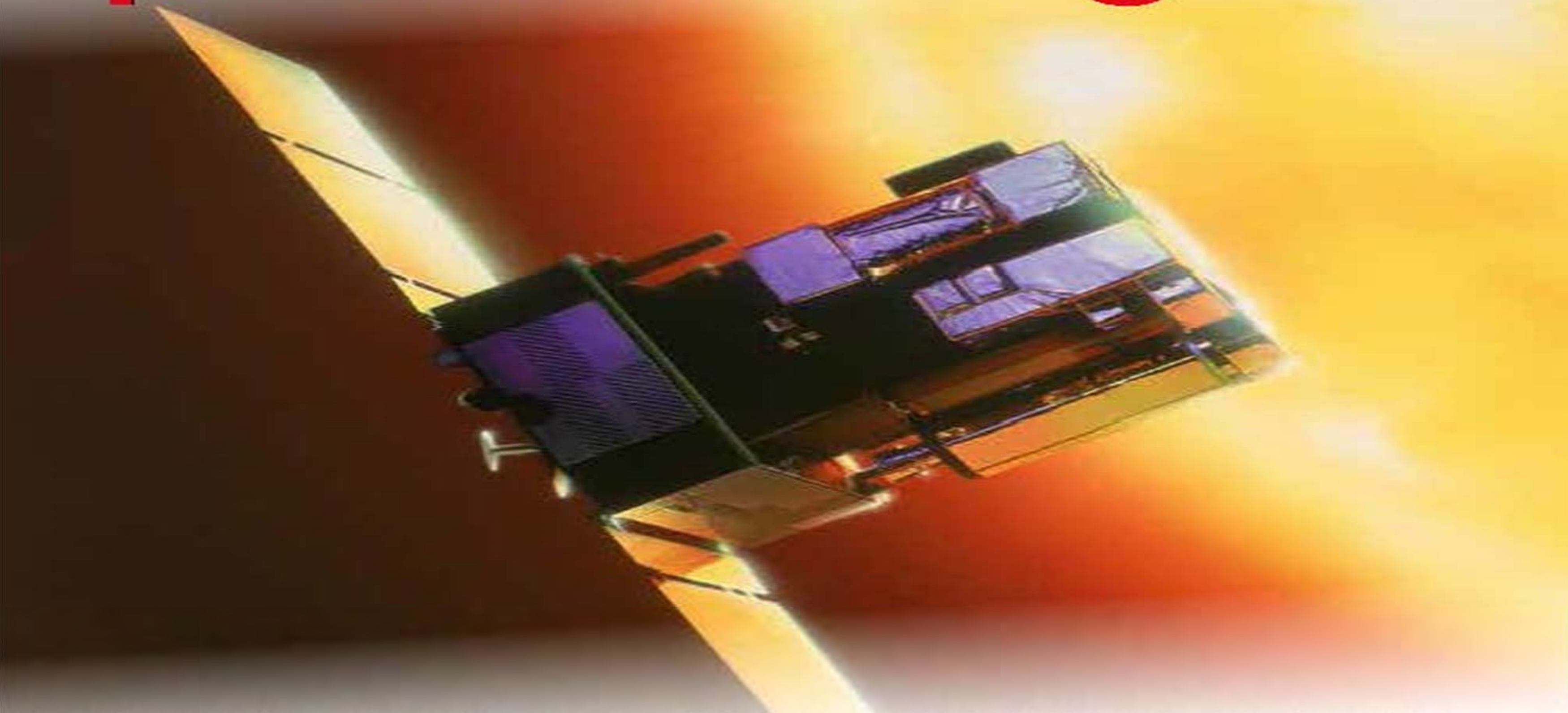
Wednesday 12 October at 12:30 pm

Académie Royale de Belgique - Palais des Académies - Salle Prigogine - Rue Ducale 1 [Metro Station Trône] - Brussels

Half a century of Space Research at the Centre Spatial de Liège



Lecture by **Professor Pierre ROCHUS,** *Scientific Director, Centre Spatial de Liège and correspondent of the Air & Space Academy*

Observatoire de Cointe

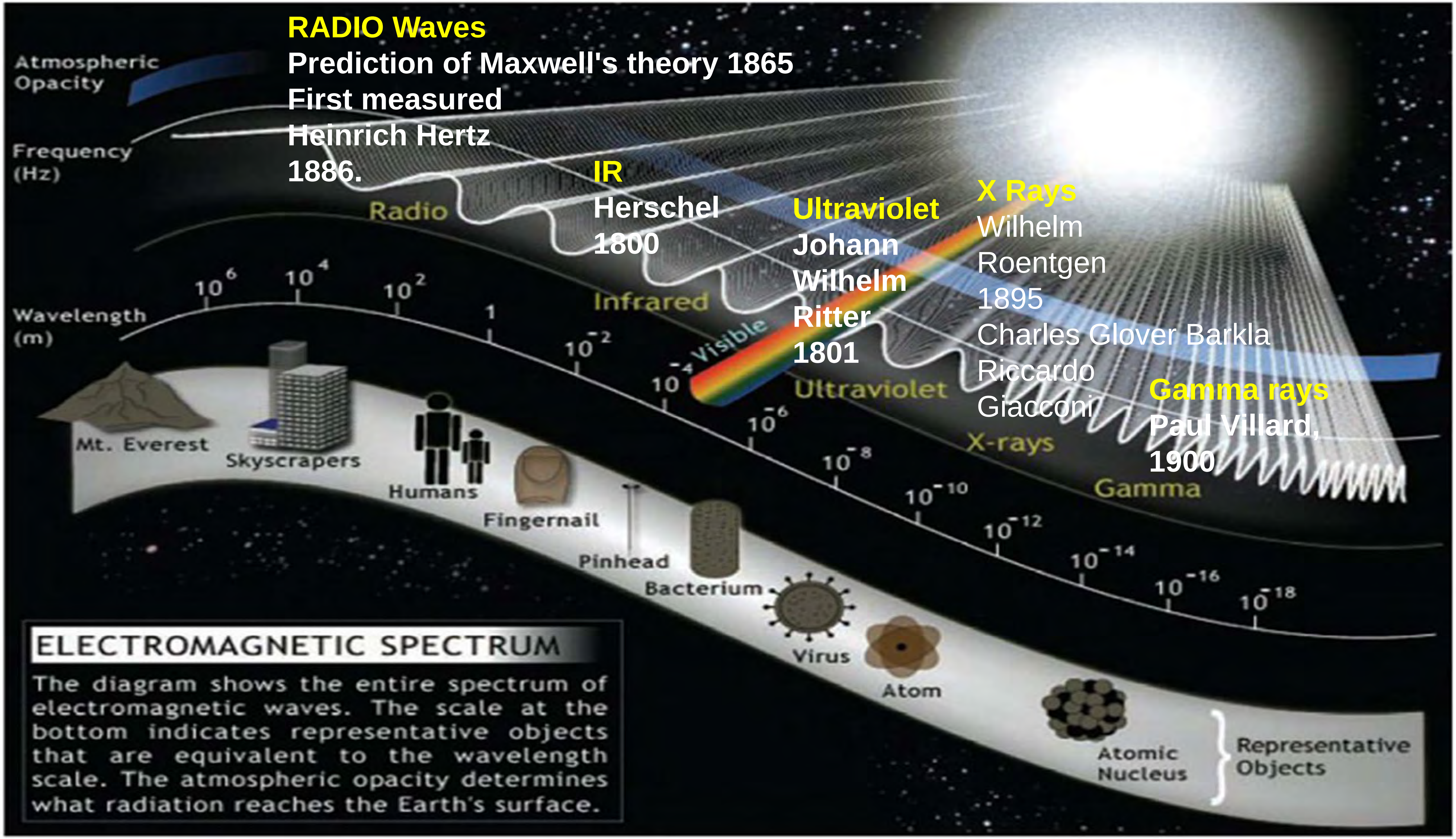
The University of Liège acquired the private park, in 1880, land owned by the family Hauzeur. The construction of the scientific complex is carried out in 1881-82 to plans by the architect Lambert Liege Noppius, to whom we also owe the zoological, anatomy and botany institutes.

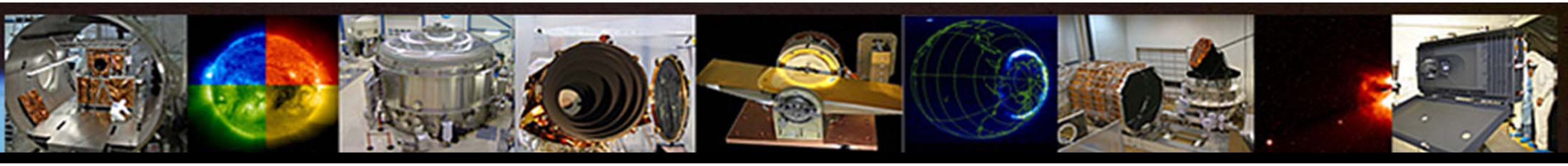
1881-82

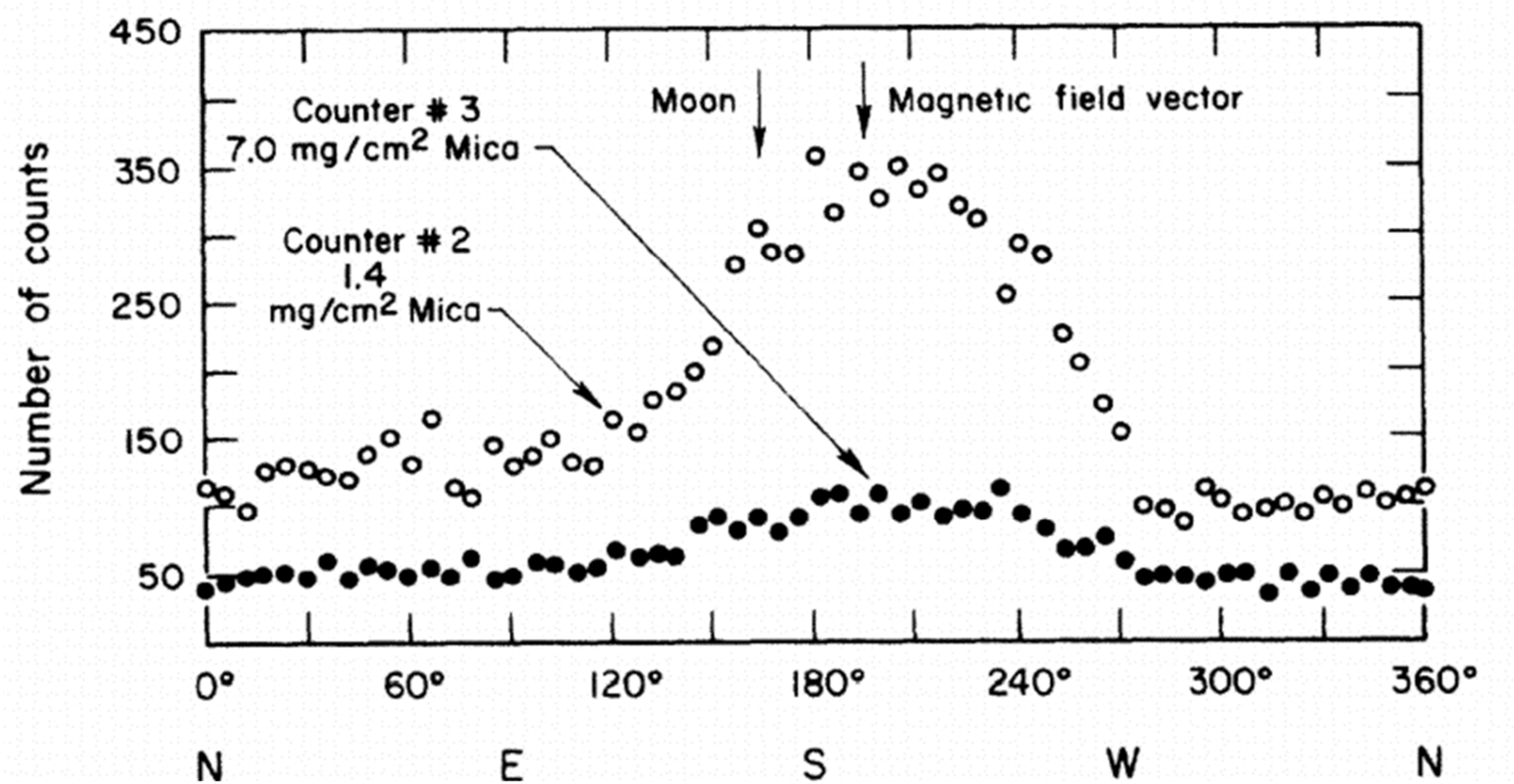
COINTE: aerial view of the late 1930s

This aerial view of the late 1930s shows the observatory (1) in a still very rural environment Even the streets of Chera (2) and Wells (3) are not urbanized. Notice the background steel plants of the Meuse valley. At the creation of the Institute of Astrophysics, some have also questioned the utility of making such observations in the middle of the local industry smoke

The Milky Way with our eyes


RADIO Waves
Prediction of Maxwell's theory 1865
First measured
Heinrich Hertz
1886.
IR
Herschel
1800
Ultraviolet
Johann
Wilhelm
Ritter
1801
X Rays
Wilhelm
Roentgen
1895
Charles Glover Barkla
Riccardo
Giacconi
Gamma rays
Paul Villard,
1900
Atmospheric Opacity
Frequency (Hz)
Wavelength (m)
Radio
Infrared
Visible
Ultraviolet
X-rays
Gamma
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
Mt. Everest
Skyscrapers
Humans
Fingernail
Pinhead
Bacterium
Virus
Atom
Atomic Nucleus
Representative Objects
ELECTROMAGNETIC SPECTRUM
The diagram shows the entire spectrum of electromagnetic waves. The scale at the bottom indicates representative objects that are equivalent to the wavelength scale. The atmospheric opacity determines what radiation reaches the Earth's surface.

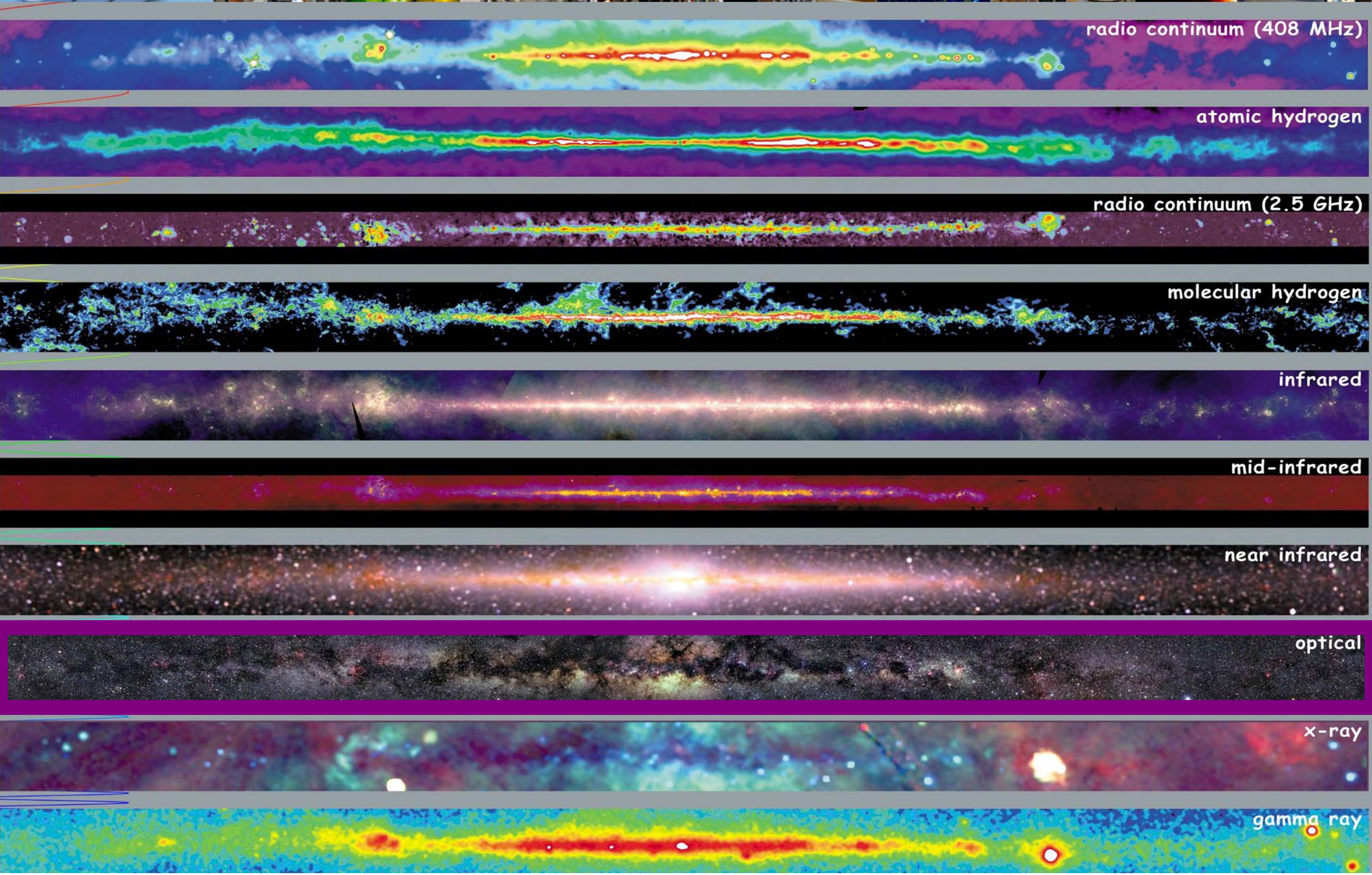




*Credit: **Giacconi**, R., **Gursky**, H. Paolini, F., & Bruno Rossi, **1962**, Physical Review Letters, volume 9, pg. 439*

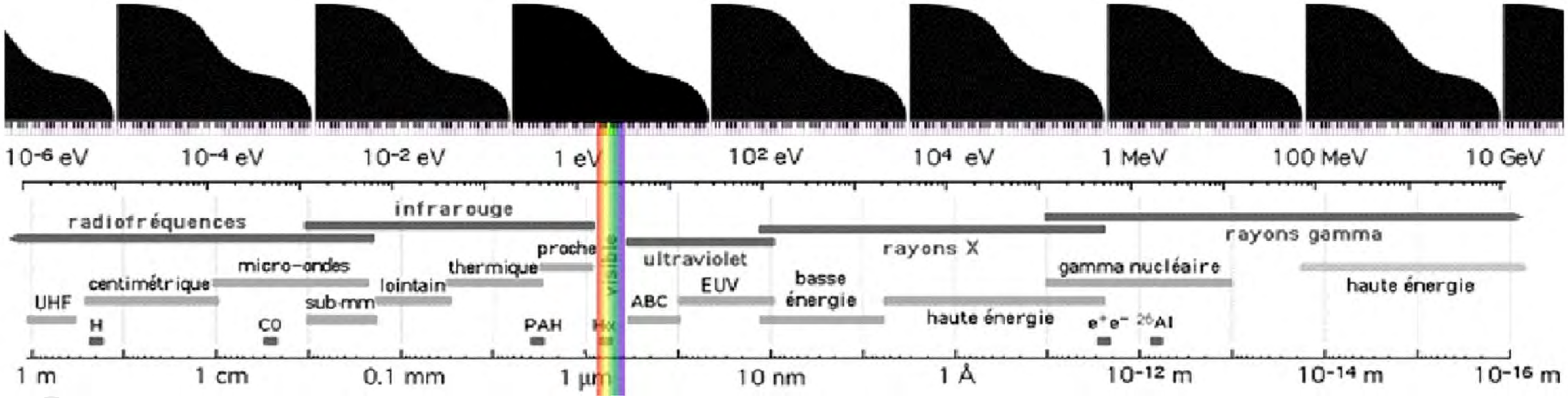
Riccardo Giacconi, widely regarded as the father of X-ray astronomy has won a share of the 2002 Nobel Prize in Physics. Giacconi, was recognized for his pioneering work in building the first X-ray detectors and telescopes and for discovering (with Herbert Gursky, Frank Paolini and Bruno Rossi) the first X-ray source outside the solar system, Sco X-1. The image above

The Milky Way at different wavelengths



Historical context

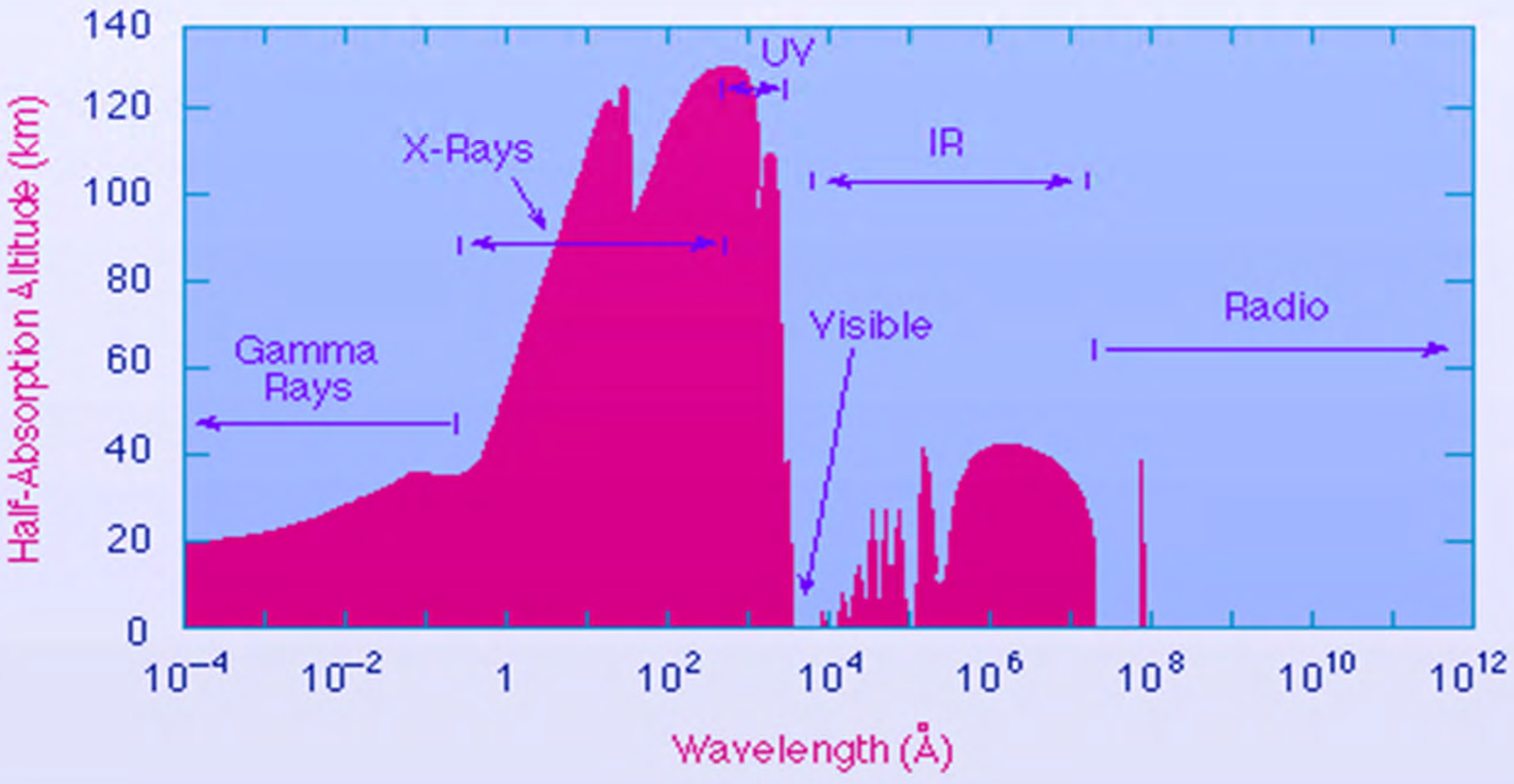
21 decades or 70 octaves



8 electromagnetic pianos

20 decades just from the sun !
when the sun is active

Need to go to Space



Historical context

Auguste Comte: **French philosopher, founder of the doctrine of positivism and the first philosopher of science in the modern sense of the term.**

The Positive Philosophy, Book II, Chapter 1 (1842)

- ***Of all objects, the planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions, but we can never know anything of their chemical or mineralogical structure; and, much less, that of organized beings living on their surface …***
- **Auguste Comte refers to the planets in the quotation above; he believed that we could learn even less about the stars**

In the mid eighteenth century, we did not know what the Sun was made of.

Auguste Comte argued we would never determine its chemical composition at distance.

He died in 1857, two years before two German chemist **Robert Bunsen** and physicist **Gustav Kirchhoff** did revolutionize astronomy by **analyzing the spectrum of sunlight**, opening the door for determining the chemical composition and physical properties not only the Sun but also star.

Historical context : helium

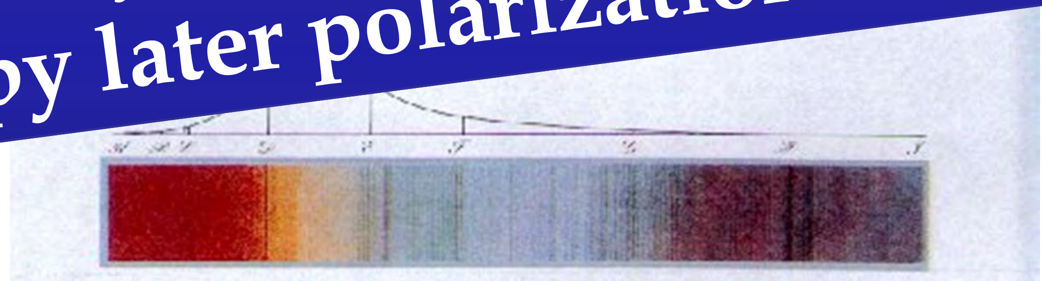
Robert Bunsen and Gustav Kirchhoff first found that any warm body emits radiation that covers the entire spectrum of light, and what is termed a **continuous spectrum**, then the spectrum of a gas at low pressure and heated to high temperature is reduced to few bright lines characteristic, which are the signature of the chemical element that is gas: **the spectrum of emission lines**.

In 1814 the German physicist **Joseph von Fraunhofer** had observed the presence of dark lines in the spectrum of the Sun. He even compiled a catalog, assigning a letter to each of lines or groups of lines. By applying the method developed by **Kirchhoff and Bunsen**, he managed to quickly identify the elements responsible for these lines: **sodium , hydrogen, calcium ions**.

In 1868, during a particularly long total solar eclipse (total phase lasted 6.5 minutes), French astronomer Jules Janssen observed in the yellow-orange region of the spectrum, just next to the sodium D doublet, a line that did not correspond any known element, and the British astronomer Norman Lockyer decided to attribute to an element unknown on Earth and called it "helium" the Greek word "helios" corresponds to the Sun.
Helium was identified in laboratory 27 years later, by the British chemist William Ramsey.
We now know that helium is, after hydrogen, the second most abundant element in the sun.
Using spectroscopy, helium was first discovered in the Sun. Spectral lines labeled coroni[…]lium did not fit into the periodic table of the elements.

The pioneers of space research were spectroscopists

Need of multi-wavelengths analyses, to go to SPACE and **perform spectroscopy later polarization**



Coronium and Nebulium

In 1869, several astronomers independently discovered a bright green emission line from the Sun's corona.
This line did not match any spectral lines known at the time for any elements on Earth.
This possible new element was called coronium.
From its location in the Sun's outermost atmosphere, the corona, scientists inferred that coronium must be lighter than hydrogen.
However, Mendeleev's periodic table left no room for elements lighter than hydrogen, which has an atomic number of 1.
In 1864 Sir William Huggins studied the spectrum of the Orion nebula and found a bright green emission line that did not match any spectral lines known on Earth.
Huggins observed this line in about a third of the nebulae he studied. He proposed the name nebulium for this possible new element.
The perfected periodic table left no place for nebulium.

→ Forbidden Lines

coronium

Group → / Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 UUb	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Forbidden Lines

In 1927, **I.S. Bowen** finally solved the **mystery of coronium and nebulium**.
Under high temperature near vacuum conditions, such as found in nebulae and in the solar corona, ordinary elements emit spectral lines that they do not emit in conditions found in laboratories on Earth. To produce these lines, atoms must remain in highly ionized states (missing multiple electrons) for relatively long times. These states do not occur on Earth without special effort, so these spectral lines are called forbidden lines.

The spectral lines of coronium and nebulium turned out to be forbidden lines of ordinary elements.
Nebulium was oxygen that was missing two electrons, doubly ionized. O^{++} or O^{3}
Coronium was highly ionized iron with 13 electrons missing. Fe^{13+} or Fe^{14}.

Bengt Edlén a Swedish professor of physics and astronomer, specialized in spectroscopy, participated in solving the Corona Mystery: unidentified spectral lines in the sun's spectrum were speculatively believed to originate from a hitherto unidentified chemical element termed **coronium**.
Edlén later showed that those lines are from multiply ionized iron (Fe-XIV). His discovery was not immediately accepted, since the alleged ionization required a temperature of millions of degrees. Later such solar corona temperatures were verified. We now know hot points in the corona can reach 20MK hotter than the sun core!!

It took about six decades to solve the mystery, but the periodic table of the elements gave scientists a unifying principle to distinguish between new elements, like **helium**, and common elements in unusual states, like **coronium** and **nebulium**.

Pioneer at ULg:Professor Pol Swings

Pol Swings born in 1906 in Ransart, Belgium, now part of **Charleroi** where he began in 1917 in the same Athénée Royal as **Léon Rosenfeld**, who was a year ahead of him.

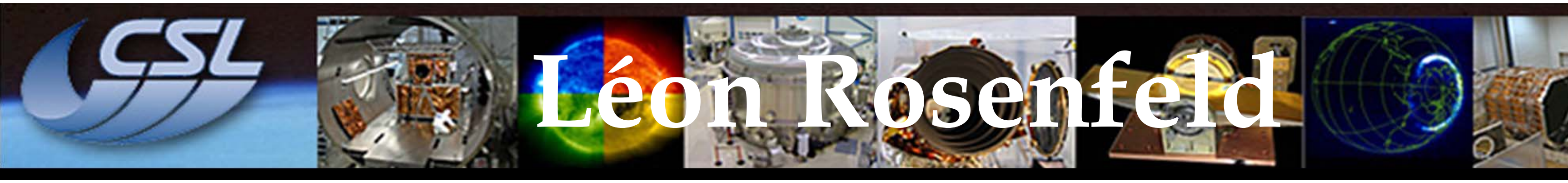
Both pursued their studies at the University of Liège where Swings graduated **in 1927** with a memoir in the field of celestial mechanics and general relativity.

He spent the academic year **1927-28** in Paris with a fellowship of the Belgian Government, frequently visiting the **Observatory of Meudon** where he made his first direct contacts with **spectroscopy and physical astronomy**. (In 1875, J. Janssen was appointed director of the new astrophysical observatory established by the French government at Meudon)

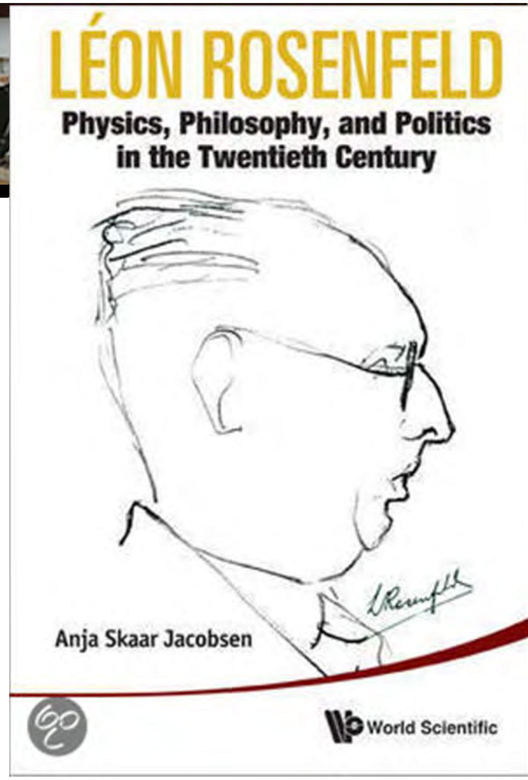
Professor Polydore Swings

Back in Liège, he founded a small team of **spectroscopy at the 'Institut d'Astrophysique'** He then spent much of his time during the next two years in Warsaw working under **Stefan Pienkowski** on **molecular spectroscopy and fluorescence phenomena**, gathering results for a **doctor's thesis in physics** which he defended in Liege in **1931.**

Stefan Pieńkowski (1883-1953) created a famous center of research in atomic and molecular optics of worldwide significance. During the 1930s about 15 percent of all papers on luminescence originated from the research of the Hoża physicists.
The first ever Congress on Luminescence took place there in May, 1936.



Léon Rosenfeld



Léon Rosenfeld (14 August 1904, Charleroi – 23 March 1974) was a Belgian physicist.

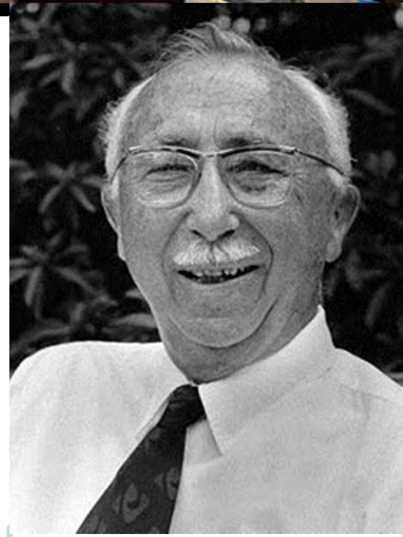
He obtained a PhD at the University of Liège in 1926, and he was a close collaborator of the physicists **Niels Bohr, Max Born, George Gamow.**. He did early work **in quantum electrodynamics** that predates by two decades the work by Dirac and Bergmann.

Rosenfeld contributed to a wide range of physics fields, **from statistical physics and quantum field theory to astrophysics**.
He was at the origin of several disciplines at the University of Liège in addition to Astrophysics and Spectroscopy.

He developped with his student **Jean Humblet**, the **Humblet-Rosenfeld expansion of the S-matrix. (Jean Humblet** as a Professor, took over the disciplines developped by Léon Rosenfeld).

Léon Rosenfeld also founded the journal **Nuclear Physics** and coined the term lepton.
Rosenfeld held chairs at multiple universities: **Liège, Utrecht, Manchester, and Copenhagen.**

Professor Pol Swings



Professor Polydore Swings

In 1936, as an advanced fellow of the Belgian American Educational Foundation, he met **Otto Struve at Yerkes Observatory** and this started a lifelong cooperation and friendship.

In Liège, where he was appointed as **professor in 1932, Swings** gathered students around him and the 'Institut d'Astrophysique' soon became a lively place, especially with **Leon Rosenfeld around for a good deal of the time**, and with distinguished visitors like **S. Chandrasekhar** in 1933 and **Bengt Edlén** a little later.

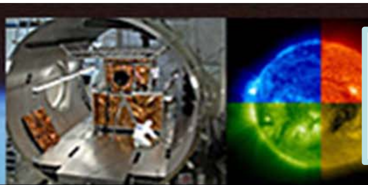
Swings also managed to get **Boris Rosen** to reinforce the spectroscopic laboratory which was mainly oriented towards problems of astrophysical interest. Many of the students were put to work on **molecular spectroscopy** in the **laboratory** or on studying the **Sun** and **stars**..

In 1937, **Swings and Rosenfeld** discovered the first **interstellar CH molecule.**

Swings also mastered atomic spectroscopy, as is shown by his early works with Edlén, Struve and others on the identification of lines forbidden or not forbidden in various stellar conditions, as well as by his analysis with Edlén of the spectra of Fe III, essential for the discussion of hot stars.

In 1939, Swings went to the U.S.A. with his wife, and was stranded there by the war in the spring of 1940. He put all his energy into his scientific work, thus starting a long, remarkable series of papers with **Struve on very hot stars, symbiotic objects, novae, planetary nebulae, WR stars, spectrum variables, etc.**

The actors



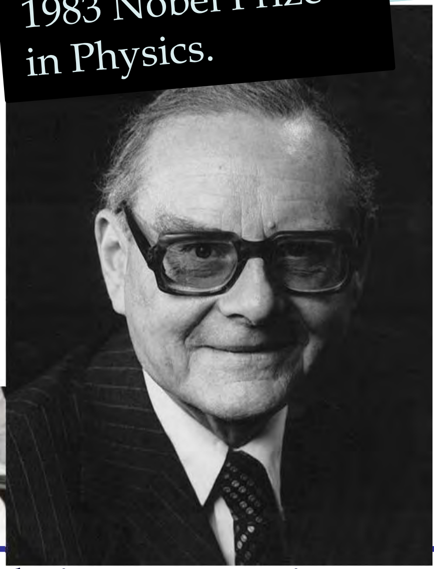
Léon Rosenfeld | Stefan Pienkowski | Otto Struve | S. Chandrasekhar | Bengt Edlén

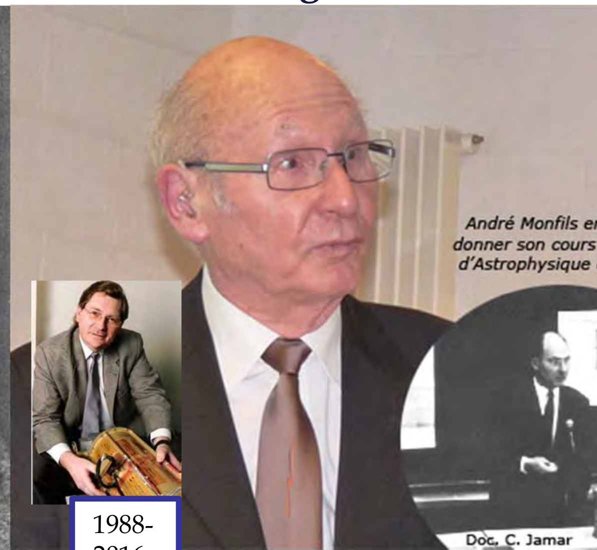
Jean Humblet

"Willie" Fowler

1983 Nobel Prize in Physics.

1974-1981





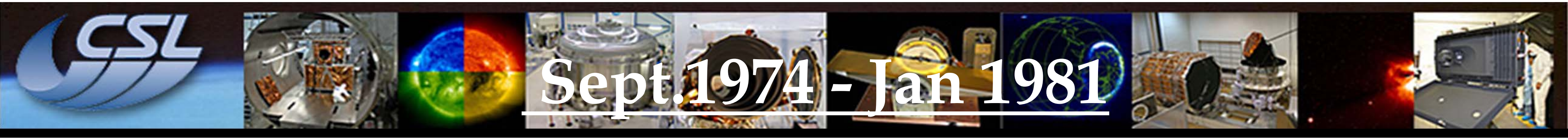
1988-2016

Claude Mahaux

Hans Bethe

Ludwig Franz B. Biermann | Leo Haser | A. McKellar | Gerhard. Herzberg | A. Monfils

1971 Nobel Prize for Chemistry



<u>iii. Sept.1974 - Jan 1981</u>

Chercheur IISN: recherche (avec thèse de Doctorat) en Physique Nucléaire Théorique et en Physique Mathématique au service de Physique Nucléaire Théorique des Professeurs Humblet et Mahaux.

Niveau Premier-Assistant à partir de juillet 1979.

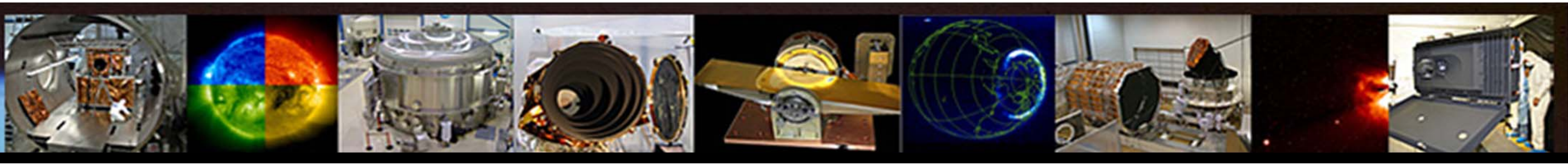
<u>Activités principales:</u>

- **Problème inverse de la diffusion**; ces études ont fait l'objet de ma thèse de doctorat en Sciences et font appel aux développements récents de l'analyse fonctionnelle, à la théorie spectrale des opérateurs différentiels et aux équations intégrales du type de Fredholm et de Volterra (Problème de Riemann-Hilbert, de Mushkelisvili qui est également utilisé dans d'autres domaines comme l'élasticité, la mécanique de la rupture,...). En deux mots, le problème inverse consiste à déterminer un opérateur différentiel à partir de son spectre. L'outil que j'ai développé pour différents types d'opérateurs différentiels (y compris des opérateurs non-Hermitiens, à voies couplées,...) en vue de l'appliquer à la physique nucléaire et à la physique des particules élémentaires (détermination du potentiel d'interaction à partir des déphasages, des états liés et des constantes de normalisation de ces états liés) pourrait être utilisé dans beaucoup d'autres domaines: problème inverse de la dynamique des structures, résolution d'équations d'évolution non-linéaire, problème d'induction magnétique, propagation des ondes élastiques et électromagnétiques, à la biophysique, théorie des réseaux électriques, analyse modale, géophysique et séismologie, ...

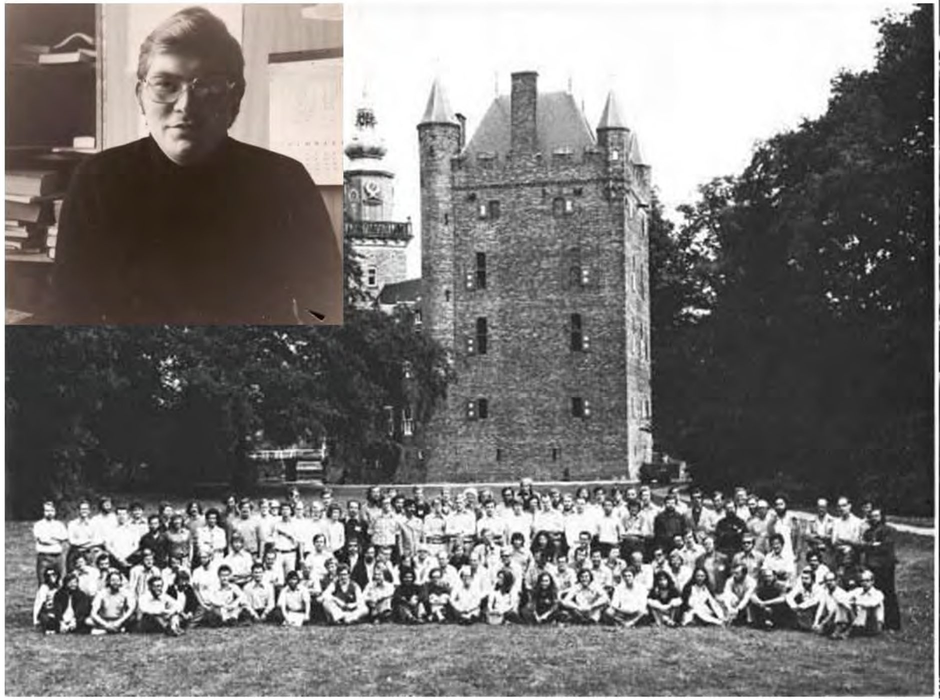
- Etude de **l'interaction Pion-nucléon**
- **Théorie relativiste des champs, appliquée à la détermination du potentiel optique nucléon-noyau aux énergies intermédiaires**

Ces dernier types d'études comprennent l'établissement d'un modèle physico-mathématique puis sa résolution par voie numérique sur ordinateur.

Ces travaux ont été publiés dans des revues internationales (à deux referees): **Journal of Mathematical Physics, Annals of Physics, Physical Review, Physical Review Letters, Nuclear Physics et lors de Conférences et Ecoles diverses**. Cette fonction m'a amené à participer à des colloques ou congrès. Certains travaux ont été réalisés en collaboration avec Prof. M. Coz (Univ. of Lexington, Kentucky), Prof. T. Mizutani (Chercheur Japonais aux USA) et Prof. Cl. Mahaux, Univ. de Liège.



a. The 1976 Nijrode Summerschool on Nuclear Spectroscopy; Ecole OTAN à Breukelen, Pays-Bas.



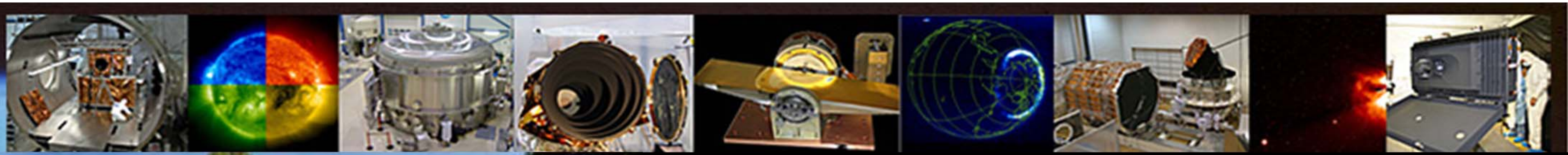
b. VII International Conference on High Energy Physics and Nuclear Structure; Zurich 1977

c. Workshop on Mesons and Isobars in Nuclei, Bad - Honnef (Allemagne) 1978.

d. Topical Meeting on the Meson Theory of Nuclear Forces and Nuclear Matter, Bad-Honnef (Allemagne) 1979.

e. Colloque sur les méthodes mathématiques de la Physique Nucléaire Paris, Collège de France. 1980.

f. International Conference on Nuclear Physics, Berkeley, California, 1980.



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Published by
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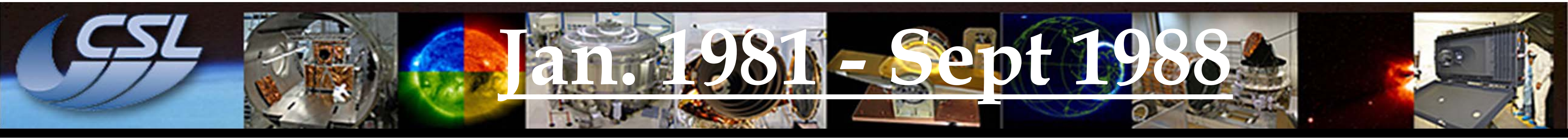


ii. Jan. 1981 - Sept 1988

Chef de Projet à F.N.Moteurs: **Département R&D** .

a) Responsable de l'étude et du développement des différents groupes de lubrification des turbo-réacteurs C.F.M. 56 (-2,-3,-5)

(en coopération avec SNECMA (France) et G.E. (USA)) (Jan 81-Sep 86)

b) Responsable de la Section Calculs

(de résistance des matériaux, de pertes de charges, thermiques, dynamiques, ...); développement de programmes FORTRAN divers sur VAX11-750. (Jan 81-Sep 88)

c) Responsable de la Conception et du Développement d'éléments du moteur Ariane 4

(**Propulseur à liquide: vanne phi 40, prise culot partie bord et partie sol, support prise culot); suivi des prototypes et cahiers des charges des essais vibratoires pour un ensemble: PGC, vanne principale et ensembles soufflets**) (comme sous-contractant de la SEP). (nov.82-déc.83)

N.B.: les groupes de lubrification CFM56-2 et -3, puis les pièces ARIANE 4 mentionnées ci-dessus, ont été les toutes premières pièces de conception F.N.M. en Aéronautique et Spatial.

d) Responsable du Département CAO (Conception Assistée par Ordinateur; Computervision CADDS 4X) et Calculs des Structures par FEM (Eléments Finis; SAMCEF).

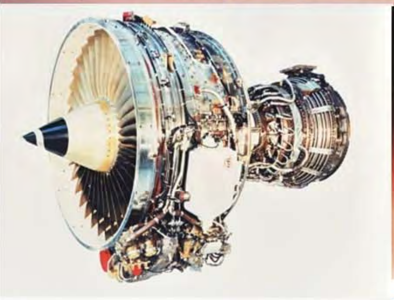
(Au service Etudes), (Fév.84-Sept.88)

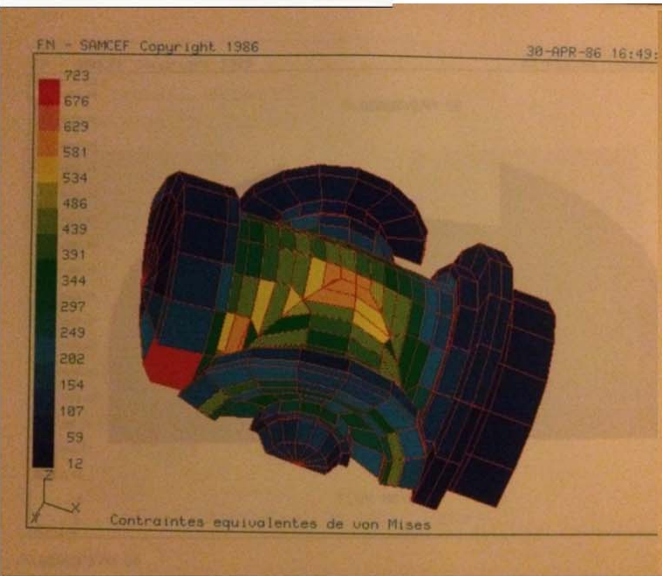
Conception et calculs statiques, thermiques et dynamiques pour les produits suivants: **Vanne d'injection de chambre, vanne gaz chauds et vanne de purge ARIANE V et de composants des moteurs CFM-56, PW4000, M88, M53, GE36, ATAR** (pour des expertises), ...

