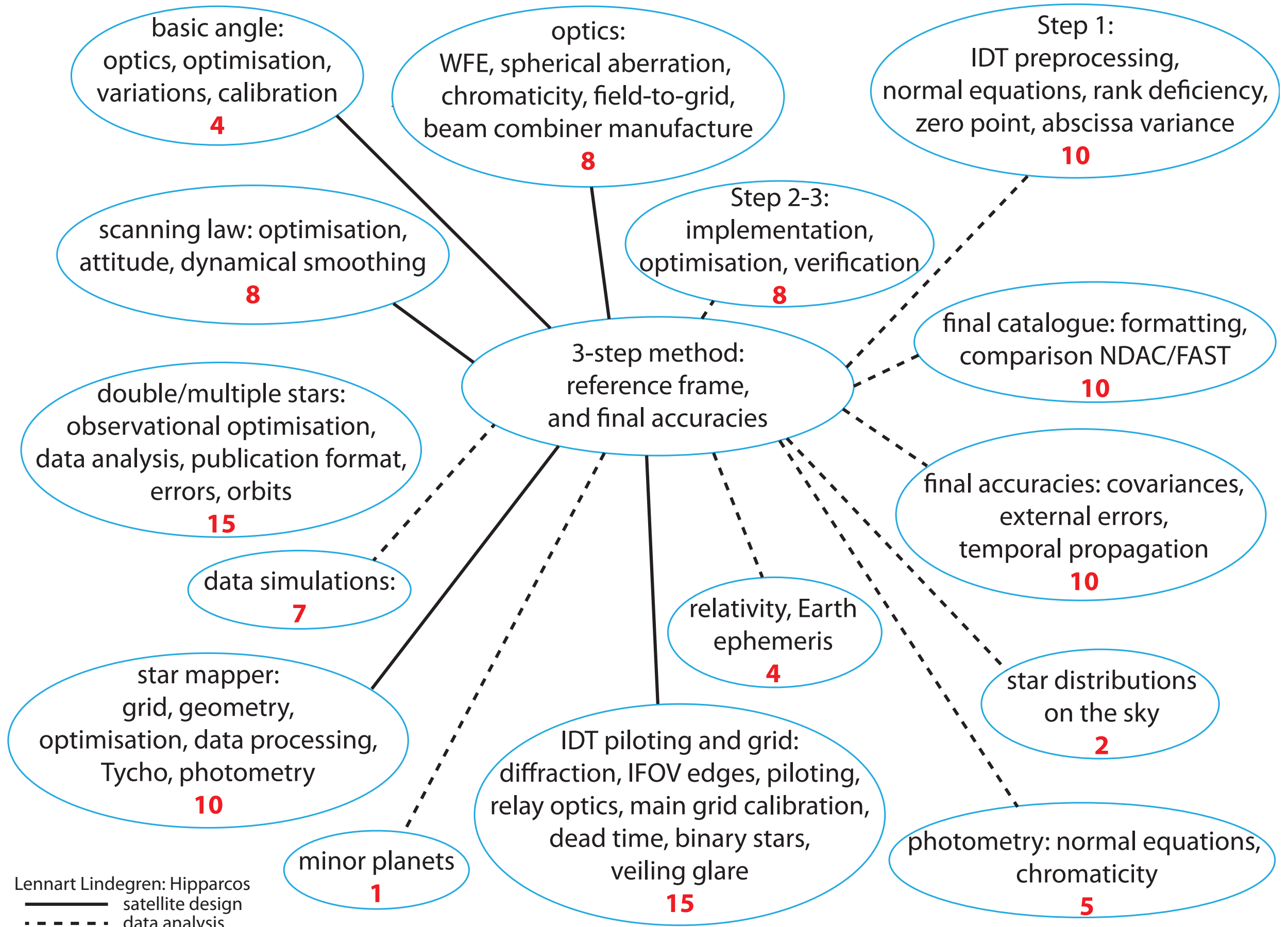
- [Gaia-LL-019 19980706 Proposed names for the GAIA instruments-fields-detectors](#)
- [Gaia-LL-020 19980626 Requirements on the attitude noise](#)
- [Gaia-LL-021 19980717 Calculated photoelectron fluxes for different filters](#)
- [Gaia-LL-022 19980921 Charge trapping effects in CCDs for GAIA astrometry](#)
- [Gaia-LL-023 19980927 GAIA mean astrometric precision versus V magnitude](#)
- [Gaia-LL-024 19881025 Calculation of chromatic displacement](#)
- [Gaia-LL-025 19881215 Point Spread Functions for GAIA including aberrations](#)
- [Gaia-LL-026 19881229 Simulation of GAIA scanning of arbitrary directions](#)
- [Gaia-LL-027 19990118 An Object-Oriented Framework for GAIA Data Processing \(OMullane and Lindegren\)](#)
- [Gaia-LL-028 19990817 Lossy compression of image data using square-root coding](#)
- [Gaia-LL-029 20000225 Detection of double stars with GAIA](#)
- [Gaia-LL-030 20000701 Attitude determination for GAIA](#)
- [Gaia-LL-031 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-032 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-033 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-034 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-035 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-036 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-037 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-038 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-039 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-040 20000721 Attitude determination for GAIA attitude](#)
- [Gaia-LL-041 20020220 Reduced spin rate and precession rates for GAIA - implications for astrometric accuracy and the analysis of periodic phenomena](#)
- [Gaia-LL-042 20020422 Photometric filter characteristics for GAIA \(Lindegren, Hog, and Knude\)](#)
- [Gaia-LL-043 20020421 GAIA astrometric error budget - Proposed approach](#)
- [Gaia-LL-044 20030710 Algorithms for GDAAS Phase II - Definition \(GAIA Algorithm Community\)](#)
- [Gaia-LL-045 20030422 Photometric systems for GAIA's Broad Band Photometer](#)
- [Gaia-LL-046 20030502 Representation of LSF and PSF for GDAAS-2](#)
- [Gaia-LL-047 20031011 Optimizing Gaia's Photometric System - Thoughts on distance measure and figure of merit](#)
- [Gaia-LL-048 20031220 Requirements on the attitude noise \(2\)](#)
- [Gaia-LL-049 20031115 Chromaticity calibration and the BBP filter change](#)