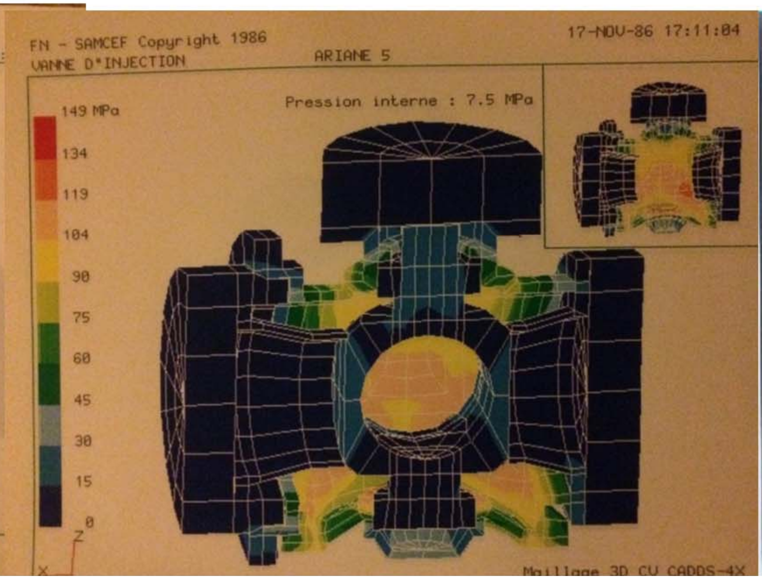
e) Responsable des Projets F.N.M./Universités

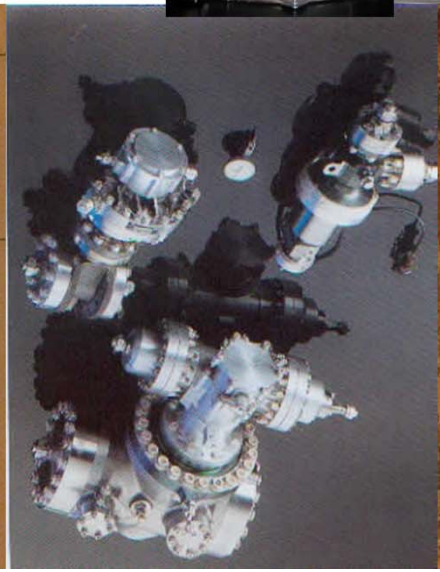
- Théorie des "**Energy Bond-Graphs**" appliquée à l'hydraulique; ce développement à été à l'origine du contrat de **modélisation des fonctionnements divers du moteur VULCAIN d'ARIANE V**)
- **Viscoplasticité dans SAMCEF**.
- C.A.P.P.: Computer Aided Process Planning; **système expert** générant une gamme d'usinage de disques plats
- **Dynamique des rotors dans SAMCEF**.

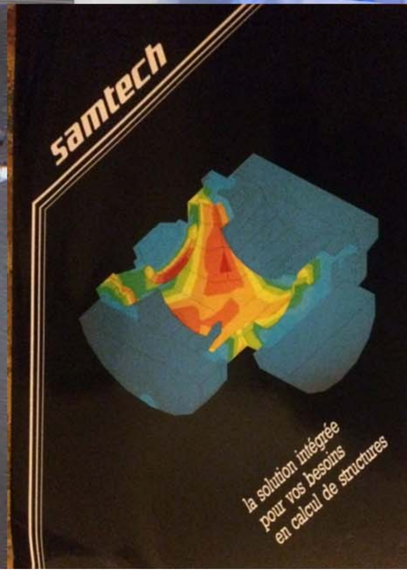
Activités à FN Moteurs / Techspace Aero /Safran Aero Boosters 1981 -1988





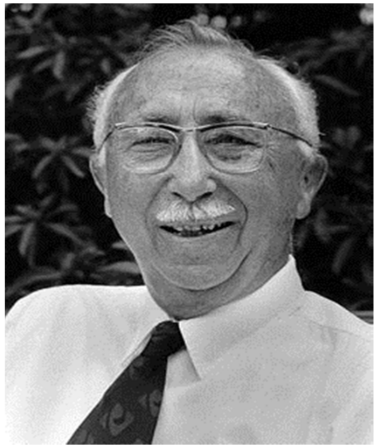






Historical Elements from the sixtieths

Belgian and European Space drivers



Professor Pol Swings

- CERN already existed (decision 1949 and build 1954) when the **International Geophysical Year** (IGY) 1957-1958
- October 4, 1957: launch of the first artificial satellites (Sputnik , Explorer, ...)
- COPERS Program **(**European Preparatory Commission for Space Research**). Italian Edoardo Amaldi and the Frenchman Pierre Victor Auger **(**appointed ESRO's first Director General**)** who 10 years before promoted CERN.
- Locally the director the Institute of Astrophysics, Professor **Pol Swings** decided in **1963** to reform the structure of his service, and defines four main fields of studies:
  - Ultraviolet Astrophysics (Mr. L Houziaux),
  - Artificial comets (Prof. Boris Rosen and Mr Harald Bredohl),
  - Solar infrared (Marcel Migeotte, and Luc Delbouille)
  - The aurora (**André Monfils** and Robert Duysinx)

IGY: The International Geophysical Year (IGY) was a set of, coordinated worldwide researches, conducted between July 1957 and December 1958, at a maximum of solar activity, for a better understanding physical properties of the Earth and the interactions between the Sun and Earth.
The COPERS (European Preparatory Comimission of Space Research) gave birth in 1962 to the European Launchers Development Organisation (ELDO), and in 1964, at the European Space Research Organisation (ESRO), both institutions merging in 1975 to form the European Space Agency (ESA) as we know it today.

Baron Marcel Nicolet, (a student of P. Swings) was a Belgian meteorologist and geophysicist who during the International Geophysical Year 1957-1958, was Secretary General of this IGY. He was **the first director of the IASB**. (1964-1965)

ESRO ELDO Key dates

1960

1 December - Intergovernmental conference at Meyrin, Switzerland, setting up a European Preparatory Commission for Space Research (**COPERS**)

1962

29 March - Belgium, France, Germany, Italy, the Netherlands, the United Kingdom and Australia (associate member) sign in London the Convention creating the European Launcher Development Organisation (**ELDO**)

14 June - Belgium, Denmark, France, Germany, Italy, the Netherlands, Spain, Sweden, Switzerland and the United Kingdom sign in Paris the Convention creating the European Space Research Organisation (**ESRO**). Approval given for ESLAR, an ESRO laboratory for advanced research to be located in Italy (later renamed ESRIN, European Space Research Institute)

1 November - Dr Alfred W. Lines (UK) nominated as Technical Director to head the European space technology centre. Under his authority, Mr A. Kesselring (CH) is named first Director of ESTEC in 1964

1963

1 January - Under Dr Sidney Shapcott (UK), later Director of Projects at ESTEC, planning of the ESTEC facility begins at the Technical University of Delft, Netherlands

Autumn - European Space Data Analysis Centre (ESDAC) established in Darmstadt, Germany (renamed and repurposed as ESOC in 1967), headed by Stig Comet (SE)

1964

29 February - ELDO Convention comes into force

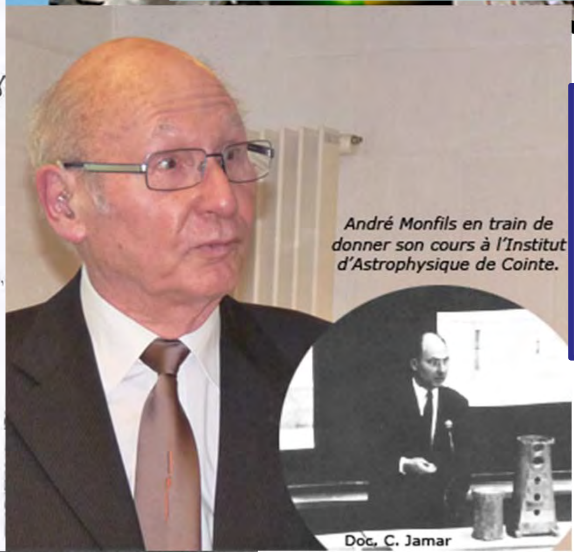
20 March - ESRO Convention enters into force

29 July - First Director of ESRIN, Hermann L. Jordan (DE) appointed

1965

1 March - Foundation pile laid for ESTEC in Noordwijk. The first major vacuum test facility is installed on 1/9

André Monfils



André Monfils visited Professor ***Herzberg*** *in Canada and spent nine months at the Observatory of Harvard University Cambridge with Professor* ***GOLDBERG*** *(1960-1971). They often visited ULg*

Goldberg's team worked diligently from 1960 to 1967 before they launched a successful satellite, the OSO IV. The next, OSO V, gave faster scans of the sun and was even more successful.
Precursors of SOHO MISSION

Professor Gerhard *Herzberg*

1971 Nobel Prize for Chemistry

Professor Leo GOLDBERG

Robert W. Kreplin

Liège starts officially in space ... in 1964

The new organization of Prof. Swings service will create a tough internal competition. The competition will crystallize around various scientific projects promoted by COPERS.

The first project for the development of a practical spatial experience is that of **artificial comets**.

Liège starts officially in space ...

Among the scientific projects proposed to COPERS, the experience of the Institute of Astrophysics of the University of Liege comes top of the list of launches for its (relative) simplicity of implementation.

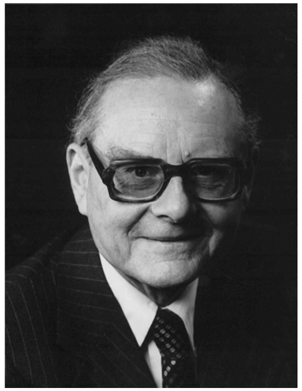
This experiment, called **R12** later ESRO, is then associated with the experience of the R33 Max Planck Garching (Professor ***Ludwig Franz Benedict Biermann)*** under the common name of **S01**.

The useful load S01 consists of two gaseous sprays delivered at over 200km altitude.

Liege load (R12) consists of **ammonia**, the German load (R33) of a **mixture of barium and strontium**.

The launch campaign must be conducted in **Sardinia** under the aegis of ESRO. This is **only the second experience of ESRO in sounding rocket launch.**

Under the direction of **Prof. Boris Rosen and Mr Harald Bredohl**, **July 6, 1964** the first rocket ejects an ammonia cloud 242km altitude The cloud is visible only a few moments. He first takes all the appearance of a small luminous sphere of orange yellow color growing rapidly. The light sphere is transformed into a yellow ring expansion, which dissipates after 21 seconds.

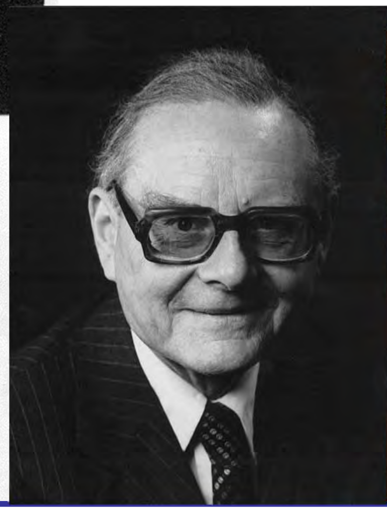


Ludwig Franz Benedict Biermann)

Historical elements

Semi-success or semi-failure?

Even if Professor Rosen judges the results encouraging , the "Comet Artificial" project is abandoned by researchers from the Institute of Astrophysics of Liege. There are other projects in the pipeline of the COPERS.



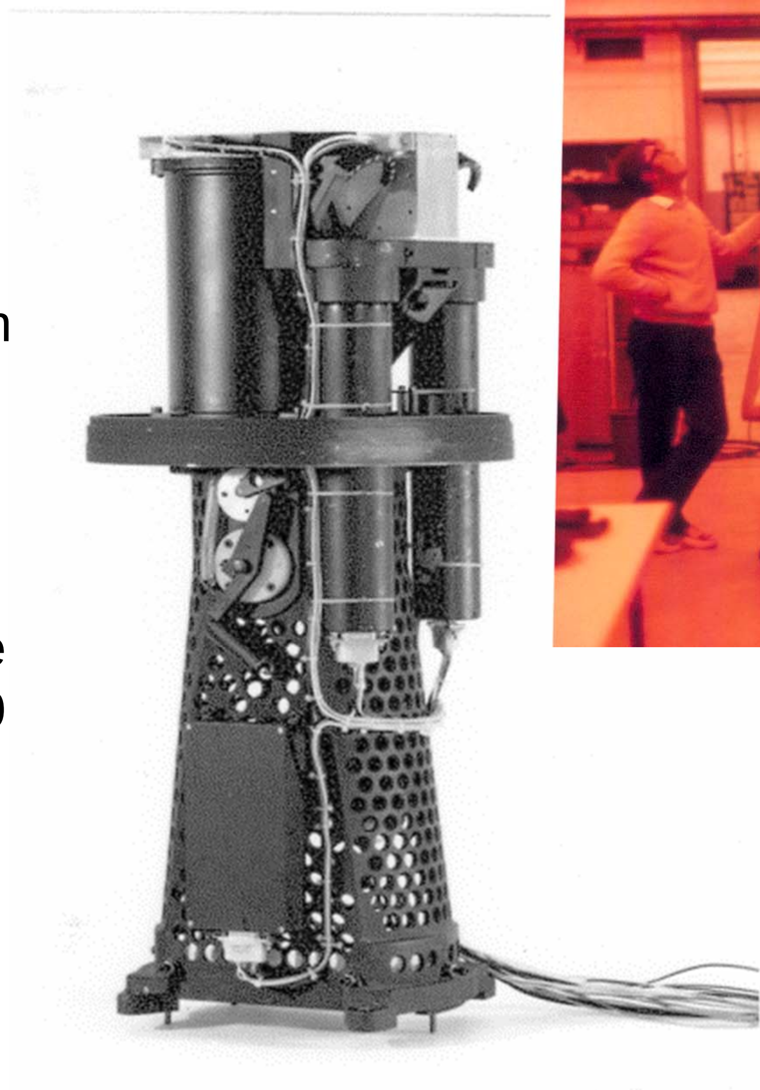
Ludwig Franz Benedict Biermann *(March 13, 1907 in Hamm – January 12, 1986 in München) was a German astronomer, obtaining his Ph.D. from Göttingen University in 1932.[1]*
He made important contributions to astrophysics and plasma physics, discovering the Biermann battery. He predicted the existence of the solar wind which in 1947 he dubbed "solar corpuscular radiation".
He was a visiting scholar at the Institute for Advanced Study in the fall of 1961.[2]
He won the Bruce Medal in 1967 and the Gold Medal of the Royal Astronomical Society in 1974.
Asteroid 73640 Biermann is named in his honor.

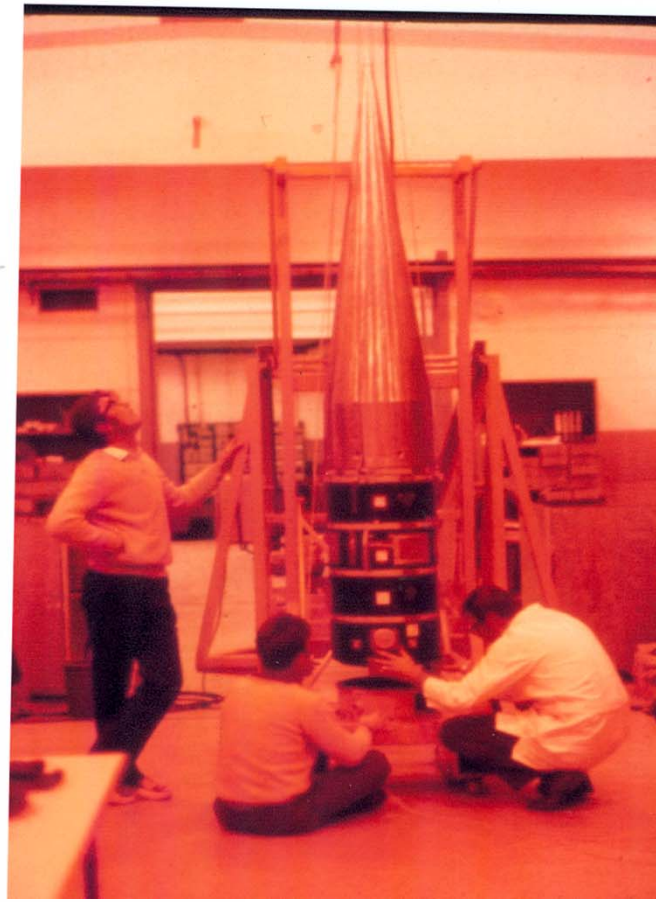
1966:First rockets firing within the "Polar Lights" group. 50 years ago

- Within the "Polar Lights“ group indeed, our first explorers dived in an exciting challenge called "**Auroral Project** ". This mission theme for the **spectroscopic study of northern lights "in situ".**

- Its experimental phase begins in **1966** in the far North, on the just operational basis of Kiruna (Sweden). A Centaur rocket ESRO carries a **Ebert-Fastie spectrograph and photometers** that must capture the emission structure of the aurora, at an altitude of about 200 km.

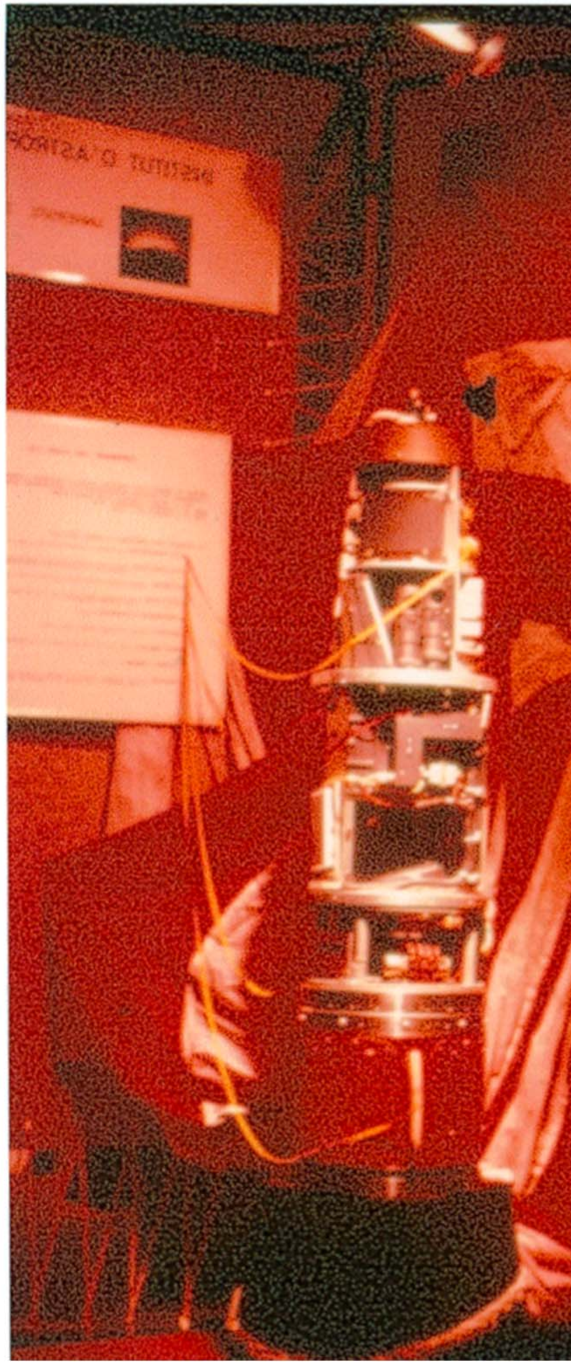
- This first shot also ended with a failure: the rocket cone of protection didn’t eject and instruments were destroyed.



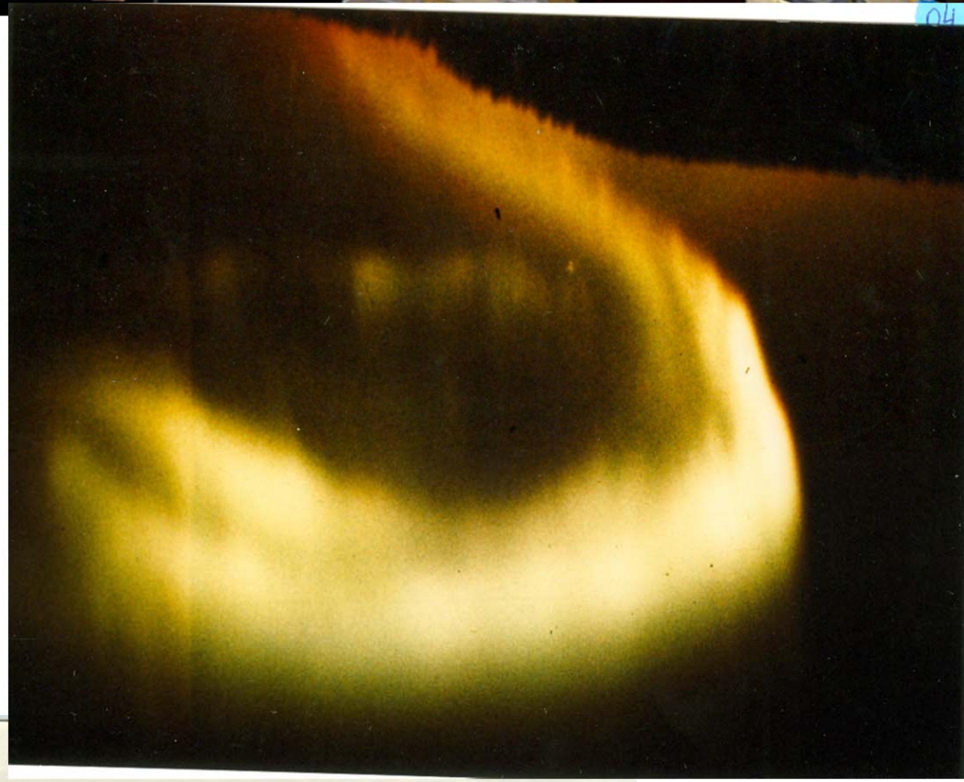


First rockets firing within the "Polar Lights" group

The incident did not discourage the team of Andre Monfils who immediately prepare a new spectrograph and returns to ESRANGE (European Space research RANGE) in **February 1967**. This time the shot goes smoothly and the instrument takes first spectrograms of the polar sky.



First rockets firing within the "Polar Lights" group



From 1966 to 1973, Monfils group participates in 14 launches of sounding rockets from Kiruna and from Fort Churchill in Canada.

Apart from the initial failure, all launches led to success and allowed the team to garner a **considerable data on the Northern Lights**.

These data are studied at the Institute of Astrophysics and shared with many institutional partners in Europe, reinforcing the scientific fame of Liege and allowing teams to the Institute to avail of a **unique experience in the preparation and management of space observation missions**.

First rockets firing within the "Polar Lights" group

Payloads back to the ground under the corolla of their parachute and the researchers did not just sink into the snows of Lapland to recover the precious images. We understand why these rockets were wearing full livery red-orange.

First rockets firing within the "Polar Lights" group

Seen from the ground

Seen from orbit later with FUVSI / IMAGE

New success for Monfils Team

Leo Houziaux

COPERS commissioned two groups formed under Professor Swings at the Institute of Astrophysics for **two separate sky mapping projects** : **an infrared (S1 Project)** and the other **ultraviolet (S2 project).**

Professor P. **Delbouille** was responsible for the first (IR) project and Professor A. **Monfils** does the second (UV). Professor L. **Houziaux** supports exploitation of results theoretically.

The Commission thus decided to combine the S2 experience to the project S68 of Professor **Butler** of the Royal Observatory of Edinburgh, which will be joined later by Professor R. **Wilson** of University College London. The subject of the study **S2 / S68 Liège-Edinburgh** ', is to **measure the intensity of the hot stars in the limited spectral bands from ultraviolet to establish the energy distribution**.

Astrophysical Institute of Cointe develops photometric portion, including the on the ground and in flight calibrations, and supports the selection of bands and data mining.

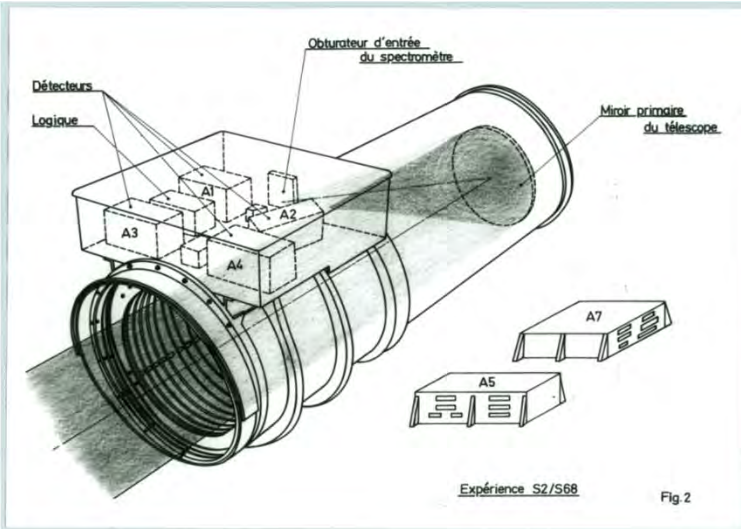
In the process, the S1 experience late compared to her rival, is associated with experience S2/S68. In September **1964**, the Scientific Committee and l'ESRO technology makes the decision to ship the three experiments on board **TD1 the first European 3 axes stabilized satellite** . This will not be enough to save the S1 experiment was abandoned in the early seventies because of lack of funding.

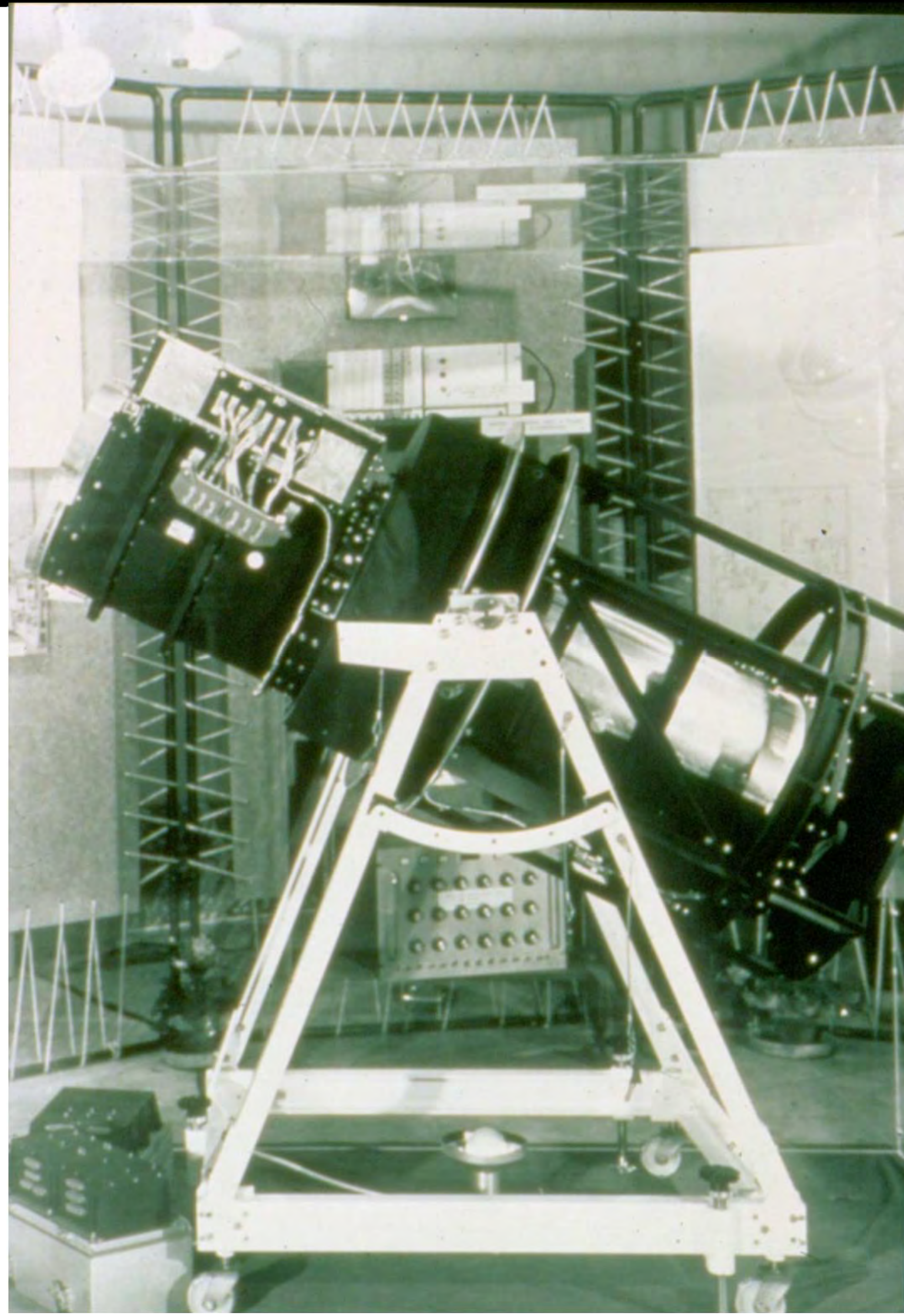
Monfils team

The Belgian-Scottish instrument consists of a parabolic mirror off-axis 275 mm in diameter. Made Cervit, it is open at f/13.5. Two slits located in the focal plane give access to a filter photometer and a plane grating spectrometer of 1200 lines/mm.

The S2/68 spectrophotometric sky survey telescope operated in the range 1350 and 2550 Å. This experiment used an off-axis reflecting telescope to focus radiation onto a set of entrance slits. These in turn fed a photometer and a three-channel spectrophotometer. The light falling on the spectrophotometer entrance slit was reflected onto a diffraction grating, and the dispersed light then passed through one of three slits and then onto individual photomultipliers. The orbital motion of the satellite caused the dispersed beam to scan across the exit slits.

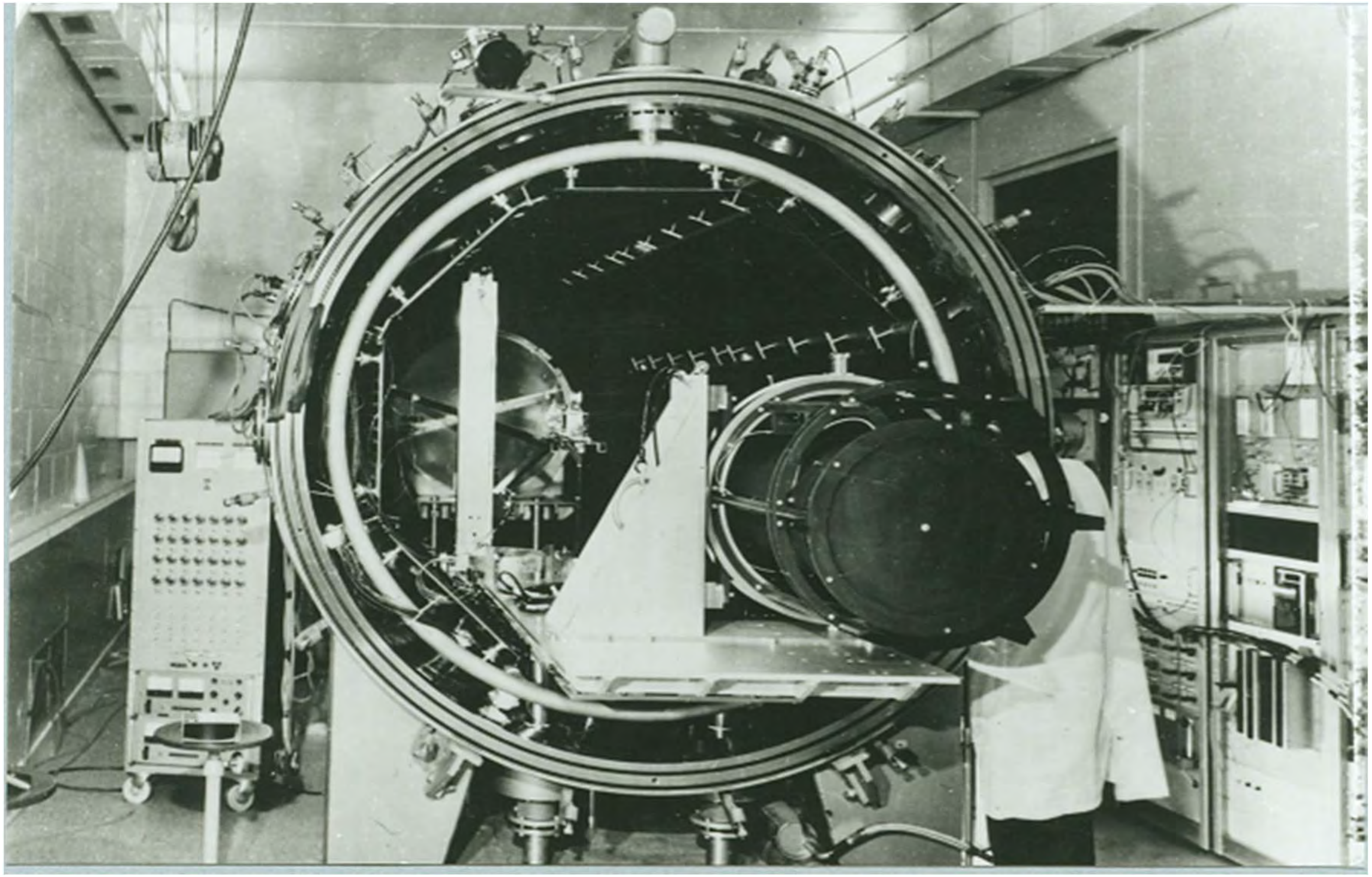
.Separate calibrations are performed by the observatory Royal Edinburgh and the Institute of Astrophysics of Liege. The detector used in Edinburgh is calibrated in an absolute reference to the Rutherford Laboratory.





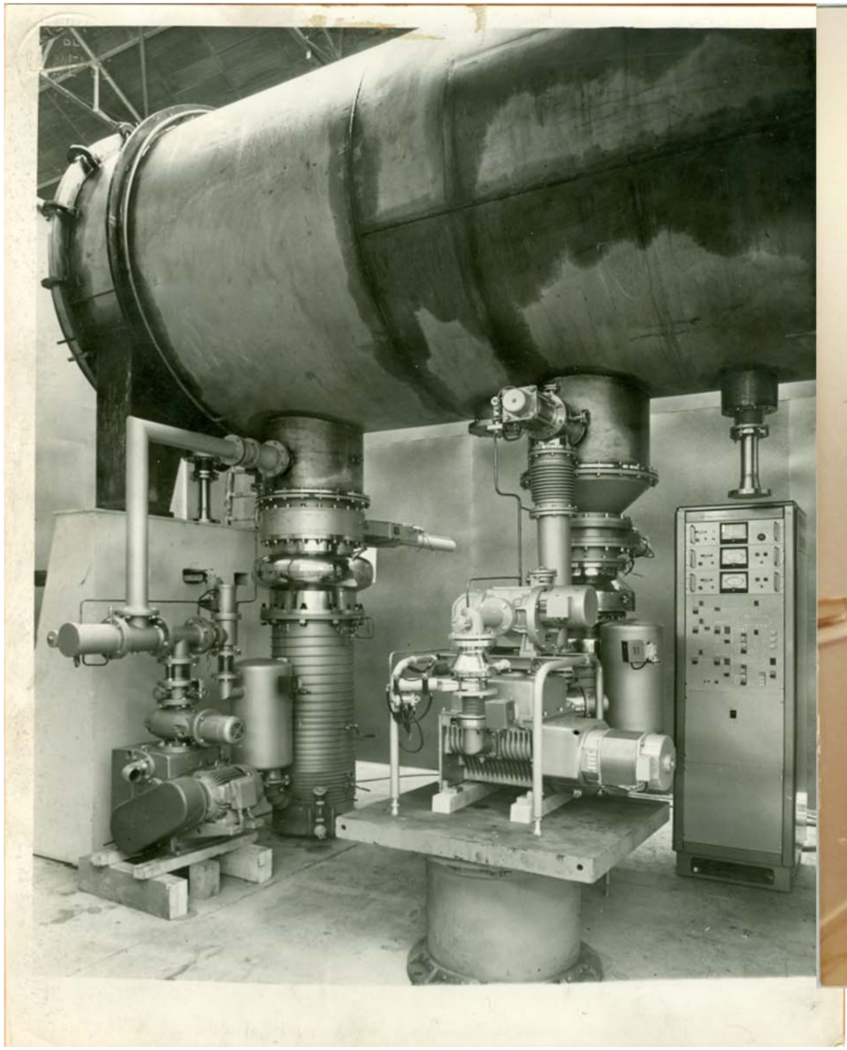
Monfils team

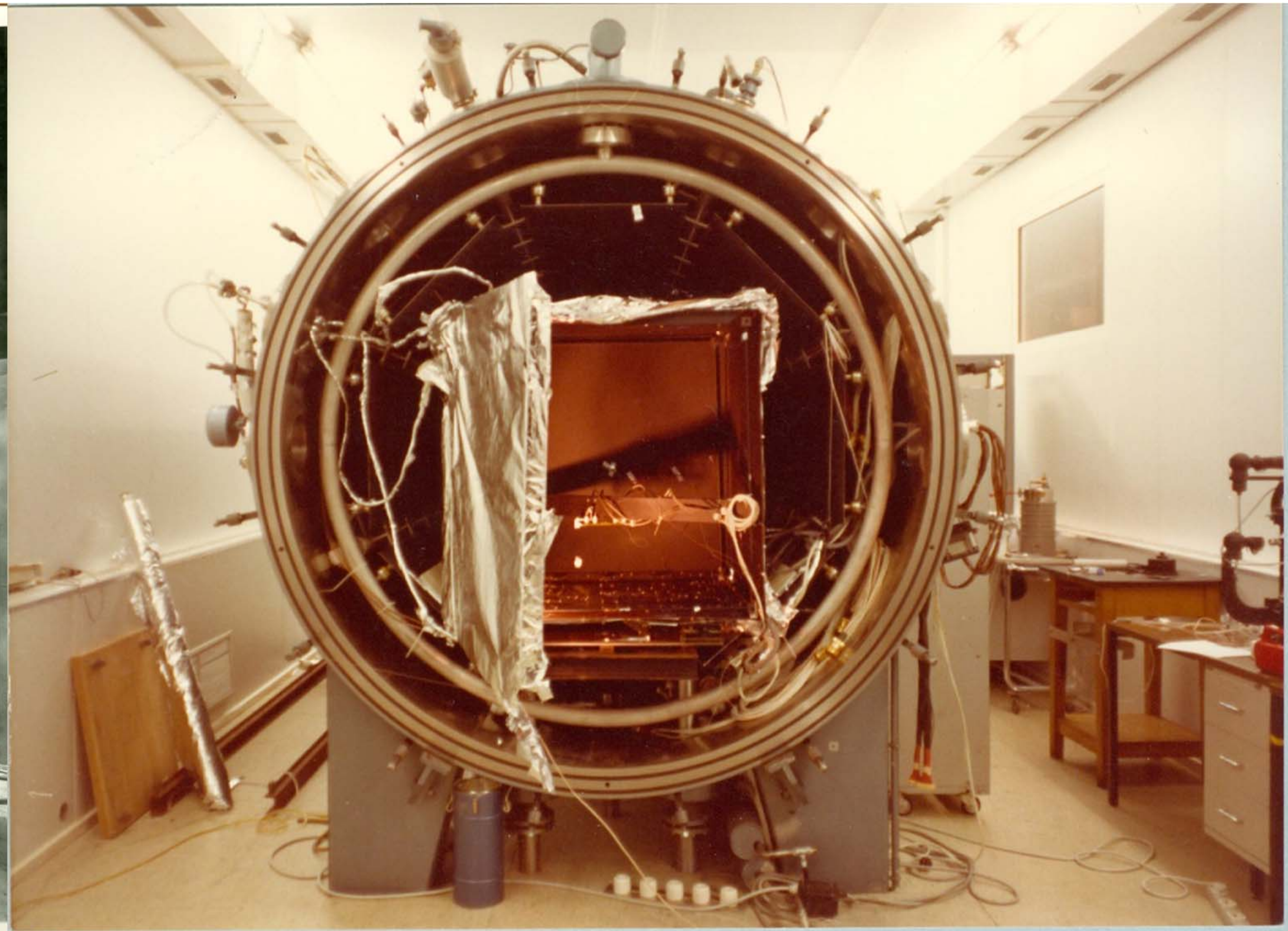
To achieve the vacuum tests necessary to check the proper functioning of the experience S2 / S68 in conditions as close as possible to the space environment, the Institute of Astrophysics has had to develop in the early seventies, a space simulator. This will be the main tool of development of the Monfils Group within the Institute. The team realized the certification and calibration testing of the S2 / S68 experience.



Monfils team

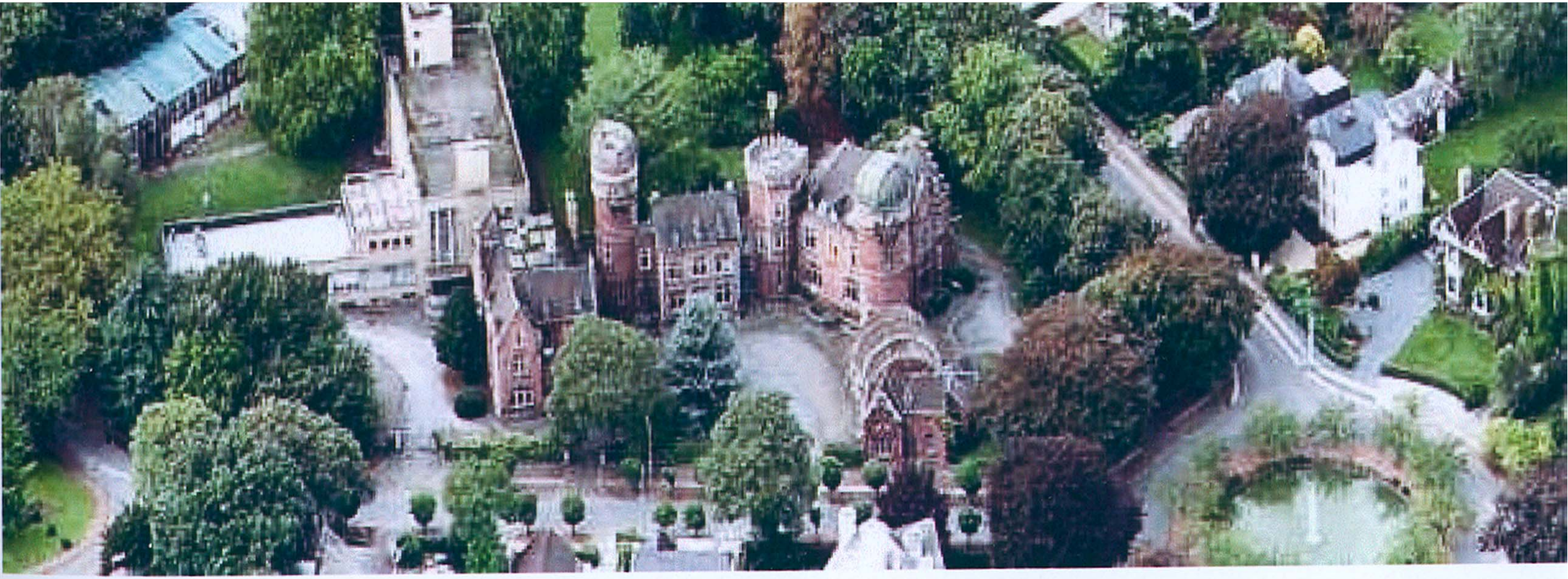
Unique in Europe, designed by the team of Andre Monfils and manufactured by the Ateliers de la Meuse, this facility has vibrations isolated optical table from the earth and the tank itself, by an ingenious system of seismic slab of concrete coupled to tight dampers.





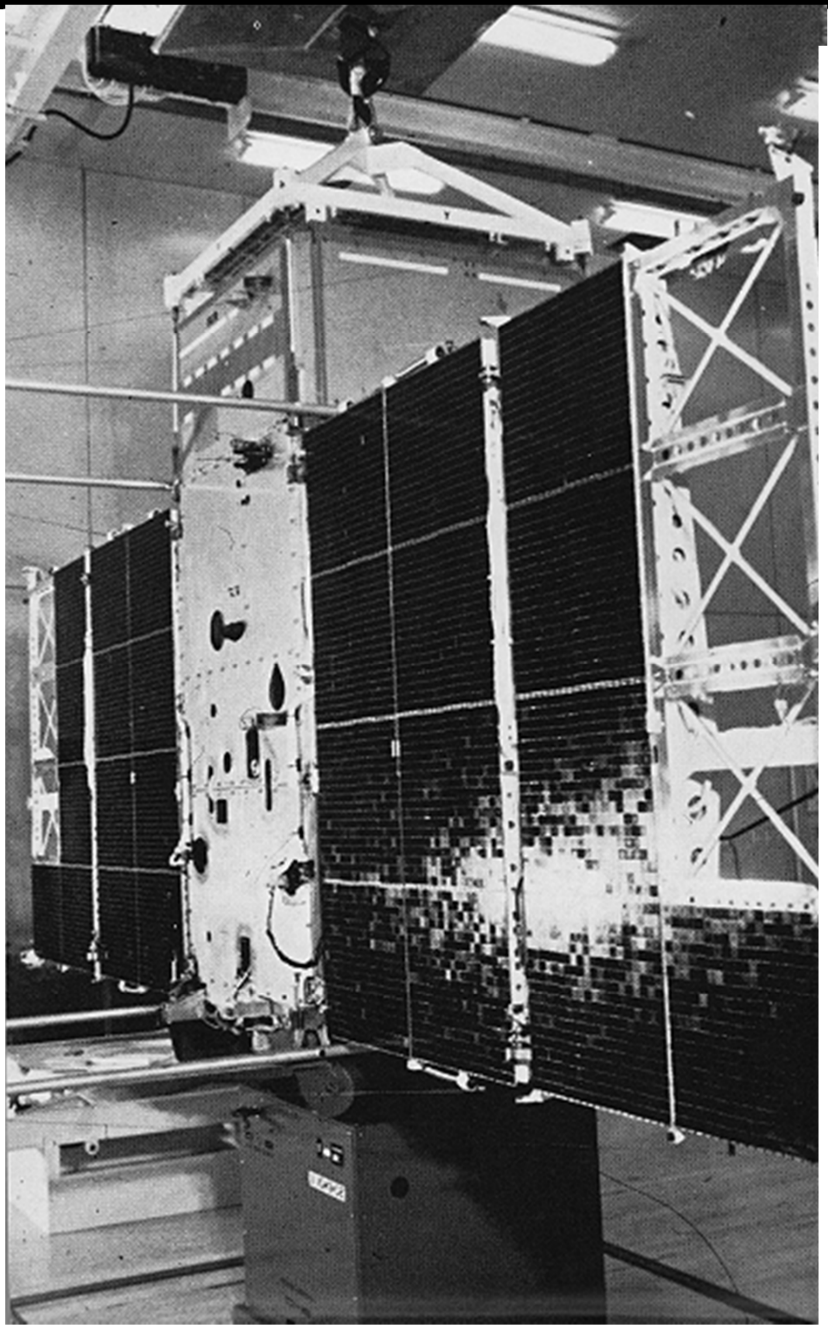
Monfils team

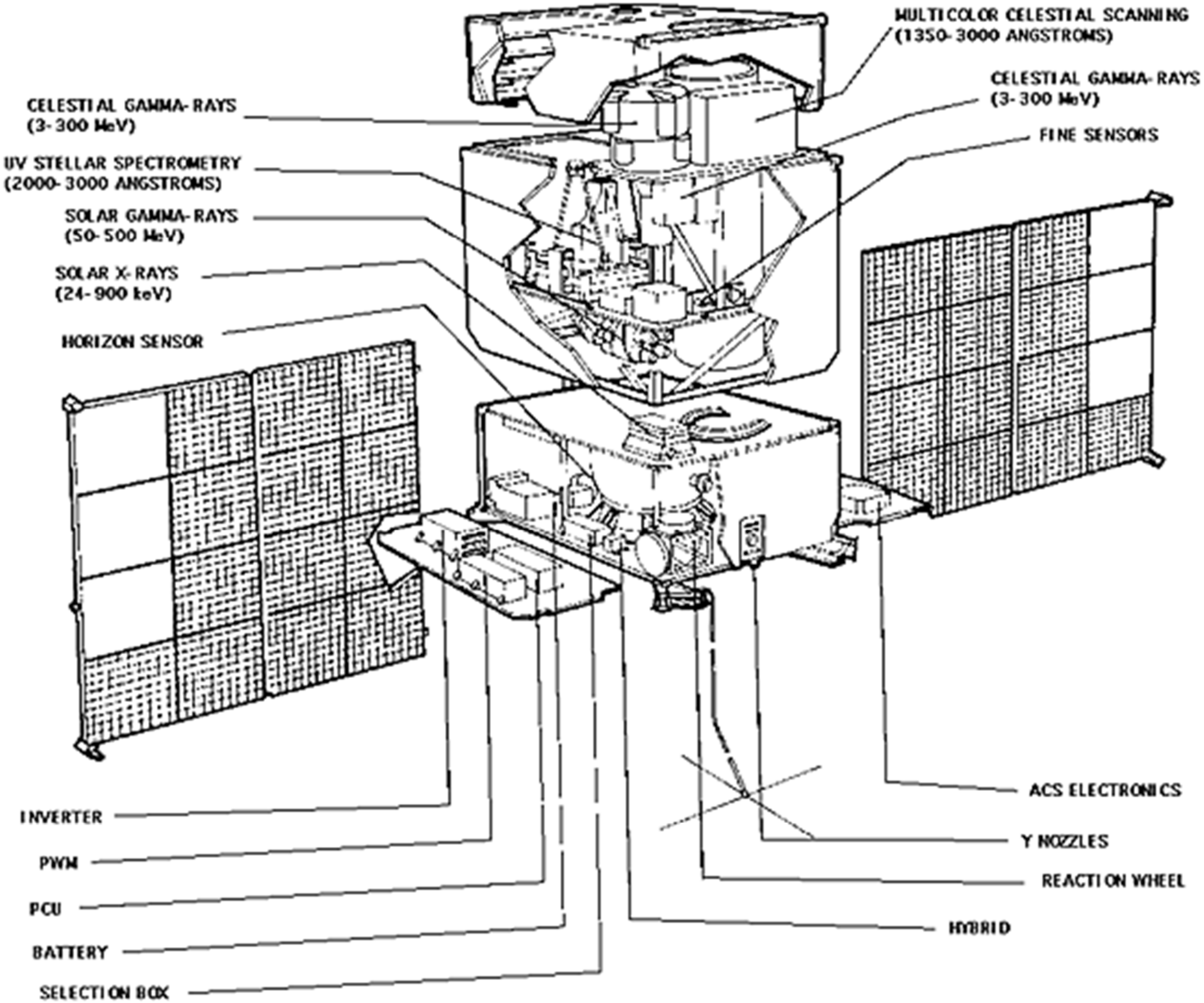
Set in an annex building of the observatory, the test equipment is quickly called FOCAL 2 for "Facility of Optical Calibration At Liege." The number 2 refers to the diameter of the tank (2 meters).



Liège Cointe L'Observatoire

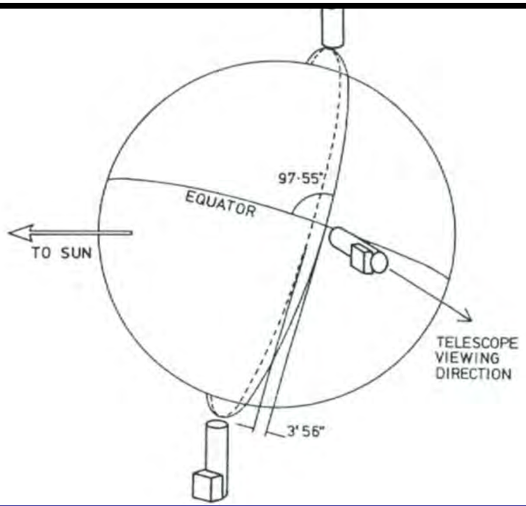
TD1

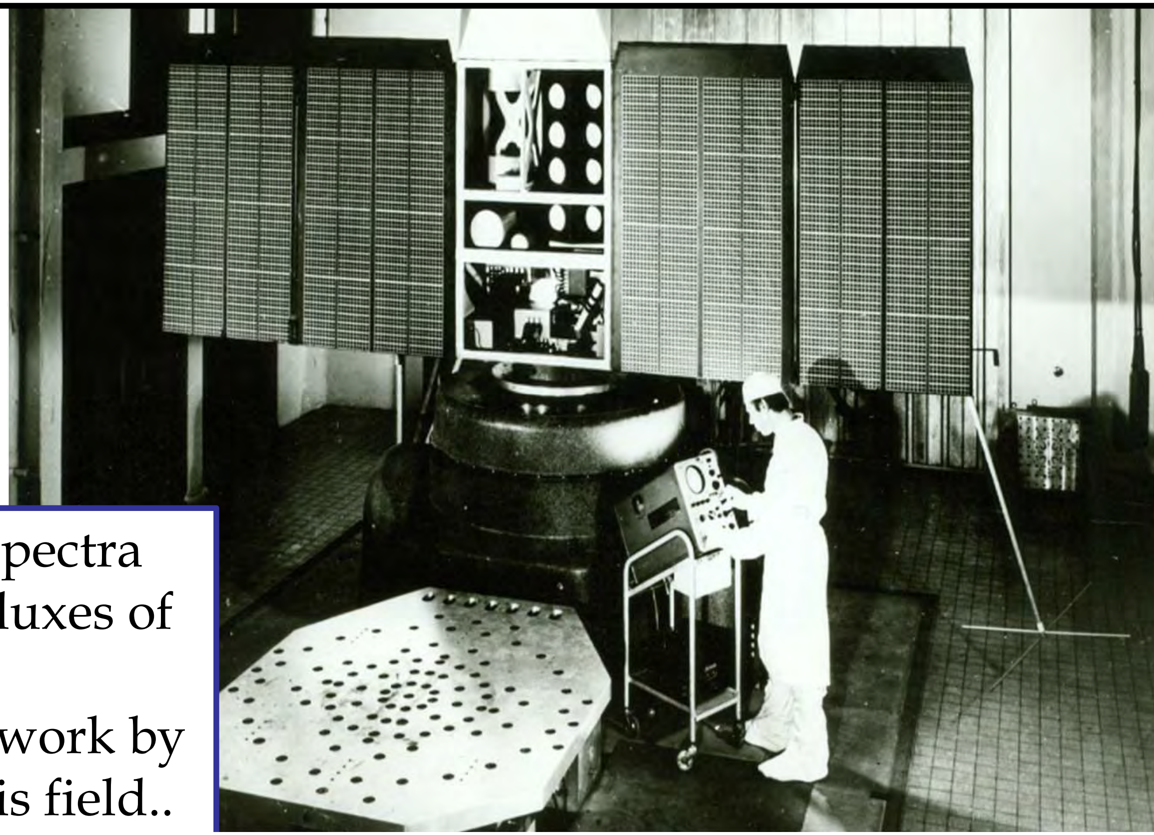



MULTICOLOR CELESTIAL SCANNING
(1350-3000 ANGSTROMS)
CELESTIAL GAMMA-RAYS
(3-300 MeV)
FINE SENSORS
CELESTIAL GAMMA-RAYS
(3-300 MeV)
UV STELLAR SPECTROMETRY
(2000-3000 ANGSTROMS)
SOLAR GAMMA-RAYS
(50-500 MeV)
SOLAR X-RAYS
(24-900 keV)
HORIZON SENSOR
INVERTER
PWM
PCU
BATTERY
SELECTION BOX
ACS ELECTRONICS
Y NOZZLES
REACTION WHEEL
HYBRID

Monfils team

TD-1A was successfully launched on 11 March 1972 from Vandenberg Air Force Base (12 March in Europe). It was put in a nearly circular polar **sun-synchronous orbit**, with apogee 545 km, perogee 533 km, and inclination 97.6 degrees. It was Europe's first 3-axis stabilized satellite, with one axis pointing to the Sun to within +/- 5 degrees. The optical axis was maintained perpendicular to the solar pointing axis and to the orbital plane. It scanned the entire celestial sphere every 6 months, with a great circle being scanned every satellite revolution. After about 2 months of operation, both of the satellite's tape recorders failed. A network of ground stations was put together so that real-time telemetry from the satellite was recorded for about 60% of the time. After 6 months in orbit, the satellite entered a period of regular eclipses as the satellite passed behind the Earth -- cutting off sunlight to the solar panels. The satellite was put into hibernation for 4 months, until the eclipse period passed, after which systems were turned back on and another 6 months of observations were made. TD-1A was primarily a UV mission however it carried both a cosmic X-ray and a gamma-ray detector.



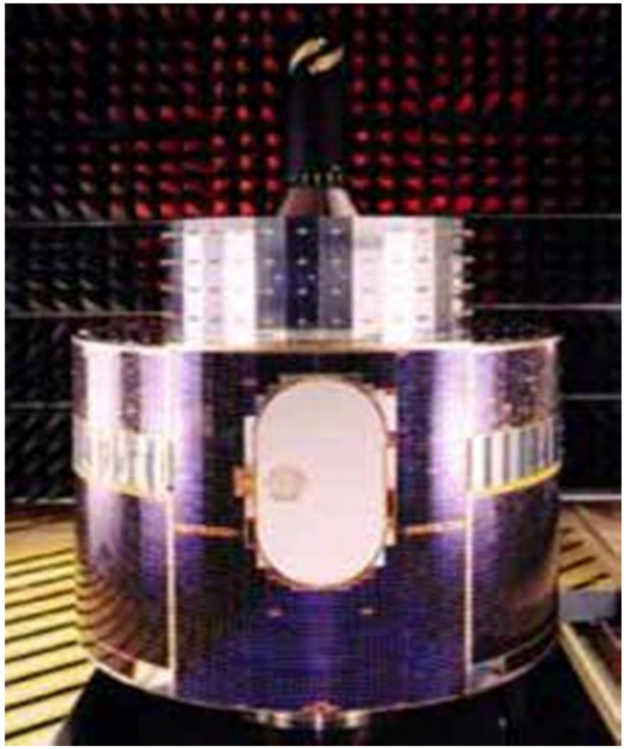


The Experiment analyzed nearly 1,800 stellar spectra in the far ultraviolet and provides ultraviolet fluxes of more than 35,000 stars.
The publications prepared on the basis of this work by Houziaux and Monfils remain references in this field..

Meteosat radiometer

The S2 / S68 tests lasted several months but even after the validation of experience, **FOCAL 2** remained not idle. At the end of the campaign, the facility was used to conduct new calibration tests on various space instruments including a **Swedish instrument to embark on a satellite Interkosmos** (USSR).

Through these campaigns, capabilities and expertise of the scientific and technical team of Professor Monfils begin to be recognized at European level and IAL Space is approached in **1974**, by the French company " Engins Matra " in charge of developing a key instrument of "**Meteosat**", sponsored by the World Meteorological Agency.



METEOSAT (1977)

The Meteosat program aims to significantly improve weather forecasts over the whole earth from a wide range of observations of the atmosphere.
Meteosat 1 & 2 are specifically assigned to the observation of European and African continents.
Meteosat 1 was placed in a geostationary orbit. It is stabilized by a rotation of 100 revolutions / min about its axis.
It had a lifetime of 5 years.

Unexpected difficulties

The Monfils group activities development is not a shared strategy within the University. Internal fighting undermines relations within the astrophysics department and leads the group to implosion.

The BAD NEWS: Eight out 11 members of the Monfils group receive, on the same day, their end of contract from the academic authorities of the University.
On expiry of this notice, the team will be reduced by three-quarters of its workforce in the midst of ongoing programs.

The GOOD NEWS: It will lead in **1976 to the signing of a memorandum giving to the Monfils Group**, the status **ESA coordinated test facility**.
This battle has left traces in the Department of Astronomy and Astrophysics which the team still belongs. It leads the Group Monfils to take distance with the Institute and differentiate from them to maintain its "more technical or industrial“orientation.

In 1978, for the first time, in correspondence of the service, appears the symbol "**IAL Space**" which embodies this evolution

The METEOSAT RADIOMETER and IAL Space

- The radiometer, is the heart and brain of the satellite must be calibrated under vacuum.
- The technological challenges are extraordinary. The operating conditions of the radiometer in geostationary orbit impose to cool the infrared detectors to - 190 ° C in a particularly demanding thermal environment.
- We must equip a cold space simulator, that is to say a screen cooled to temperatures close to absolute zero. This is only possible by **using liquid helium (4 K)** and this application will mark **the beginning of an important collaboration between the Monfils Group with the Laboratory of Low Temperatures led by Professor Roger Blanpain at the University of Liège.**

Cryogenics

Meteosat radiometer at IAL Space

Thus, no less than 6 radiometer models are tested and calibrated jointly by teams of **IAL Space** and Engins Matra in FOCAL 2 **between 1975 and 1979, at COINTE**.

The tests are taking place in excellent conditions.

The quality of images sent by Meteosat exceed, in fact, the most optimistic forecasts.

Being involved in MFG (Meteosat First Generation) from this period, CSL in the future will be involved in MSG and MTG (UVN calibration and flight hardware)

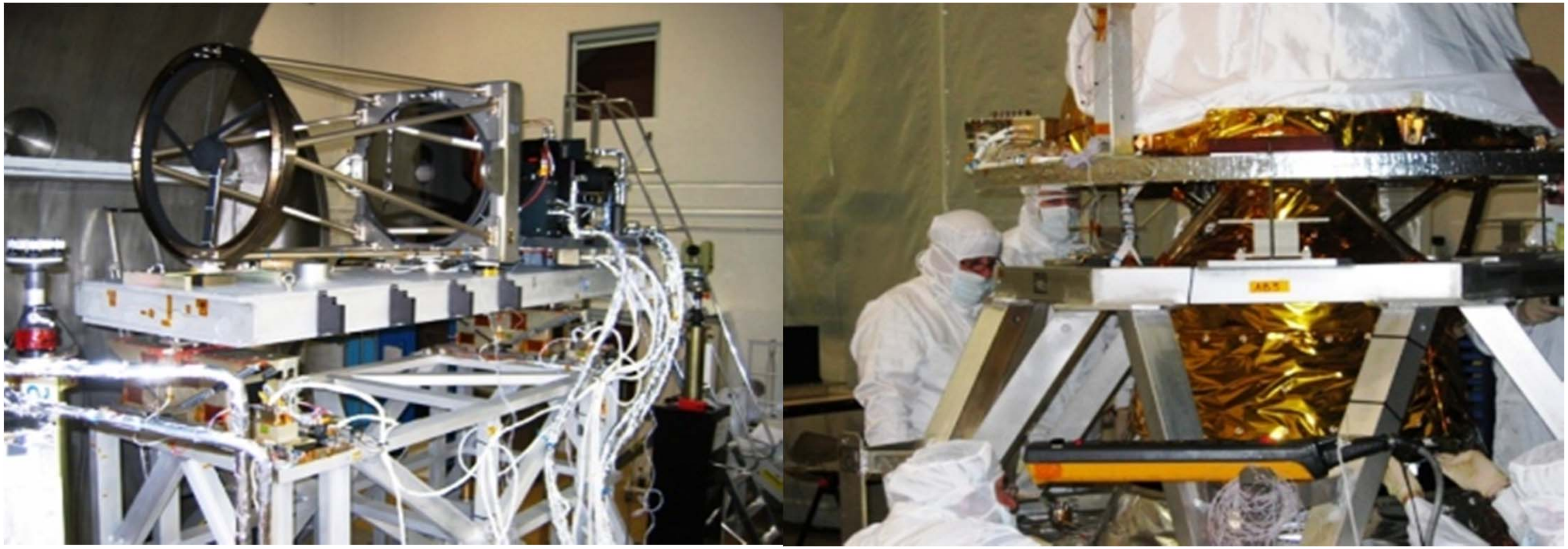
CSL in the future will be involved in ENVISAT (Meris, GOMOS, ASAR) and SENTINEL 1,2,3,4 and 5 .

CSL is involved in Earth observation and its atmosphere since the beginning of the century … on the testing side (later for harware)

METEOSAT

Since the first METEOSAT in the late sixties, CSL has performed tests of various METEOSAT instruments.

SEVIRI (MSG) on test at CSL 1994



CSL is deeply involved in the optical calibration of METEOSAT by testing different parts of the payload (called SEVIRI for Spinning Exhanced Visible and InfraRed Imager) :
Focal plane elements, Focal plane passive cooler and whole instrument.

Meteosat Third Generation (MTG)

Meteosat Third Generation (MTG) will see the launch of six new satellites from 2020. The MTG programme should guarantee access to space-acquired meteorological data until at least the late 2030s.

Third Generation — Bigger and Better

Twin Satellite Concept, based on 3-axis platforms.

Four Imaging Satellites (MTG-I) (20 years of operational services expected)

Two Sounding Satellites (MTG-S) (15.5 years of operational services expected)

Payload complement of the MTG-I satellites:

- The Flexible Combined Imager (FCI)
- The Lightning Imager (LI)
- The Data Collection System (DCS) and Search and Rescue (GEOSAR)

Payload complement of the MTG-S satellites:

- The Infrared Sounder (IRS)
- **The Ultra-violet, Visible and Near-infrared Sounder (UVN)**

The sounder will be one of the key innovations in the new programme, for the first time allowing Meteosat satellites to image weather systems and analyse the atmosphere layer-by-layer, therefore, performing far more detailed chemical composition studies.

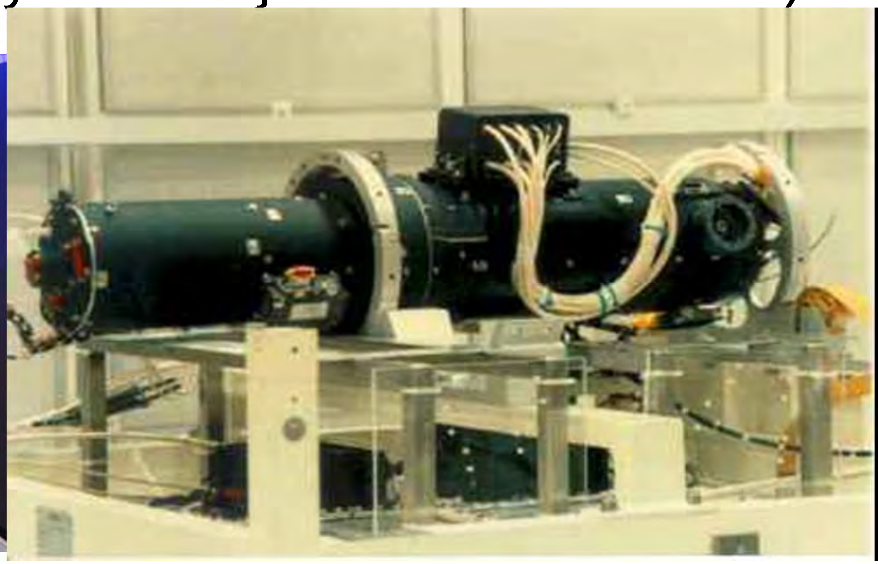
FOC HST

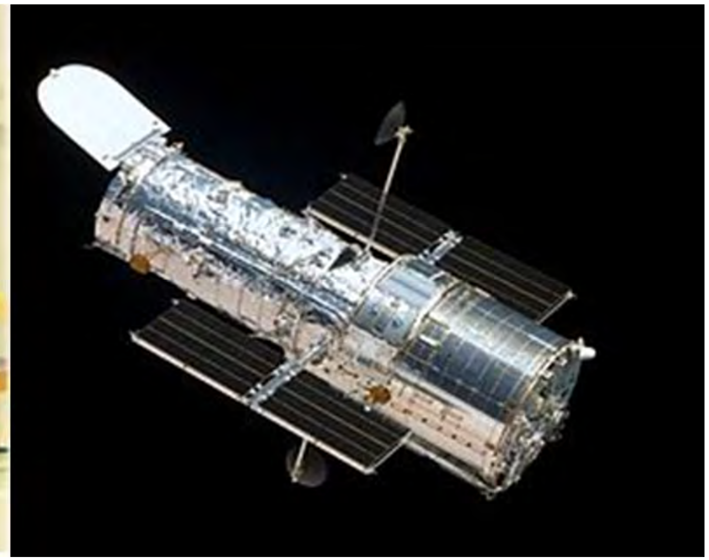
With the visibility provided by the Meteosat program, IAL Space sign new contracts with British Aerospace and Matra.

The team is selected to participate in the certification of the **Faint Object Camera** (FOC), one of the first instruments of the mission "**Hubble Space Telescope**“.

FOC is a very high resolution camera for the study of extremely distant and faint objects.

IAL Space is responsible for certifying and calibrating its sensors (**Photon Detector Assembly - PDA**) as well as to participate in a consortium conducting thermal testing of the complete instrument at ESTEC (Test Centre of the European Space Agency Noordwijk in the Netherlands).





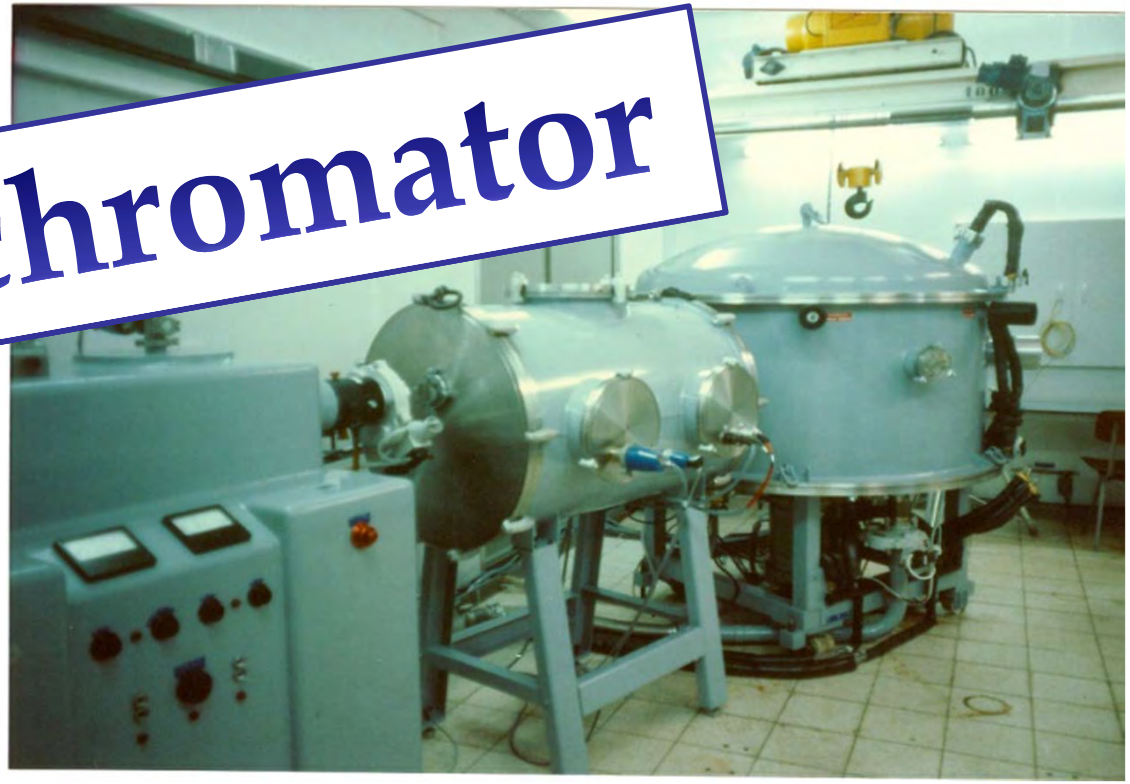
Focal 1.5

This project offers a unique opportunity to IAL Space to develop its test facilities.

In order to calibrate the "PDA“, FOCAL 2 is not suitable because it is not equipped to perform measurements in the **far ultraviolet (120nm - 650nm)**.

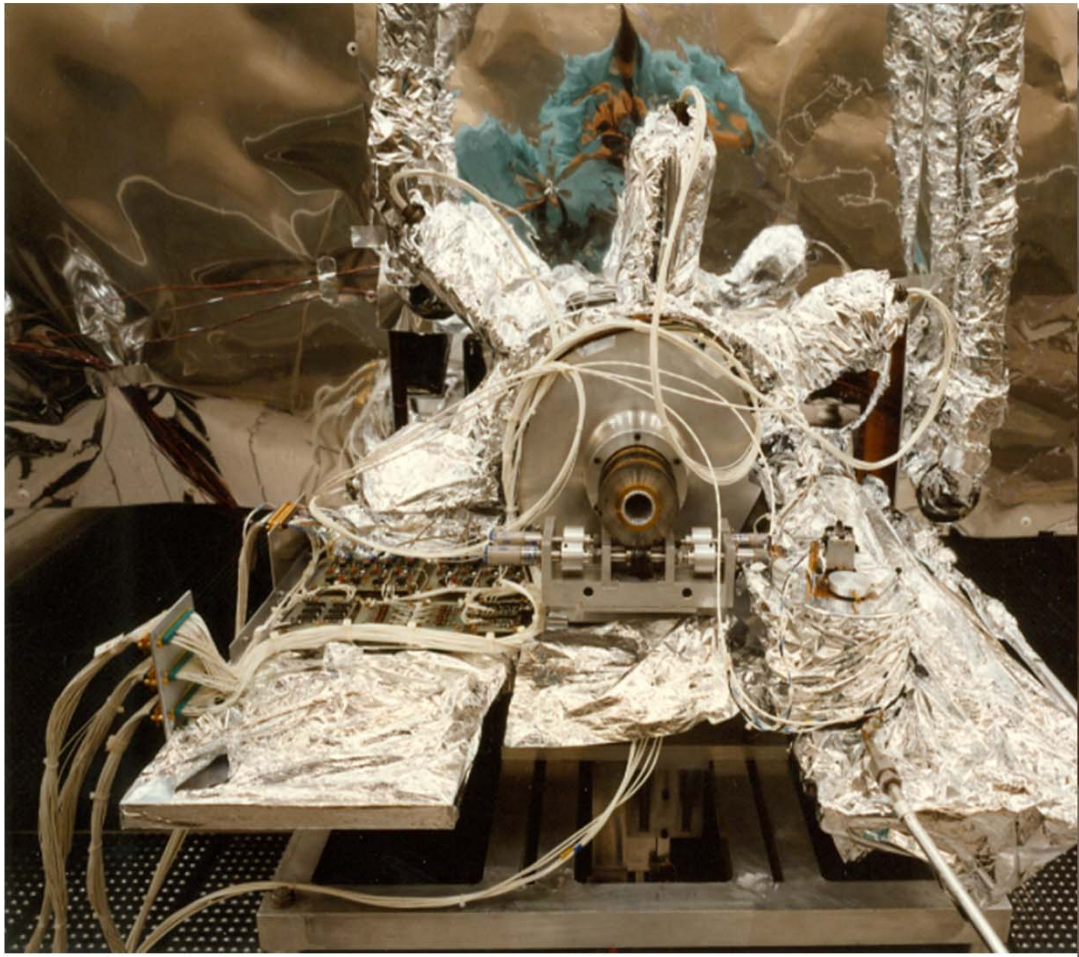
IAL Space then order a new vertical axis vacuum chamber of 1.5m in diameter and 0.7m in
with a r
This tan ... least 10^{-5} mB of intern... pressure and reproduce controlled thermal environments between + 120 °C and -190 °C. Commissioned in 1978, it was named "Focal 1.5" by analogy with its bigger sister “FOCAL 2”.

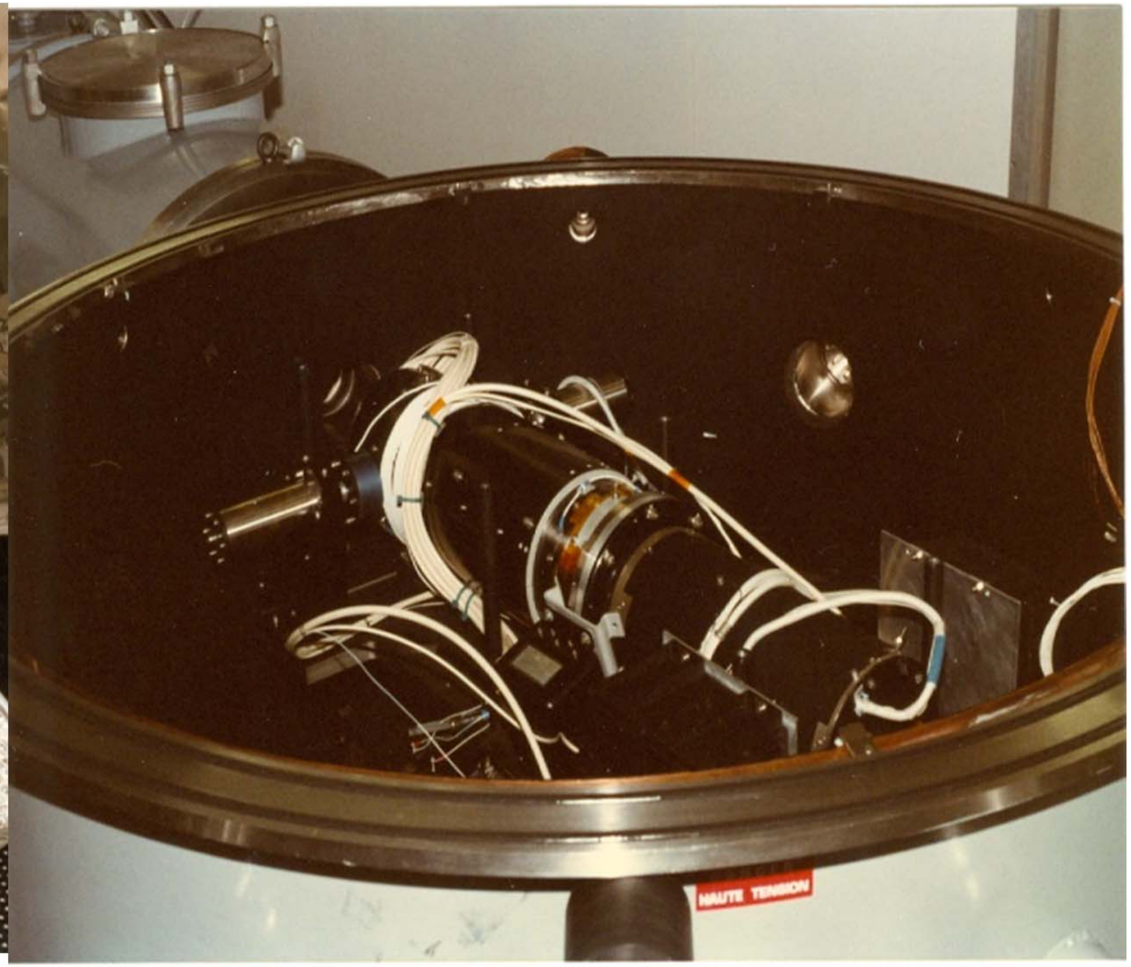
FUV monochromator



Used later in 1995 by FUVSI / IMAGE and 2015 by FUVSI / ICON and …

FOC – PDA under calibration

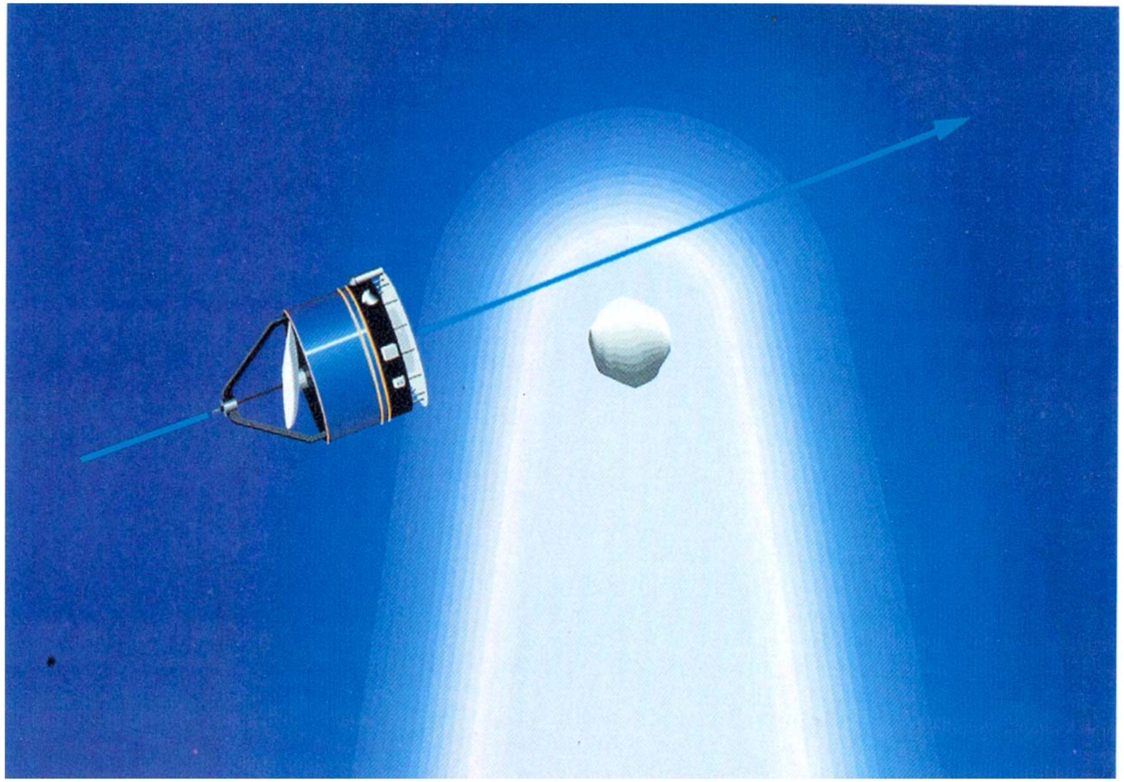


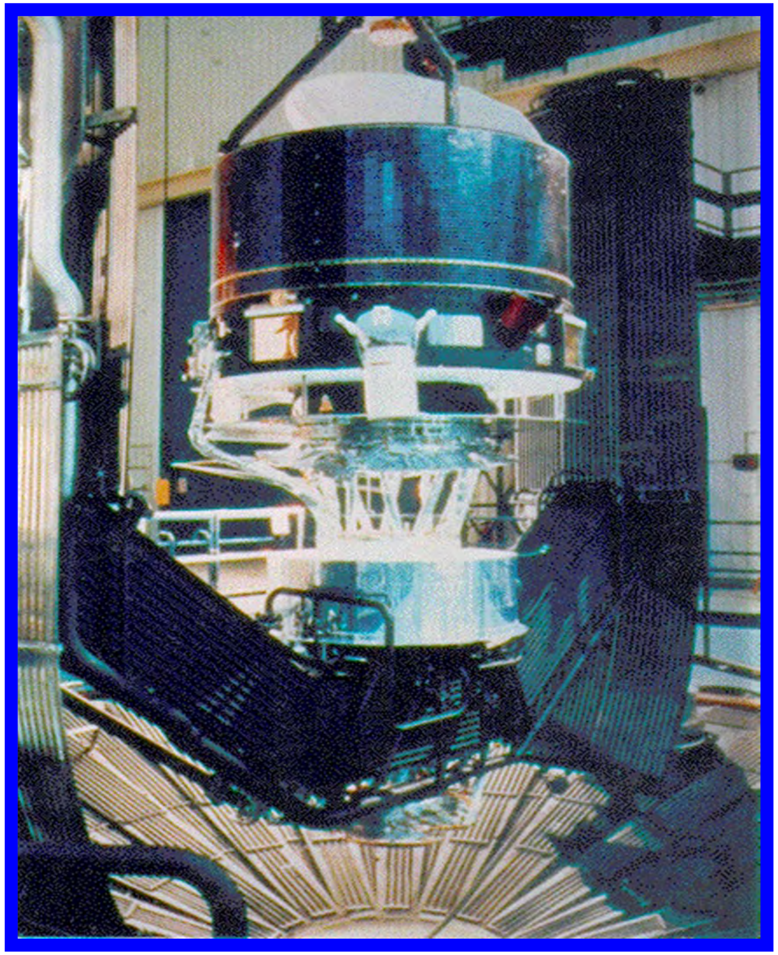


IAL Space, a leading location in Europe for certification and calibration of instruments combining optics and electronics in space

With these investments, IAL Space gets a new recognition of the European Space Agency being distinguished as **a leading location in Europe for certification and calibration of instruments combining optics and electronics in space environment**.

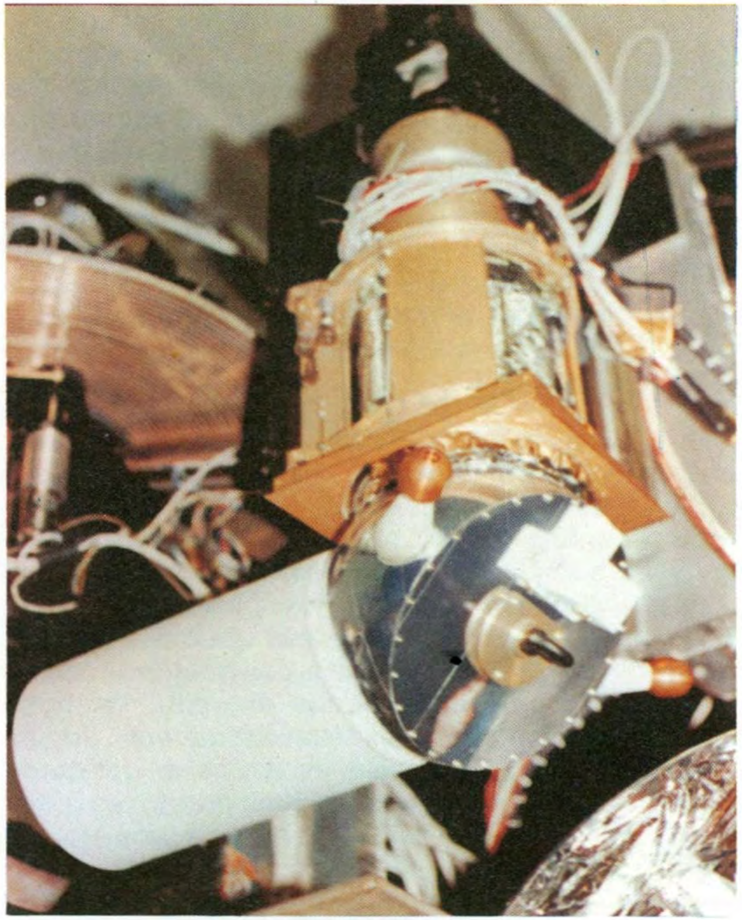
This recognition will have an immediate effect. IAL Space is integrated in a consortium of European research institutes who proposed an instrument to the space probe "**Giotto**".

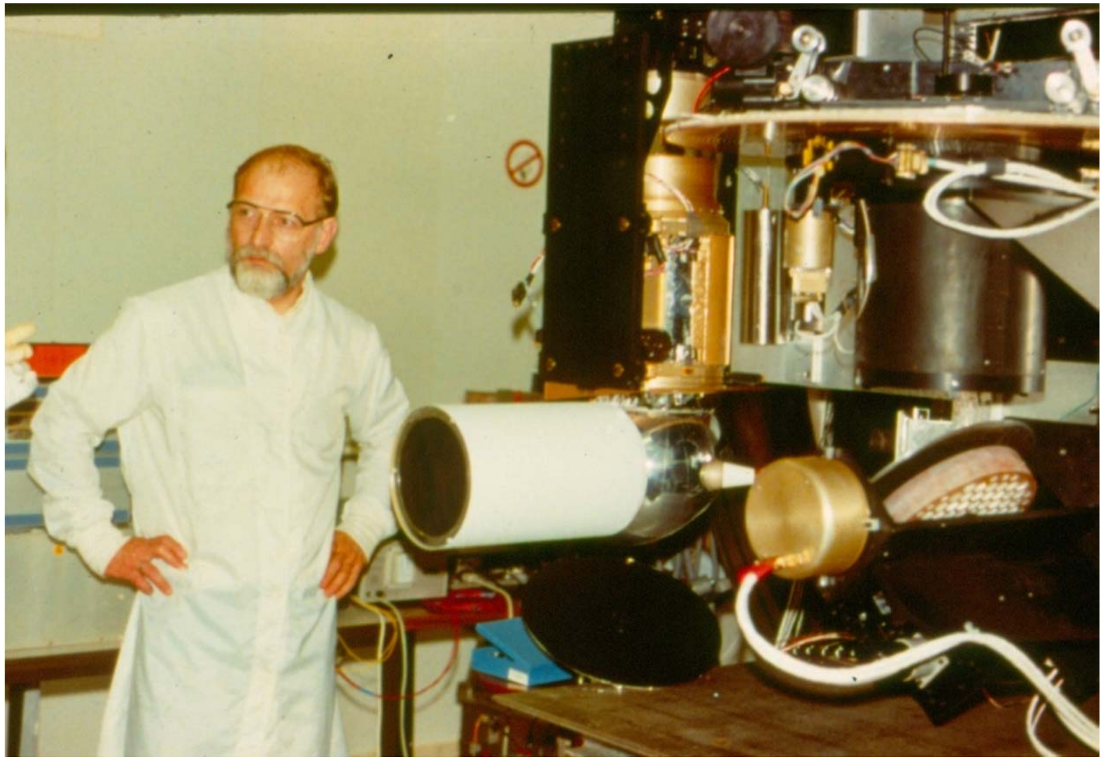




HMC - GIOTTO

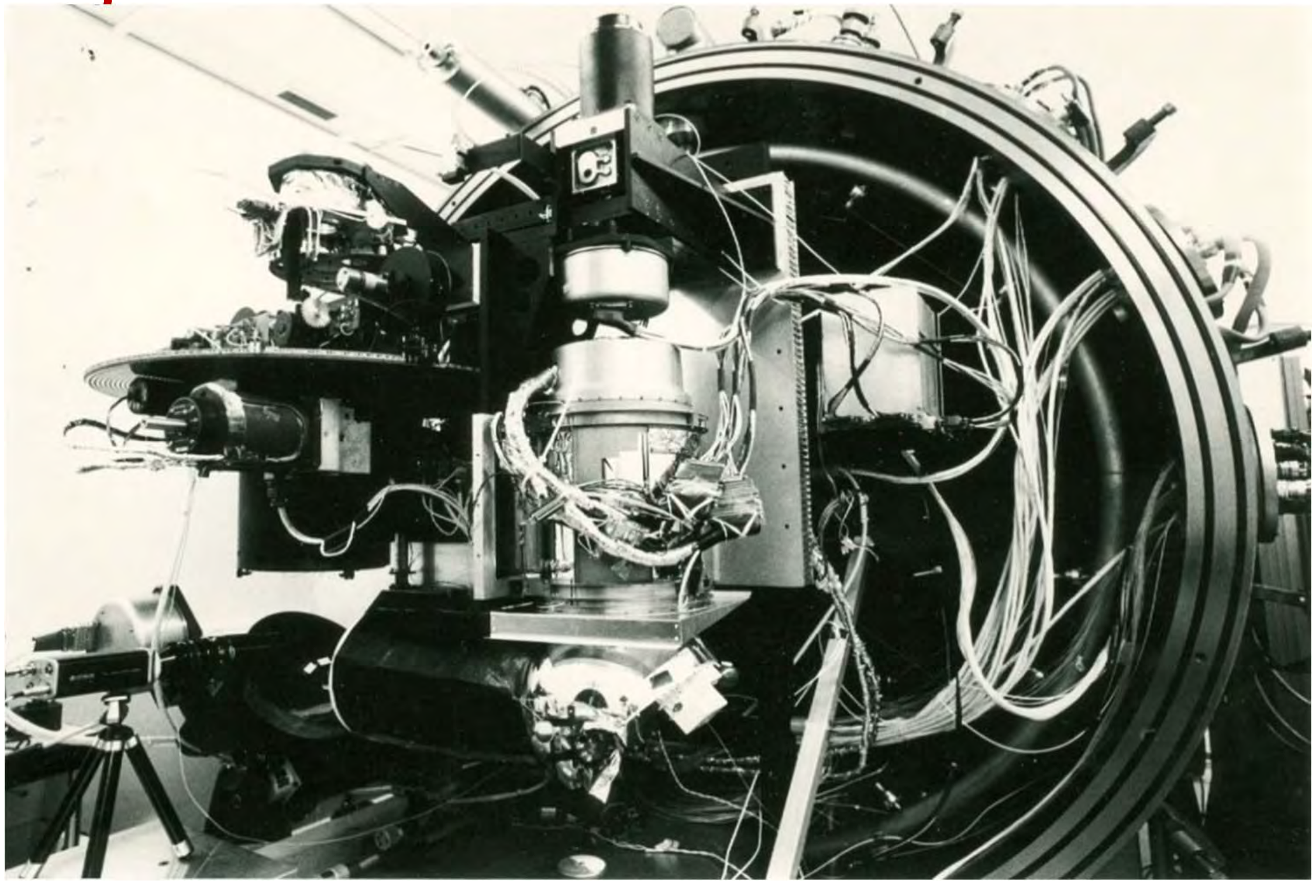
Giotto is an extraordinary ESA mission. Its ambition a little crazy to go to the Halley's Comet which is coming back in the vicinity of the earth after 76 years of loop in the solar system. To achieve these objectives, the probe carried a payload consisting of not less than 10 scientific experiments designed and conducted by various European and American scientific institutions. Among these groups, mass spectrometers, various plasma analyzers, a maqnetometer and a HALLEY Multicolour Camera (HMC)





HMC – GIOTTO under tests at CSL

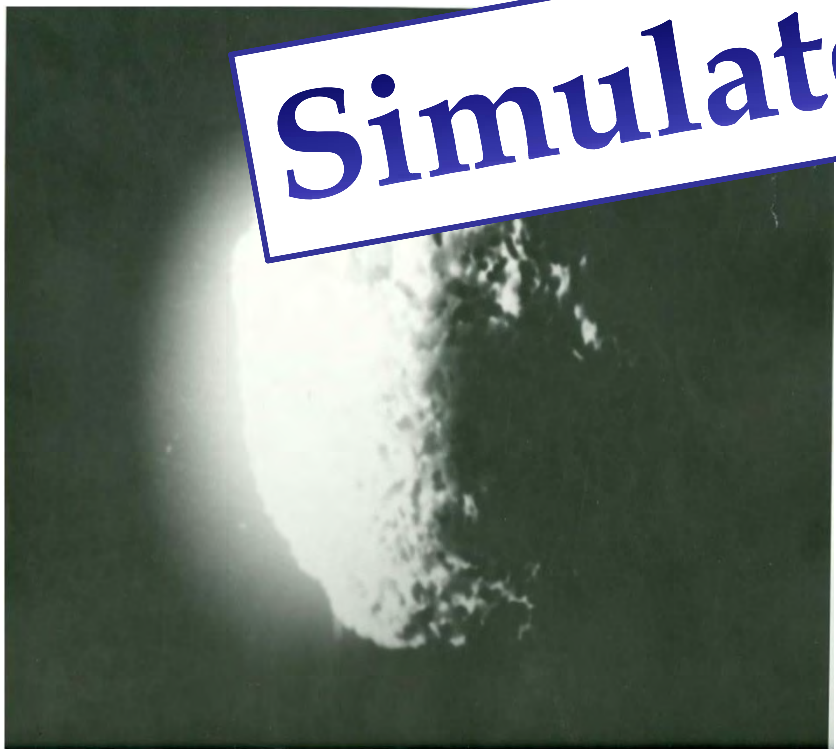
The instrument was remarkable but still not easy to certify. This task was devoted to IAL Space. Given the severe constraints of the encounter, it was necessary to design and implement an optomechanical system with 7 degrees of freedom, computer driven, allowing **not only to perform an optical diagnostic and calibration of experience, but also define the dynamic capabilities of the shooting in the acquisition and pursuit of the comet.**

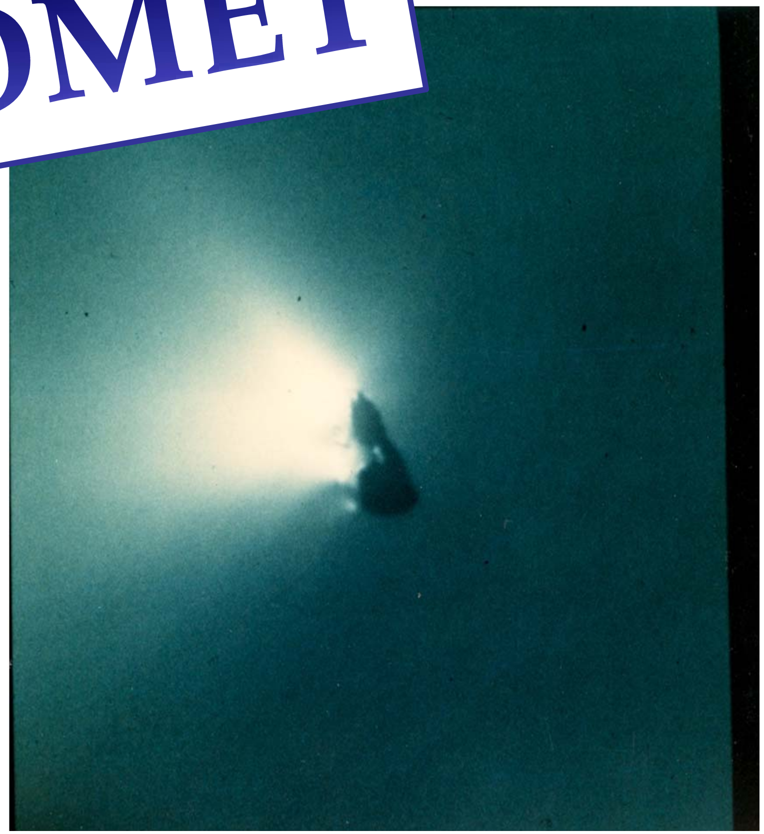


How to simulate a encounter

The evolution of the parameters of the approach is not easy to replicate; indeed, the probe moves at 64 km /s or 230,000 km/h relative to the comet ... It is therefore to be quick! Then, the probe turns on itself quickly to ensure better stability. Therefore how to acquire a target and keep it in the camera's field if it turns on itself once every 4 seconds? Finally how to simulate a encounter if one ignores what the target looks like?