121 TN on  
Gaia

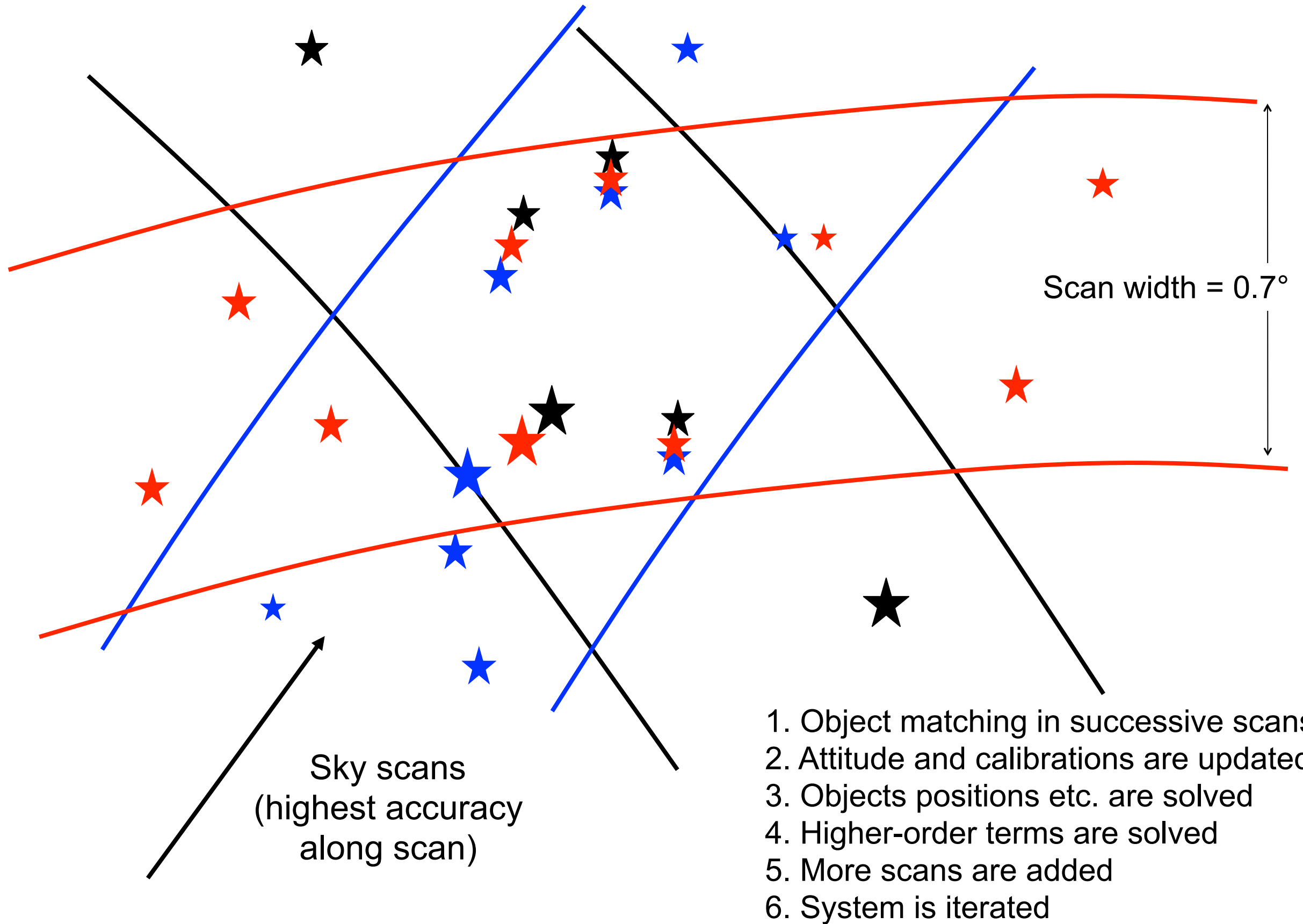
# Hipparcos optical design



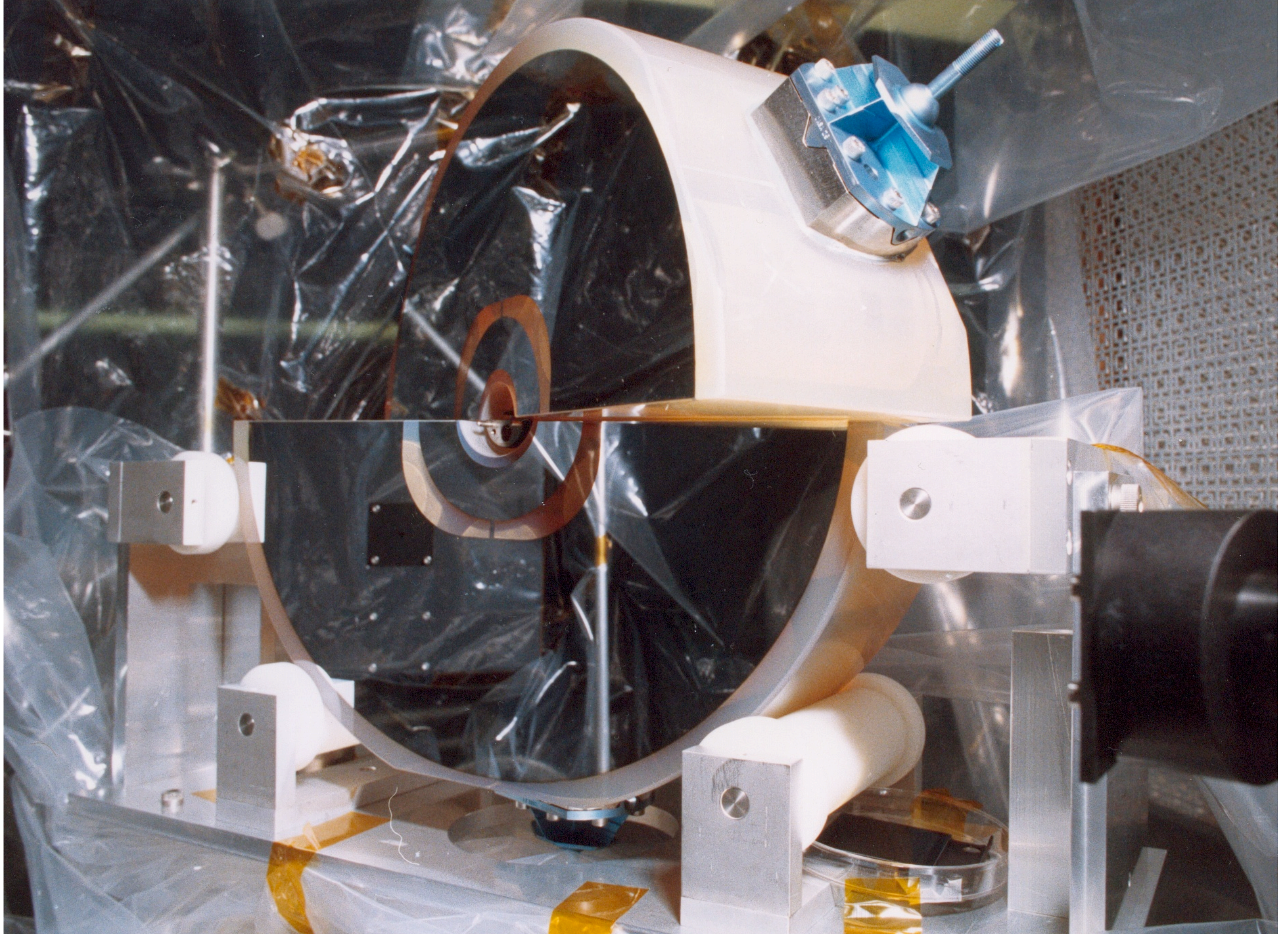
# Lennart's Technical Notes: Hipparcos



# Star Observing Principles: Hipparcos & Gaia







The 30 cm diameter beam combining mirror



## **Perryman to Lindegren, 4 August 2017 14:38**

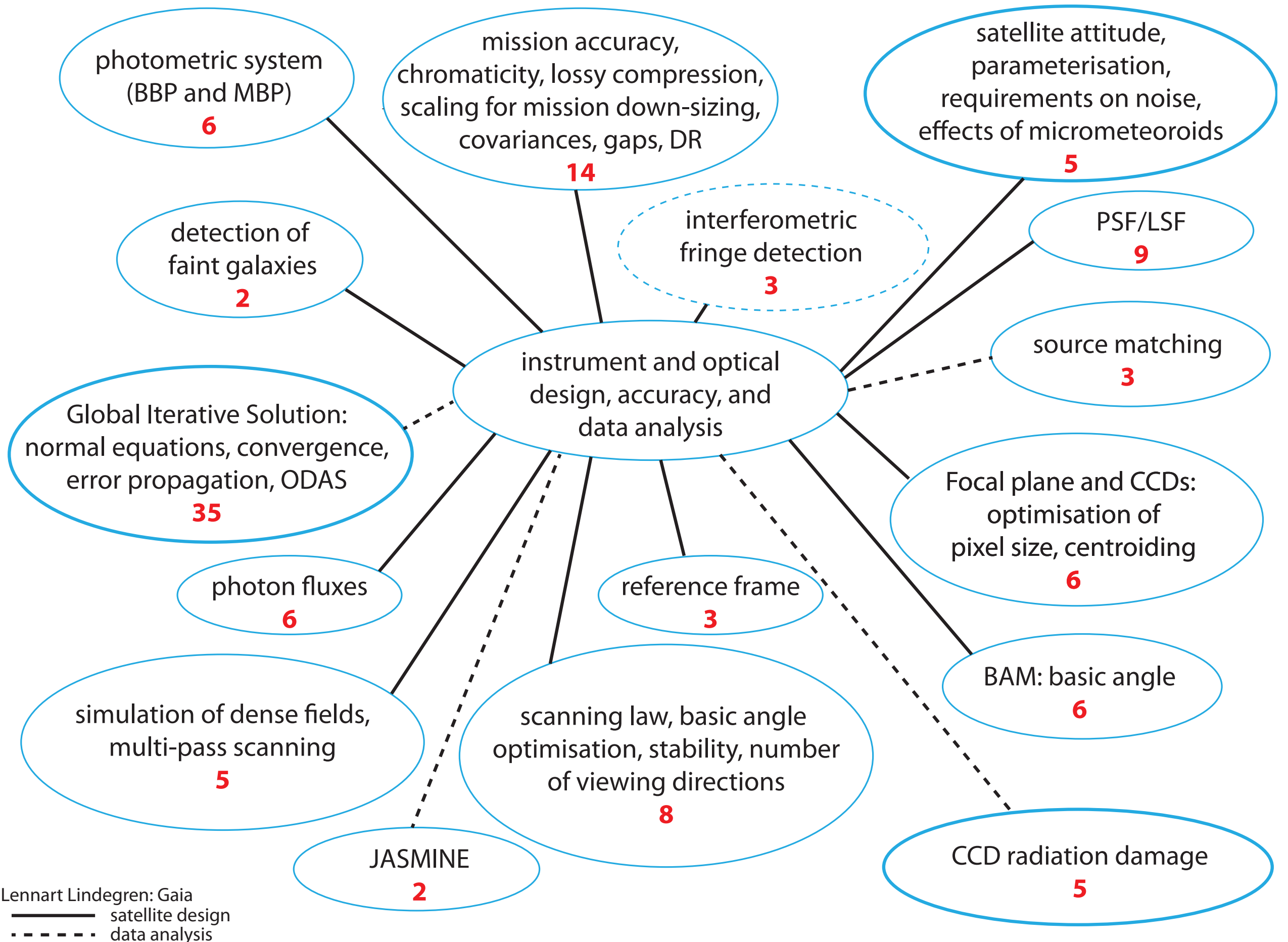
How did you come up with that idea to slice the edge off the beam combiner before re-gluing?

## **Lindegren to Perryman, 4 August 2017 15:15**

In a Schmidt telescope the spherical aberration is compensated by the wavefront error produced by the aspherical corrector plate. This corrector has a circularly symmetric profile, i.e. the contours are concentric circles around the optical axis. To get a similar correction from the beam combiner, where the two faces are inclined by 14.5 deg to the optical axis, the contours should ideally be elliptical with an axis ratio  $1 : \cos(14.5 \text{ deg})$ . But the manufacturing process could only make a circular profile. The solution was to cut off a bit in the middle, so the two circular arcs approximate an ellipse



# Lennart's Technical Notes: Gaia



# Preparing the Gaia Global Iterative Solution, ESTEC, June 2005





**Launch of Gaia, Kourou,  
French Guyana 19 Dec 2013**



# In addition to a rock-solid scientific career

- Lennart has always provided wise and objective council
- he has set the highest standards of scientific writing
- he has been an innovator in public relations and communication
- he has been an inspirational teacher and guide

No one can really say whether Hipparcos and Gaia would have existed without Lennart...