Simulate a COMET





GIOTTO

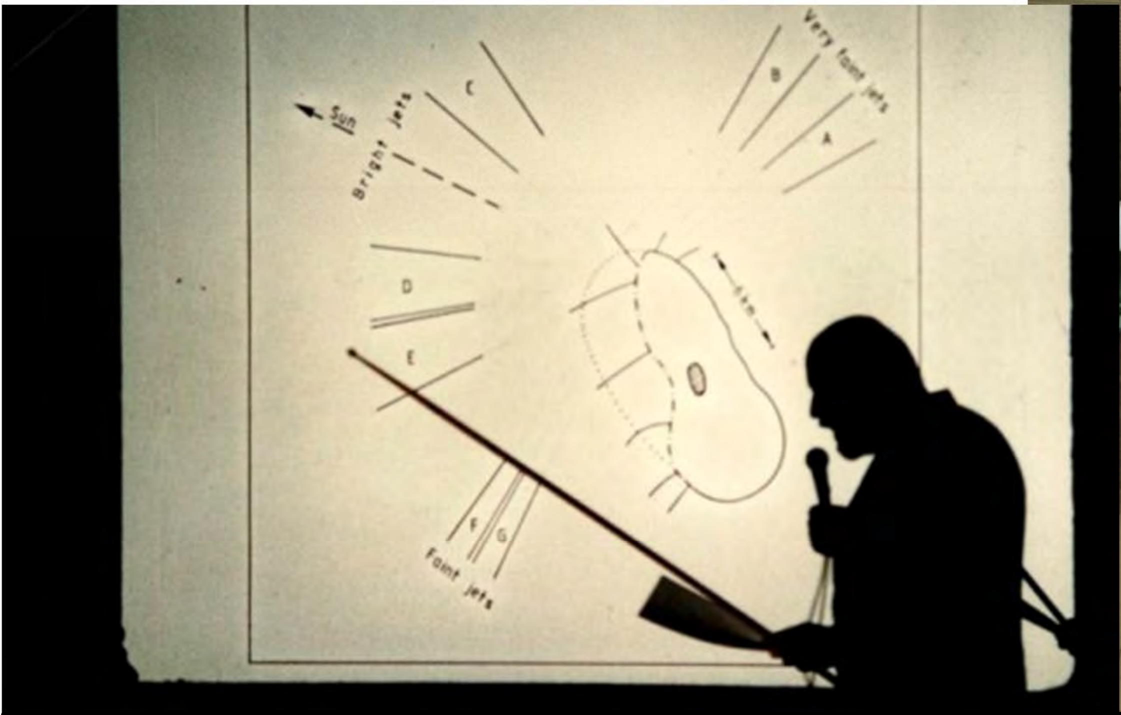
GIOTTO, launched in 1985, passed a few hundred kilometres away from the well-known comet of HALLEY in 1986. CSL has taken part, in an international collaboration, to the development of the HALLEY Multicolour Camera and has made its delicate qualification and

GIOTTO satellite assembling

First image of the nucleus of the Halley's comet

First images of HMC

HMC PI U Keller



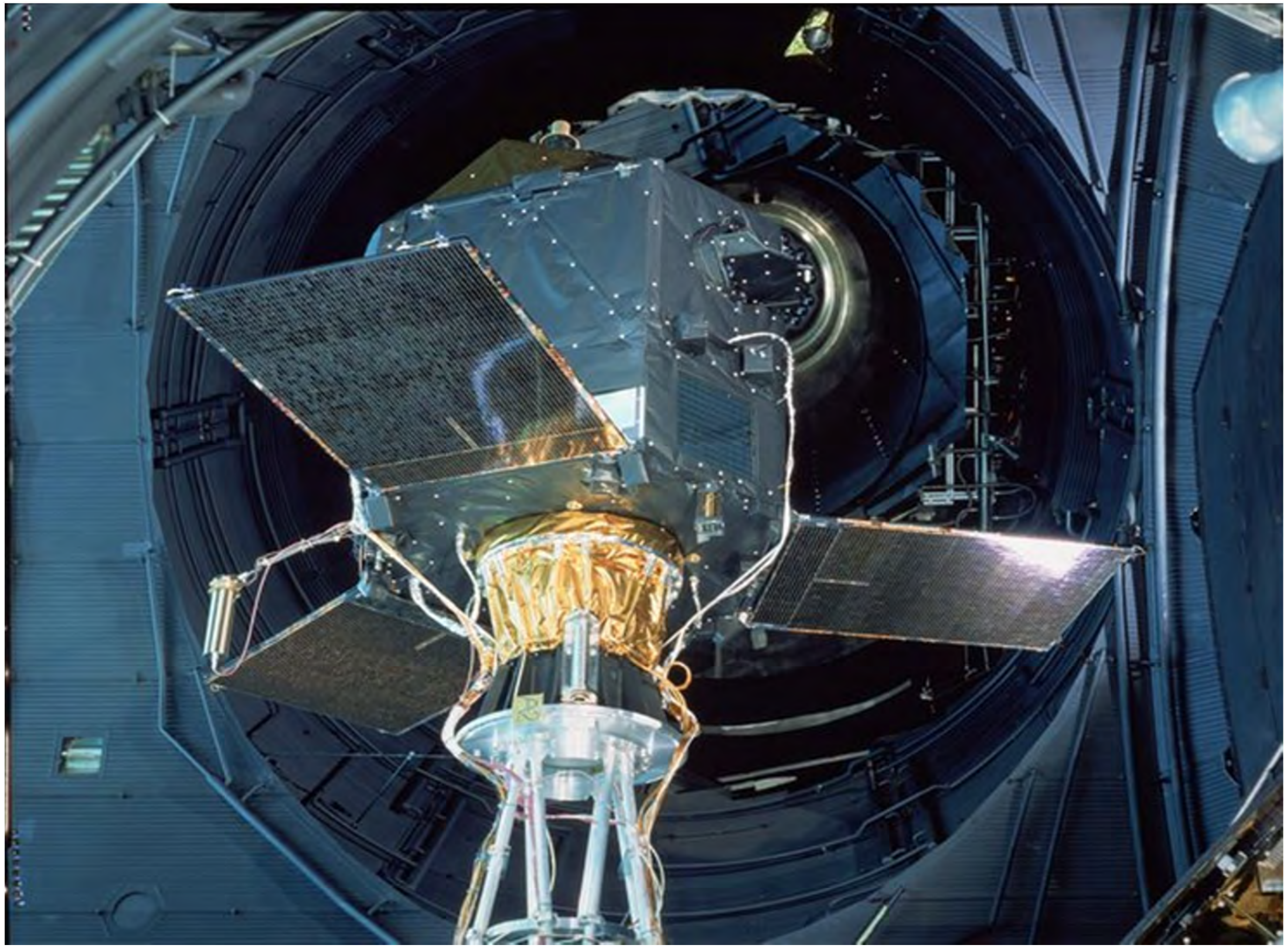
Dr Uwe Keller, Principal Investigator for Giotto's Halley Multicolour Camera, describes a projection of findings from the comet encounter, at ESOC in March 1986.

Visit at CSL of Uwe Keller, 2016, 30 years later, for a future planetary mission

Reconnaissance de l'ESA

haley.mp4

While IAL Space engineers and technicians simulates Halley's comet, the European Space Agency is launching new science projects. Among these is an ambitious survey project of stars in our galaxy. This project, initiated in 1980, named after the Greek astronomer who compiled one of the first star catalogs **"Hipparcos" (for HIgh Precision Parallax Collecting Satellite).**



Hipparcos at Sart-Tilman

The realization of the satellite and its equipment is attributed to Aeritalia and Engins Matra. Almost naturally, Engins Matra turns to IAL Space to achieve the vacuum testing of the double field of view telescope, the satellite payload. Teams of IAL Space are enthusiastic but soon realize that there is a huge difficulty.

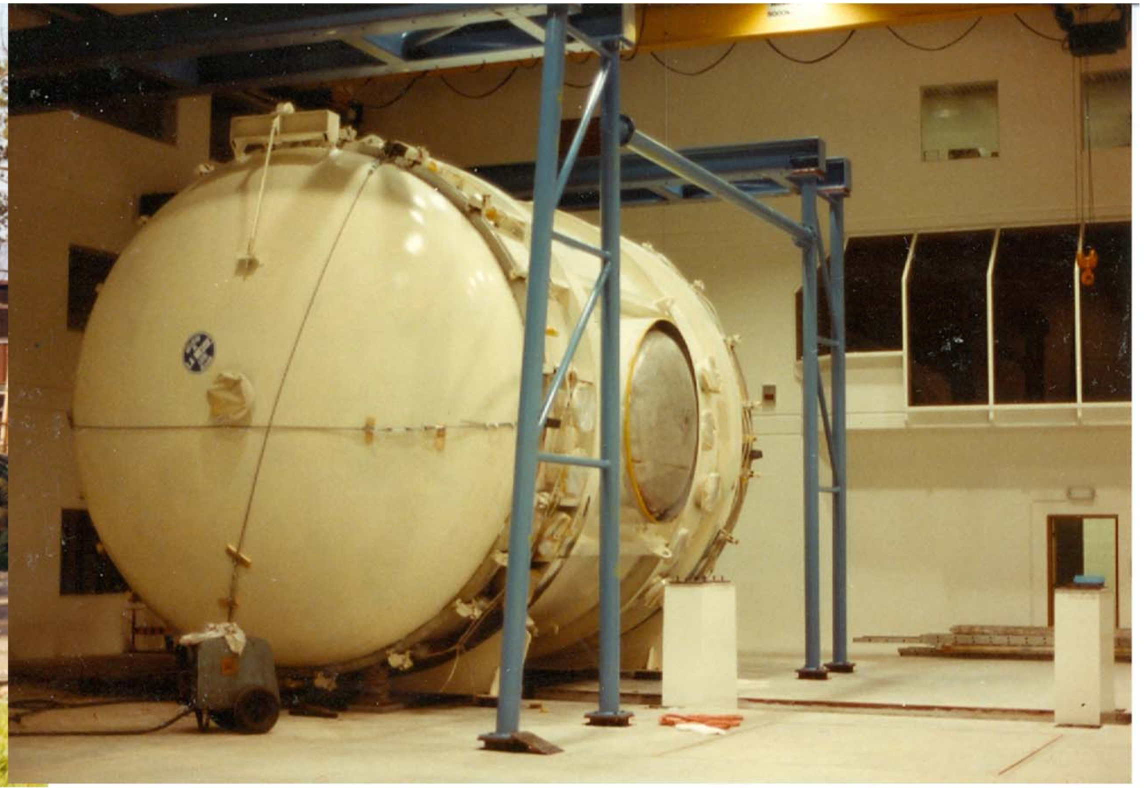
A new vacuum chamber FOCAL 5 larger than FOCAL 2 is necessary and adequate room is needed to install it. But there is no way to extend the **Institute of Astrophysics building in Cointe**. During the year **1983**, the decision was taken to construct a new building for IAL Space. Largely funded by the Walloon Ministry of Technology and supported by the European Space Agency, **a building of 3640 m² will be erected in the Science Park of Sart-Tilman** where the technological spin-offs of university begin to settle.

Hipparcos at Sart-Tilman

The new facilities were inaugurated in **November 1984**.

For IAL Space, it is a new era which begins.

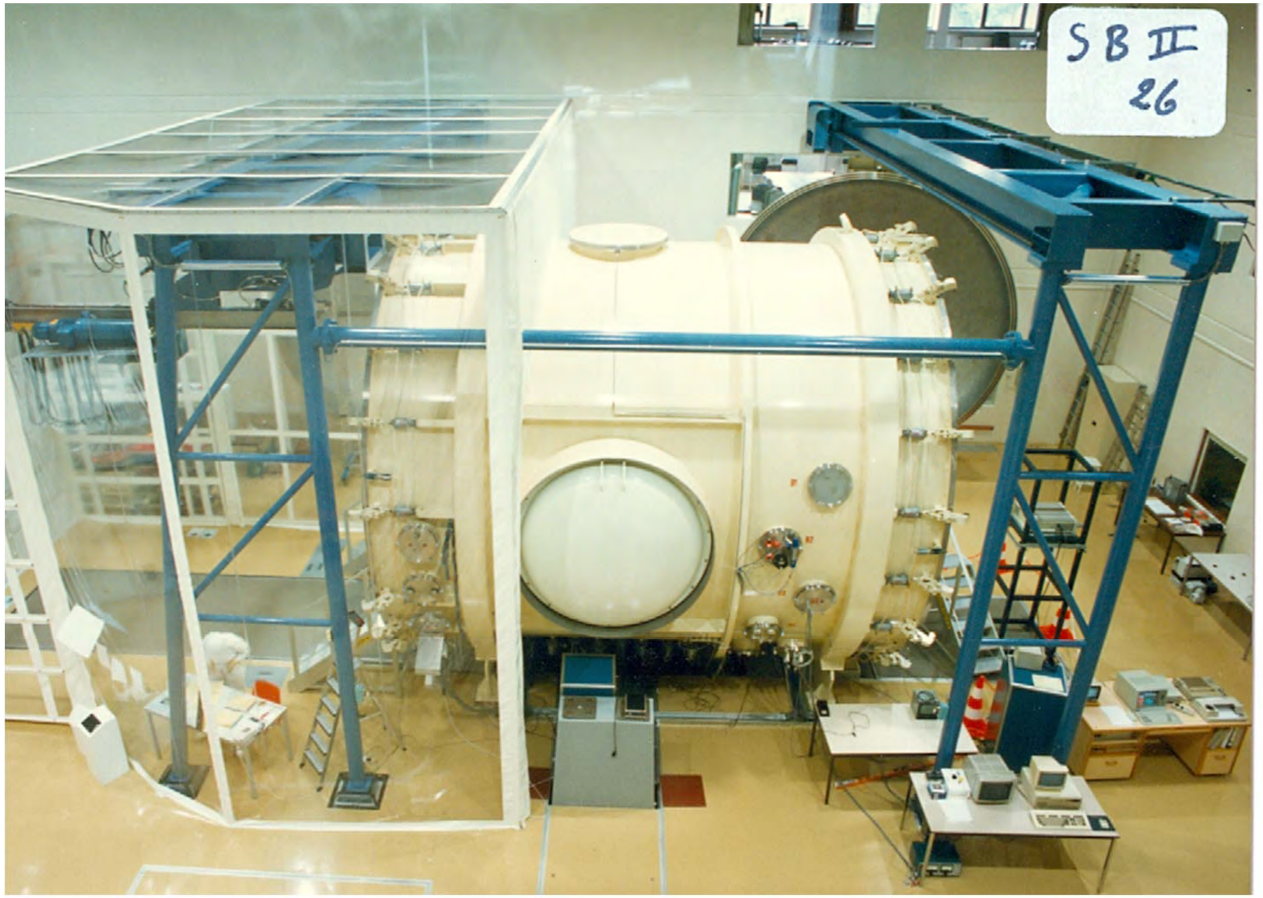
The building is designed around a **large cleanroom of 480 m² of floor area and 10 meters high**. Equipped with a bridge of 5 tons, it will house the **new space simulator "FOCAL 5"**, a cylindrical steel monster **5 meter diameter and 7 meters long**, made also by the Ateliers de la Meuse.



Hipparcos at Sart-Tilman

Like its sister Focal 2, it includes **an optical table that is completely decoupled from the tank and the building resting directly on a seismic block 300 tons of concrete T-shaped; in order to avoid the transfer of a maximum of mechanical vibrations.**

In his opening address, Professor Monfils will hammer: *"IAL Space is a university department managed like a private company."*



Hipparcos at Sart-Tilman

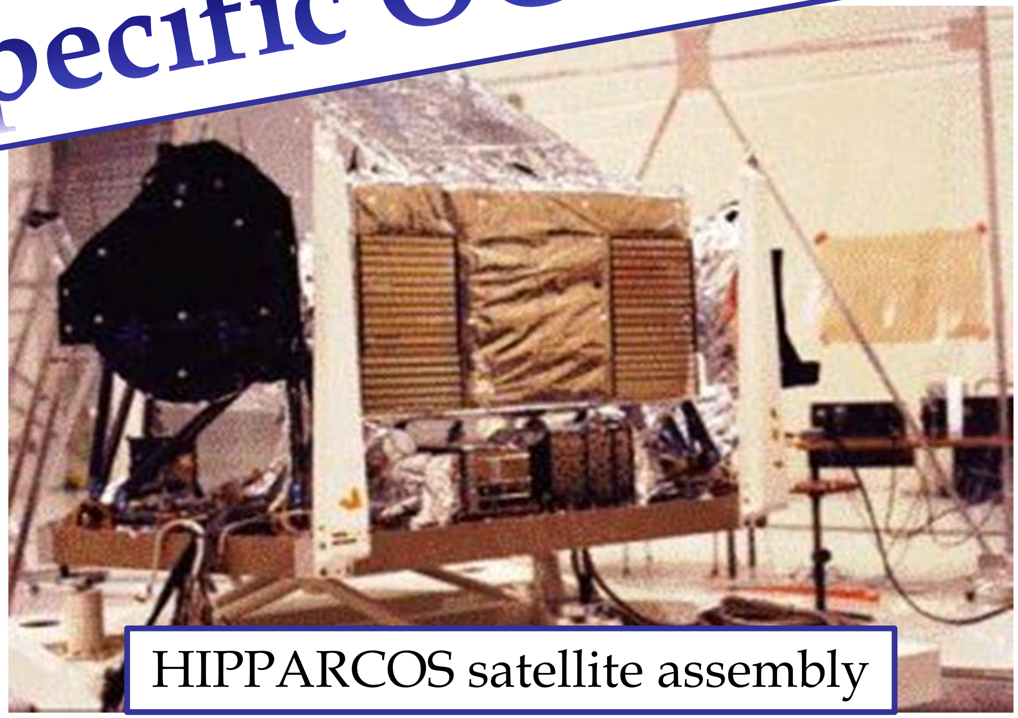
The new facility is quickly requested. While Giotto's validation campaign continues at Cointe (it was not until the end of the Giotto certification campaign before Focal 2 is transferred in early 1986 in the new building), two models of the Hipparcos instrument are tested and calibrated under vacuum in this new facility between 1985 and 1987 using optical calibration means specially (OGSE Optical Ground Support Equipment) designed and assembled at CSL.

HIPPARCOS

High Precision Parallax Collecting Satellite (HIPPARCOS) measured, until March 1993, the parallaxes and brightness of more than a million stars, with precision hundred to thousand times better, than what can be achieved from ground observations. Among other numerous new data, this satellite allowed to revise entirely the distance scale of a large number of objects in the

Development of Specific OGSE's

HIPPARCOS payload on test at CSL



HIPPARCOS satellite assembly

Start of a new activity : Development of high accuracy metrological tools

In order to verify the misalignment of the two FOV while the thermal environment around the telescope was changing IAL Space developed the “HIPPARCOS TWIST OGSE

Development of a polarimeter (TWIST).

Polarimetry is a sensitive technique for measuring optical activity exhibited by compounds. It can so be suited to measure rotation along the line of sight between two units.

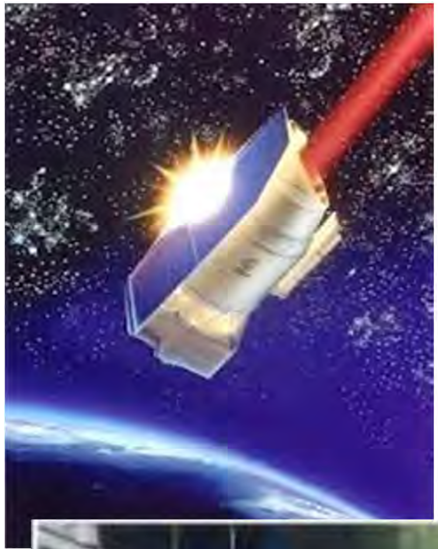
It consists in measuring the variation of intensity trough two cross polarisers. By introducing an electro-optical modulator, a great sensitivity can be achieved.

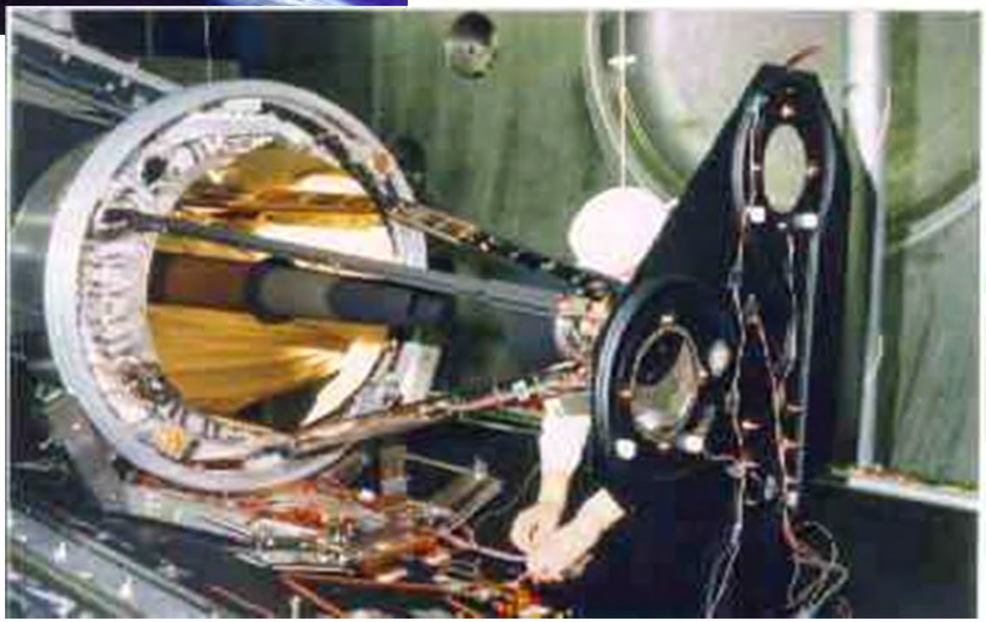
Visit of HM King Baudouin

The importance of this project also raised the interest of HM King Baudouin, whose appeal for astronomy was well known, and honored us with a long visit on this occasion. It will be followed by other princely visits, royal and prestigious that take place throughout the years.

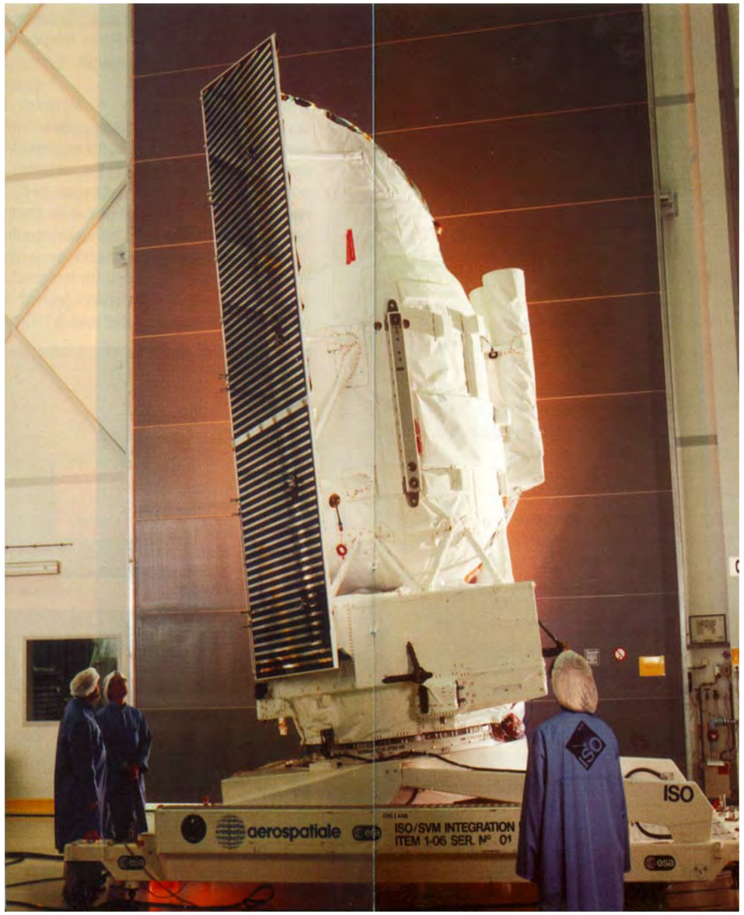
ISO : Infrared Space Observatory

The Infrared Space Observatory, cooled down to 5 K, launched in November 1995, has observed very cool matter in the universe until April 1998 when it ran out of helium, its cooling fluid. Its observations were entirely achieved at long infrared wavelengths with unprecedented angular resolution and sensitivity.





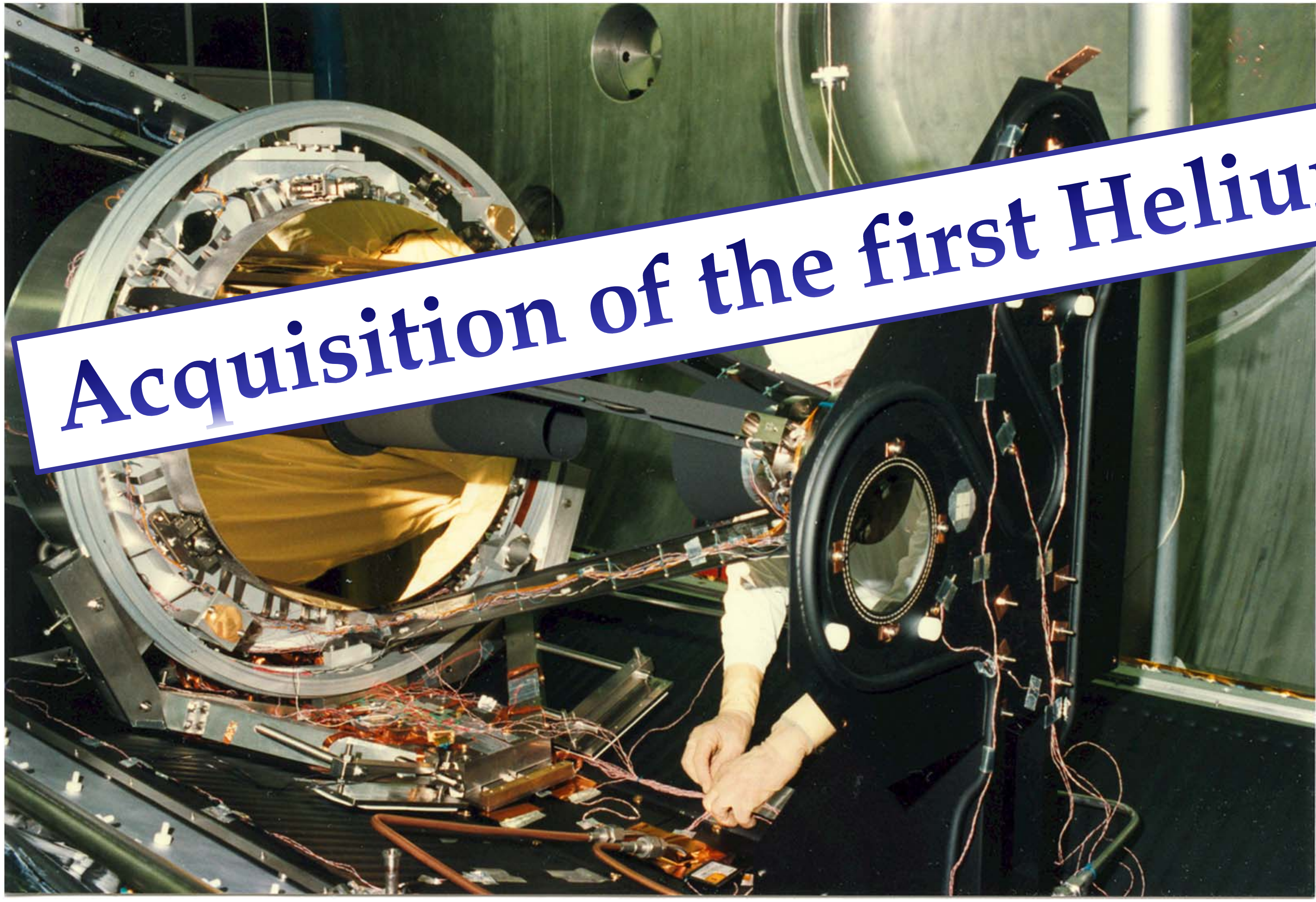
ISO Telescope in FOCAL 5 at CSL



Technical developments for ISO

Creative ways including a double-wall thermal enclosure disposed in the simulation chamber Focal 5 and fed with nitrogen and liquid helium. This chamber also allows the sight of the focal plane by a interferometric collimator measuring the optical quality of the instrument.

The helium consumption needed for these tests requires the acquisition of the first liquefier of IAL Space, the Koch 1630, still operational today, capable of producing liquid helium at -296 ° C (4 ° K) from pure gaseous helium.



Characteristics of optical measurement methods

Interferometry applied at visible wavelengths to the ISO telescope

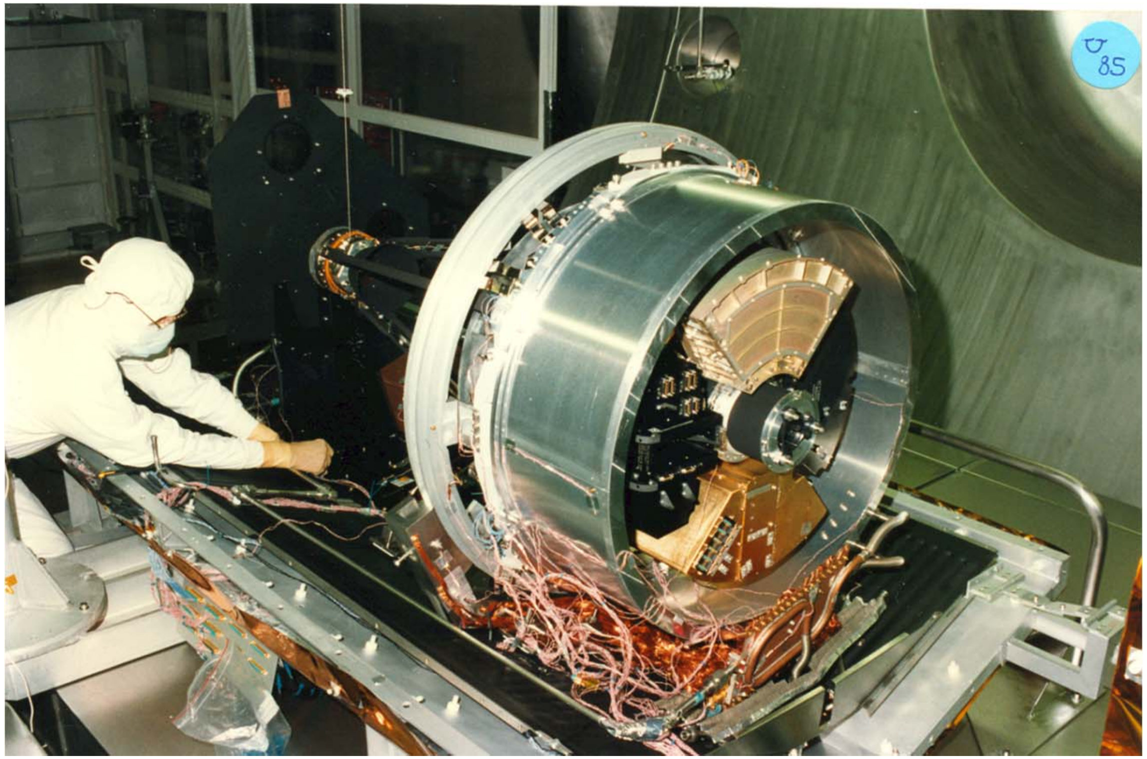
- Optical test program conducted by Aerospatiale Cannes.
- Validate the optical combination of the two mirrors at cryogenic temperature. The end-to end wavefront quality was measured.

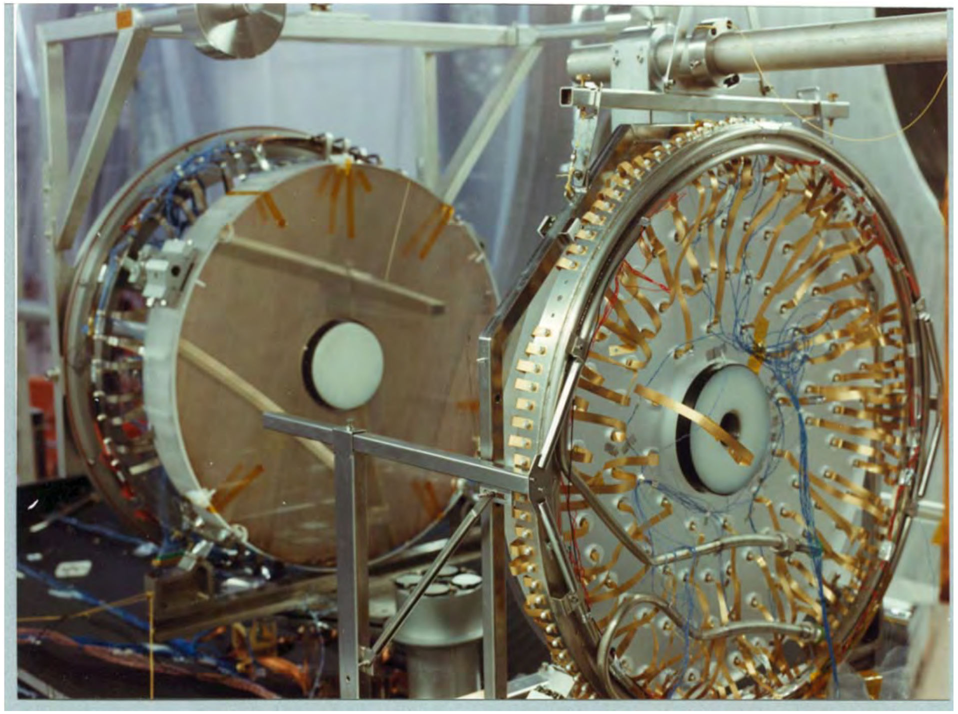
Acquisition of the first V Interferometer

Typical interferogram obtained during a thermal vacuum of the ISO telescope

ISO telescope integration at CSL

ISO



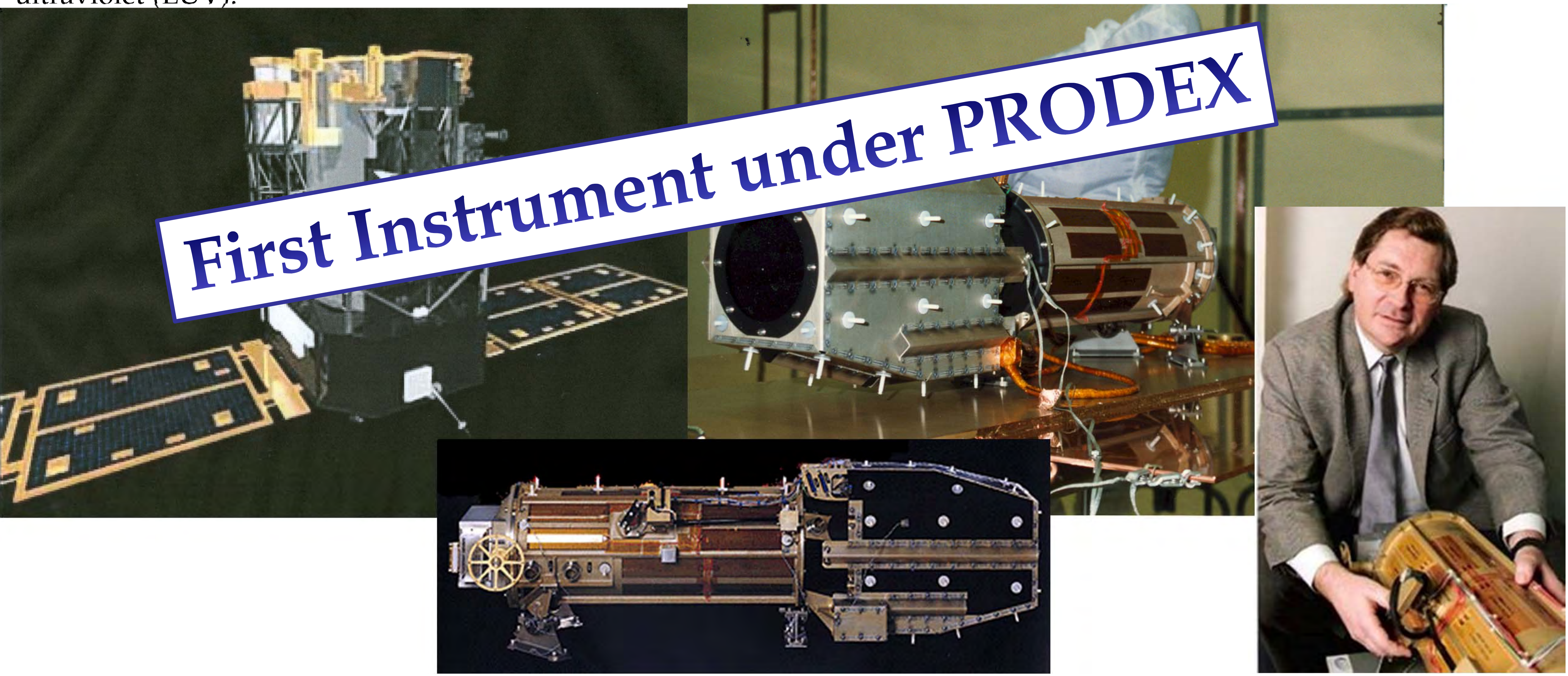


EIT SOHO

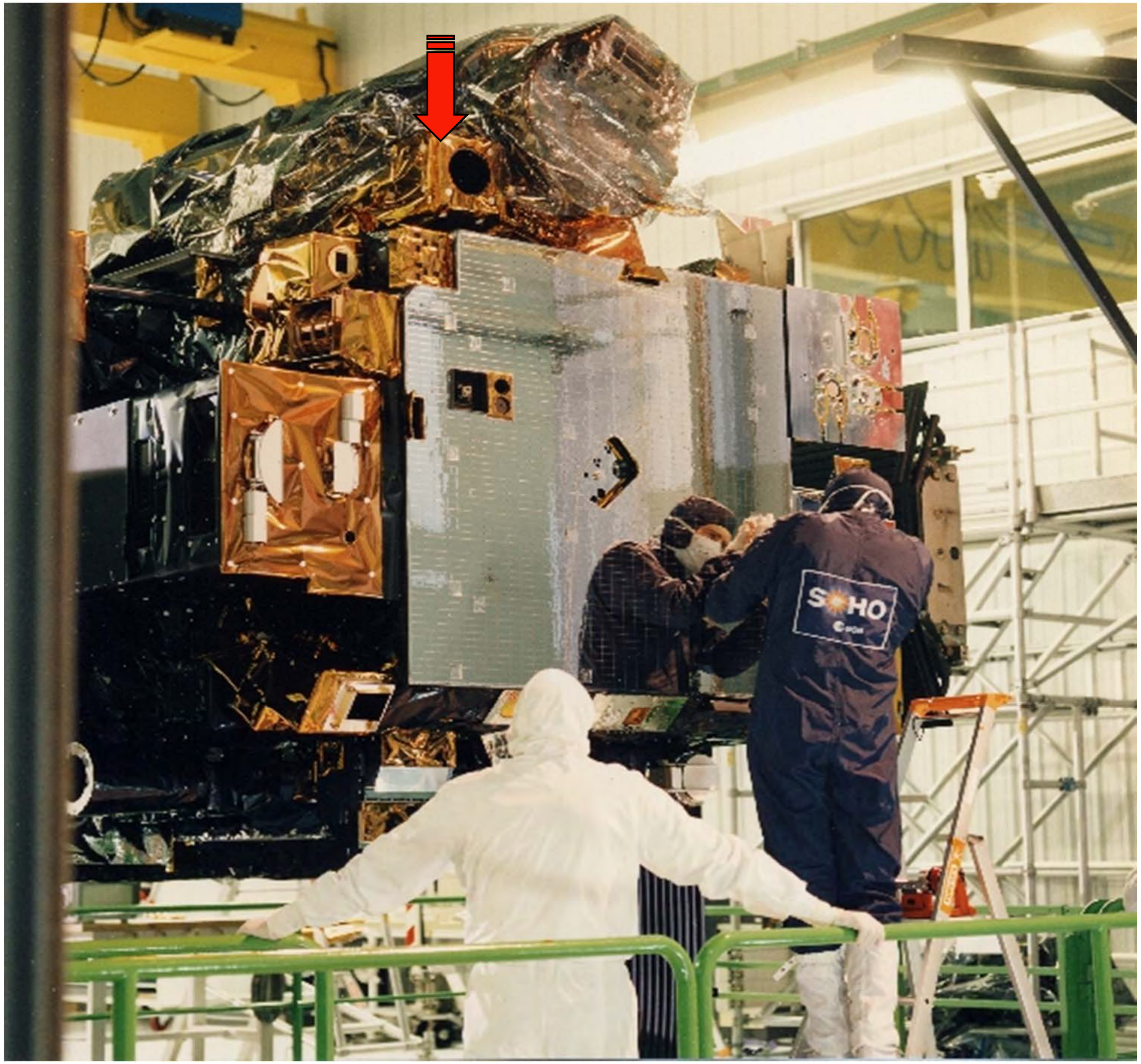
In 1988, IAL SPACE is involved in the ESA Solar Mission SOHO (SOlar and Héliocentric Observatory), with the Extreme UV Imaging Telescope EIT. IAL Space (with P. Rochus as International Project Manager) has the management of an international team composed of 3 Countries (Belgium, France and USA) and 7 laboratories.

SOHO is the first corner stone mission of the Horizon 2000 ESA scientific Programme.

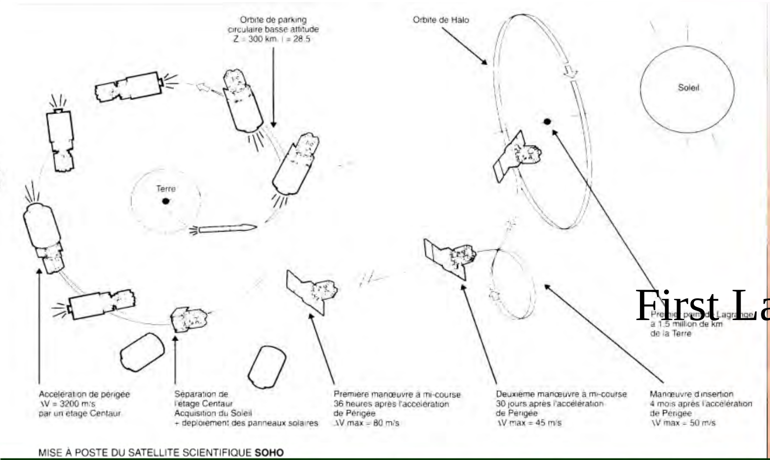
It is an ambitious mission where NASA contributes for 30% of the overall budget.
In collaboration with its partners, EIT was therefore designed, built and tested in the IAL Space facilities would become during the program CSL (Centre Spatial de Liège) .It is intended to observe the hot solar corona in the field of extreme ultraviolet (EUV).



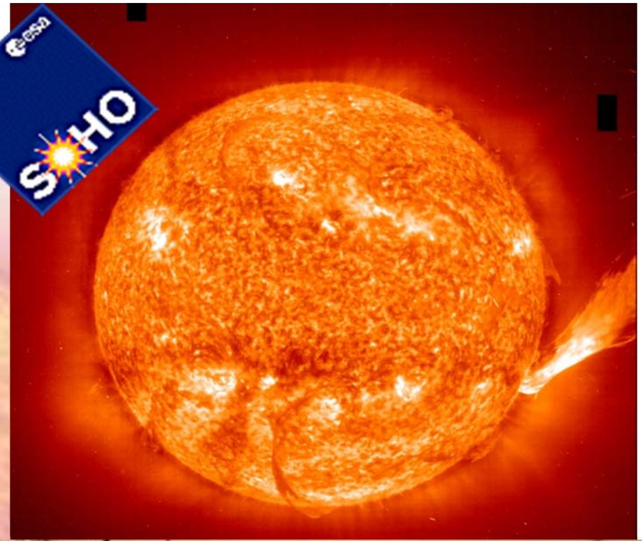
EIT SOHO

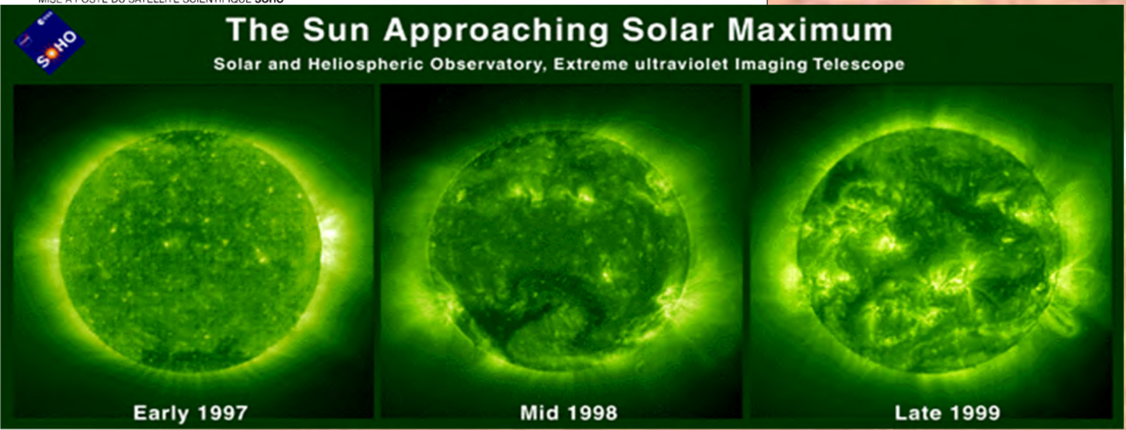


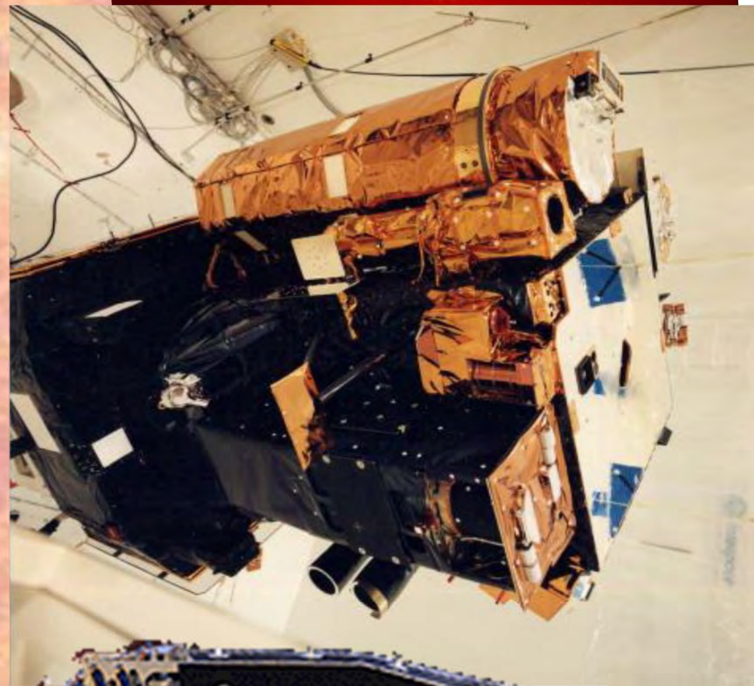
1988-1995 : SOHO EIT

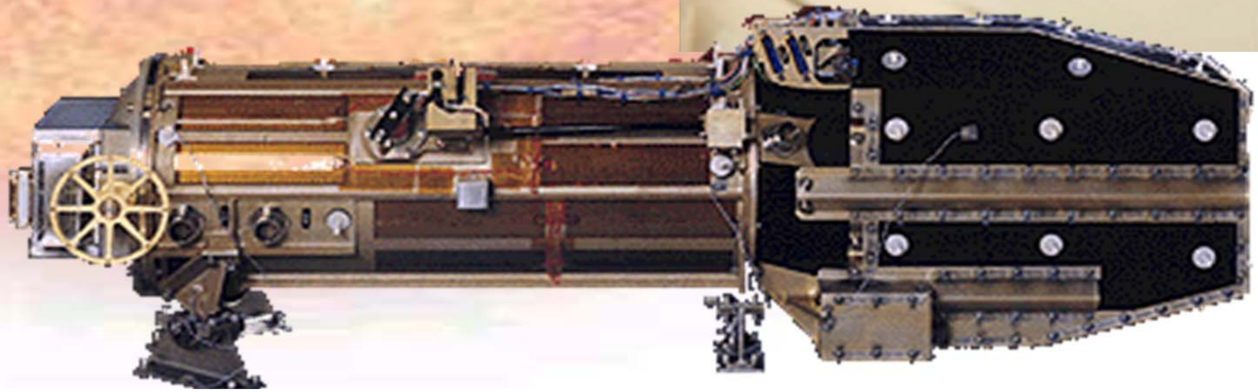


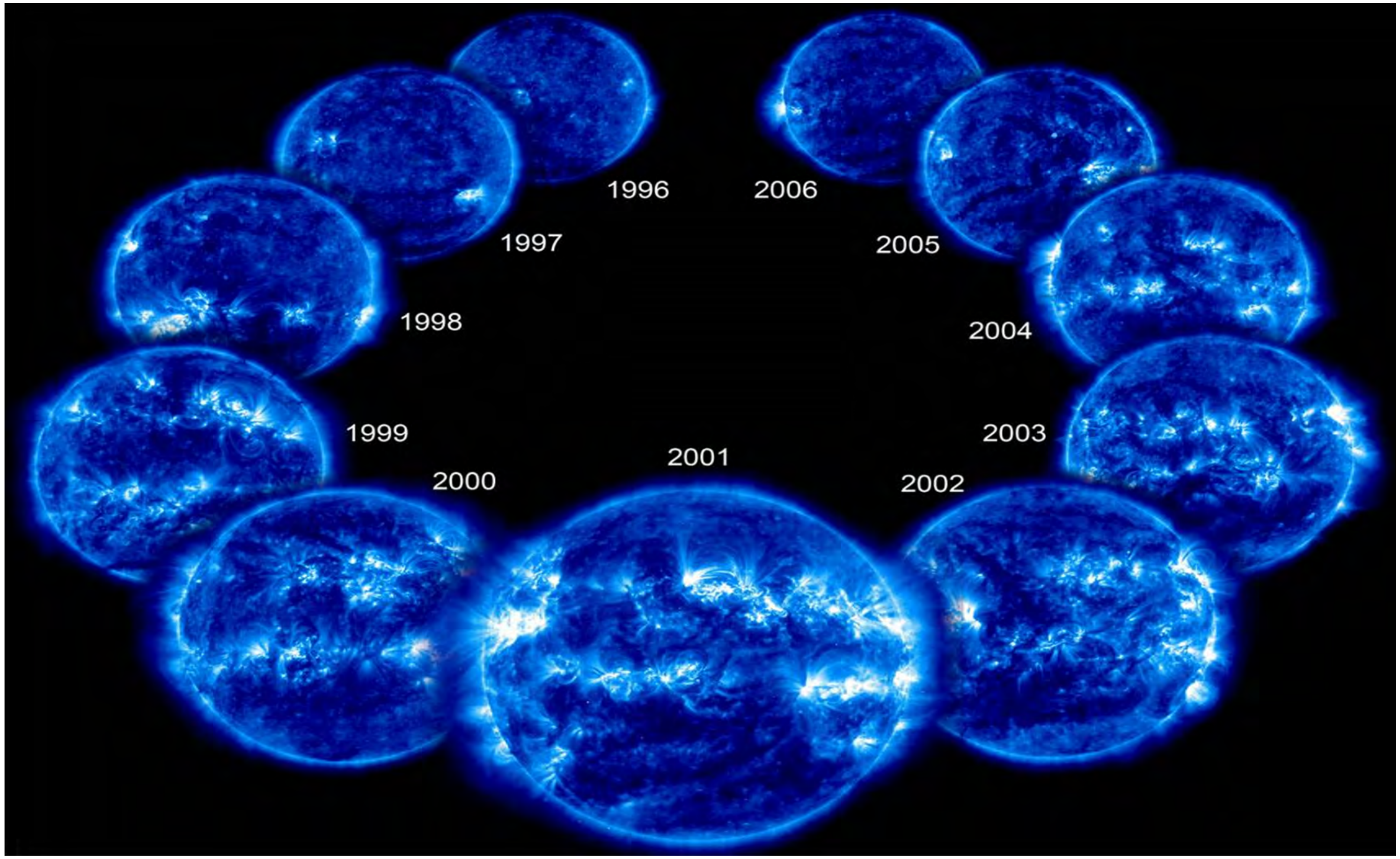
First Lagrangian point





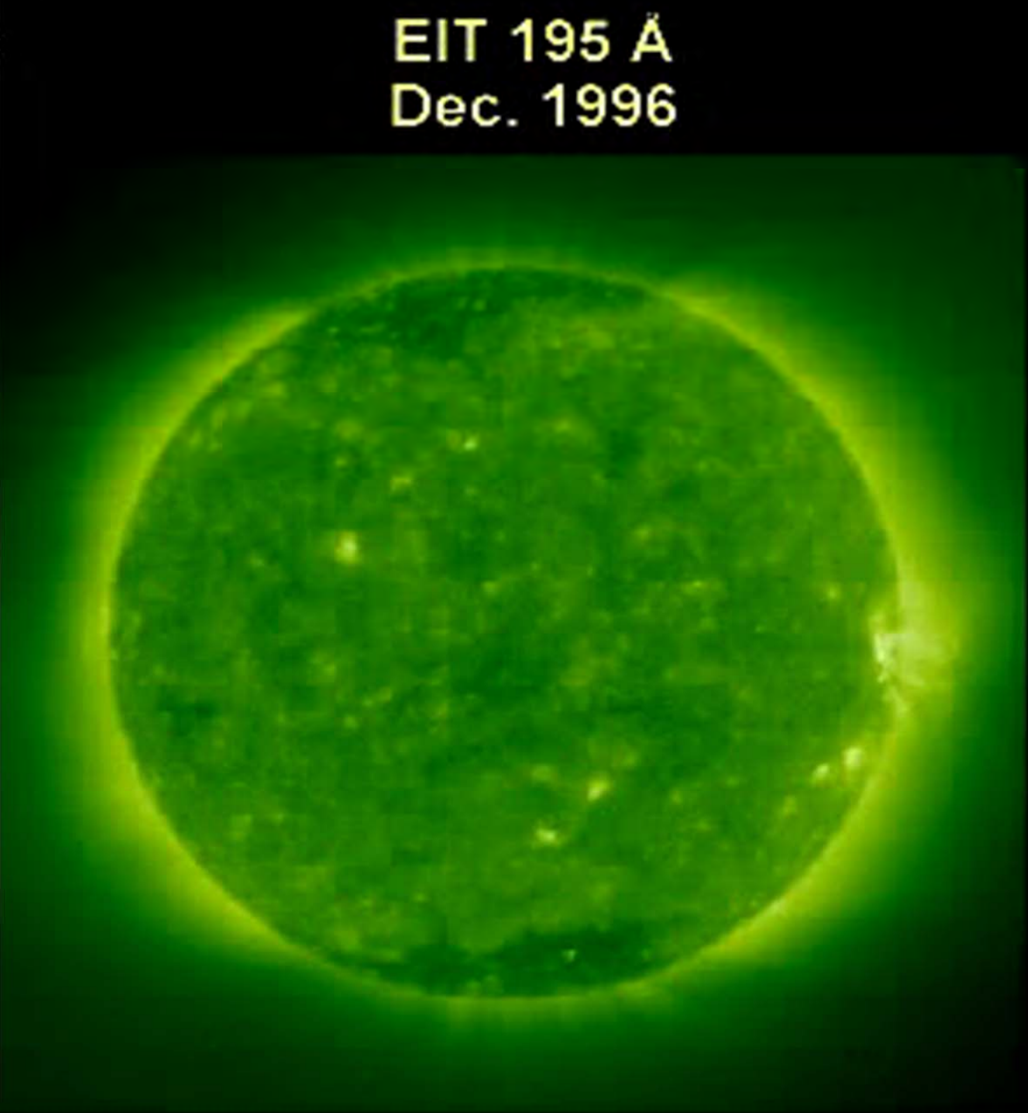




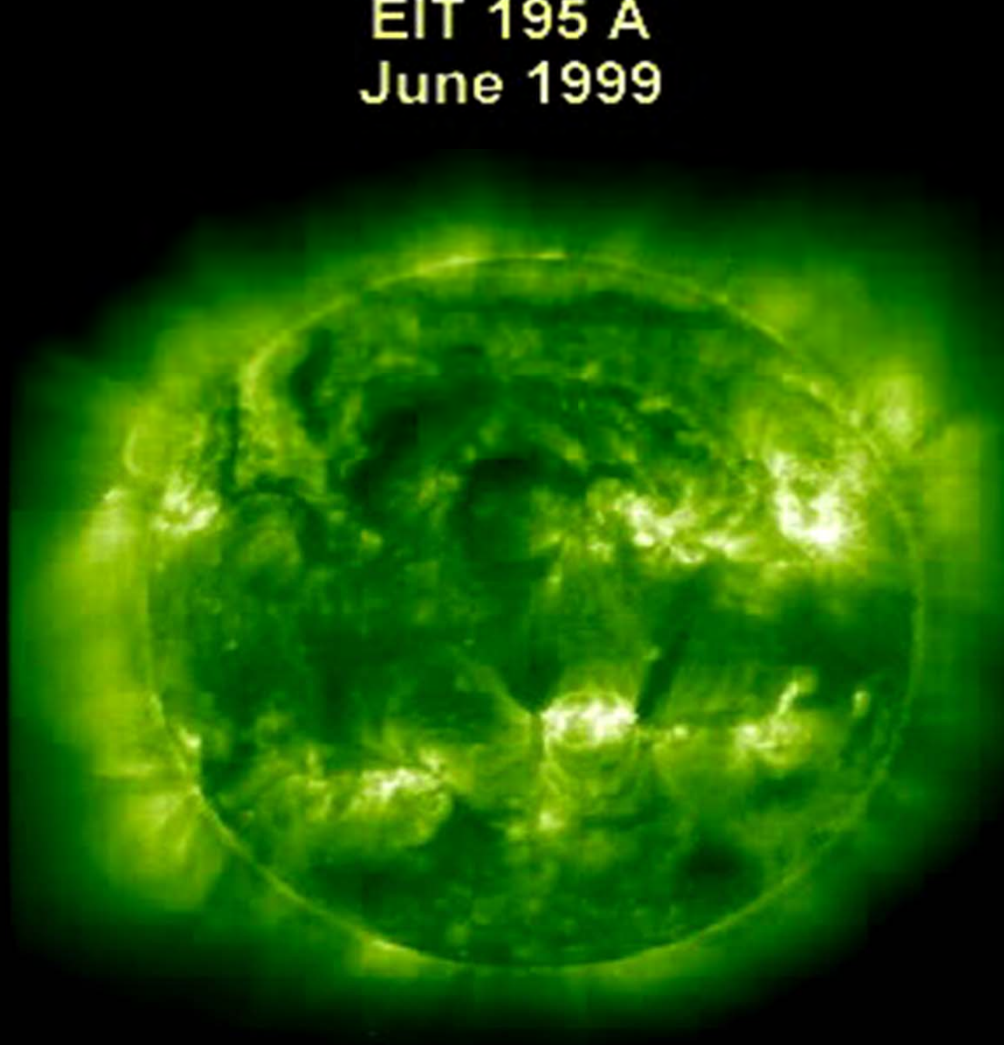


EIT/SOHO

https://www.youtube.com/watch?v=60NDkhpPnP0&list=TL4reKehRUdSQxMjEwMjAxNg



Quiet Sun



Active Sun

En hommage à Jean-Pierre

We lost our friend JP Delaboudinière on the 14th of June 2016

L'Institut d'astrophysique spatiale (IAS), unité mixte du CNRS, de l'université Paris-Sud et de l'université Paris-Saclay,

a la grande tristesse de faire part du décès de

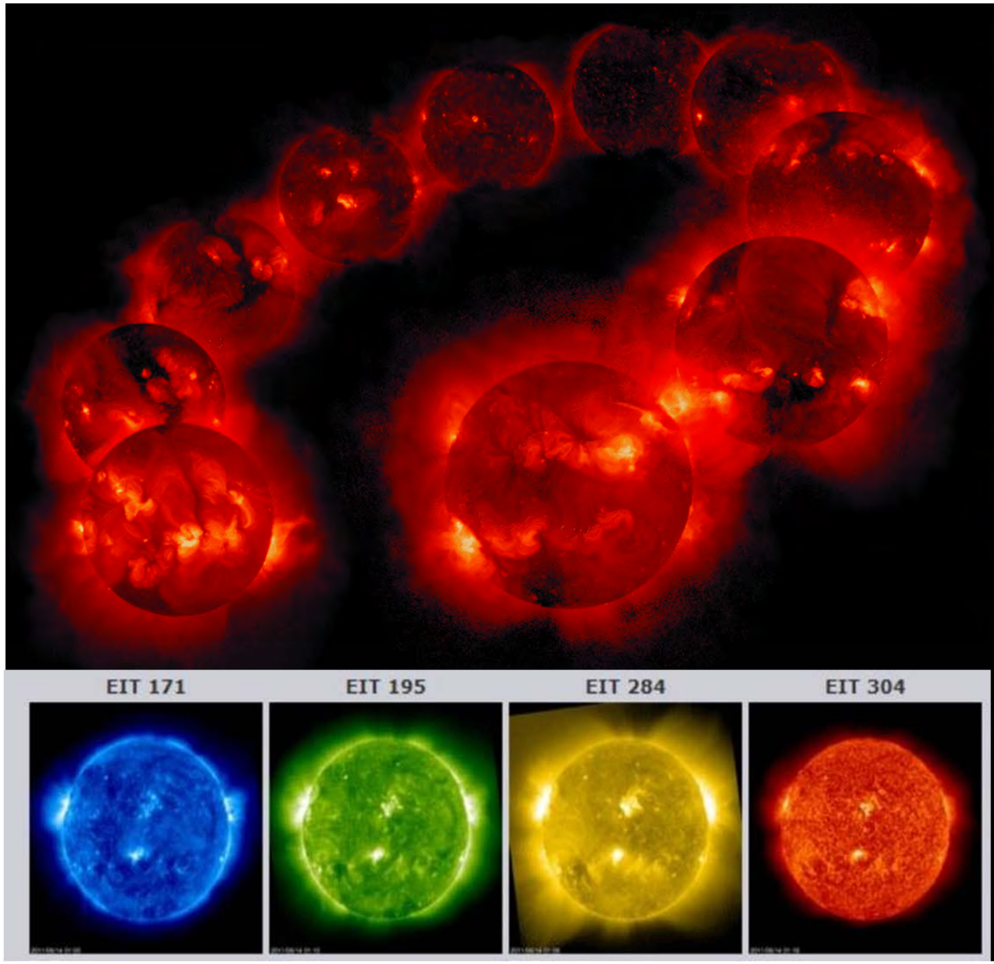
Jean-Pierre DELABOUDINIÈRE,
directeur de recherche
au CNRS.

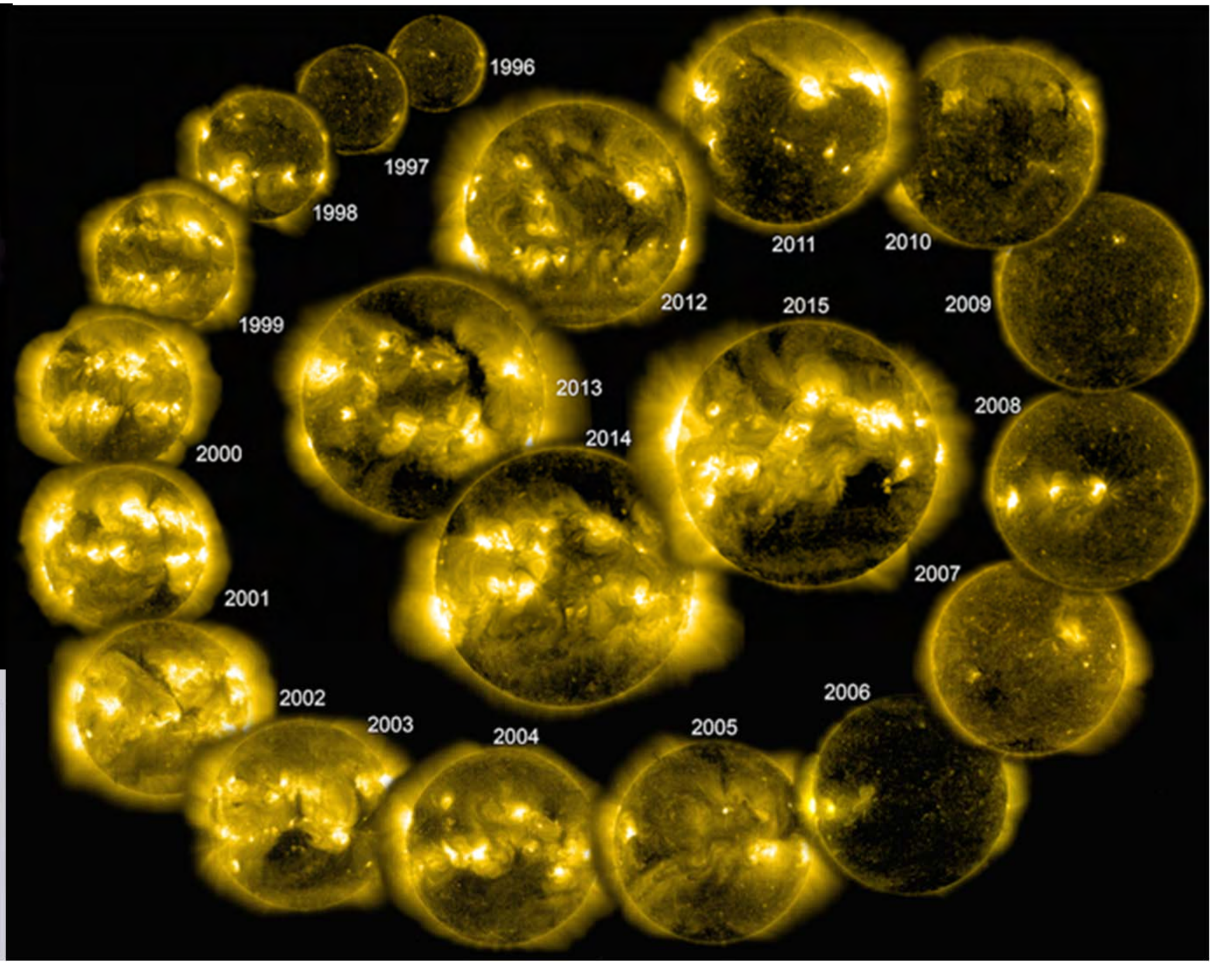
Ancien élève de l' ENS, Jean-Pierre Delaboudinière a effectué ses travaux de physique solaire spatiale au service d'aéronomie, au laboratoire de physique stellaire et planétaire, puis à l'IAS à Orsay.

Il a notamment construit l'imageur EIT de la mission SOHO, qui fournit depuis plus de vingt ans, des images du soleil dans l'extrême ultra-violet.

L'inhumation a eu lieu le mercredi 29 juin 2016, au crématorium Sud-77, Saint-Fargeau-Ponthierry (Seine-et-Marne).

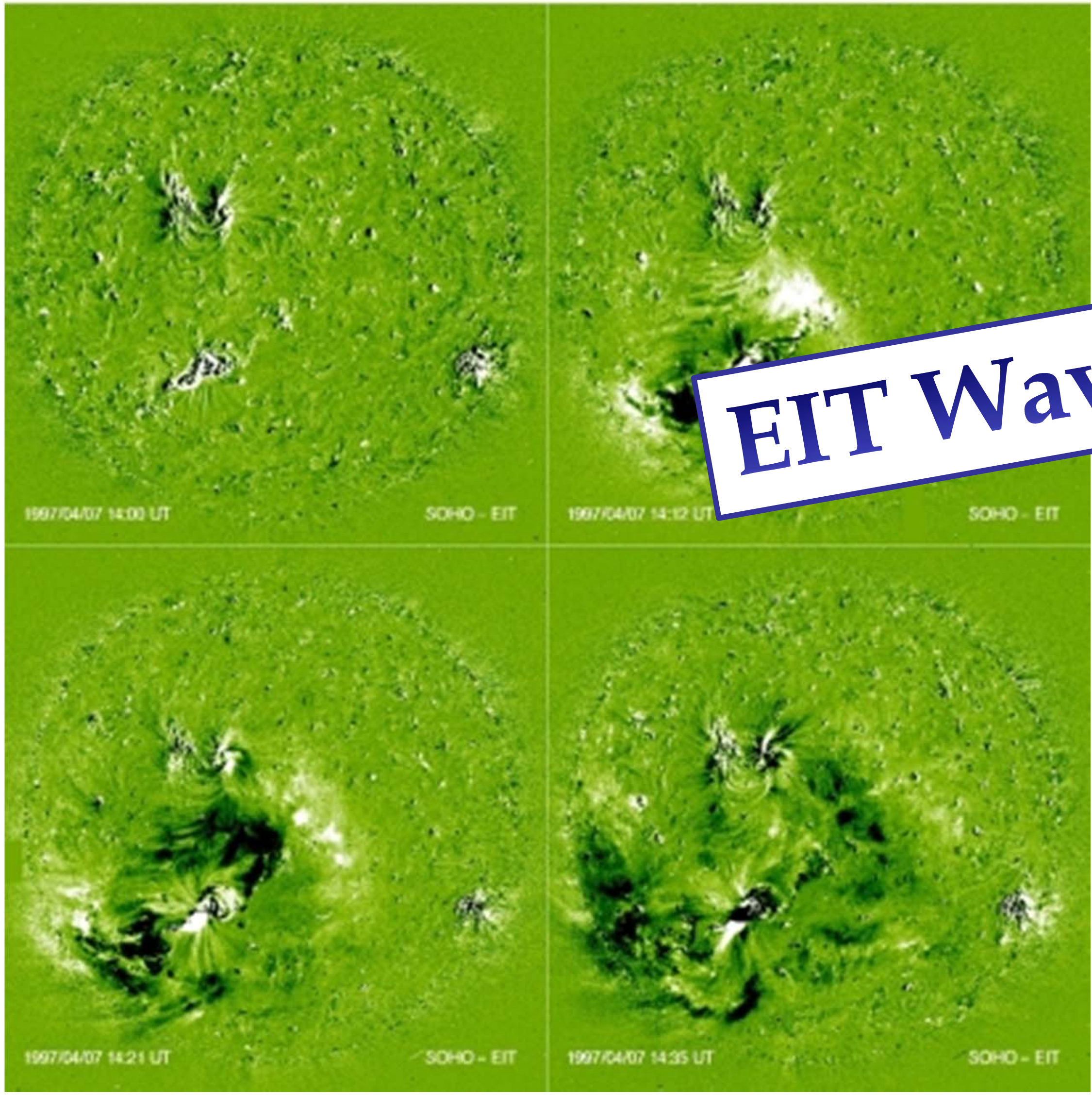
More than 20 years EIT SOHO 1995 – 2016





EIT Waves

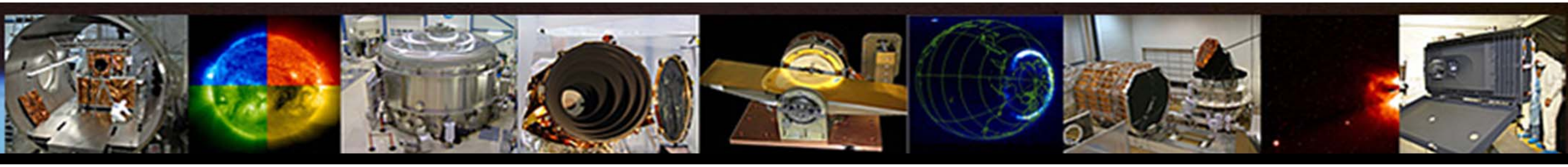
SOHO EIT
running difference sequence
from April 7, 1997 CME event



This sequence of images shows a wave propagating in the solar corona at a speed of about 300 kilometres per second. The four images have been taken over a time interval of just over half an hour. The moving wavefront is a result of a Coronal Mass Ejection (CME), a colossal eruption during which enormous amounts of gas are released from the Sun into outer space.

The images have been taken by SOHO's Extreme ultraviolet Imaging Telescope (EIT) at a wavelength of 195 Å, corresponding to the emission line of 11-times ionised iron atoms (Fe XII) and showing material at temperatures of about 1.5 million Kelvin.

This series of snapshots was taken on 12 May 1997.



140_EITmill_HD_3601.mov

Important changes

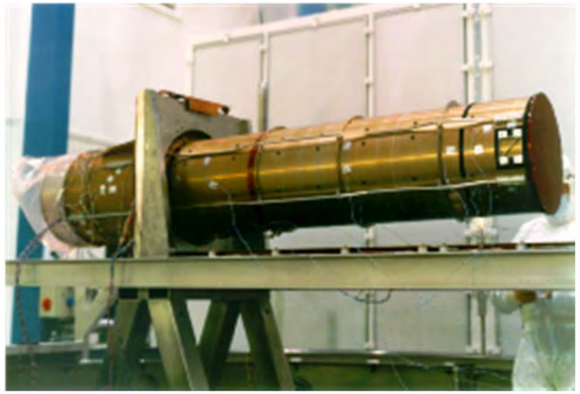
In the summer of 1991, Professor André Monfils retired. The board of the University nominated C. Jamar at the management to IAL Space.

André Monfils Claude Jamar

April 1992**, IAL Space** officially became "**the Centre Spatial de Liège (CSL)"**

XMM - Newton

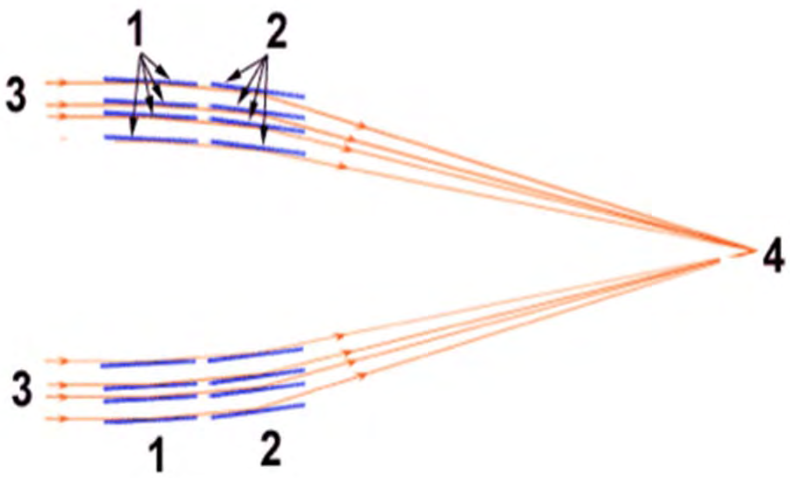
EIT barely out of the simulator, looming a new mission that, by its importance, will once again transform the CSL. It bears the name of a famous astronomer Newton.
XMM-Newton (X-ray Multi-Mirror) actually refers to a space observatory developed by the European Space Agency to observe the soft X-rays.



XMM OM

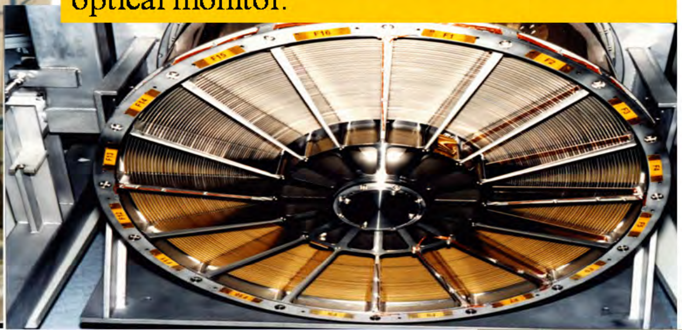
XMM - Newton

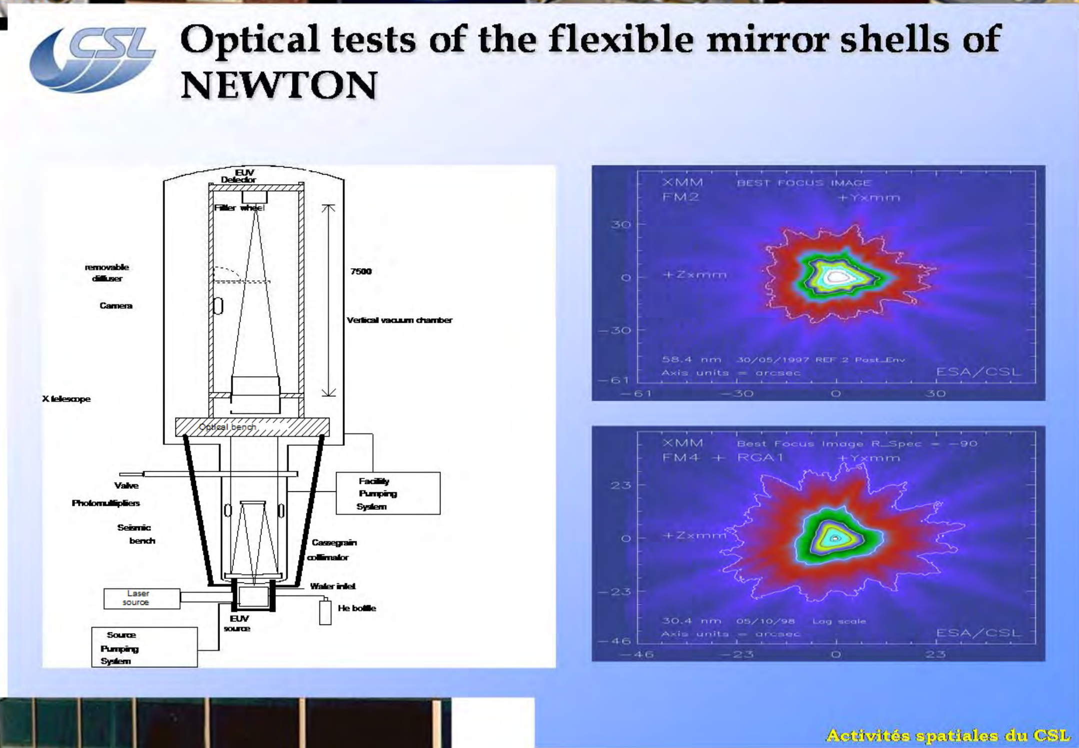
XMM-Newton is one of those sheep with five legs, as we like both CSL. It is even a ram because it is solidly equipped. Indeed, the satellite is formed by the telescope tube of 7.5 meters length. This is actually the height and shape of the cover of Ariane 4 that have limited size. The mirrors are grouped at one end of the tube while at the other end are the scientific instruments analyzing the collected X-ray. To be thoughtful and focused to the detectors, X-rays must arrive at a grazing incidence.

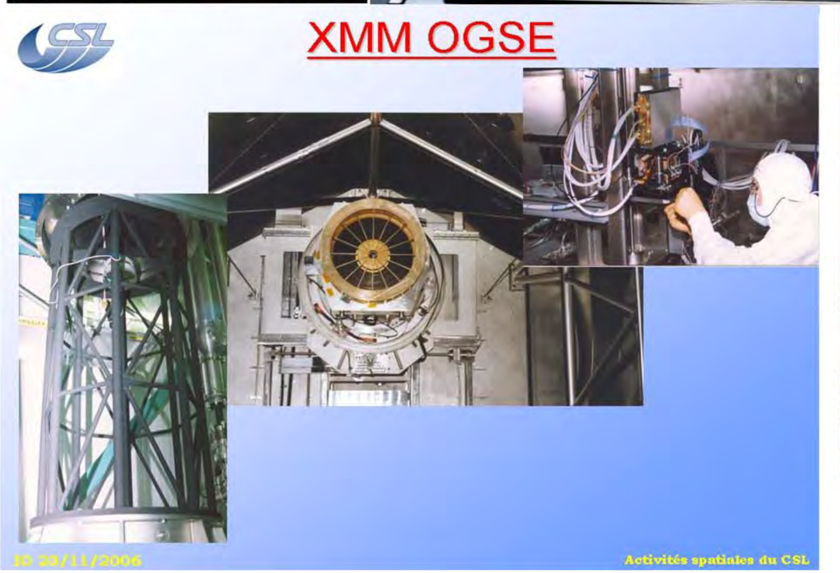


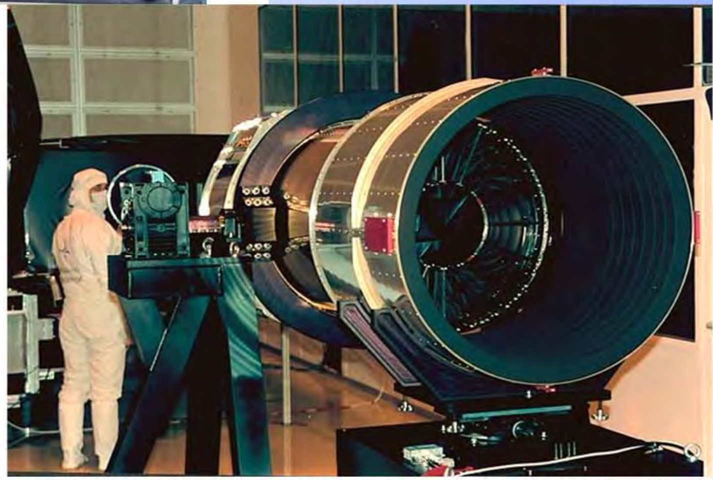
We have to think “verification and testing feasibility” from the very beginning of the design

Very good sensitivity, good spectral resolution spectrale and moderate spatial resolution from 0.1 to 15 keV
The satellite has 3 X ray telescopes (composed of 58 mirror shells) and one optical monitor.









XMM mirror module flight model #3 on a test bench at DASA in Ottobrunn, Germany. ESA's X-ray Multi-Mirror (XMM) high-throughput X-ray spectroscopy mission will be launched by Ariane-5 in early 2000. XMM will carry three mirror modules, each comprising 58 thin gold-plated nickel nested mirror shells of 300-700 mm diameters. [Image Date: 1998] [99.01.005-002]

XMM Newton telescope optical verification at CSL

Development of a new vertical facility

Decision Sept 1993
Start tests Sep 1995
End tests all the models 1999

Was the second « Cornerstone » project in the ESA Long Term Programme for Space Science. CSL had in charge an XMM dedicated optical test facility, named FOCAL X. with the needed tools : vacuum chambers, optical beams (EUV, visible and X-ray), detectors, cleanrooms, handling tools.

Short chronological list of events

September 93 : first contacts between ESA and CSL about a vertical EUV and X-ray test facility.

December 93 : Decision to perform an horizontal EUV test in order to validate the concept of an EUV optical test of XMM X-ray optics.

May 94 : CSL proposal for the development of a vertical facility for testing the XMM Mirrors.

The only facility existing in Europe at that time to test XMM mirrors was the horizontal PANTER facility in Neuried (Munich). It is able, using an X-ray source located at about 130 m from the optics, to illuminate in a slightly divergent beam, the full aperture of an XMM MM. Nevertheless, this method suffers two drawbacks :

- the first 100 mm of the shells are not correctly illuminated because of vignetting effect and nonnominal reflection caused by the beam divergence,
- because of the horizontal set-up, gravity affects the shape of the optics and of their mechanical support to be tested. The gravity effects are minimised in a vertical configuration.

The realization of a vertical optical test facility using an EUV collimated beam covering the full XMM aperture and partial X-ray beams is decided. This facility is complementing the PANTER test facility. History showed that, with the huge number of tests required by XMM, the two facilities have been intensively used during all the XMM test period.

June 94 : Kick-off meeting for the Vertical Test Facility development. The X-ray Multi Mirror

XMM NEWTON Mission

July 94 : Digging works are started. To house the facility, a new building is necessary. The building construction and the activities linked to the test facility itself were run in parallel. Moreover, the horizontal test set-up is used to acquire knowledge and debug as much as possible in advance the EUV vertical channel. Lessons learnt thanks to this test were implemented immediately in the design of the vertical facility.

October 94 : Seismic block installation tested

December 94 : The horizontal test is completed successfully but the set-up is maintained operational in order to perform subsystem tests of the EUV source (after servicing and adaptation), the EUV filters, the CCD cameras. The tightness of the building is reached. The pumping systems with valves and pressure gauges are delivered at CSL.

April 95 : Vacuum chamber introduction in the building trough the roof (see picture 2)

From September 95 to February 96 : Integration of mechanisms, detectors (3) and sources (3), integration and alignment of EUV collimator, integration of X-ray collimator, cleanrooms implementation. The shaker is also upgraded and installed in class 10 000 cleanroom to meet the XMM vibration test requirements.. Finally, facility acceptance tests are carried out with the XMM DM2 MM.

PICTURE 1 : Seismic block installation.

PICTURE 2 : Main chamber introduction.

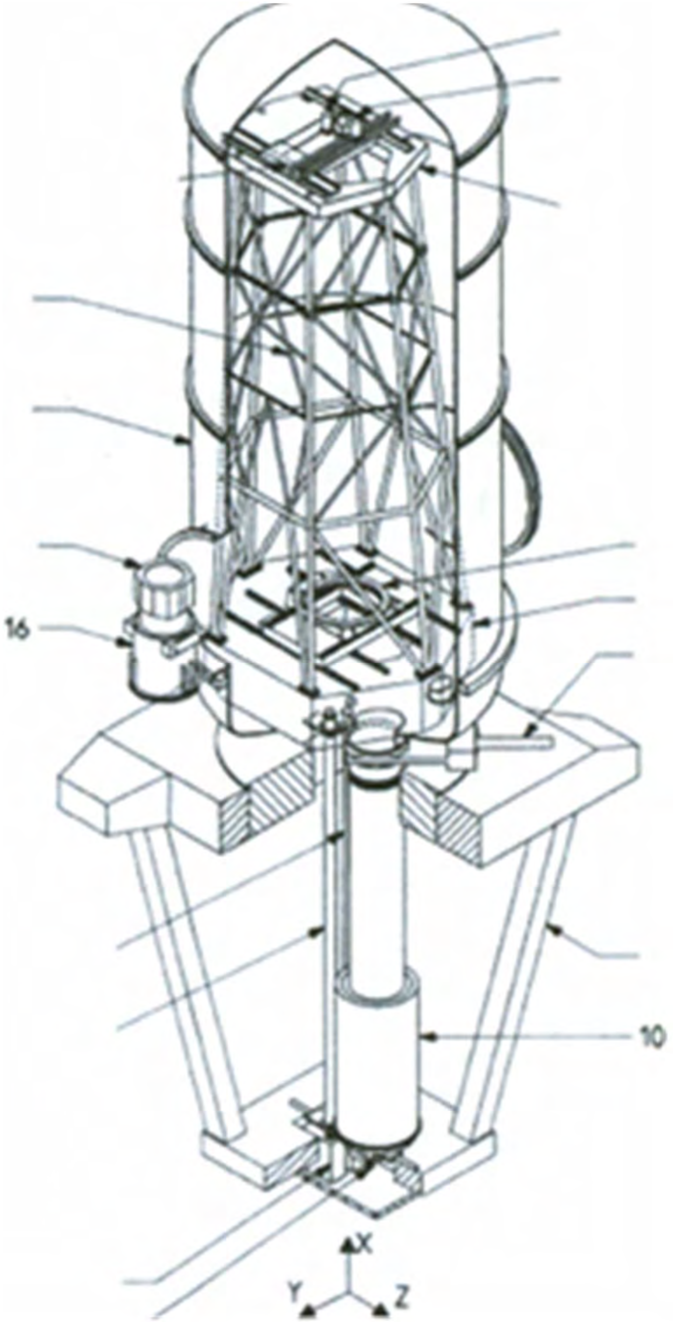
April 95 : Vacuum chamber introduction in the building trough the roof.

From March to August 96 : QM tests are performed. They consist in optical, vibration, thermal and opto-thermal sequences.

From September 96 to January 97 : Vibration tests of Structural/Thermal models with and without Reflexion Grating Assembly are performed. In parallel, facility improvements and calibration measurements are run.From February 97 to June 97 : environmental tests (optical, vibration, thermal) of FM1 and FM2 MMs are taking place.

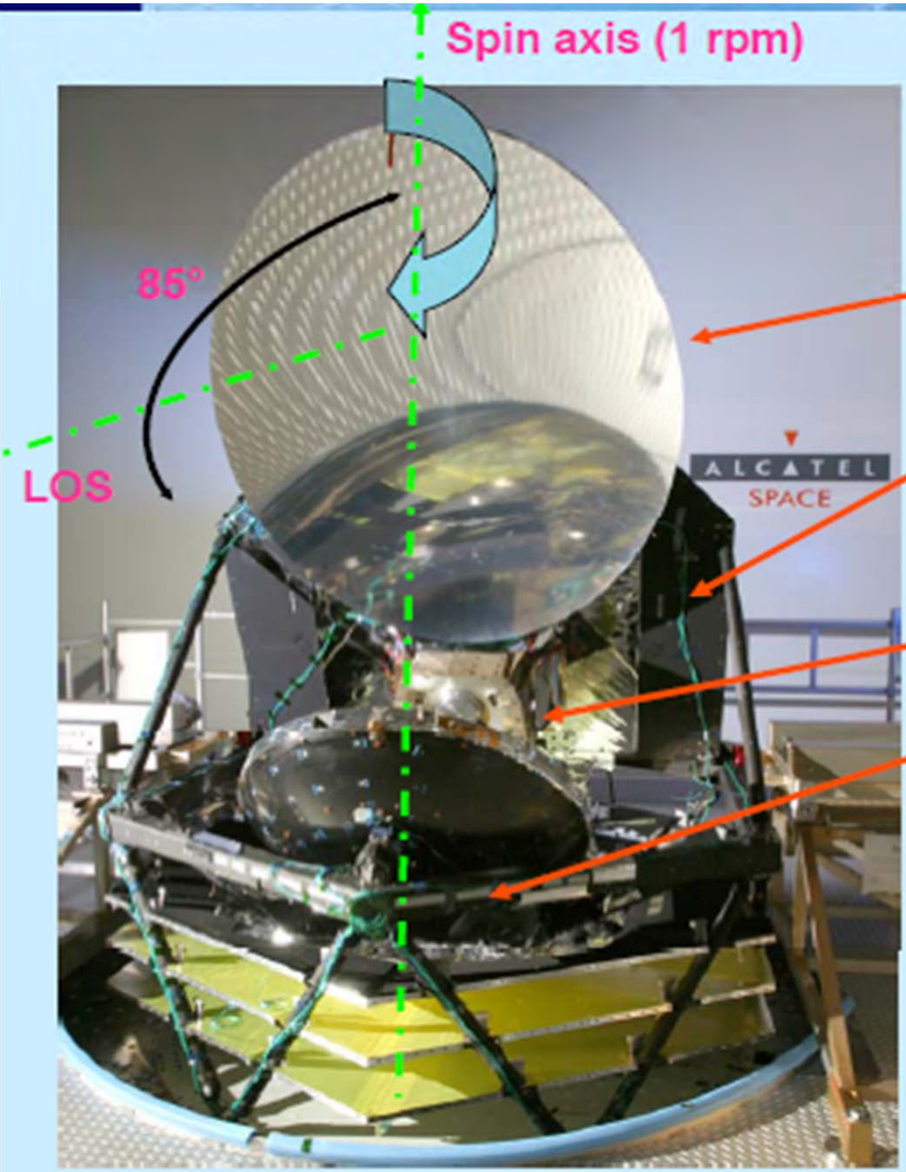
From July 97 up to 1998 : FM3 and FM4 MMs environmental tests, XRB test sequences for QM, FM1, FM2, FM3 and FM4, RGA1 and RGA2 test campaigns with FM1 and FM2, FM3 MMs are performed. The final flight configuration of M3MM+RGA2 is also tested

XMM - Newton



XMM - Newton

The different test campaigns occupy the CSL team until 1999.



- **Planck Telescope main design features**
  - Reflectors provided by ESA/DSRI (manufacturing by Astrium, Friedrichshaven)
  - Telescope structure – Contraves (CH)
  - Baffle
  - FPU (IAS, Paris & Laben Italy)
  - Mechanical IF with the S/C
    - LOS orientation wrt spin axis leads to a non classical telescope architecture (PR at a high position wrt the Cog) : 6 interface points are required to withstand the mechanical loads.
    - Cryo-structure/telescope Interface loads is one of the major contributors to the telescope performance budget

CRYOGENIC TESTING OF PLANCK MIRRORS SEPARATELY

The PLANCK reflectors are 2 **CFRP off -axis ellipsoids** to be tested separately (Secondary reflector: 1050 mm x 1100 mm and Primary reflector: 1550 mm x 1890 mm).

The cryogenic tests of the reflectors were performed at CSL. One of the test objectives is the measurement of the **changes of the surface figure error** (SFE) with respect to the best ellipsoid, between 293 K and 40 K, with a 1 mm RMS accuracy. Therefore, the measurement instrument needs to have a resolution better than 1 mm RMS. The second objective is the **focus position change measurement**, with an accuracy of 20 mm. The Primary reflector inter-focal distance is 21 m.

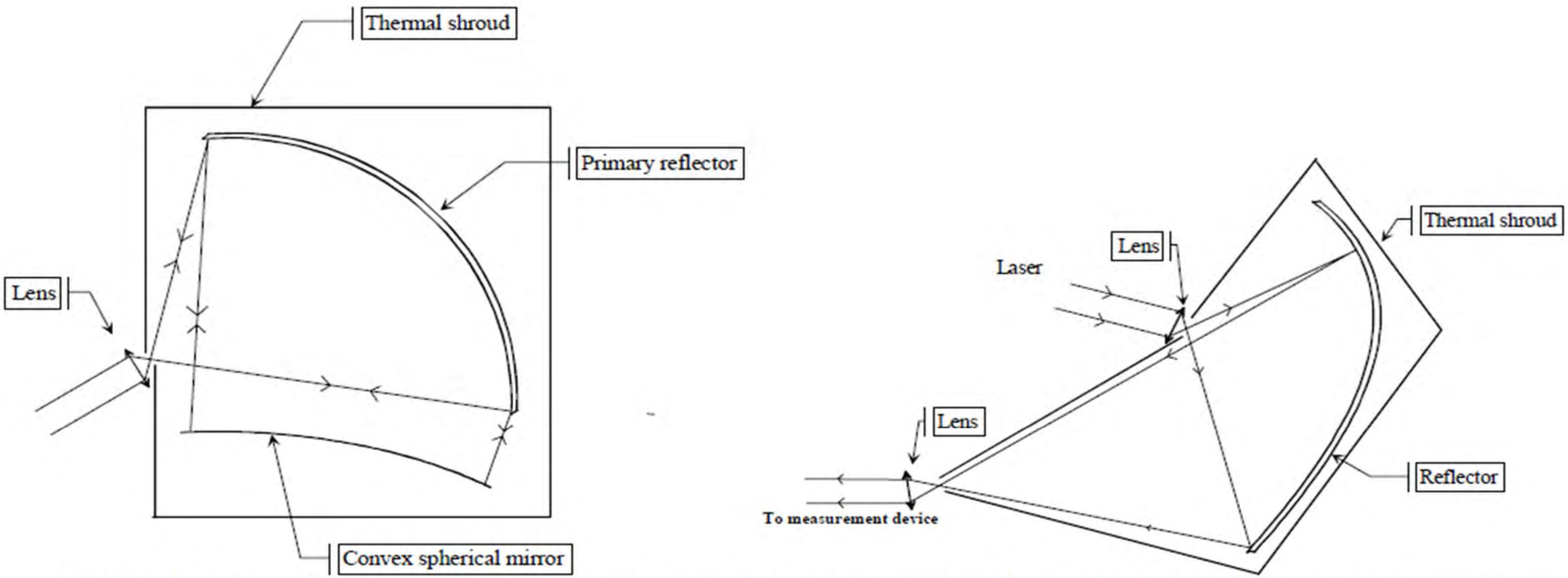
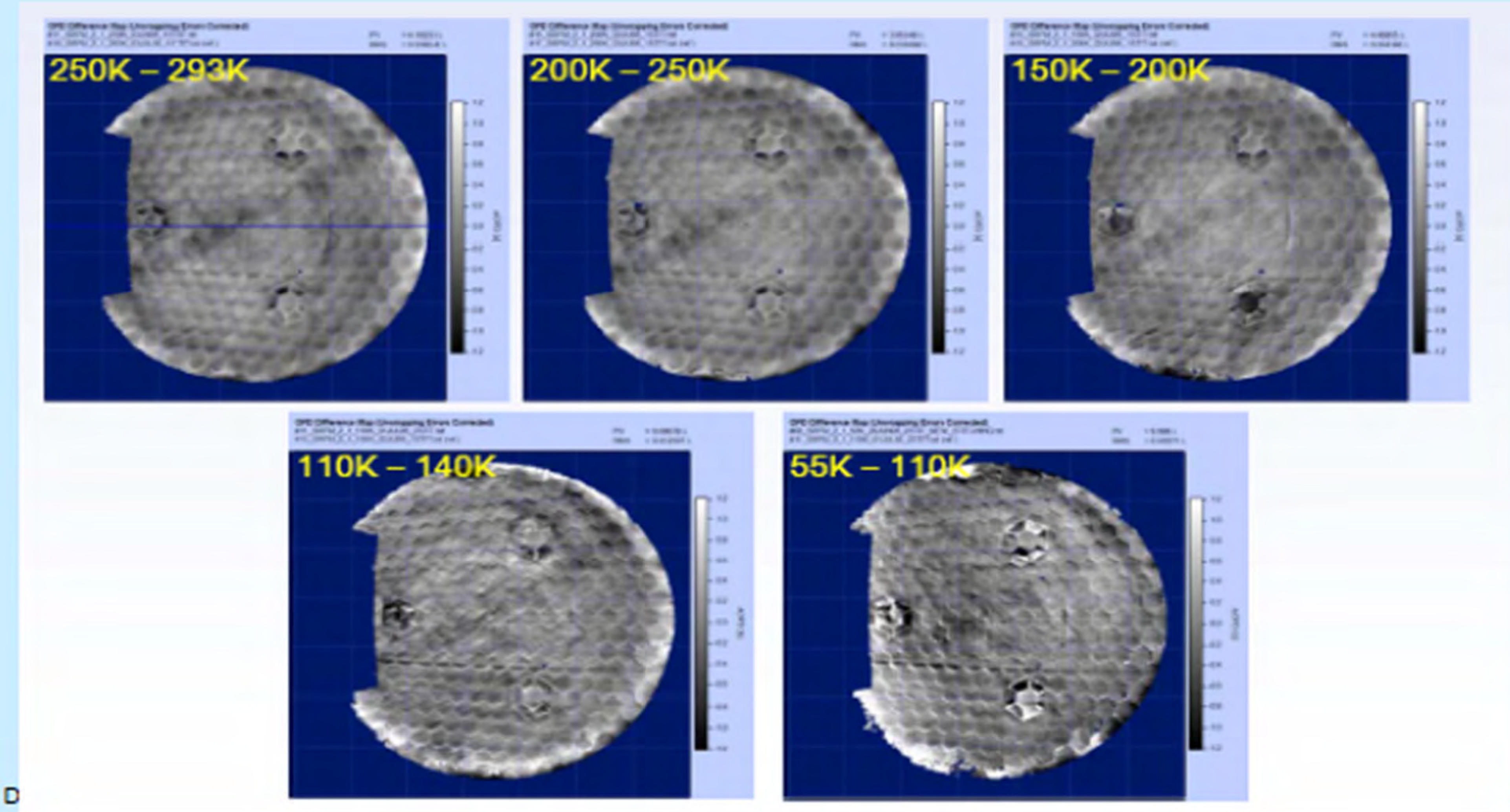


Figure 1. Stigmatic test configuration proposed for the primary reflector test (double pass) and secondary reflector test (single pass).