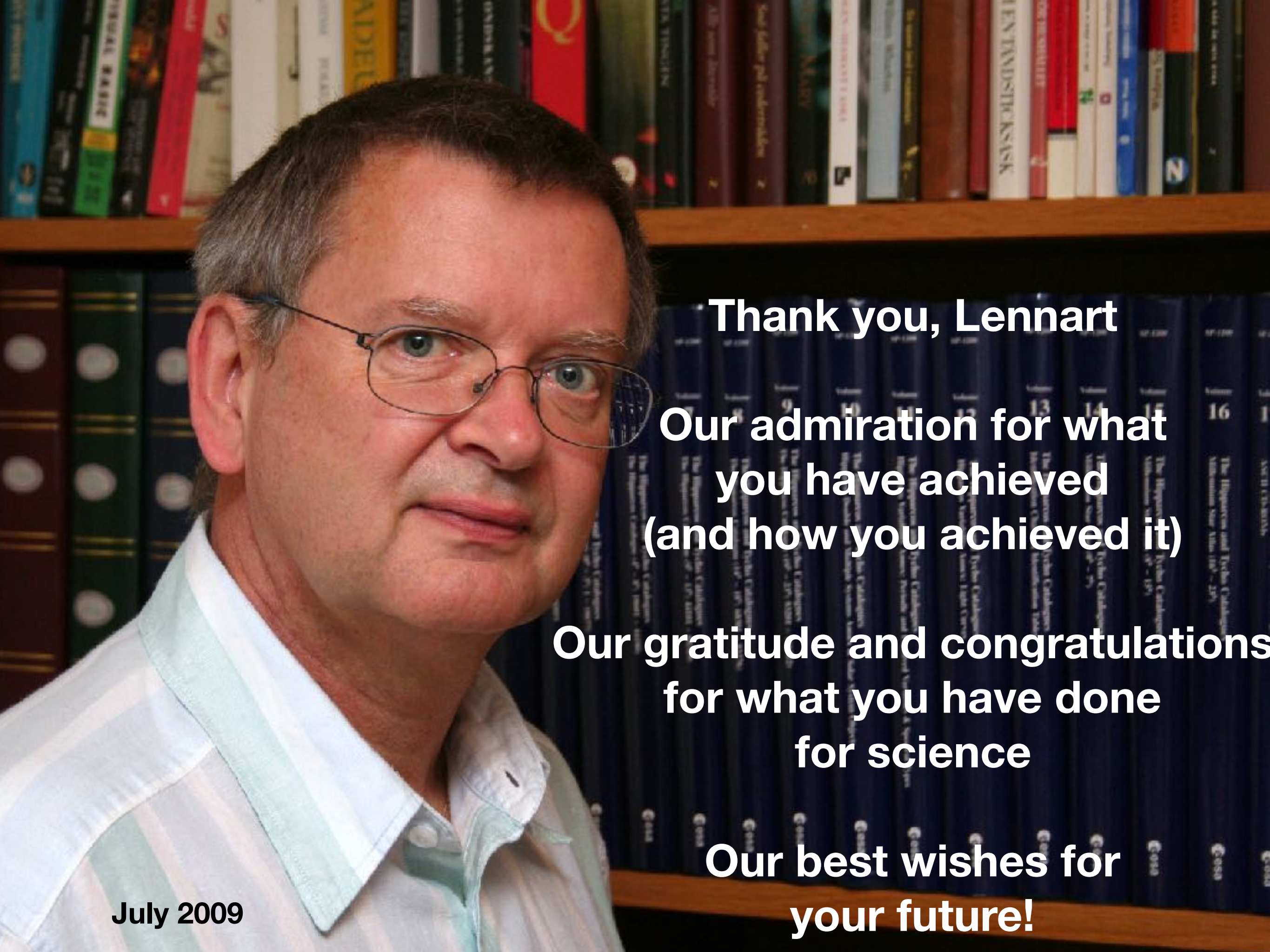
...but we can say that they would have been very different missions without him

# Finally, some economic considerations...

- scientists often consider their work as “valuable” (if non-quantifiable) for society
- some governments are placing an increased emphasis on applied R&D
- economists (e.g. C.A. van Bochove, Leiden University) find a factor 5-7 in economic return for investments in space (NASA claims 7:1)
- for Gaia, at 500M€, this suggests an economic return to Europe of 2-3 B€
- Lennart’s catalytic role in Gaia (with others) has led to:
  - some hundreds of high-technology industrial jobs
  - many scientific positions
  - an economic legacy that is, I suspect, very significant

This is a very worthy additional consideration, on top of an enormous scientific legacy that will be felt across many future decades and generations





**Thank you, Lennart**  
**Our admiration for what**  
**you have achieved**  
**(and how you achieved it)**

**Our gratitude and congratulations**  
**for what you have done**  
**for science**

**Our best wishes for**  
**your future!**

**July 2009**