10.6 µm Interferometry at cryogenic

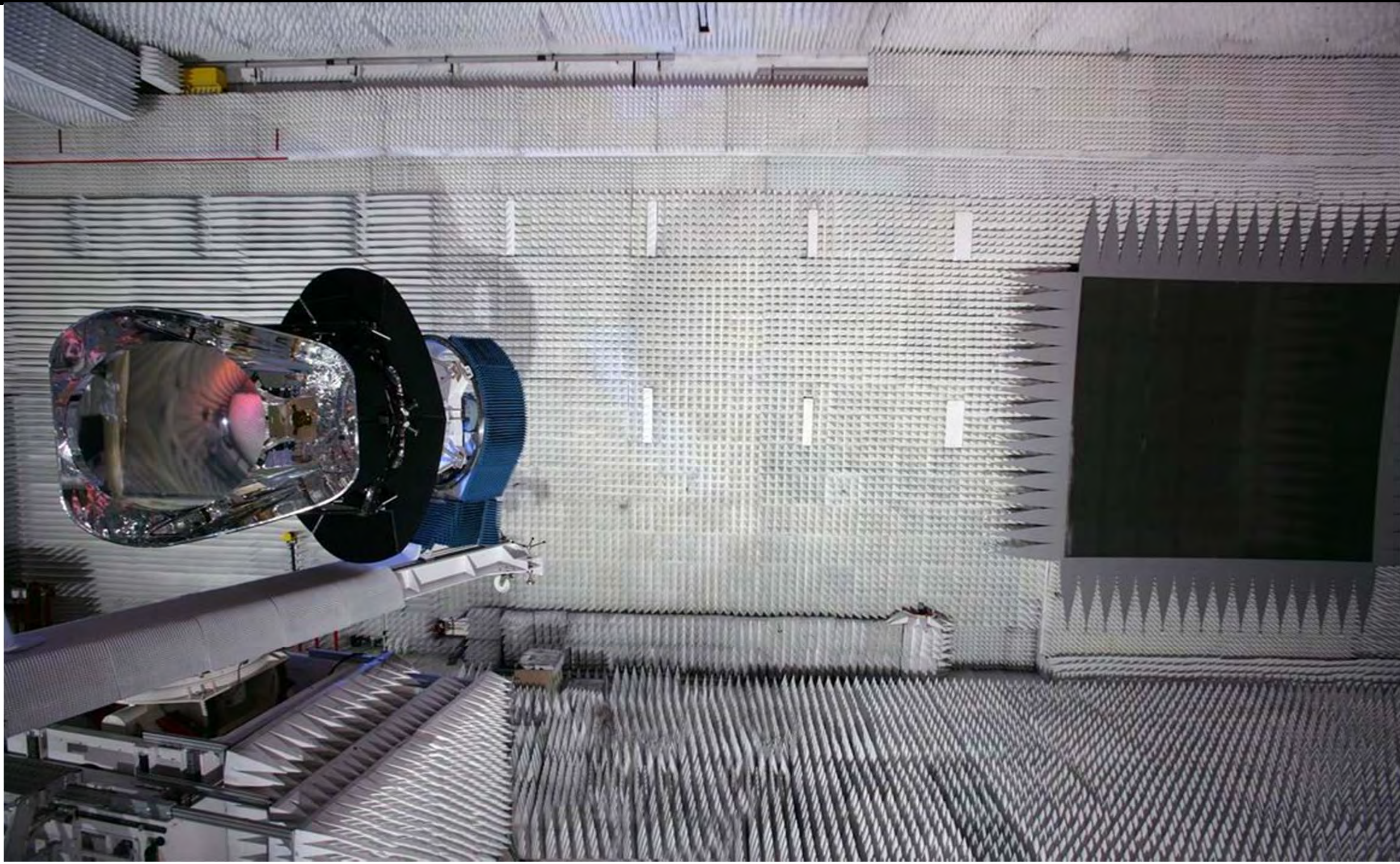
- 10.6 micron interferometer developed for purpose at CSL (B)
- Local large slopes due to honeycomb print-through (quilting) proved to be a limiting factor giving unwrapping errors



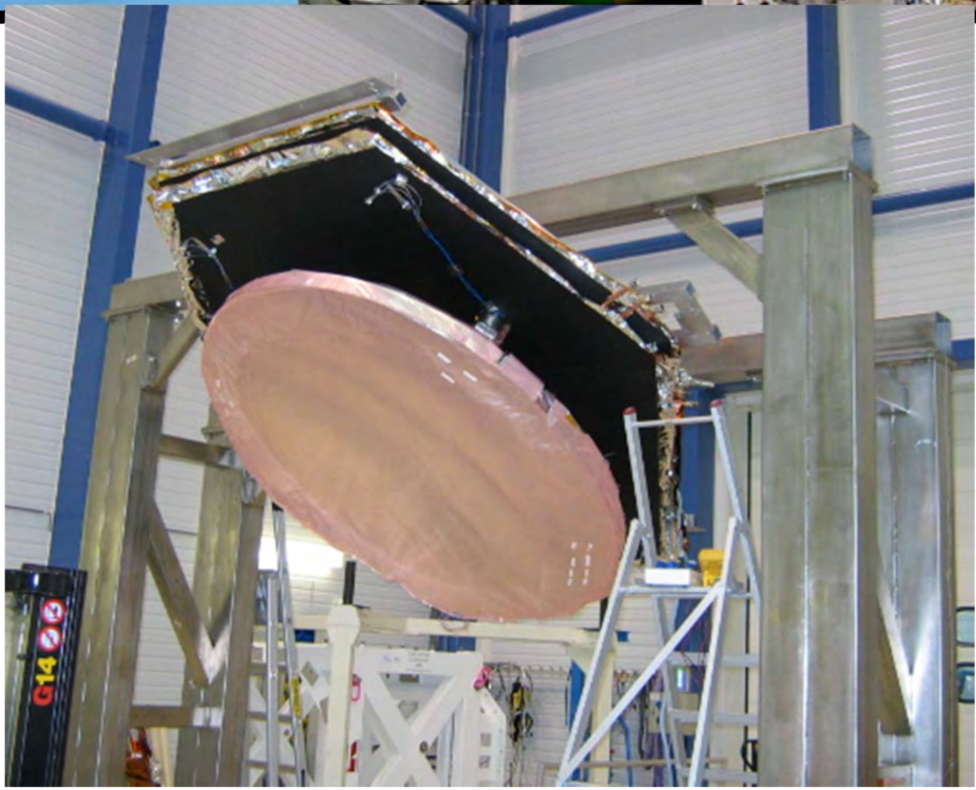
Lessons learned

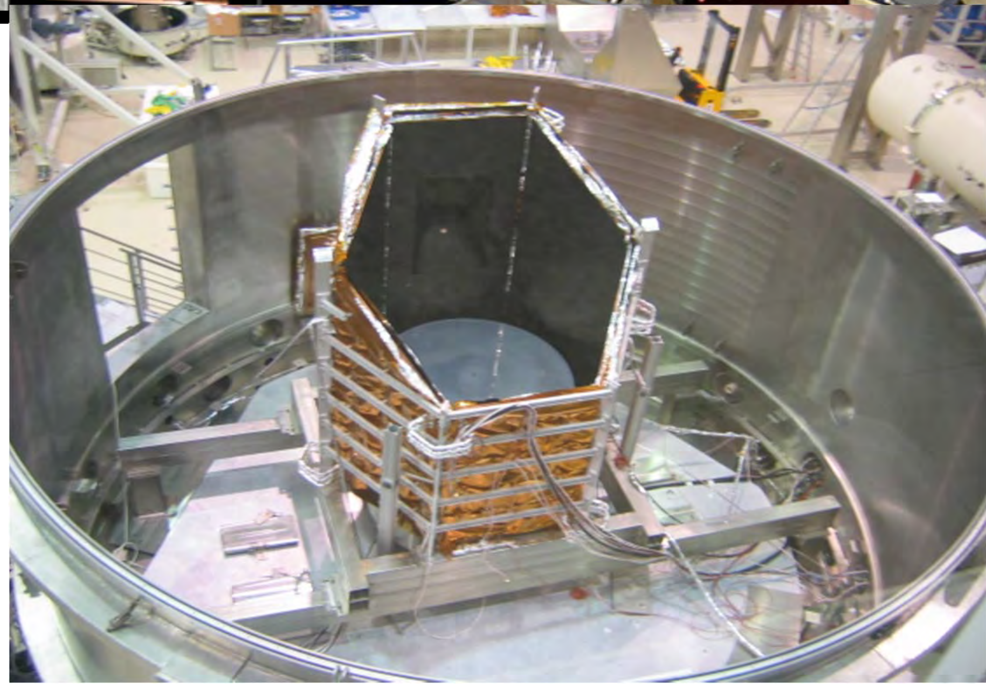
- Planck Telescope lessons learned
  - CFRP remains a challenging material system for high performance optical reflectors (mirrors), especially at cryogenic temperatures
  - Writing meaningful and clear specifications for telescope performance in the sub-mm is not easy – could have been done better (optical & RF engineers think differently!)
  - High (spatial) resolution surface form error metrology of large reflectors remains a significant challenge under cryogenic vacuum conditions
  - End to end telescope performance testing of Planck (at operational temperatures) proved to be unfeasible => a new approach needs to be determined for next sub-mm system
  - Multiple contractor procurement strategy was a significant disadvantage

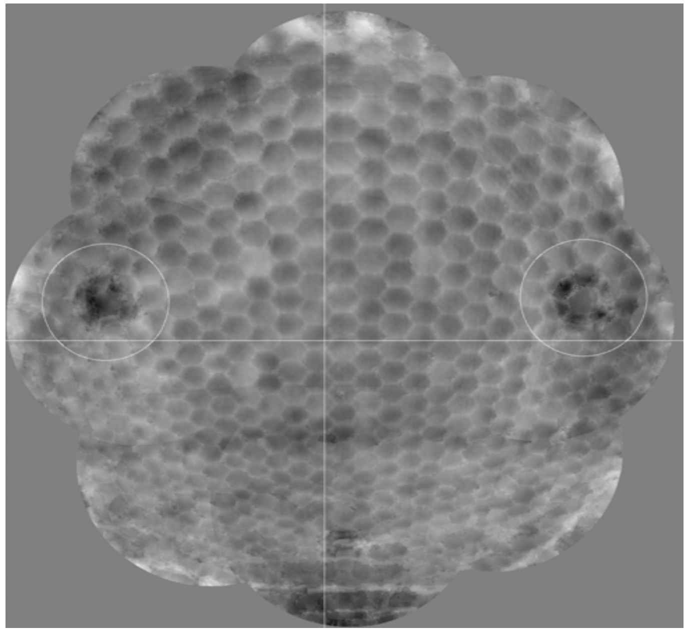
The Radio Frequency Qualification Model (RFQM) of the Planck spacecraft at the Compact Antenna Test Range of Alcatel Alenia Space in Cannes, at room T°.



We have to think "verification and testing feasibility" from the very beginning of the design





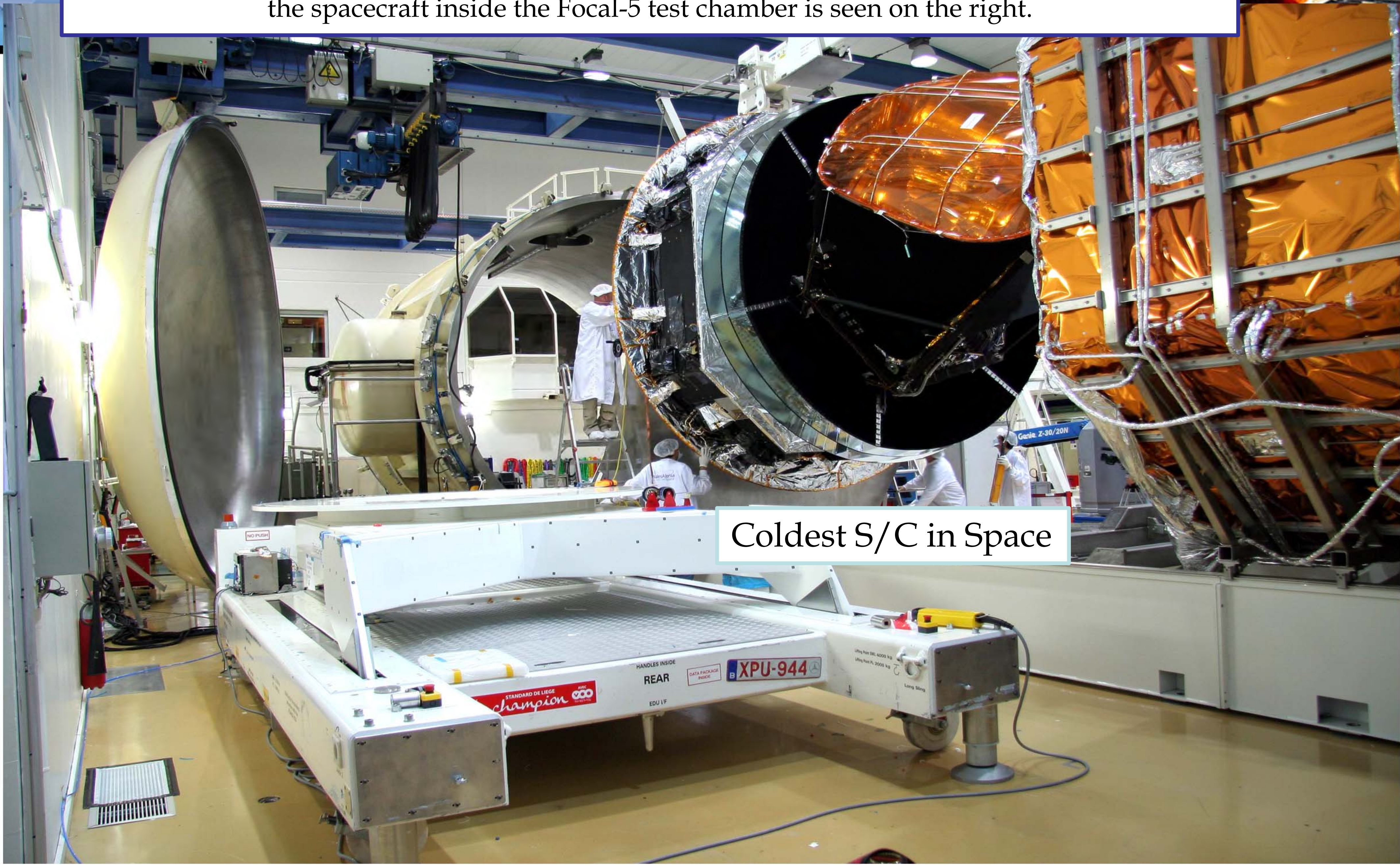


Planck Wavelength, 350 to 10,000 µm
Low Frequency Instrument (LFI) 30–70 GHz receivers High Frequency Instrument (HFI) 100–857 GHz receivers

Optical testing of PLANCK mirror by **IR** (10µm) interferometry at **cryogenic temperature (**at about 40 K**) at CSL**

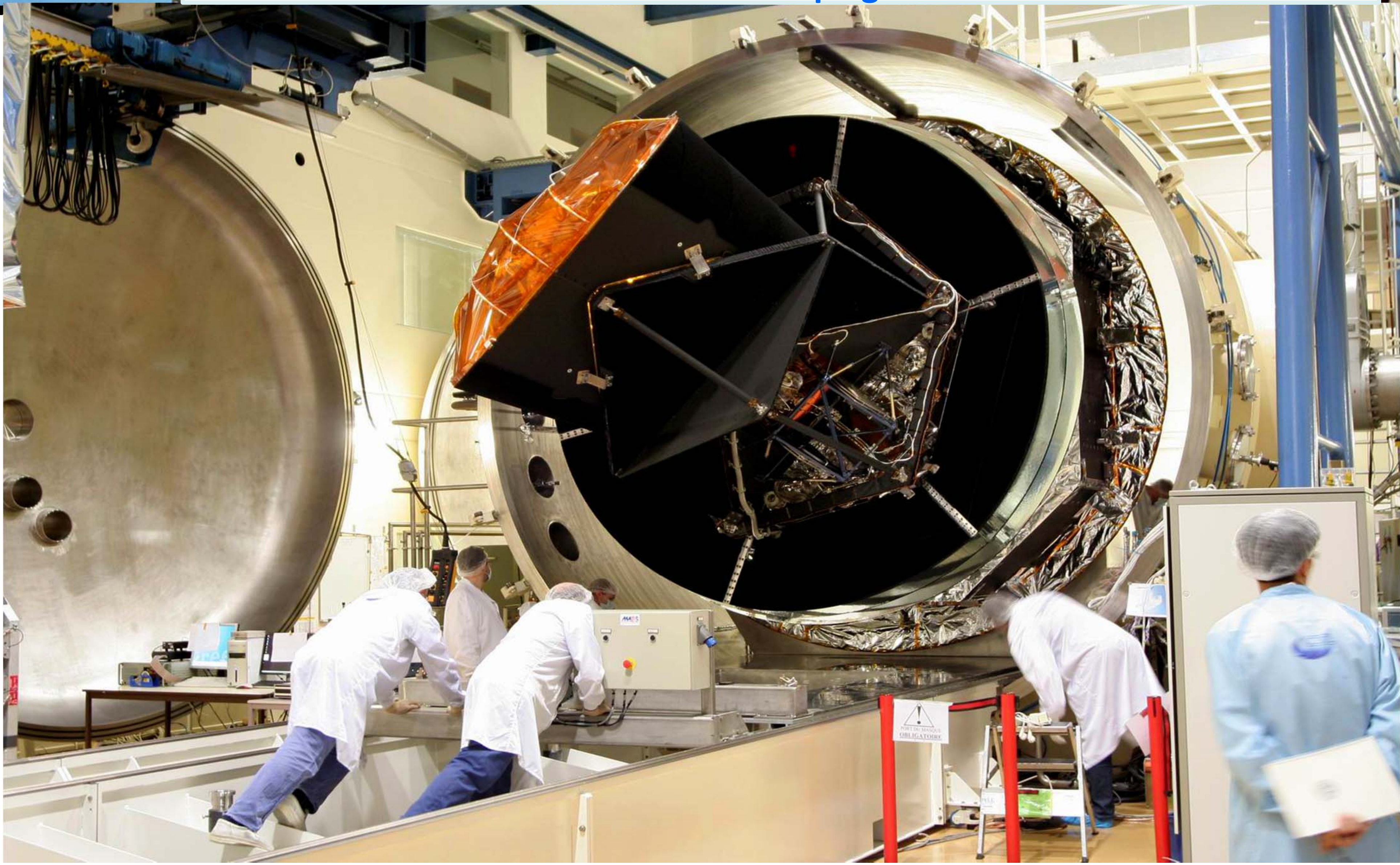
OGSE must always be 10 times better than the tested instrument

View of the Planck spacecraft during the preparations for the chamber fit check on 19 May 2008. The Focal-5 test chamber CSL is visible in the background and the thermal tent that will surround the spacecraft inside the Focal-5 test chamber is seen on the right.



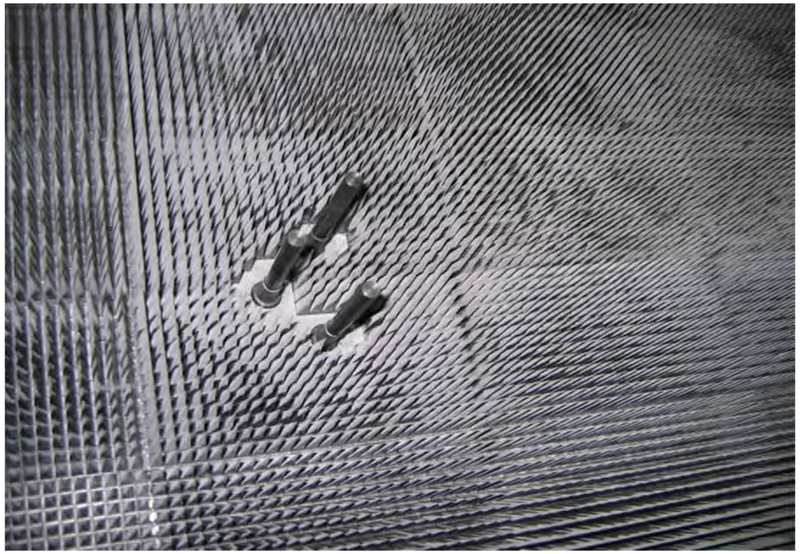
Coldest S/C in Space

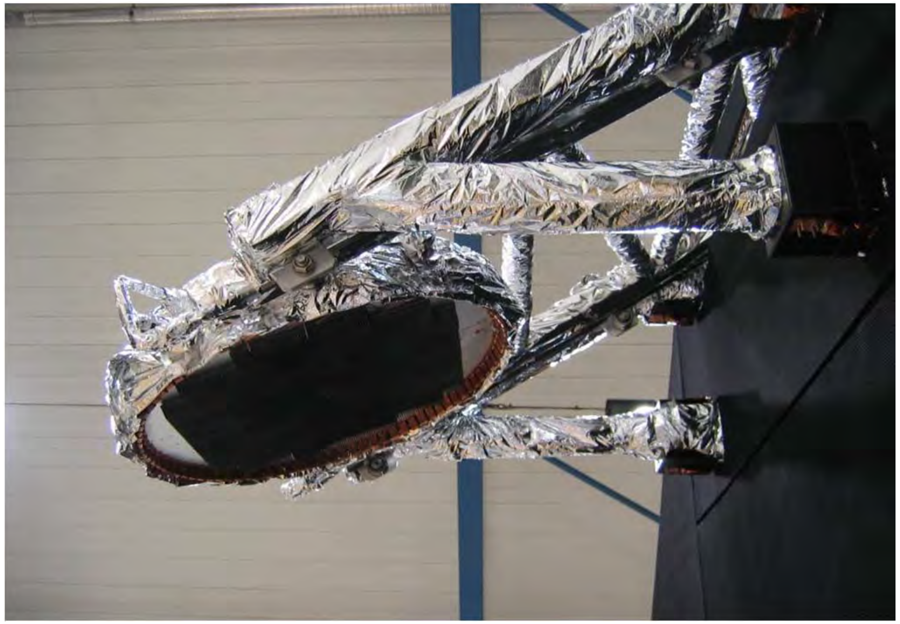
Secured in a horizontal position the Planck spacecraft is pushed into the FOCAL-5 vacuum chamber for Phase 1 of the thermal balance / thermal vacuum test campaign at CSL.

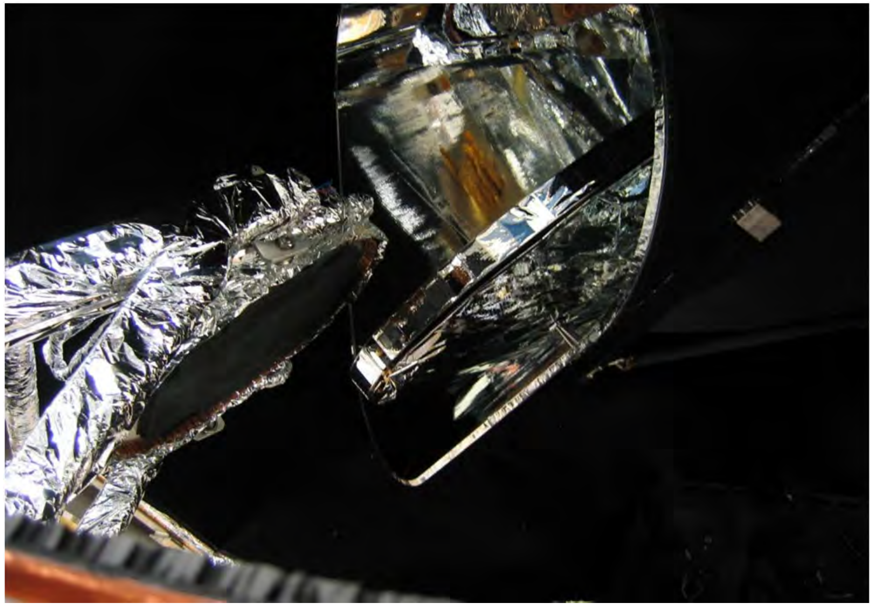


Planck S/C

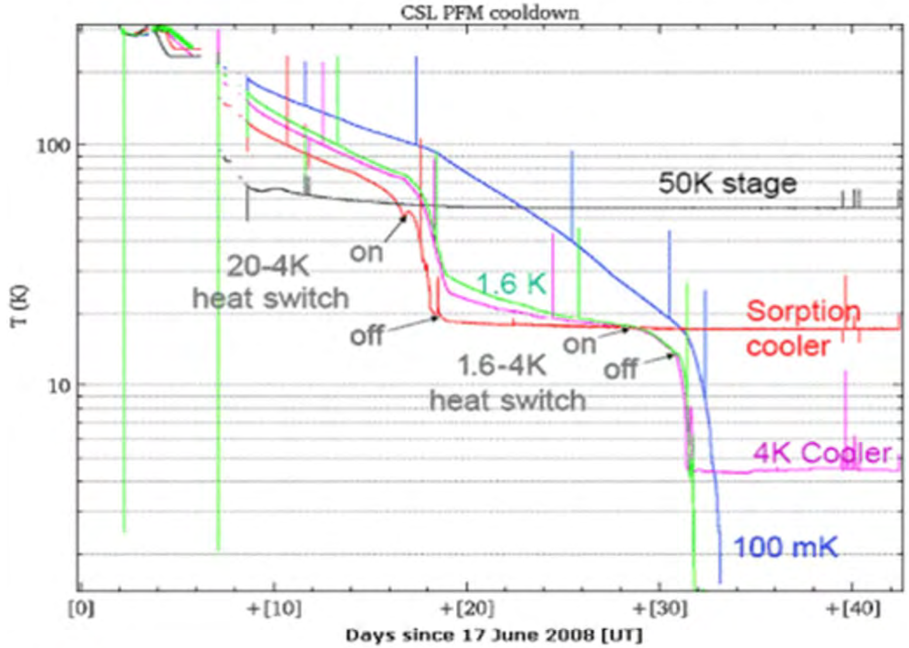
- Optical shield, for HFI/LFI verification
  - RF Black body
  - with IAS sources
  - inserted inside the telescope
  - LHe bath for T° stability
  - achieved better than 0.001 [K]

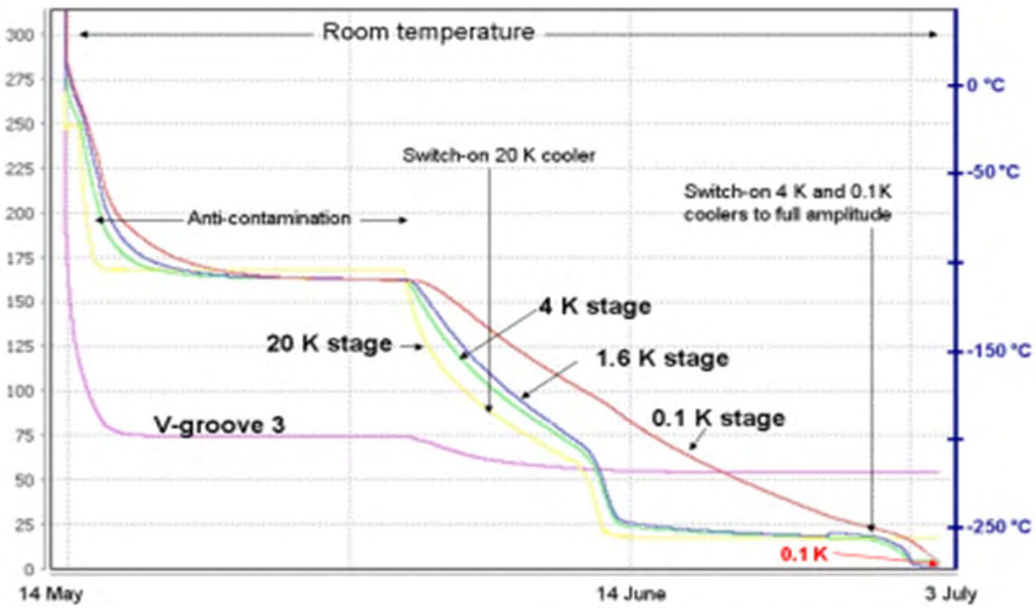






Planck S/Ccool down





HERSCHEL TELESCOPE

- Detailed Herschel Telescope design specs

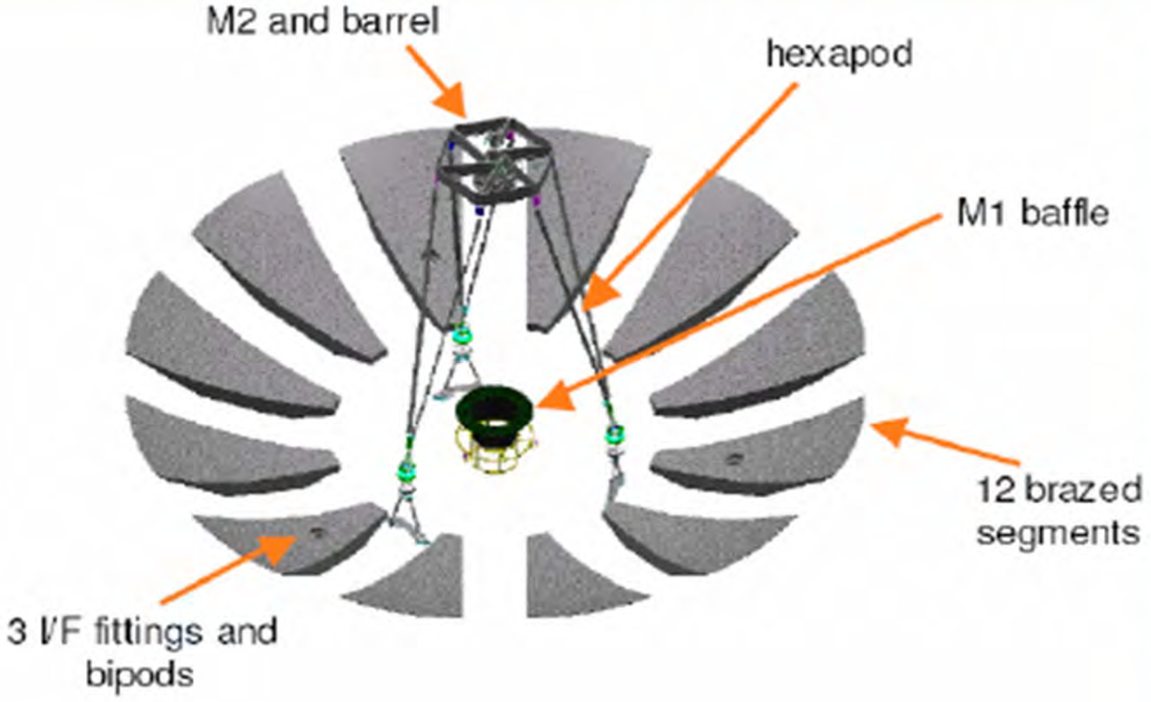


Figure 2-3: Exploded view of the Telescope

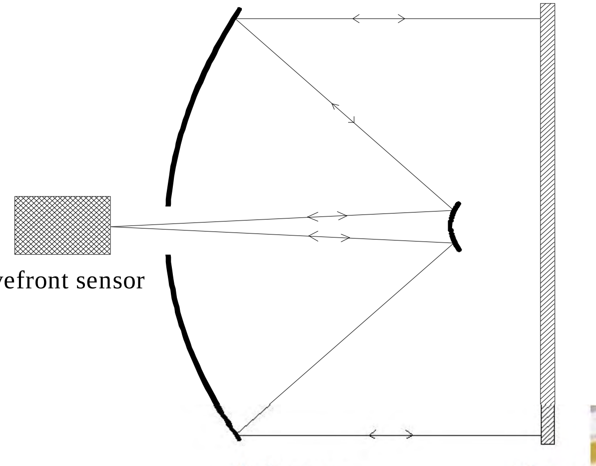
Primary reflector		
Radius of curvature	*3500 mm*	*± 2 mm (*)*
Conic constant	*-1*	
f-number	*f/ 0.5*	
(Free) diameter	*3500 mm*	*0, +2 mm(*)*
Secondary reflector		
Radius of curvature	*345.2 mm*	*± 0.4 mm (*)*
Conic constant	*-1.279*	*-*
Diameter	*308.1 mm*	*± 0.2 mm*
Image surface		
Radius of curvature	*- 165 mm*	*-*
Conic constant	*-1*	*-*
Diameter	*246 mm*	*-*

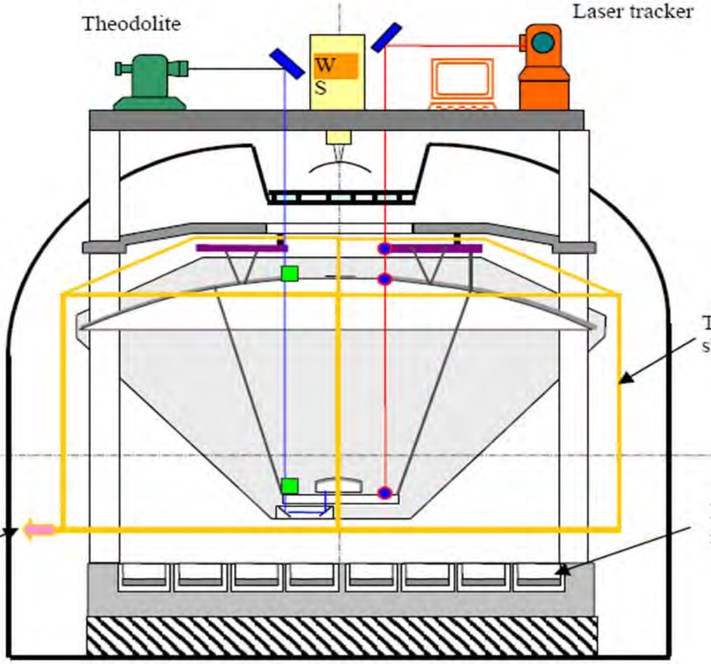
Focal length = 28.5 m (+/- 150 mm), f/no = 8.68 (+/- 0.02), Transmission 0.975

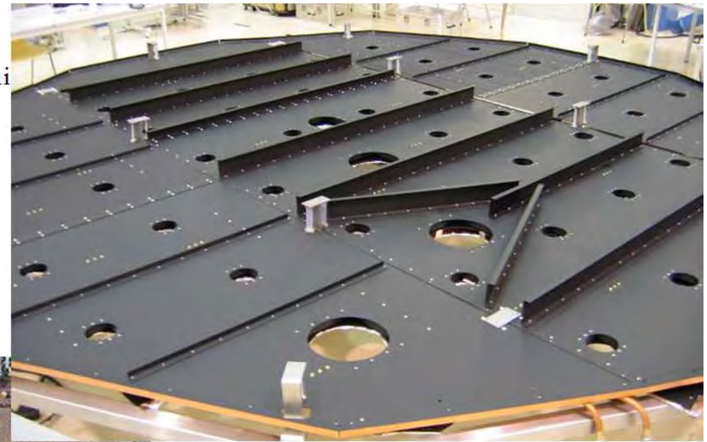
And the KILLER sensitivity => longitundinal magnification = 200 (10µm M2 = 2 mm delta focus)

Herschel telescope optical test

- 3.5 [m] diameter telescope
- optical testing at 60 [K]
- need of flat mirror
  - 3.5 [m] diameter ?
  - set of liquid small mirrors
  - lot of openings ⇒ shutters

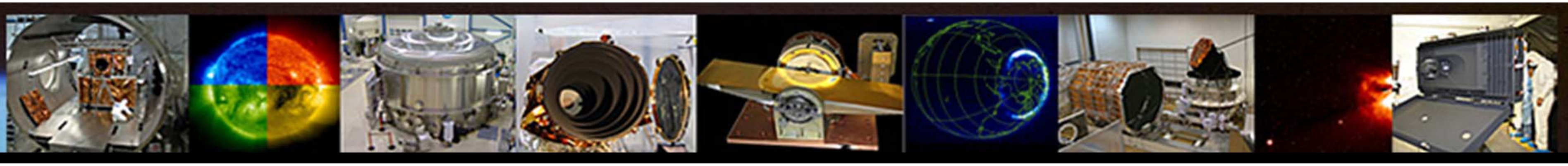






- **Herschel telescope requirements**
  - As large as possible (largest space telescope to date !)
  - As cold as possible 70K (for low emissivity) – passive cooling
  - As lightweight as possible (0.1 areal density of Hubble = 30 kg/m^2)
  - As stable as possible (thermal & mechanical)
  - Fixed focus (no mechanism risk at cryo) => “a-thermal” performance if possible [Build at ambient & operate at cryo]
  - Diffraction limited optical performance at < 90 microns (< 6 micron WFE rms)
  - FOV 0.25 degree
  - Optimised for minimum straylight
  - Must survive launch loads

  - Verification on ground at operational temperature, under vacuum and with gravity offloading (PM sags under it’s own weight)



- **Herschel chosen design:**
  - – Cassegrain (original concept RC)
  - – 3.5 m diameter primary
  - – Pupil on secondary (for stability)
  - – Anti-narcissus cone integrated into secondary
  - – Material system SiC 100 (sintered)
  - – Construction – modular from 12 petals & components
  - – Made to approx shape, ground & polished with diamond tooling
  - – Coating – Al & Plasil protective layer

HERSCHEL TELESCOPE

- **Herschel telescope metrology**

  - Dilemma; measure & verify performance with “good enough” accuracy under both room temp & cryogenic vacuum conditions (70 K).

  - Cool telescope efficiently without disturbing metrology tools

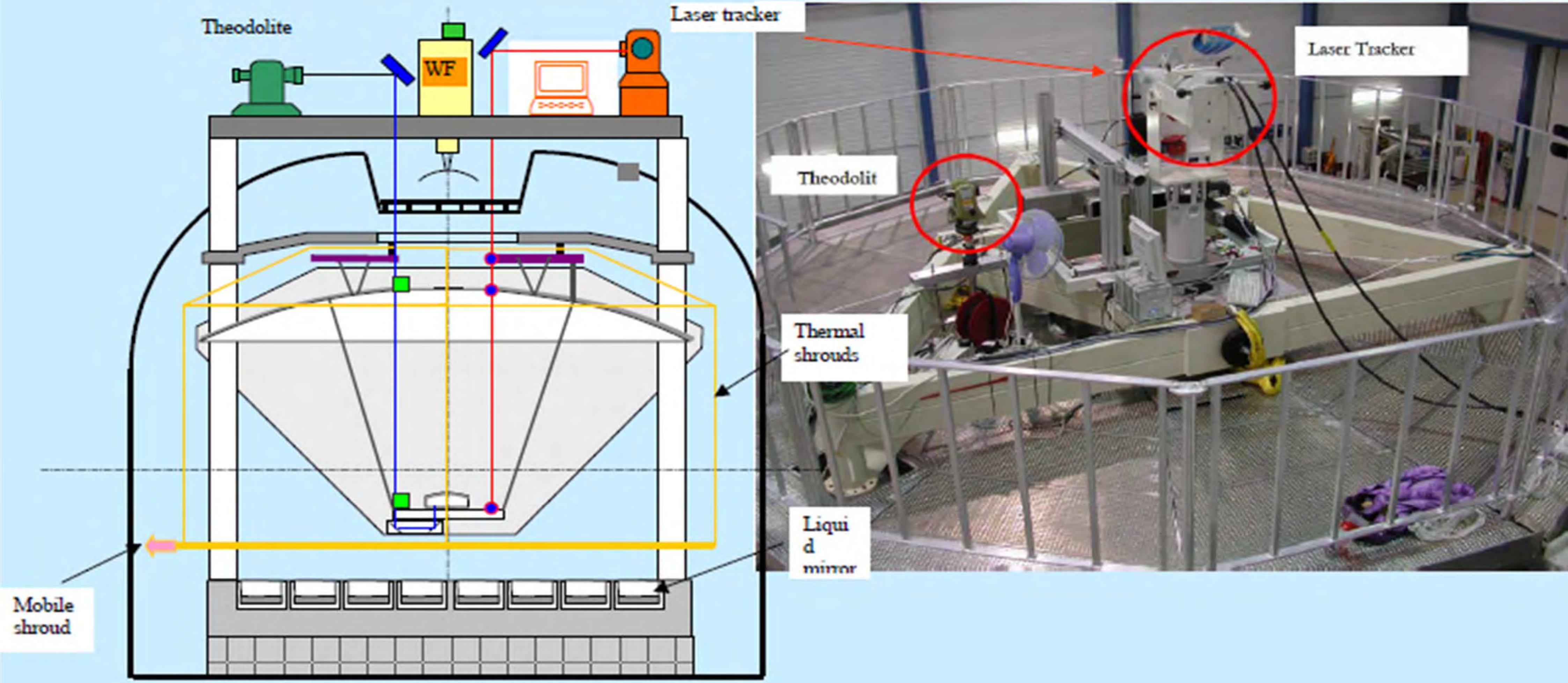
  - 3.5 m diameter auto-collimation mirror? BIG problems: Cost, Lead time, Manufacture, Calibration and thermal stability verification.
  - Decision: Use liquid mirror.

  - Choice: Interferometry or Hartmann

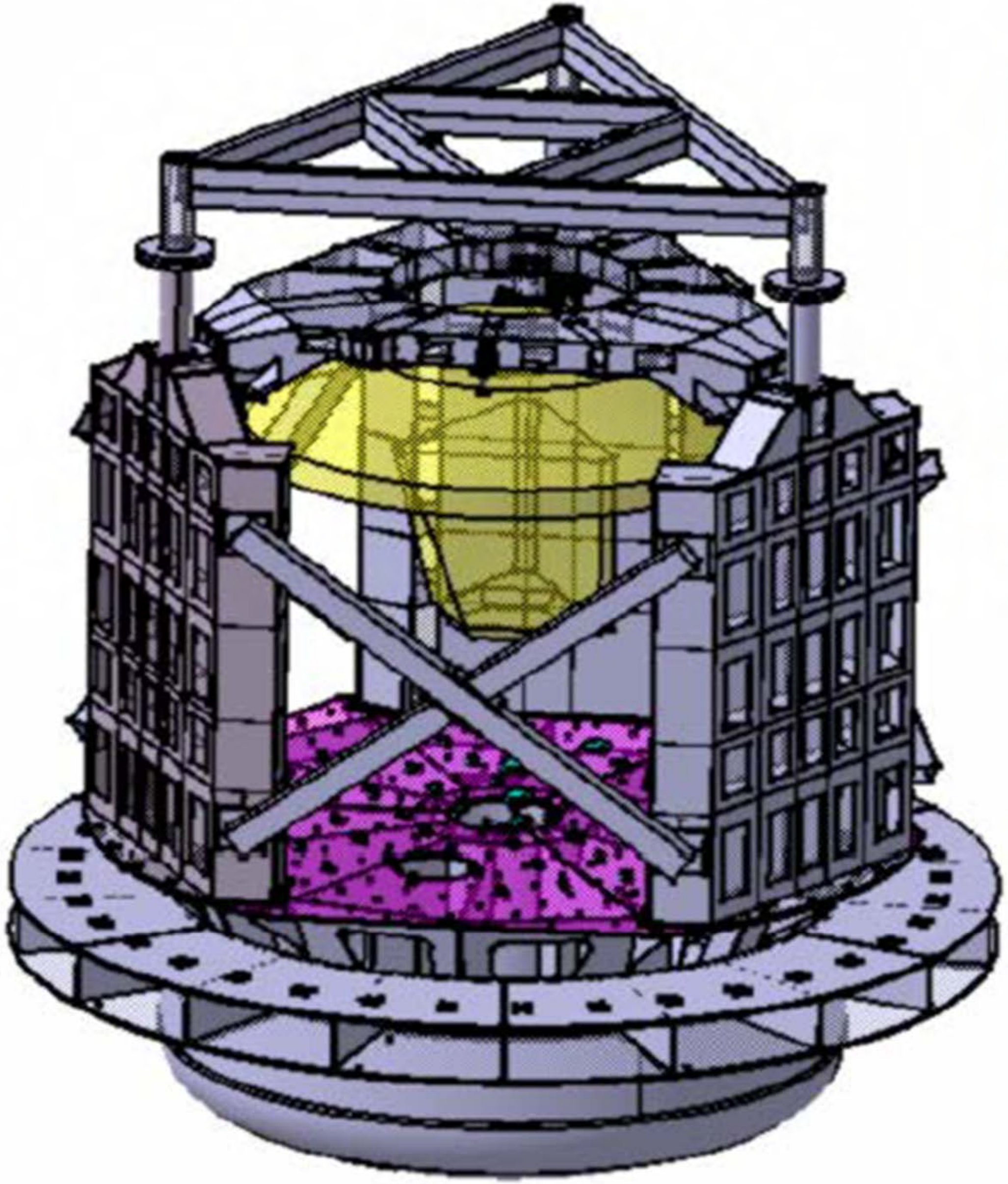
  - Decision: Hartmann => 2 steps 1) Full resolution (64 x 64 or 48 x 48) absolute WFE map @ ambient, 2) Low resolution (8 x 8) Delta WFE at cold temps. (with Leica Laser Tracker for WFS position measurements)

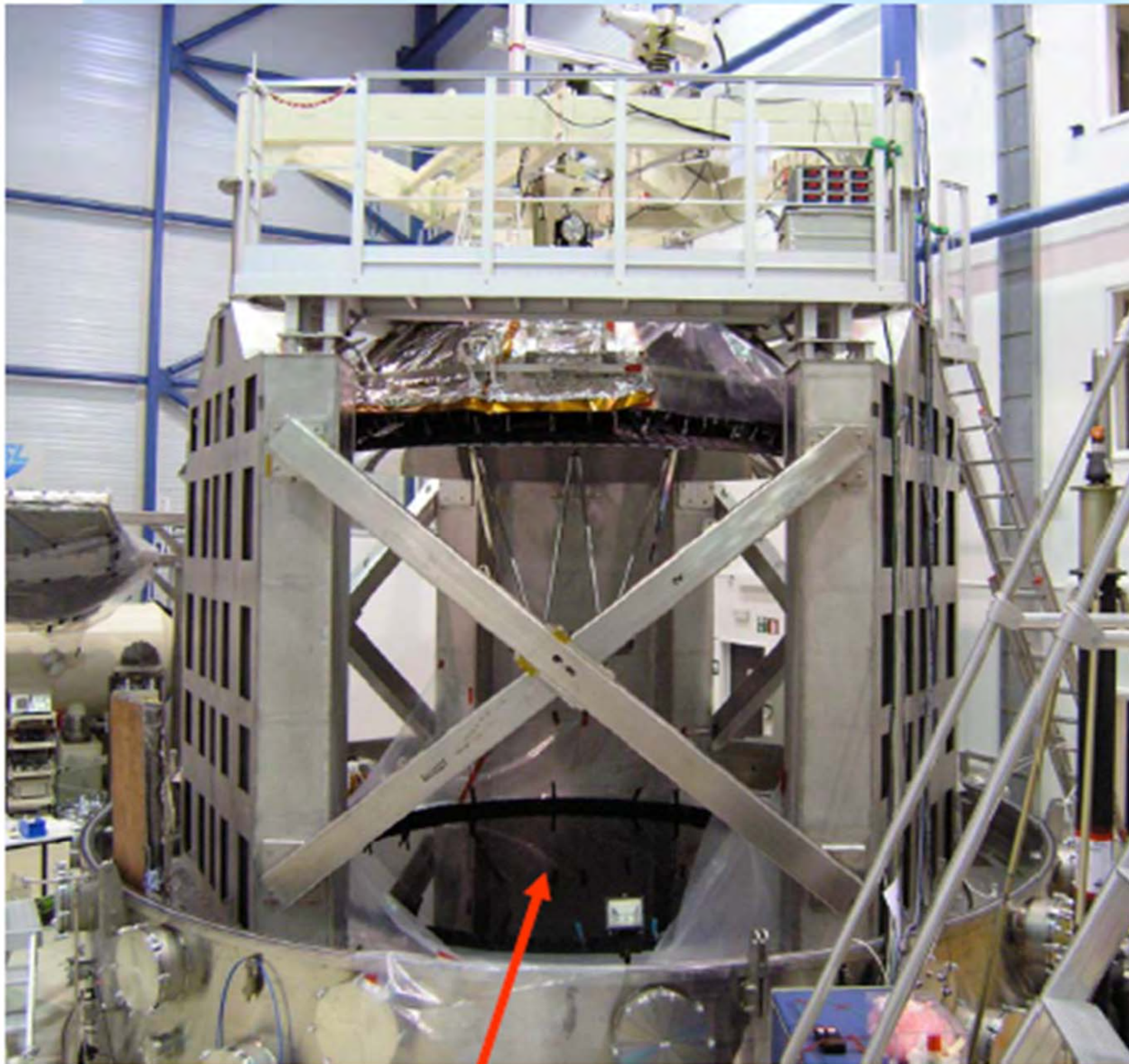
  - Major assumption => no high spatial frequency components induced (or changed) during cooldown.

- Herschel telescope test metrology



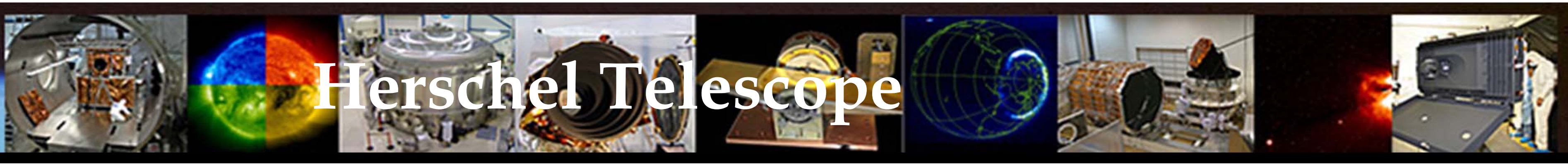
TESTS of HERSCHEL TELESCOPE



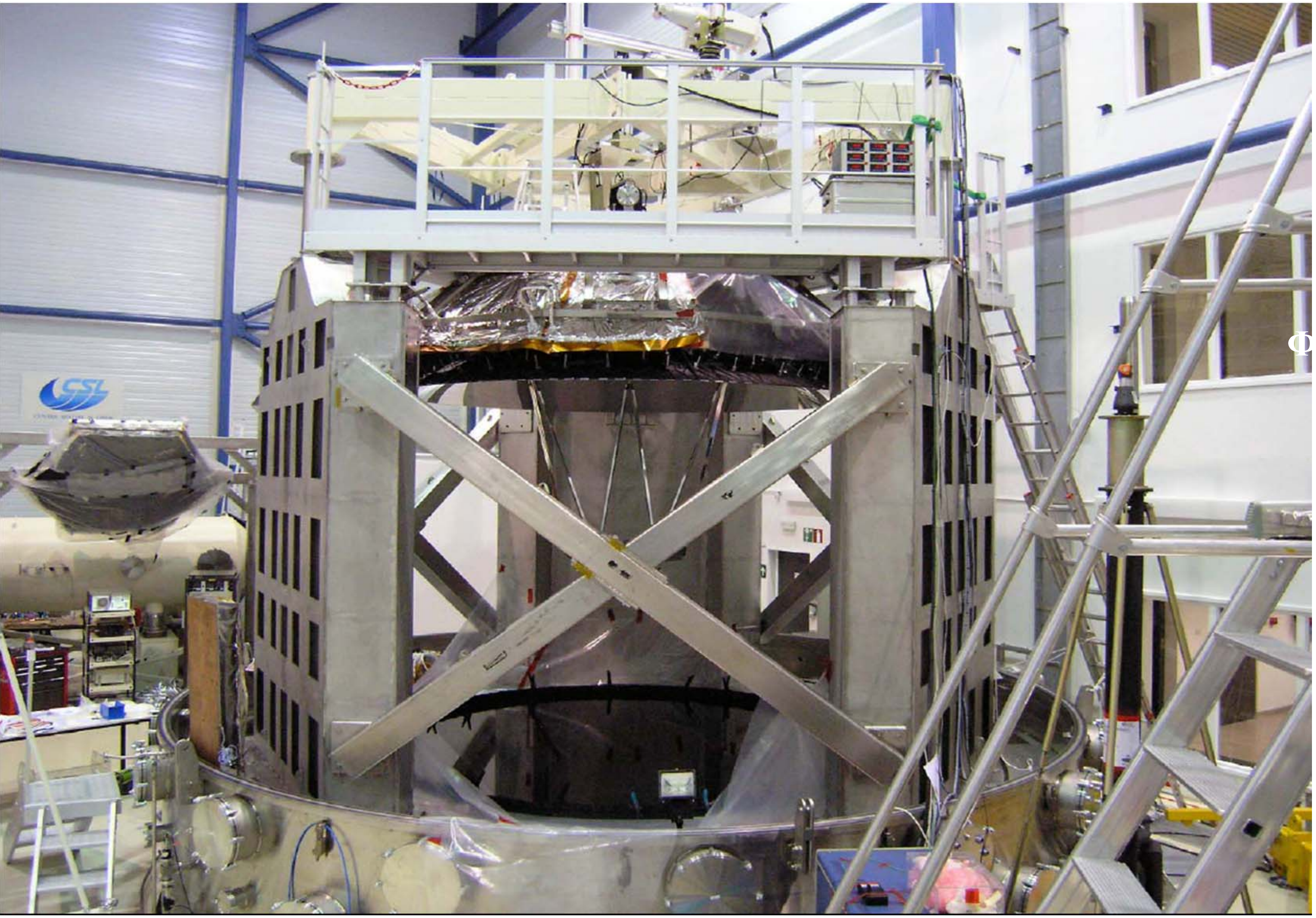


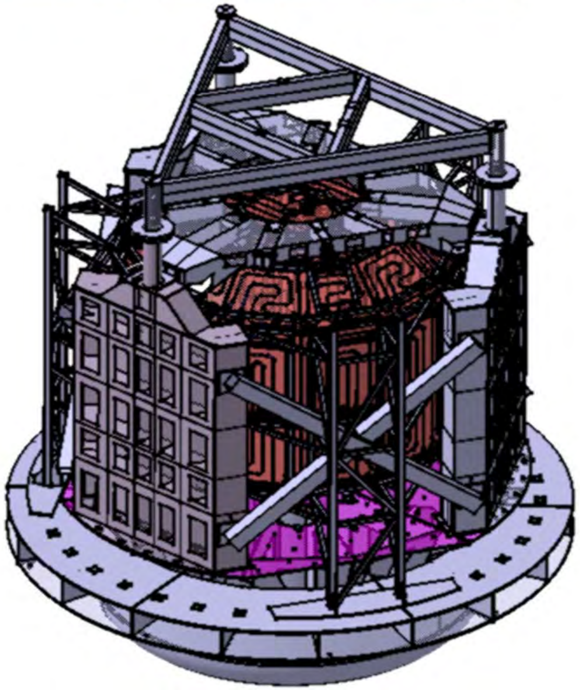
TESTS of HERSCHEL TELESCOPE

52 liquid mirrors are aligned on optical bench inside the chamber



Herschel Telescope



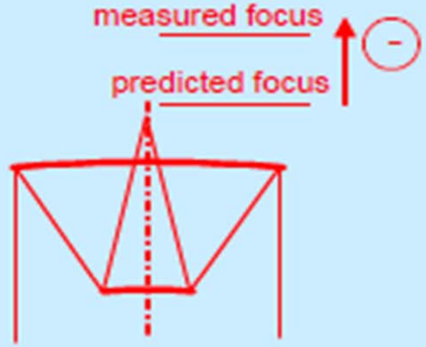


ASTRIUM (Toulouse, France), BOOSTEC (Tarbes, France),

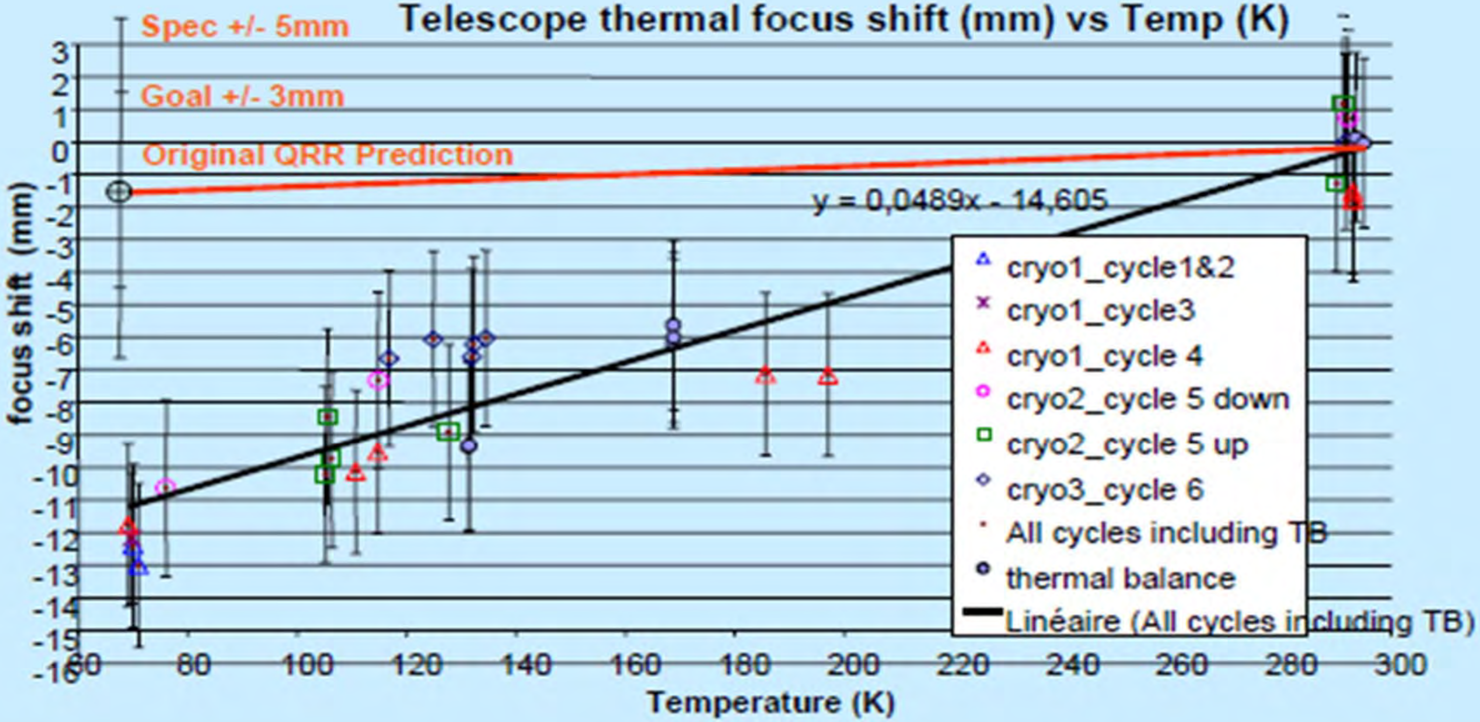
TESTS of HERSCHEL TELESCOPE

The test results revealed a problem

- Telescope design: Fixed focus & athermal
- As built: Focus moves with temperature – WHY?



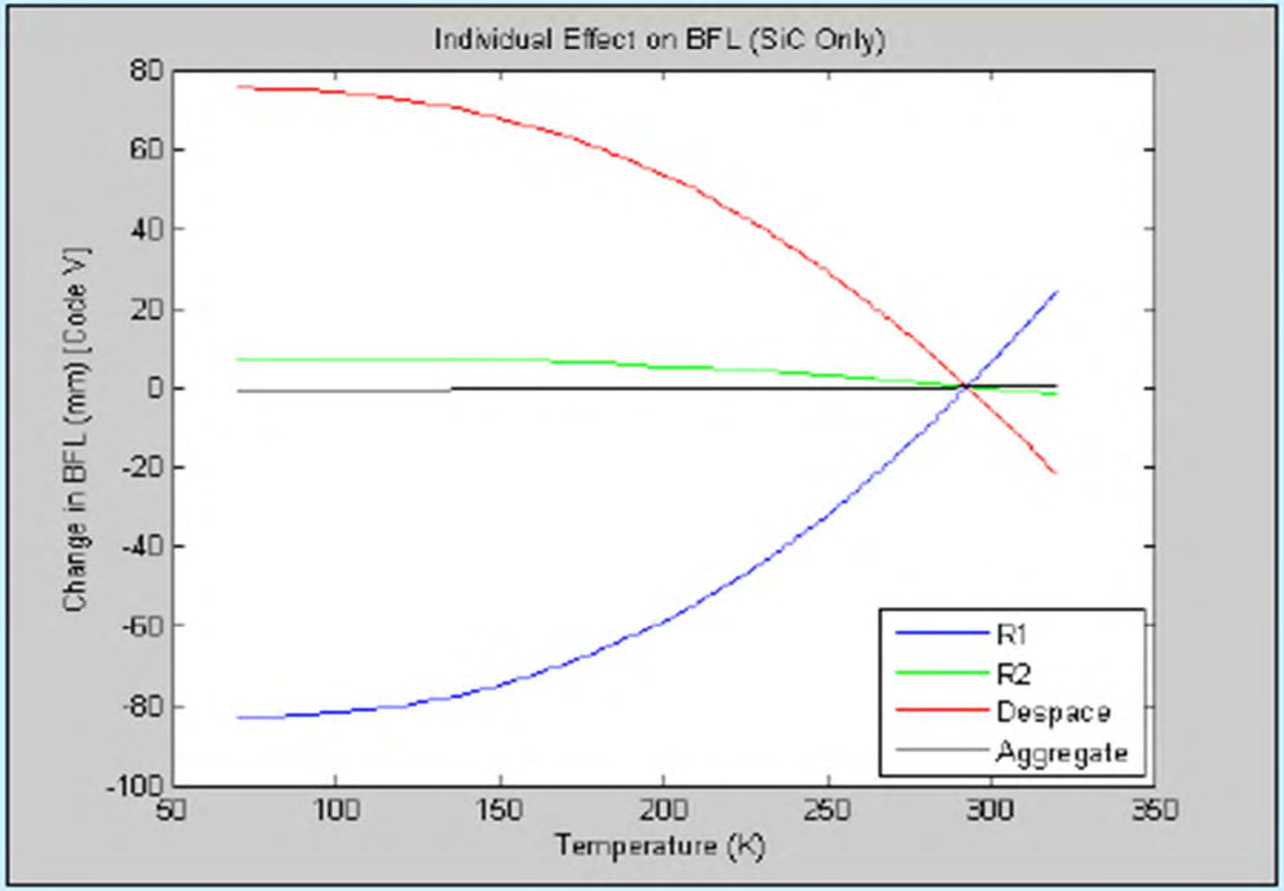
Anomaly = discrepancy between the measured focus shift at 70K (-11,7mm) and that predicted (-1.6mm, at QRR)



Why did we have a problem?

BFL is Difference of Large Numbers

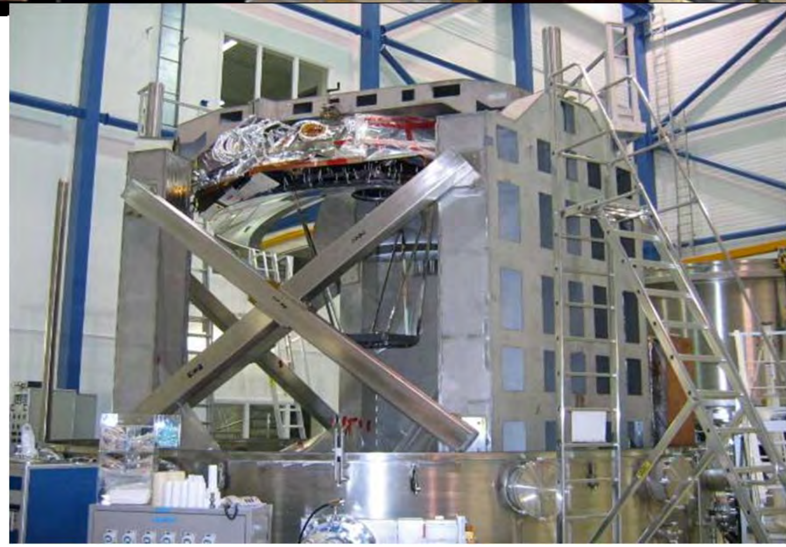
- R1 and Despace
- Despace vs temp is a function of delta CTE between Invar and SiC
- Example with Nominal Material Properties

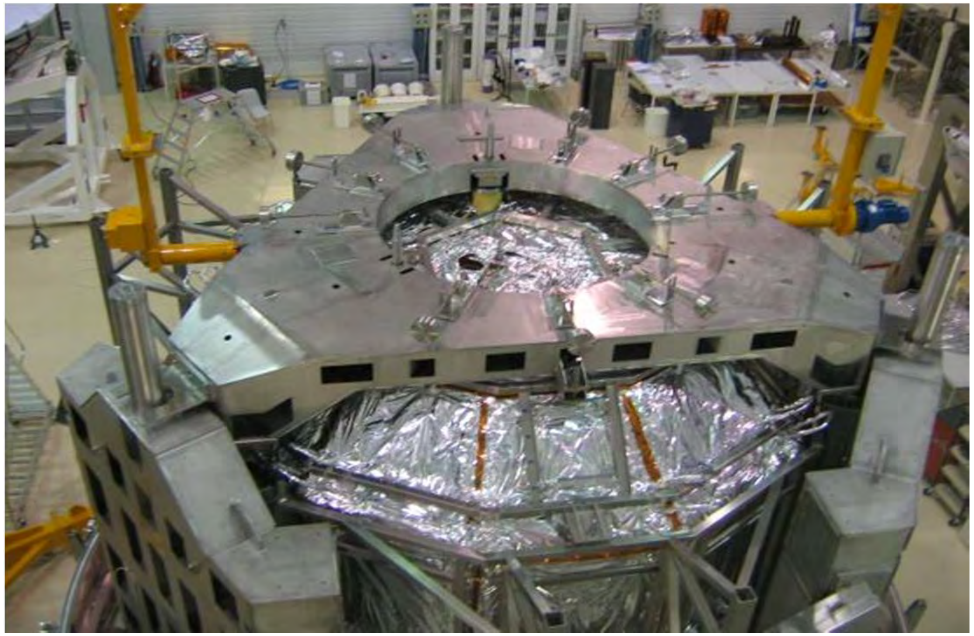


Herschel Telescope optical tests

High stability for Telescope
- 0-g system used
- 0 flux system at telescope interface

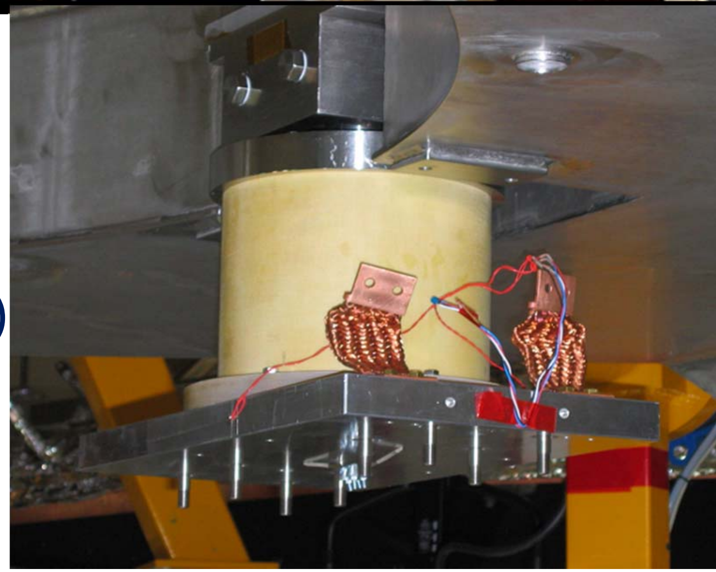
Inserted in thermal tent
- single wall for cost reasons
- thermal cycling 70 – 318 [K]

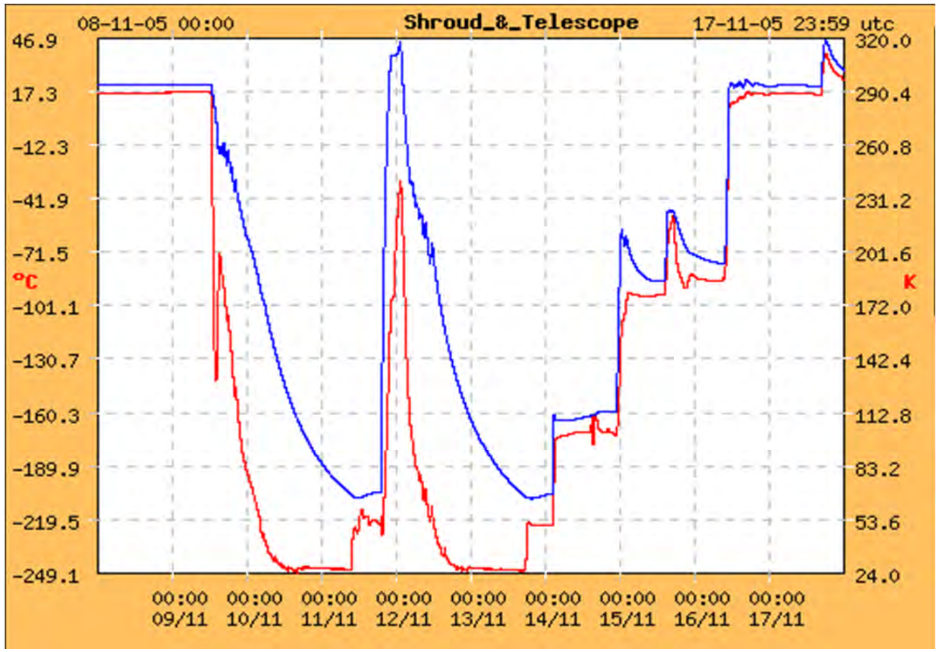




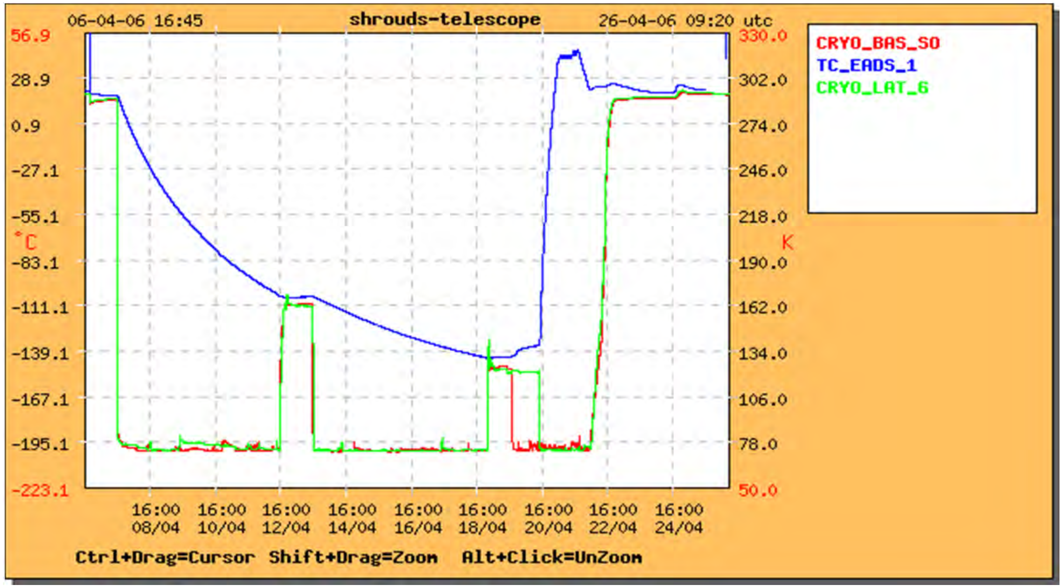
Thermal control

- straps / heaters at interfaces
- with IR lamps at rear side
- shrouds temperature adjustment (GHe or GN_2)





Telescope cycling



Thermal balance with gradient simulation

- Materials in the optical cavity of the telescope

–SiC–CTE values measured 1.03 to 1.52 ppm/K

–M93 Invar -CTE values 1.35 to 1.93 ppm/K

–Measurements made over several years in different labs.

–Choice made for values included in FEM model

–=> Prediction of cold focus based on this model

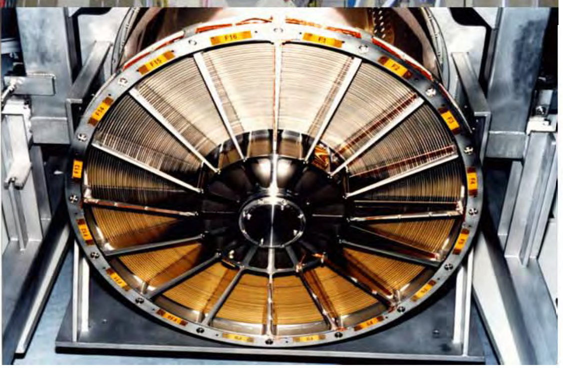
–Delta CTE(SiC–M93) 0.1 to 0.7 ppm

- Insufficient CTE measurement accuracy achieved at cryogenic temperatures

Herschel Telescope lessons learned

- At cryogenic temperatures accurate knowledge of every material properties is always critical
- Testing optical performance of large telescopes under cryogenic vacuum conditions is NOT easy => always leave margins for unexpected problems
- Always use different tools (and independent experts) for analysis of difficult problems; complementarities & cross-verification can be vital
- Single contractor approach very good

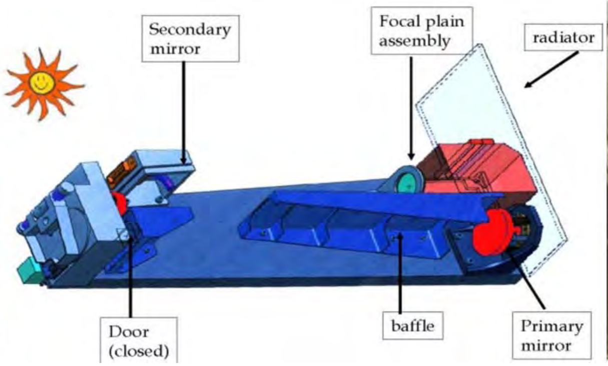
Lessons learned

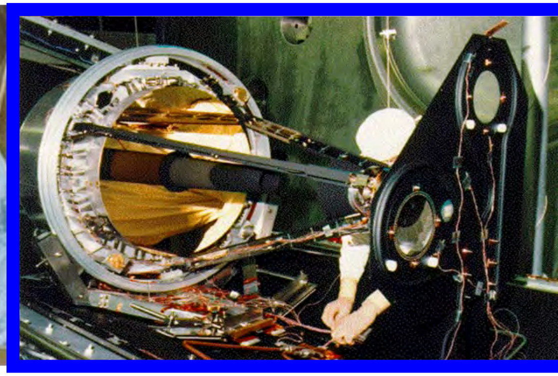


Telescopes tested at CSL

Lessons learned

	Functioning wavelength range	Test wavelength
Herschel	60 to 670 µm	V Shack Hartmann
Planck	HFI : 100 GHz to 857 GHz (6 Bands), 30 GHz to 70 GHz (3 bands)	IR interferometry
XMM NEWTON	1 - 120 Å (12 keV - 0.1 keV)	EUV collimator
EIT, SWAP, EUI	17.1, 19.5, 28.4, 30.4 nm	ZYGO 543.5 nm
ISO	2.5 to 240 µm	ZYGO 543.5 nm



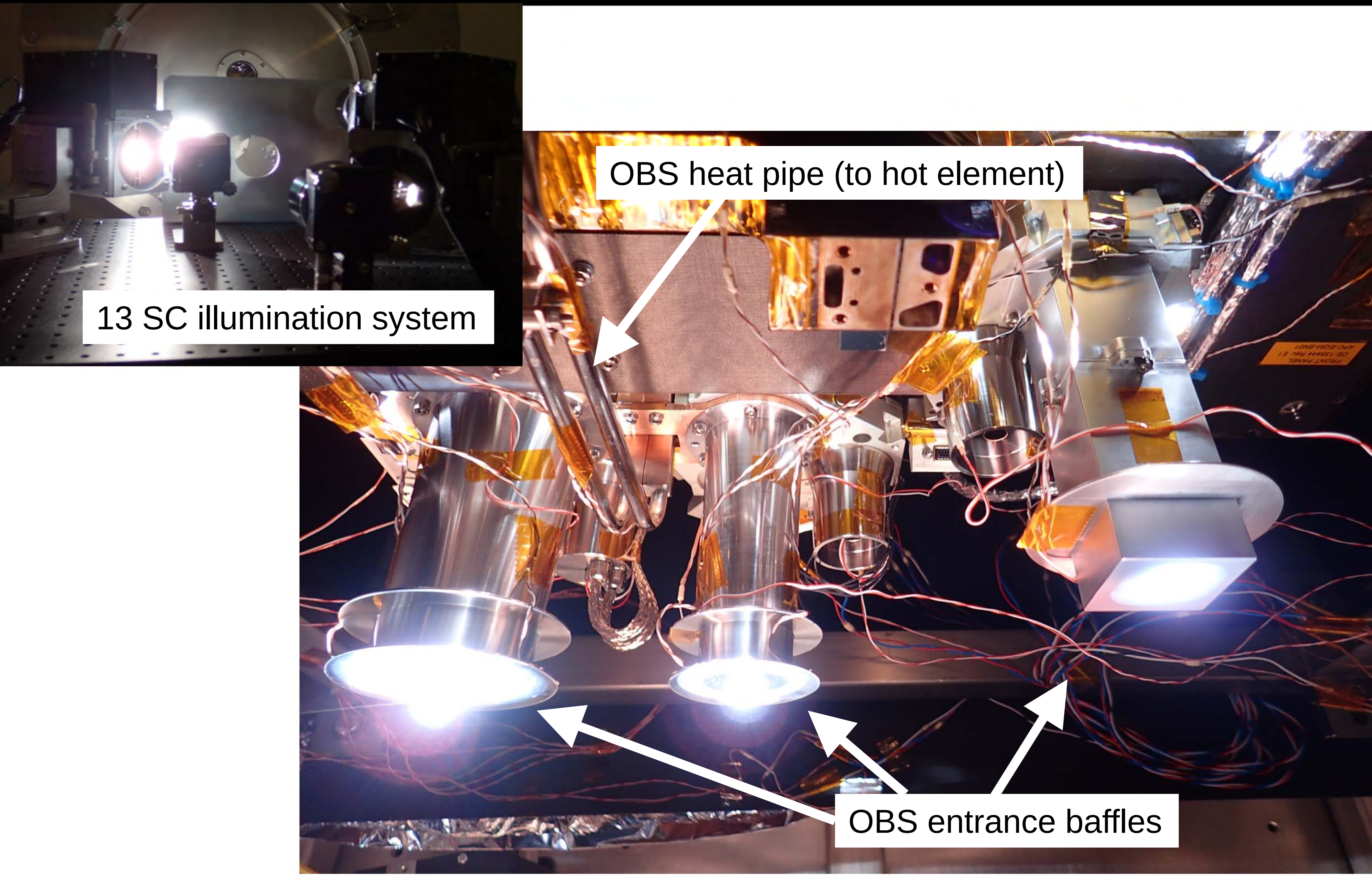


Tests of Gaia

Gaia will create a three-dimensional map of the Milky Way, revealing information about its composition, formation and evolution. The mission will perform positional measurements for about one billion stars in our Galaxy and Local Group with unprecedented precision, together with radial velocity measurements for the brightest 150 million objects. Gaia was **launched** on the **19th of December 2013** for a nominal five-year mission, with a possible one-year extension.
The spacecraft will operate in a Lissajous orbit around the second Lagrange point of the Sun-Earth system (L2). This location in space offers a very stable thermal environment, very high observing efficiency (since the Sun, Earth and Moon are all behind the instrument FoV) and a low radiation environment.

Thermal balance and thermal vacuum testing of the Gaia Flight Model (FM) Payload Module (PLM) from early November to mid December 2012. The actual test process lasted 40 days without interruption and was designed to verify the thermal performance of the payload.
Particular attention was paid to the **thermoelastic behaviour** of the module and the possible effects of thermal perturbations on the basic angle ('Gaia Basic Angle Monitor delivered for integration' for an explanation of the basic angle).
A fully functional Video Processing Unit (VPU), normally part of the Service Module (SVM), was located outside the vacuum chamber and connected to the Focal Plane Array (FPA) in the PLM.
The passage of star images across the FPA was simulated during the tests, allowing end-to-end performance measurements under realistic thermal conditions.

EUI in a 13 SC simulator



Story of IAL Space / CSL in short

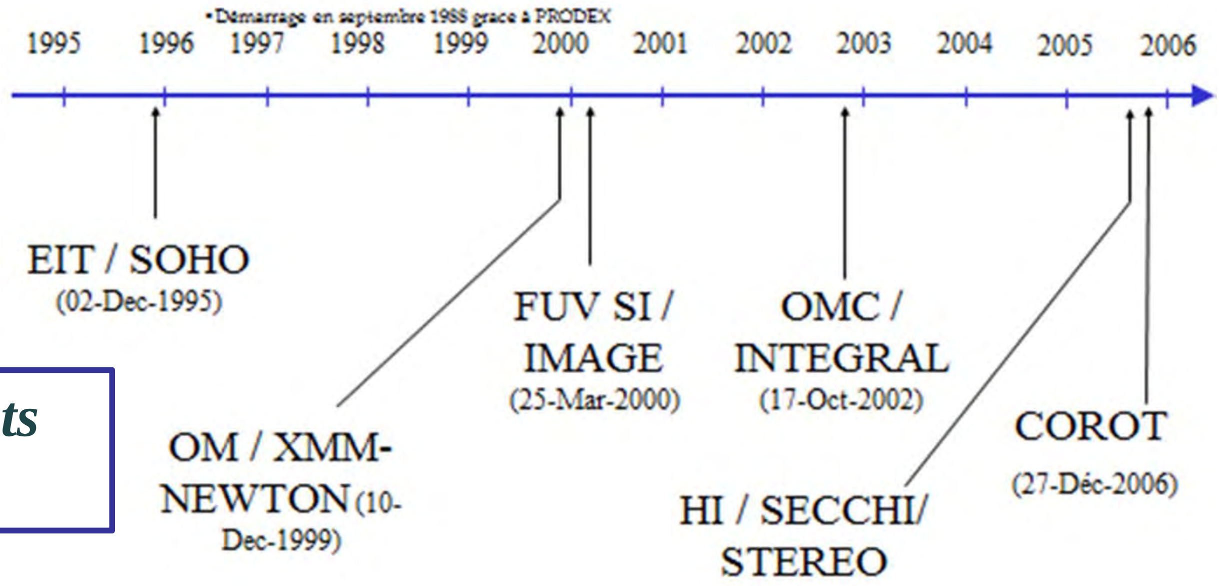
The story of CSL can be simplified in different periods corresponding to small changes in activities and orientations.

Period 1 (1960-1975): Space Instruments and the research associated to the in house developed instruments

Period 2 (1975 -1988): ESA Coordinated Test Facility associated with assembly, alignment, calibration, space qualification of Remote Sensing Instruments for ESA Science or Earth Observation Directorates, coming from ESA or European Industry. During that period, the fundings for in house Space Instruments and associated research were drastically reduced.

Period 3 (1988 à 1999): With the creation of PRODEX in 1986 and the adoption in Belgium in 1991, funding became available on a more regular basis for the development of Remote Sensing Instruments up to launch (without the associated research which became funded to other Institutes associated to CSL); this started slowly in addition to the ESA Coordinated Test Facility; CSL got an Institute Agreement in the frame of PRODEX. The first instruments developed under PRODEX are outlined in Figure 2.

Space Instruments developments between 1988 and 2005



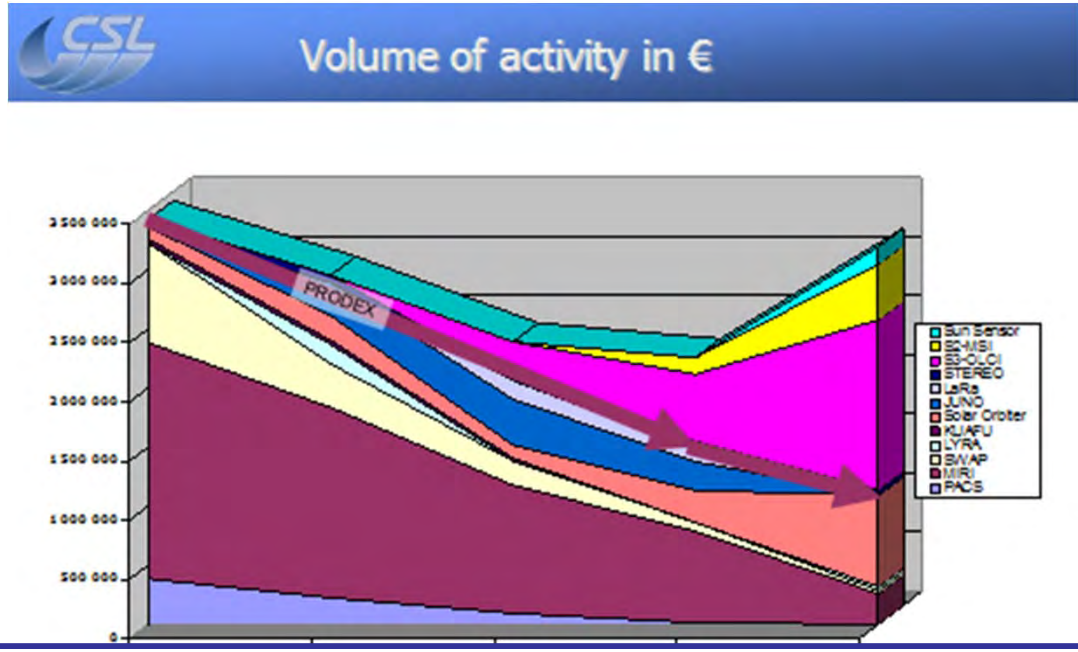
Story of IAL Space CSL in short

Period 4 (1999-2005): In addition to the already existing activities, the University of Liège and the Walloon region push **CSL to develop new products and create around 10 Spin-offs** in the domains of **Optical Metrology, Earth Observation image analysis, LASER technologies and others.**
CSL was at the origin of the creation in 1999 of **Wallonia Space Logistics (WSL)** an incubator which is focused on technologic start-up firms whose technologies are most of the time the result of spatial R&D projects. The incubator's mission is to support young entrepreneurs coming mainly from Walloon universities in creating their company, to help to get it going and to accompany the project during its first years of growth so as to contribute to increase the number of high tech firms in Wallonia.

Period 5 (2005 - now) : While CSL is still performing tests for ESA and Industry, this is no more coordinated as an ESA Coordinated Test Facility since 2005 but due to the specific tasks realized by CSL and the expertise of CSL in Optical metrology (ISO, NEWTON, Tiger team on Herschel Telescope, PLANCK optical testing, …) and in Straylight Testing and Simulation (COROT and CHEOPS baffle, STEREO HI, SO HI, SPP WSPR, PROBA V), CSL becomes a

Center of Excellence in Optics.

From that period, the Space Instrumentation development is no more limited to PRODEX and the Science Directorate but also to **Industrial Contracts for Earth Observation Instruments and subsystems**. (See Figure).



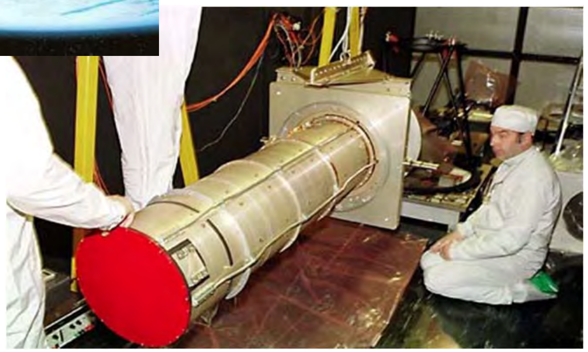
The volume of Space Instrumentation activities for PRODEX under the arrow was decreasing and this was partly compensated by the volume of Space Instrumentation under Industrial contracts.

Past Projects (1/2)

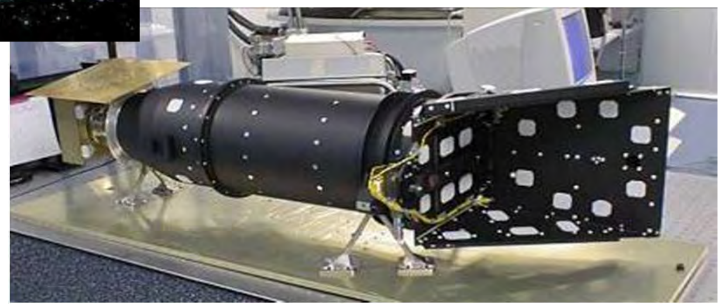
SOHO/EIT (1995)

IMAGE/FUV-SI (2000)

XMM/OM (1999)



INTEGRAL/OMC (2002)

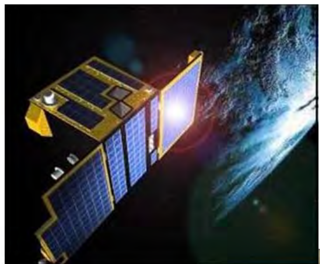


Past Projects (2/2)

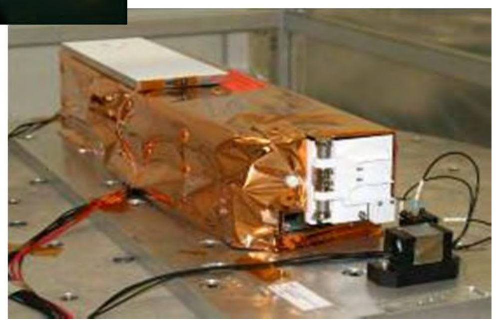
STEREO/HI (2006)

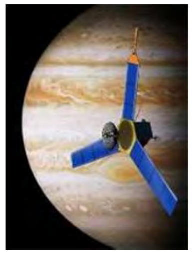
CoRoT (2006)

Herschel/PACS (2009)

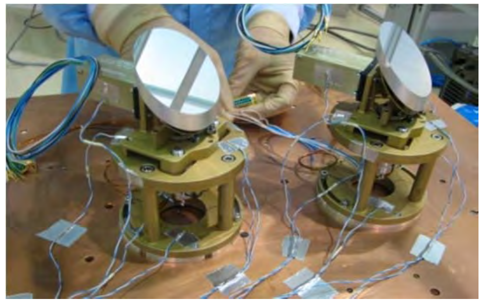


PROBA-2/SWAP & LYRA (2009)





JUNO/UVS (2011)

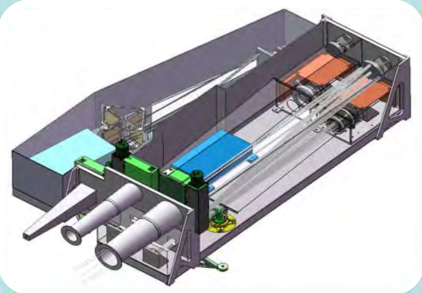


Products & Services: 3 Business Lines

Testing (Resp. Christophe Grodent)

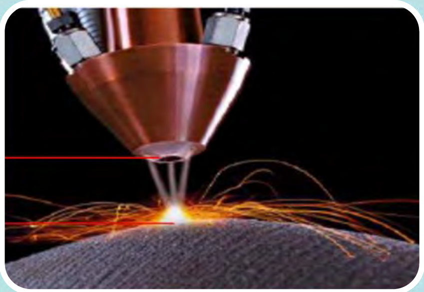
- Environmental test services (thermal-vacuum, vibration…)
- Development of test systems (thermal systems…)
- Rare & complex test equipment

ISO, NEWTON, HERSCHEL Tel, PLANCK, GAIA, PROBAV, TROPOMI, …, 3MI



Space Systems (Resp. Etienne Renotte)

- Space mission studies
- Space instrument, payload elements
- Technology development for space applications
- Ground calibration, ground support equipment

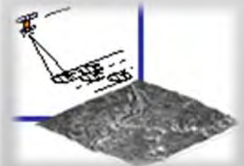


Technological Partnering (Resp. Jean-Hervé Lecat)

- R&D support, expertise to industry
- Technology upgrade or validation (TRL raising)
- Technology transfer and services
- Customized training

Competences

Signal Processing
Ch. BARBIER



• Image & Data processing (mainly SAR)

• Optical and spectral data processing

• Training

Surface Engineering
K. FLEURY

•Surface coating for space applications

•Surface micro texturing

•Laser Ablation process

•Ion Beam Polishing

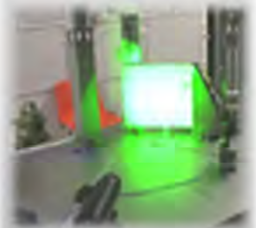
Electronics
N. MARTIN

• Space adapted (extreme temperature, vacuum, radiation) electronics

• Smart Sensors

• Design of ITAR free solutions.

Lasers & NDT
M. GEORGES



• Optical Non Destructive Testing (holography, interferometer, IR, …)

• New materials control (composites, high tech metals, …)

Optics : Design & Metrology
Y. STOCKMAN

• Innovative optical and spectral payloads design

• Optical system calibration in space. Optical metrology.

•Straylight simulations

•BRDF calibration.

Thermo-mechanical Design
JY. PLESSER9IA

• Advanced thermal models

• Cryo expertise

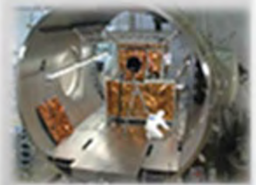
• Solar Energy efficiency

• Space payload mechanisms

• Design of GSE facilities

Test Center

I. TYCHON

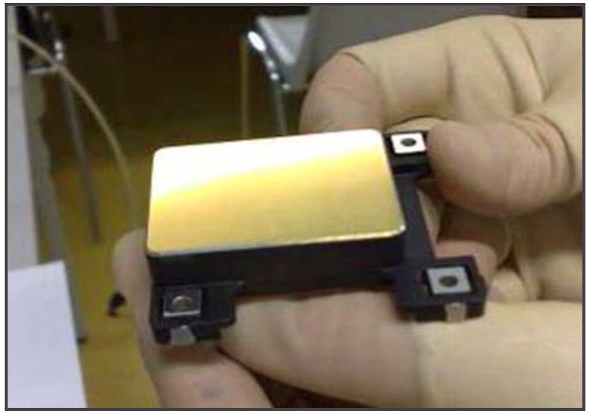


• 5 ThermalVac facilities equipped with optical bench

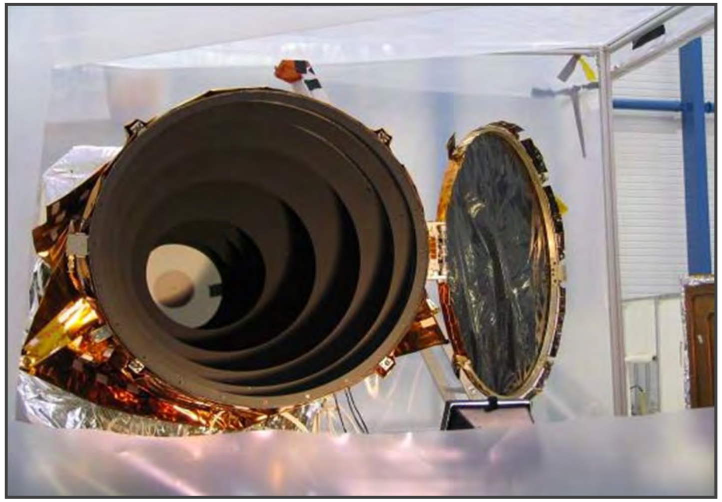
•Clean room class 10000 (& 100 locally)

•2 Vibration shakers..

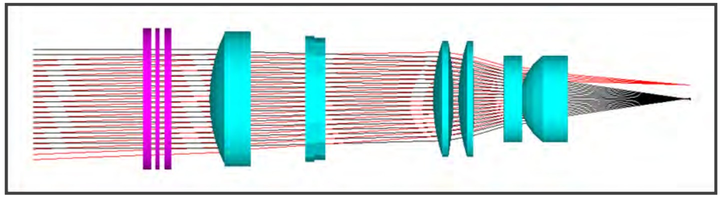
Optical Systems



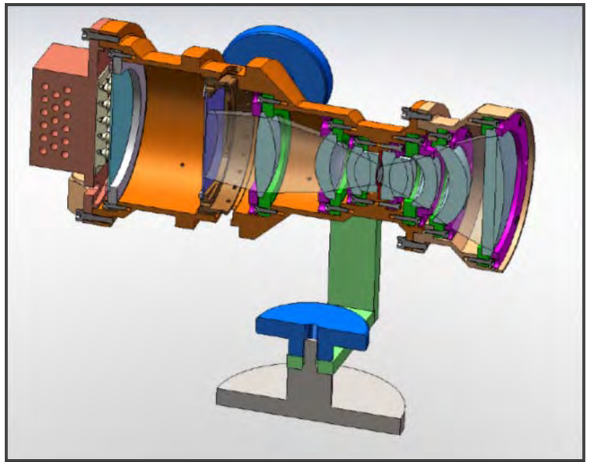
Optics & coatings

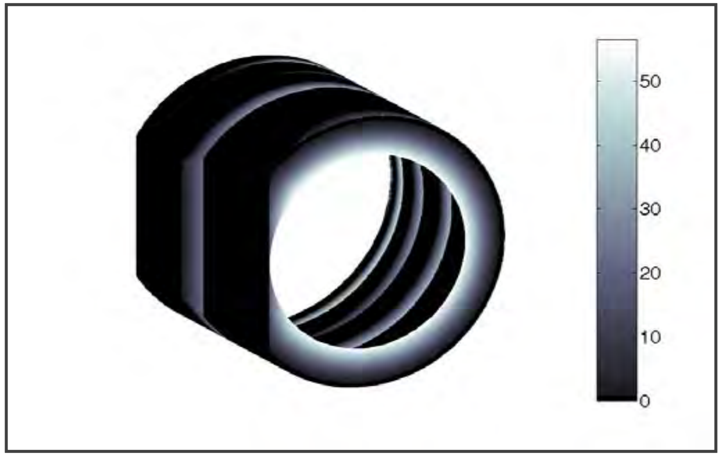


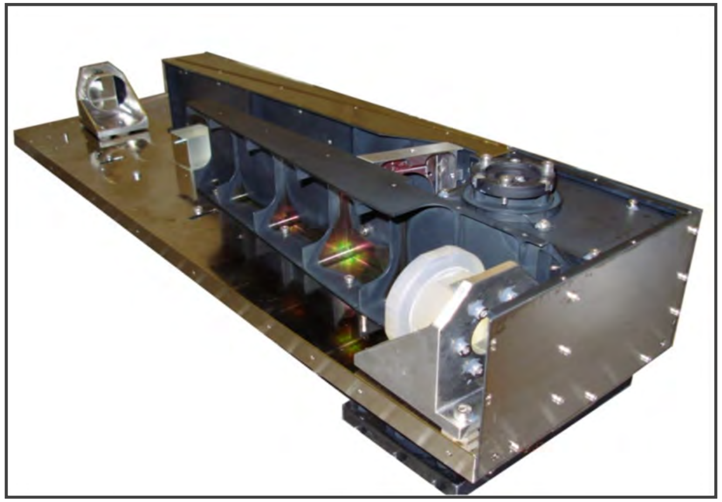
Baffle design &
stray-light analyses



Ray-tracing

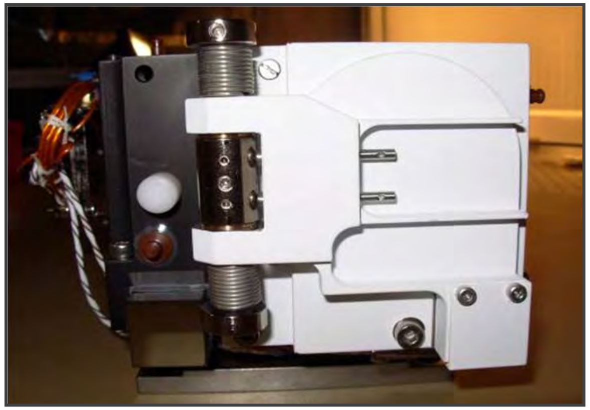




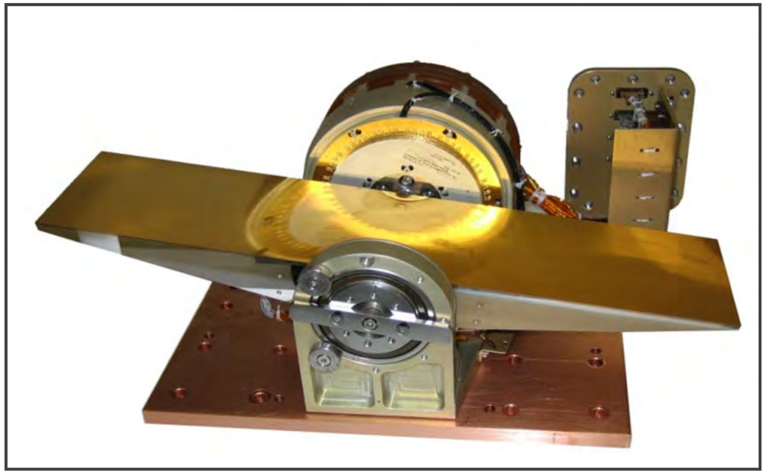


Complete optical instruments
or sub-assemblies

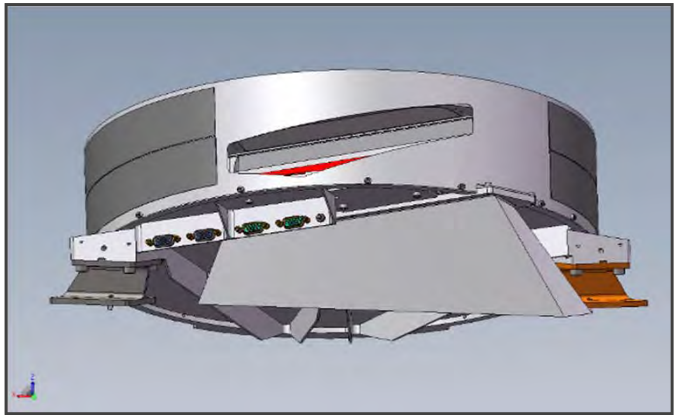
Mechanisms



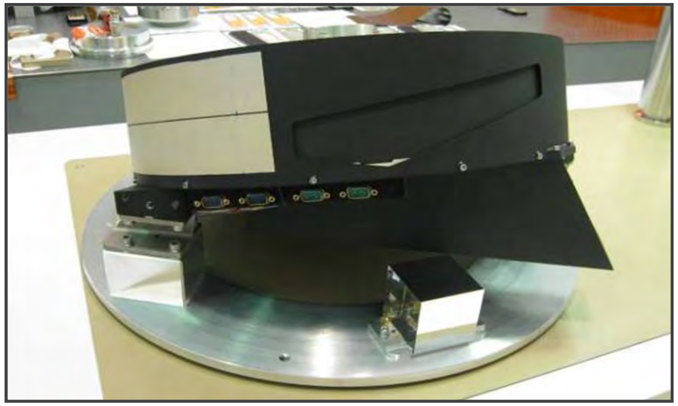
Cover mechanisms



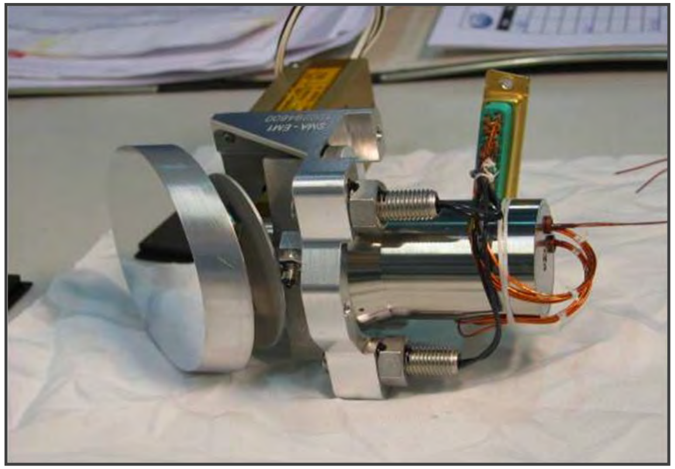
Positioning mechanisms operating in extreme environment (4K)

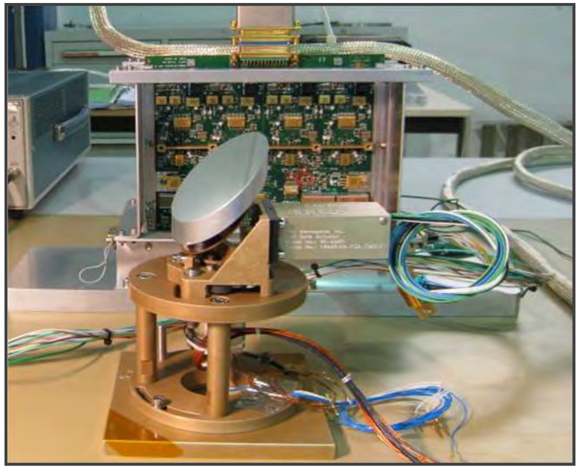


Wheel mechanism

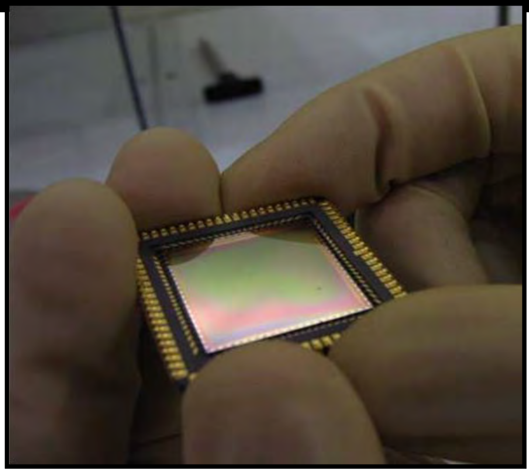


Scan mirror



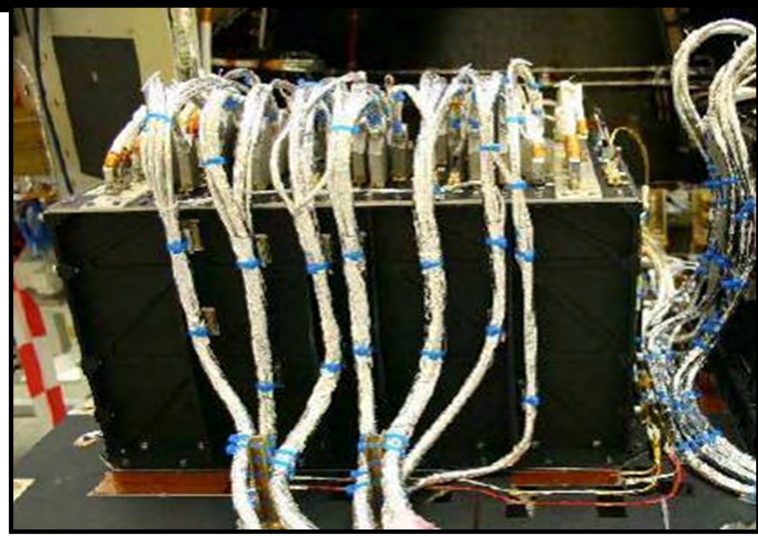


Electronics

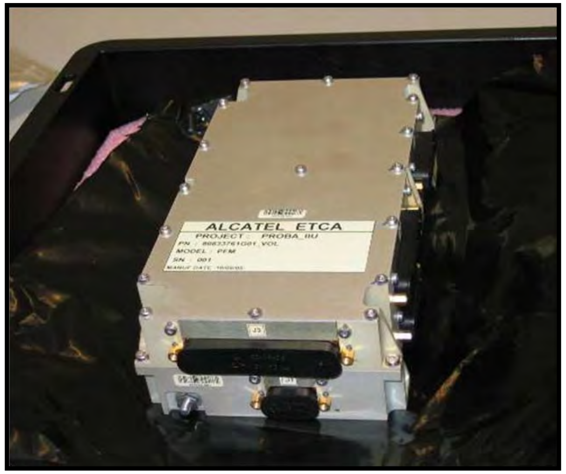


Detectors

Processor & software



Detector controllers

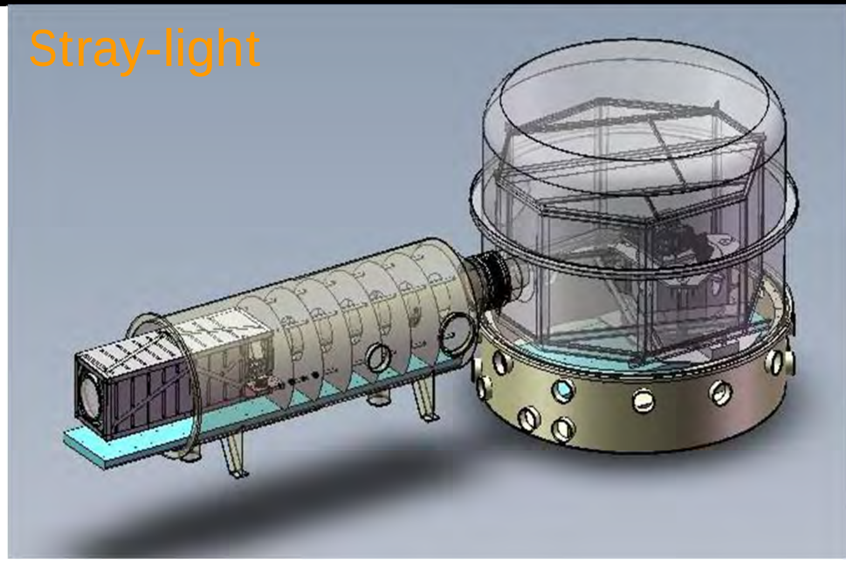


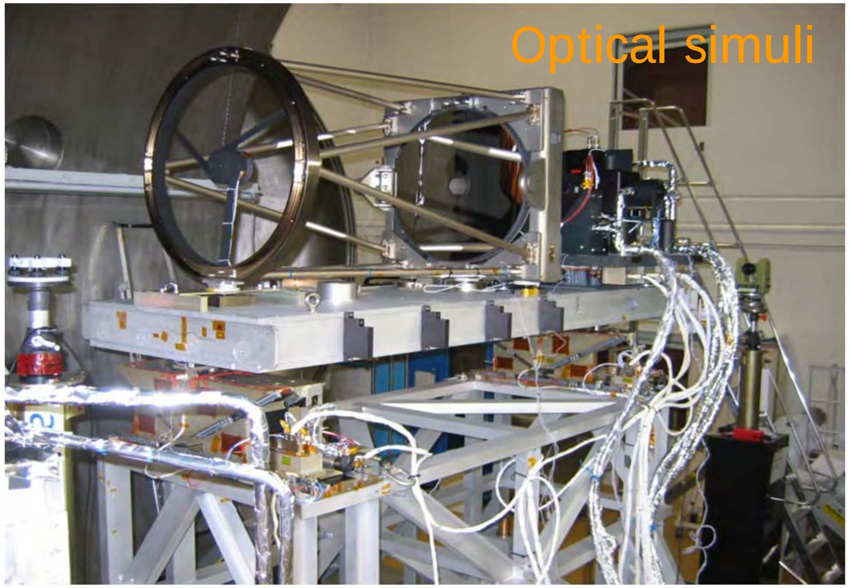
Power conditioning

EGSE

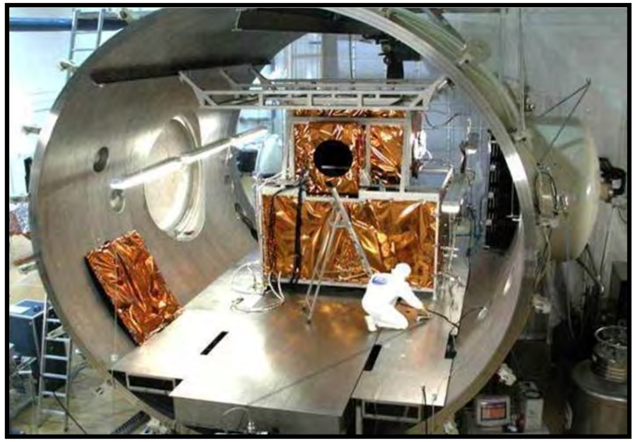
Mechanism controllers

GSE & Calibration Facilities





AIV, Testing Facilities



1,000-m² integration clean rooms (ISO-7 / ISO-5)

Cryogenics (LN_2 & LHe)

Th. Vac. chambers from ∅1.5-m… up to ∅6.5-m

Shakers (90 kN – 200 kN)

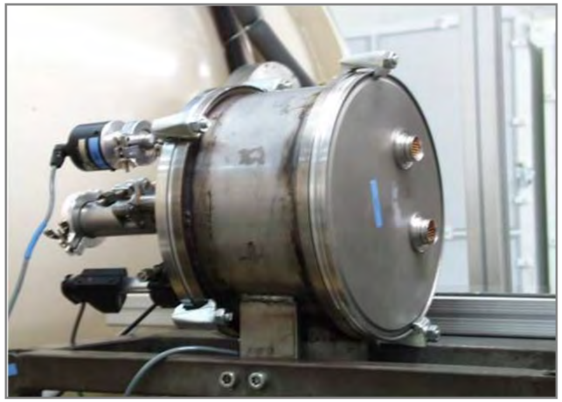
Vacuum Environment

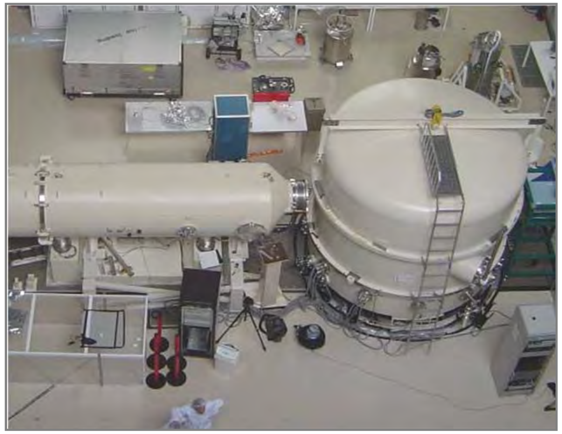
✓ CSL houses chambers with extended vacuum capabilities and with 0.25-m to 6.5-m diameter

✓ The chambers are equipped with primary and turbo pumping system

✓ Cryogenic pumping available as well

✓ Most of the chambers are equipped with optical bench laying on seismic device allowing ground vibration decoupling





Vibration Facilities

✓ Allows vibration (200-kN shaker) on 3 axis under cryogenic and vacuum conditions (down to 15K).

Shaker 4522 LX:

- Slip table: 1500 x 1500 mm²
- Head expander: 1500-mm diameter
- Maximum sine force 200 kN
- Maximum random force: 160 kN
- Bandwidth: 5-2000 Hz

Shaker 2016U:

- Slip table: 900 x 900 mm²
- Head expander: 900-mm diameter
- Maximum sine force: 88 kN
- Maximum random force: 72 kN
- Bandwidth: 5-3000 Hz

Cooling system specification

- Available cooling power
  - 1 liquefier / refrigerator KOCH 1630 (installed 1987)
  - customised for ISO telescope testing (LHe + GHe available)
  - 45 [l h^{-1}] in LHe, about 150 [W] @ 6 [K] and 300 [W] @ 18 [K]

Cooling system upgrade

- Cooling machines
  - second Helium liquefier / refrigerator installed
  - Linde TCF20, also customised
  - 50 [l h^{-1}] in LHe, ~150 [W] @ 6 [K] and 300 [W] @ 18 [K]
  - installation by CSL
    commissioning by Linde

Space Systems Projects

Science

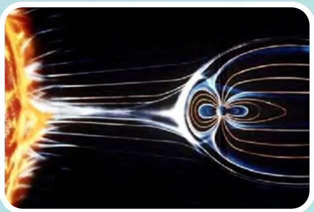
- TD1, HST, SOHO, XMM, INTEGRAL, CoRoT, PROBA-2, Herschel, JWST…
- S1 (CHEOPS); M1 (SolO); M2 (Euclid); M3 (EChO/Plato); L1 (JUICE/Athena)…
- MoO (Proba-3, SPICA, ICON…)

Exploration

- ExoMars/TGO 2016 (NOMAD)
- LaRa, Lunar Lander

Earth Observation

- VEGETATION, ENVISAT, METOP, Sentinel-2, Sentinel-3, Sentinel-4, MTG…
- (SAOCOM/TreeVol), PROBA-V, PROBA-V Successor



SSA (Space Weather)

- IMAGE (with NASA) ICON (NASA)
- STEREO (with NASA)
- KuaFu (with China)
- ESIO, ICON, WFCC

+ technologies

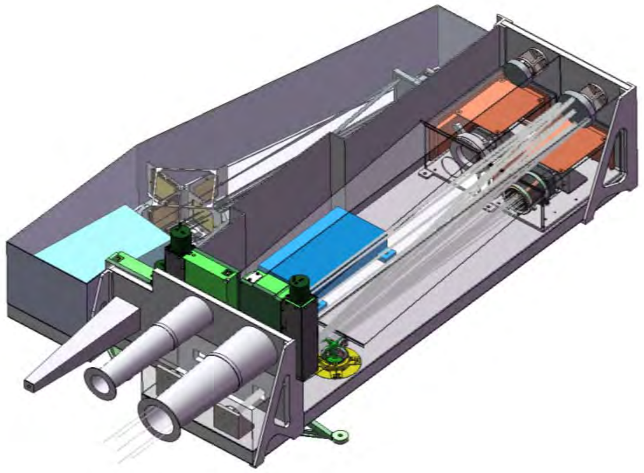
Types of missions and calls

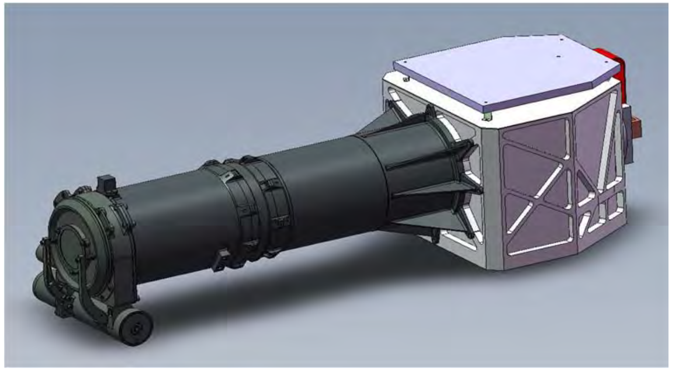
	one every	cost	dev. time	techno	intern. coop.
L	7 y	≈ 2 LoR ≈ 900 M	15 y	challenging	≤ 20%
M	3 y	≈ 1 LoR ≈ 500 M	11 y	limited	any
S	4 y	≤ 50 M ESA 150 M total	4 y	no risks	national agencies
MoO (no call)	5 y	≈ 100 M			any

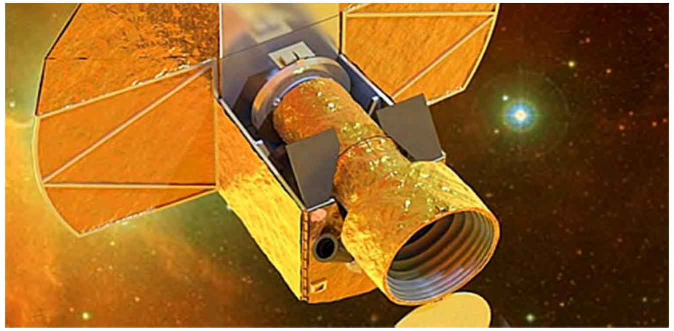
CHEOPS, SMILE

Target = 1 launch/year

Running Projects: Science (Prodex)







- PROBA-2 SWAP (in operation)
- JWST MIRI (delivered to NASA)
- (M1) Solar Orbiter EUI
- (M1) Solar Orbiter HI/SPP-WISPR
- (M4c) SPICA Safari
- PROBA-3 ASPIICS
- (M2) EUCLID
- (S1) CHEOPS
- (NASA Explorer) ICON FUV
- (M3) PLATO
- (L1) JUICE MAJIS & UVS
- (L2) Athena X-IFU

Missions in the Cosmic Vision 2015-2025 Programme

L1 mission	(2022)	JUICE
L2 mission	(2028)	ATHENA
M1 mission	(2018)	Solar Orbiter
M2 mission	(2020)	Euclid
M3 mission	(2024)	PLATO
S1 mission	(2017)	CHEOPS
S2 mission	(2021)	SMILE

CSL

L3 mission is still to be announced. ESA has selected **the gravitational Universe science theme for its L3 mission**. LISA is a main candidate for L3 mission. It is a proposed space mission concept designed to detect and accurately measure gravitational waves. Its launch is planned for 2034

M4 Candidate Missions in the Cosmic Vision 2015-2025 Programme

ARIEL, THOR, XIPE

Involvement of CSL in Space Instrumentation

Sun	Solar System	Astrophysics	Fundamental Physics

IMPLEMENTATION

Sun:
- [2018] Solar Orbiter

Solar System:
- [2017] BepiColombo
- [2022] JUICE

Astrophysics:
- [2017] CHEOPS
- [2018] JWST
- [2020] Euclid

Fundamental Physics:
- [2015] LISA Pathfinder

OPERATIONS / POST-OPERATIONS

Sun:
- [2009] PROBA2
- [1995] SOHO
- [1990] Ulysses

Solar System:
- [2005] Venus Express
- [2004] Rosetta
- [2003] Mars Express
- [2003] Double Star
- [2000] Cluster
- [1997] Cassini-Huygens

Astrophysics:
- [2013] Gaia
- [2009] Planck
- [2009] Herschel
- [2002] INTEGRAL
- [1999] XMM-Newton
- [1990] Hubble

COMPLETED

Solar System:
- [2003] SMART-1
- [1986] Giotto

Astrophysics:
- [1995] ISO
- [1989] Hipparcos
- [1983] EXOSAT
- [1978] IUE
- [1975] Cos-B [1972] TD-1

NASA Scientific Missions
- 2018 JWST
- 2018 SPP
- 2017 ICON
- 2011 JUNO
- 2006 STEREO
- 1995 IMAGE
- 1990 HST

CSL

Historically, students did their Master Thesis on Instruments developed at CSL. Since 2005, we also involve students on Student μSat (ESEO, ESMO, FLT) and nSat (Oufti, QB50)

Astrophysics

ATHENA (2028)
PLATO (2024

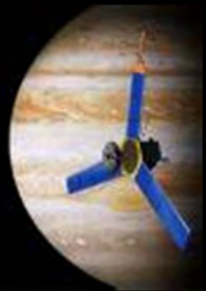
Design & Development of Optical Payloads under PRODEX 1/2

Mission	Agency	Launch
EIT on SOHO	ESA	1995
EIT Sounding Rocket	NASA	1997
OM on XMM Newton	ESA	1999
FUV on IMAGE	NASA	2000
OMC on INTEGRAL	ESA	2002
HI on STEREO	NASA	2006
PACS on Herschel	ESA	2007
COROT	CNES	2006
LYRA on PROBA2	ESA	2007
SWAP on PROBA2	ESA	2007
MIRI on JWST	ESA	2018?
UVS JUNO	NASA	Aug. 5, 2011
NOMAD ExoMars/TGO	ESA	2016

Design & Development of Optical Payloads under PRODEX 2/2

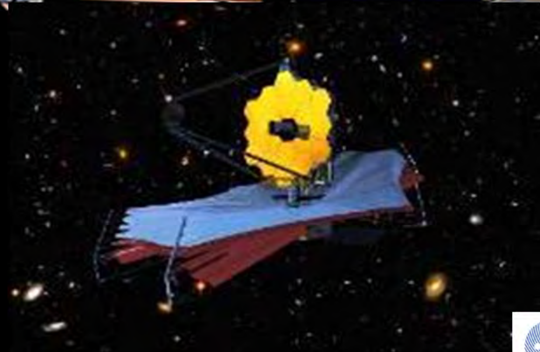
EUI Solar Orbiter	ESA	2018
HI Solar Orbiter	ESA	2018
WSPR SPP	NASA	2018
UVSI ICON	NASA	2017
CHEOPS Baffle & Cover Assembly	ESA	2017
EUCLID	ESA	2020
UVS & MAJIS JUICE	ESA	2022
PLATO Camera AIV	ESA	2024
ATHENA X-IFU	ESA	2028
UVSI SMILE	ESA	2021
LaRa ExoMars 2018	ESA	2018

Instruments under development



JUNO – UVS (2011)

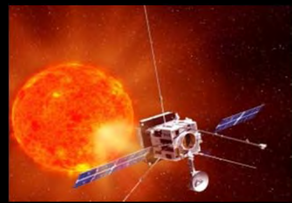
Launched Aug. 5, 2011



JWST – MIRI (2014)

Sentinel 2 – MSI (2012)

Launch 2-A 23 June 2015
Sentinel-2B 2017

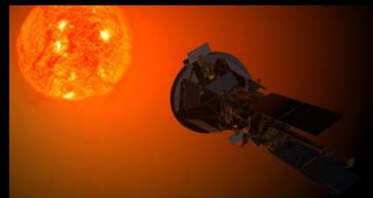


Solar Orbiter - EUI
& Sun Sensor (2018)
Solar Orbiter – HI (2018)

Sentinel 3 – OLCI (2012)

Sentinel 4-UVN (2017)

Launch Sentinel-3A - February 2016
Sentinel-3B - Scheduled for 2017
Sentinel-3C - Before 2020



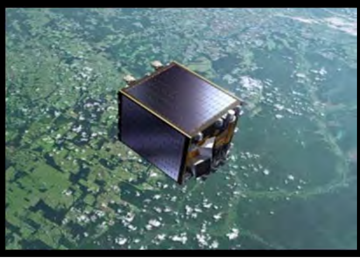
SPP WISPR

JULY 30, 2018

PROBA-3(2 sat.)
ASPIICS(coronograph)

[ExM2016] NOMAD

Launched March 2016

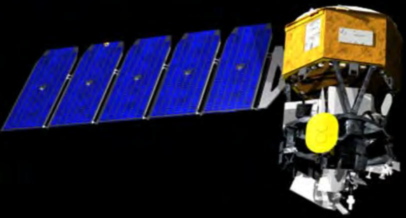


PROBA-V Launched 7 May 2013

ICON FUVSI

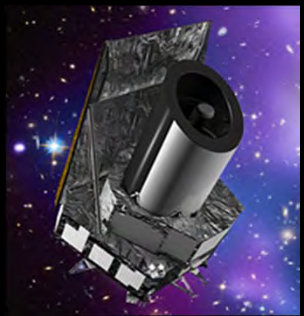
June 2017

Instruments under development



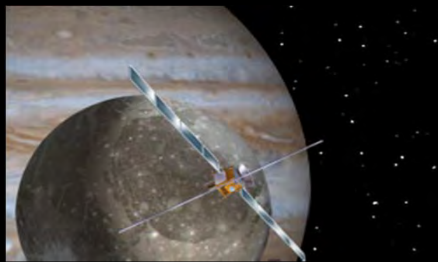
ICON FUV
June 2017

CHEOPS Baffle & Cover Assembly
End 2017



EUCLID

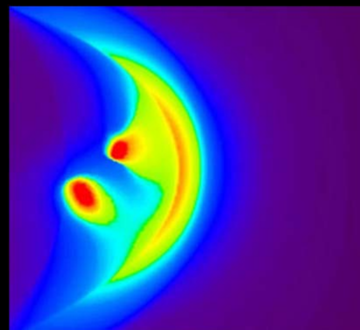
2020



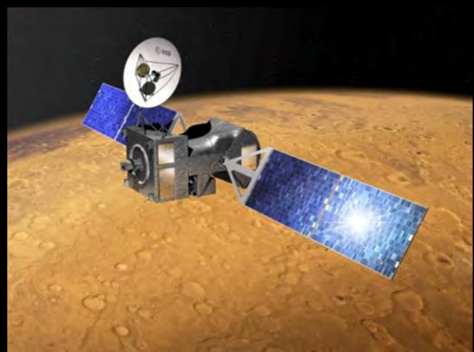
JUICE
UVS & MAJIS
Launch 2022 and arrival at Jupiter in 2030

PLATO Camera AIV
Around 2024

ATHENA X-IFU
Around 2028



SMILE UVSI
2021

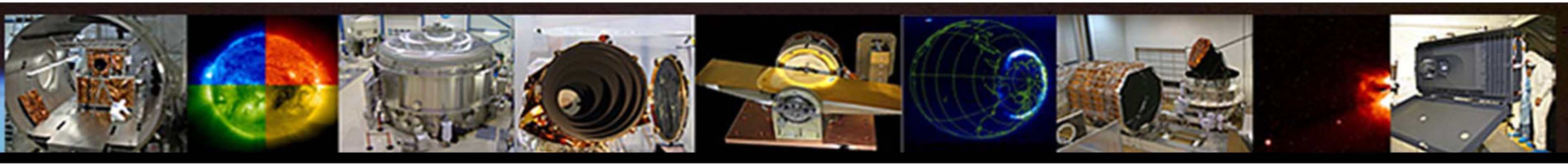


[ExM2018] LaRa
2018

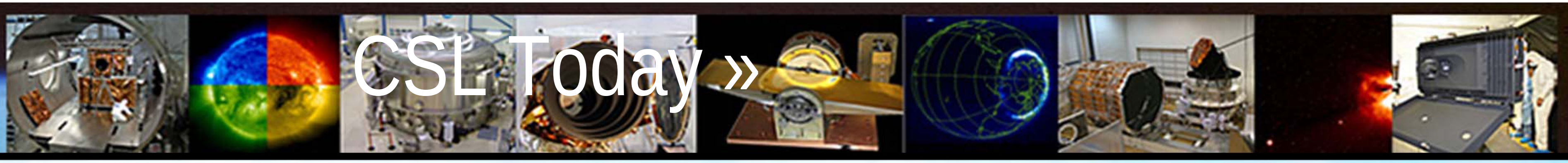
©Doc.C.Jamar

En 1984, IAL Space passe de la colline de Cointe au Sart Tilman dans ce nouveau bâtiment « style nordique » construit autour du simulateur FOCAL-5.

En 1992, IAL Space devient CSL (Centre Spatial de Liège) comme facilité coordonnée pour les essais spatiaux de l'ESA. Il s'agrandit pour accueillir le FOCAL-XXL pour le satellite scientifique XMM.



CSL Today »



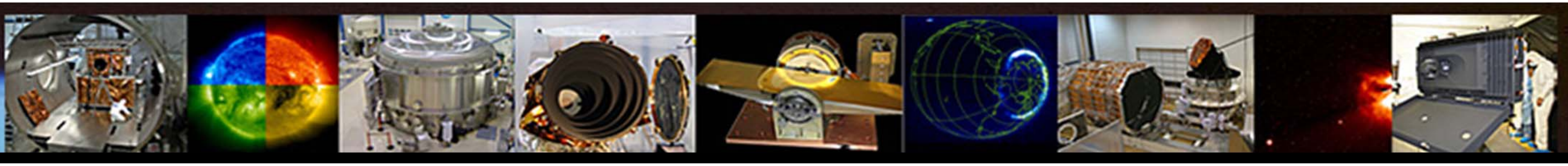
Siemens LMS
Samtech
Spacebel
AMOS
WSL
CSL
GDTech
Open Engineering
Centre Spatial de Liège
Université de Liège
50 ans de recherche spatiale

CSL

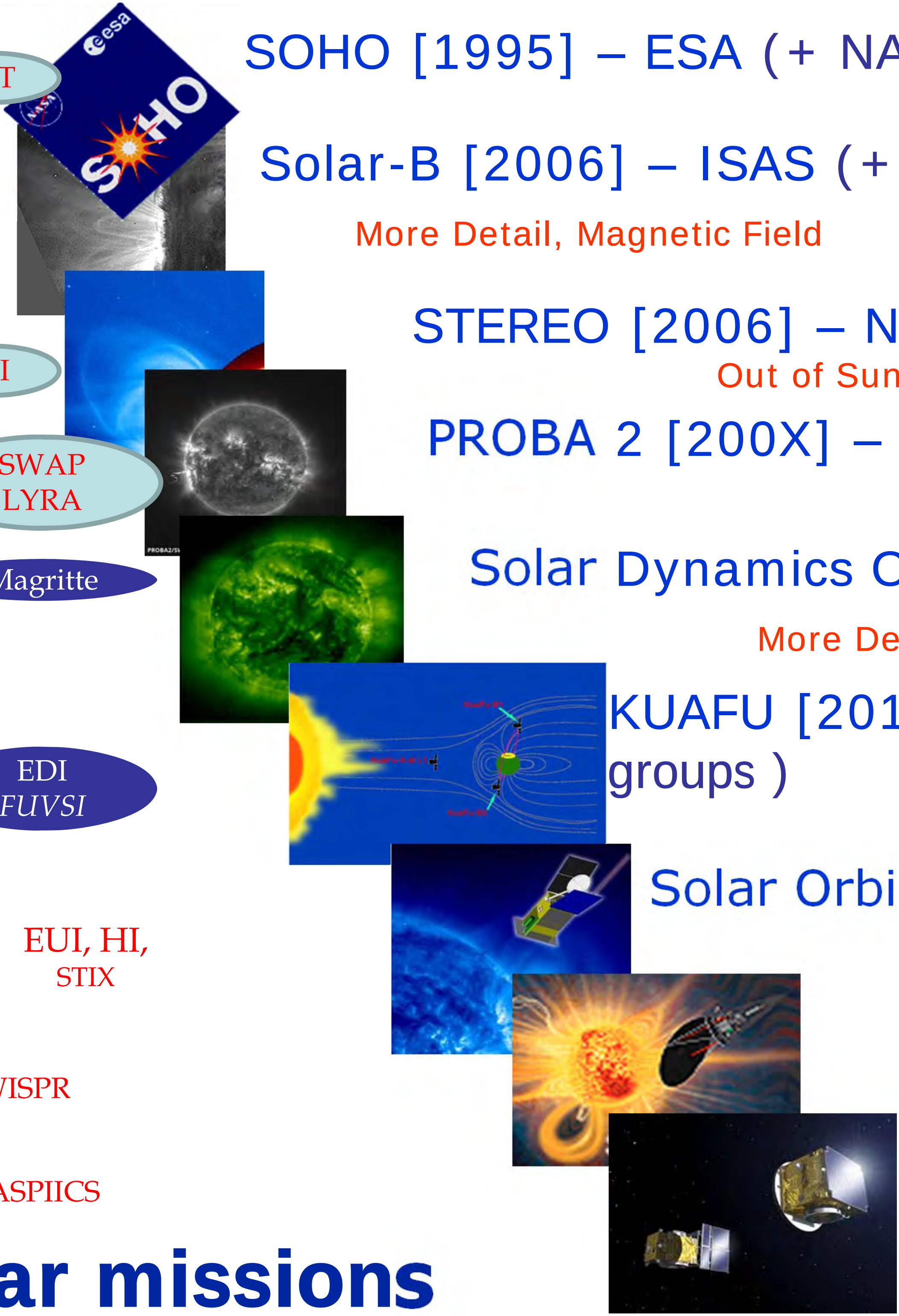
Centre Spatial de Liège

Université de Liège

BACK UP Slides



SOLAR PHYSICS and SPACE WEATHER



EIT

SOHO [1995] – ESA (+ NASA) First solar observatory

Solar-B [2006] – ISAS (+ NASA & PPARC)

More Detail, Magnetic Field

HI

STEREO [2006] – NASA (+Europ. groups +ESA)

Out of Sun-Earth Line, 3-D, CMEs

SWAP
LYRA

PROBA 2 [200X] – Belgium ESA Heliosynchronous, CMEs

Magritte

Solar Dynamics Obs. [2008] – NASA (+ESA)

More Details, Helioseismology, CMEs

EDI
FUVSI

KUAFU [2011+] – CNSA (+CSA +Europ. groups) Space Weather 3 satellites

EUI, HI,
STIX

Solar Orbiter [2018+] – ESA (+NASA)

Out of Eccliptic, Far-Side, Co-Rotation,

Inner Heliosphere/Corona

WISPR

Solar Probe Plus - NASA

A Closer look, high resolution

ASPIICS

PROBA 3 - ESA

Coronography

Solar missions

Aurora & Sun / Planet interactions Observing Instrument developments at Centre Spatial de Liège

1962-1972: CSL launches 25 sounding rockets observing polar auroras

1972-1994: Participation to the FOC Calibration for HST (First aurora image on JUPITER)

1994-1997: CSL leads the development of FUV SI-IMAGE

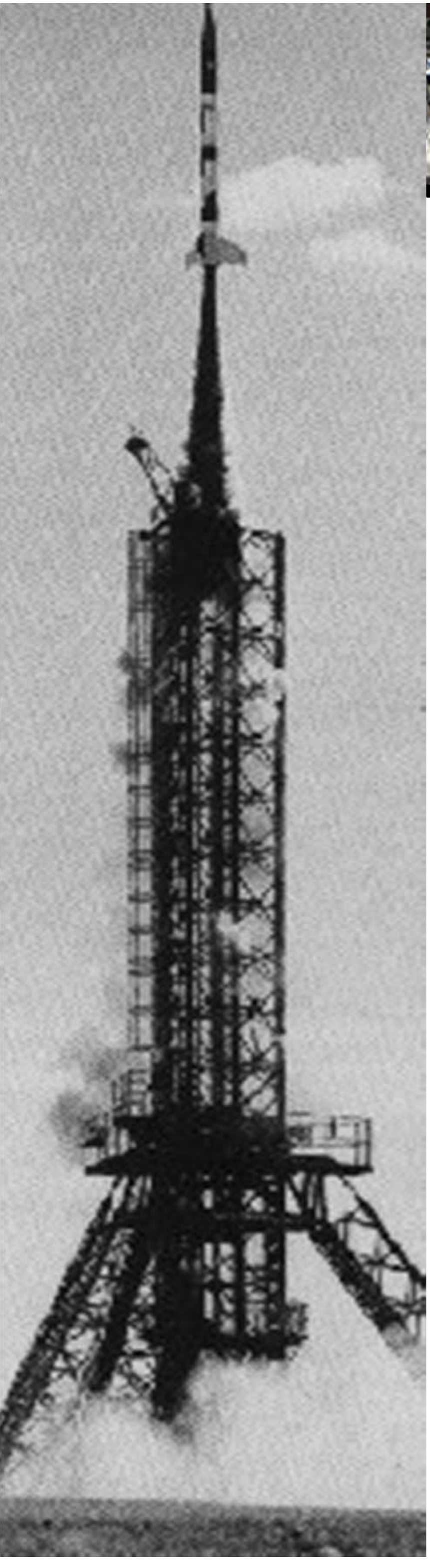
2003-...: CSL leads the development of LYRA on PROBA-2

2006-...: Participation to JUNO

2013-...: Participation to ICON (Atmosphere / Ionosphere connections)

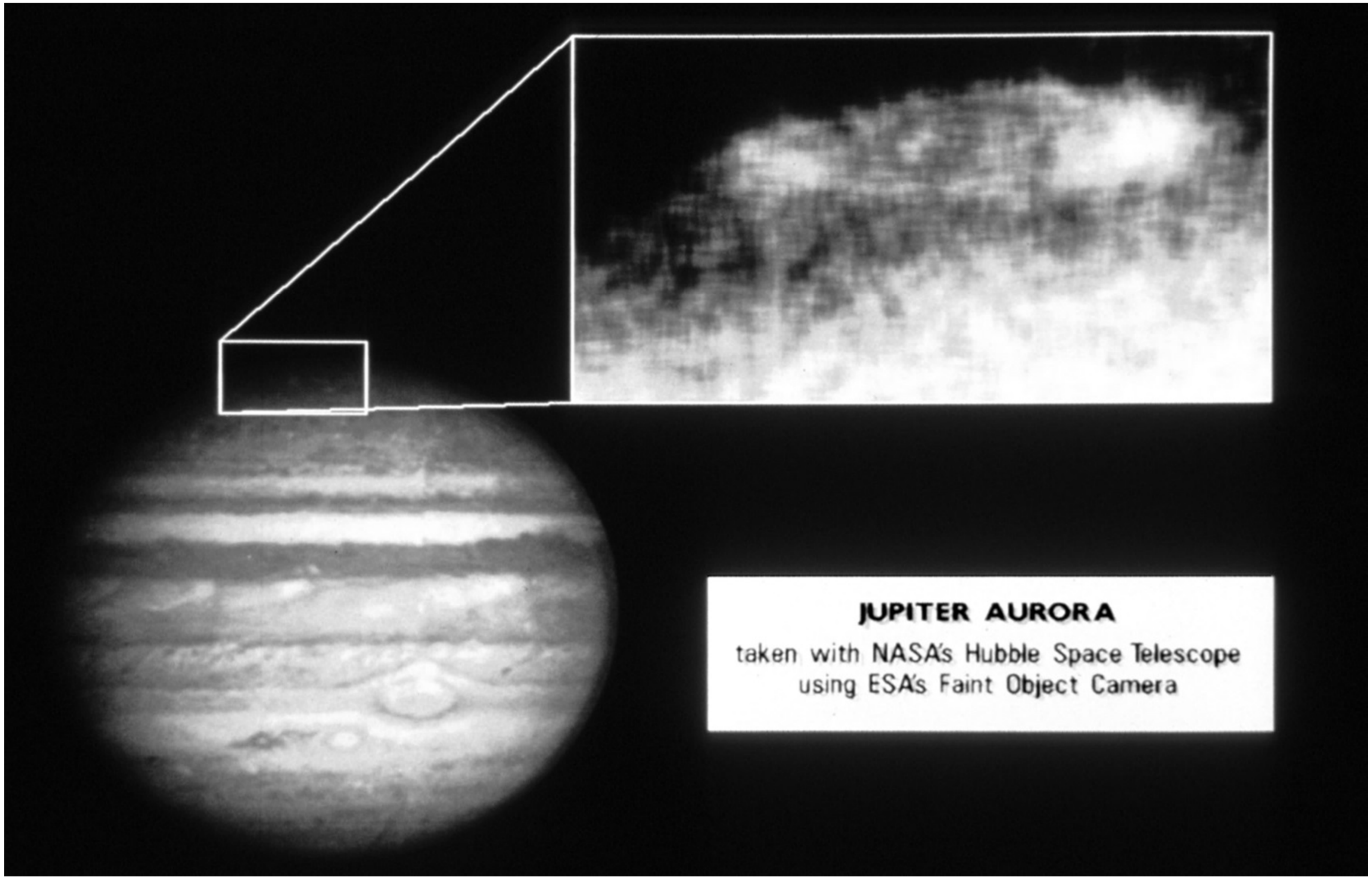
201X-...: Participation to ALFVEN, BEADS, RAVENS, JUICE

25 sounding rockets and the HST Faint Object Camera (FOC)



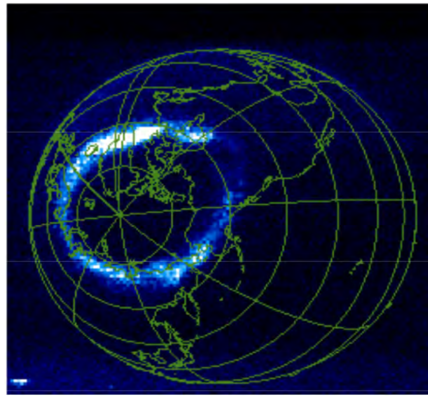
The first experiments we developed, were on sounding rockets launched from North of Sweden for **auroral observations**.

IAL Space was involved in the detector calibration of the Faint Object Camera (FOC) on board HST launched I, 1990 and which took the **first pictures of auroras on Jupiter**.



FUV-SI/IMAGE

The NASA satellite **IMAGE** (Imager for Magnetopause-to-Aurora Global Oscillation) launched in March 2000 successfully observed the earth outer atmosphere and the Sun-Earth connections with great sensitivity for 5 years until 2005.
On board , the instrument **FUV-SI (Far UltraViolet Spectrographic Imager**) was specially designed to observe the auroras produced by protons and electrons.
CSL was responsible, with an international consortium, for the opto-mechanical design, the hardware completion and all the tests of the optical system.



FUVSI Science requirements

To image the entire auroral oval from a spinning spacecraft at 7 RE apogee altitude,

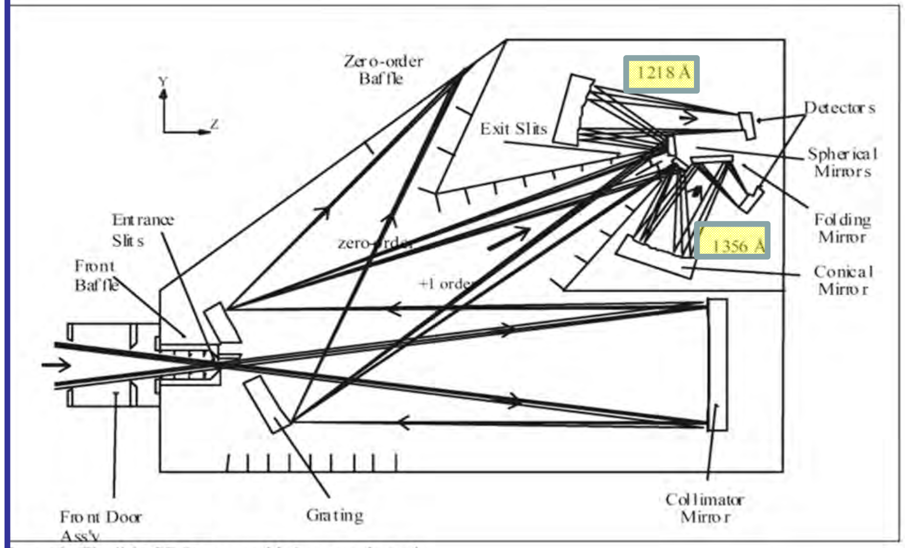
The first requirement involves a large field of view: 15x15° .

To separate spectrally the hot proton precipitation from the statistical noise of the intense, cold geocorona,

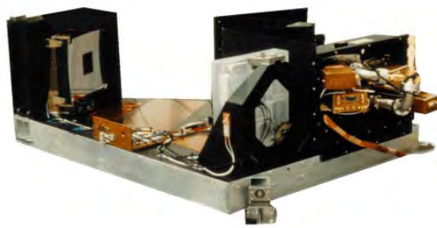
The second requirement needs a high spectral resolution, better than 0.2 nm : The the 121.8 nm line Doppler-shifted Ly-α signal to be detected is 100 times less intense than the Ly-α coronal emission at 121.6 nm. Nitrogen emissions near 120 nm (triplet lines at 119.955, 120.022 and 120.071 nm) also have to be filtered out.

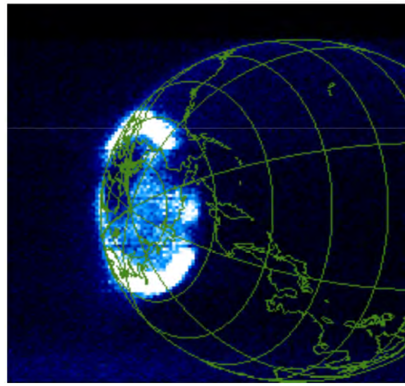
To separate spectrally the electron and proton auroras and to separate the different e-lines.

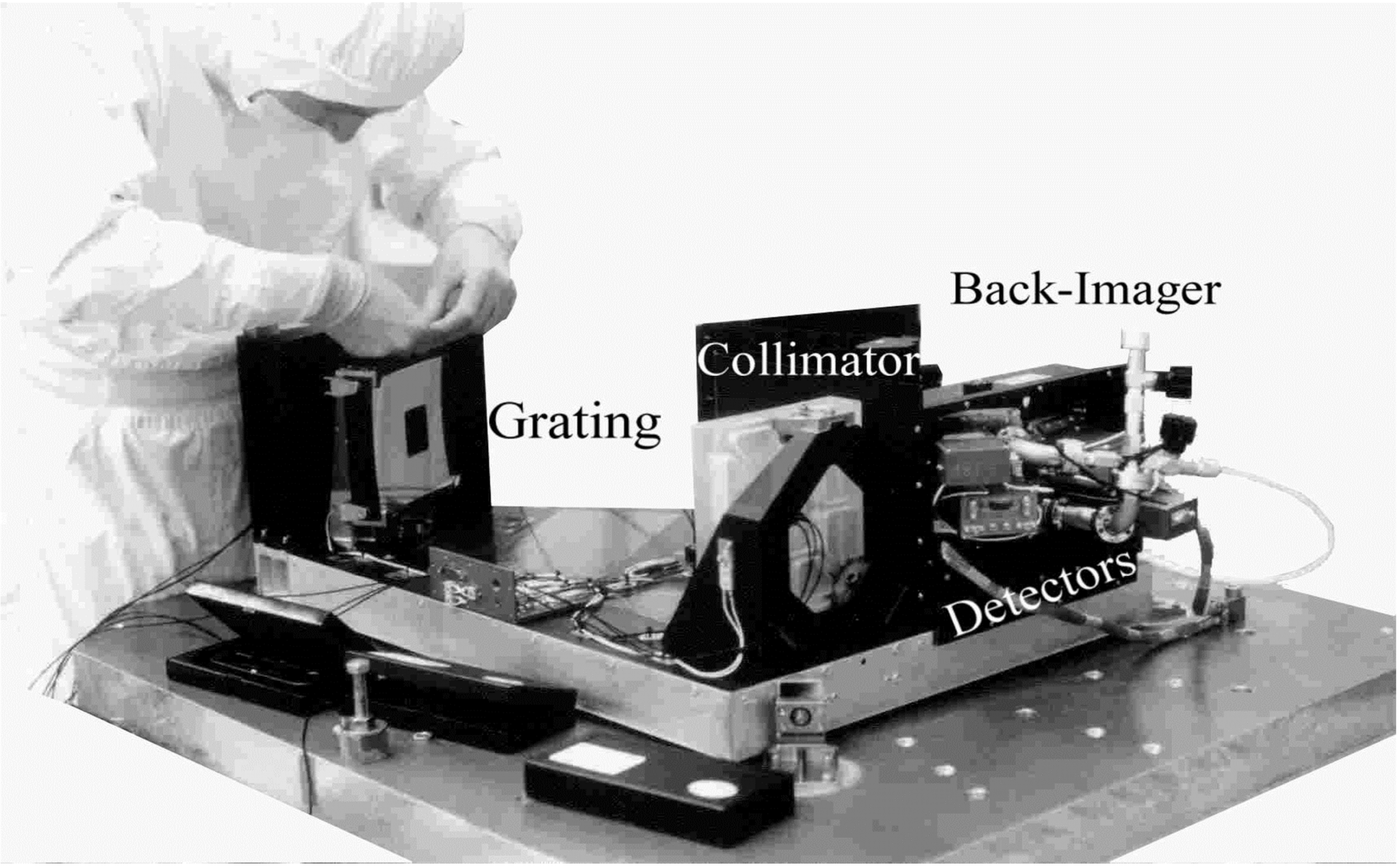
The third requirement is that the OI 135.6 nm line signal has to be isolated from the 130.4 nm line.



igure 3. The IMAGE Specrographic Imager schematic.





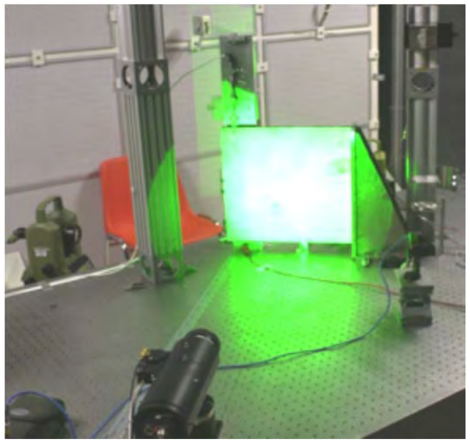


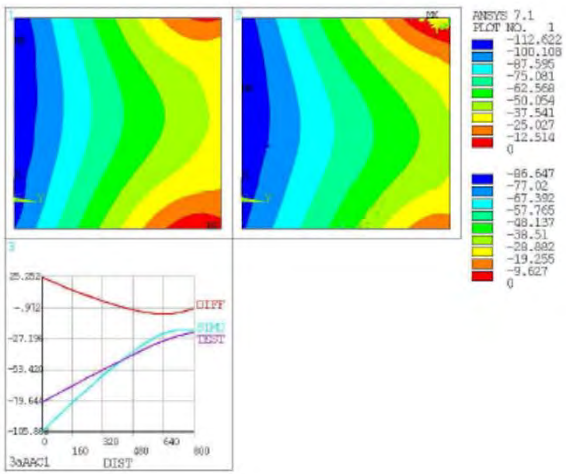
Picture of the FUV-SI IMAGE instrument during integration

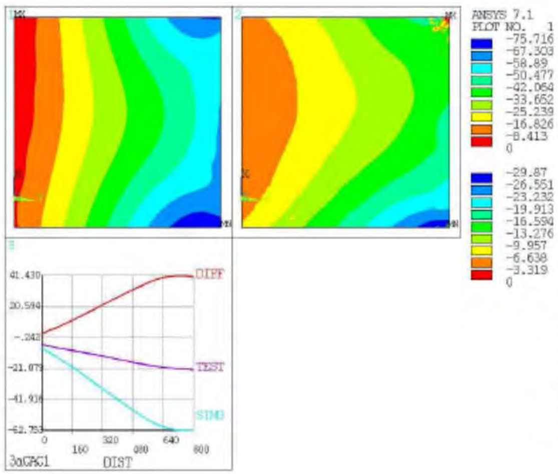
STABLE STRUCTURES

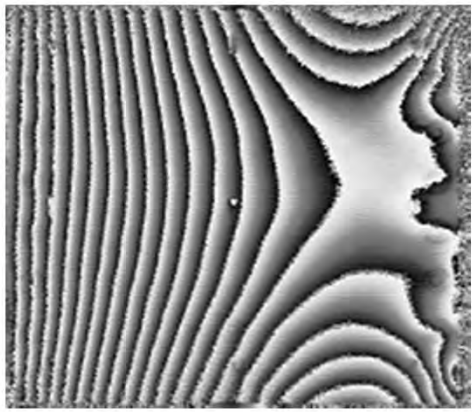
Past projects

- Comparison Finite Element Modelling - Metrology
- ESA project (2001-2005)
- Composite panels (sandwich-honeycomb)+assembly
  - HTS : FEM
  - CSL : Development of metrology method
    - Holographic interferometry at visible wavelength
    - Out-of-plane deformation : from 10s of nm to 10s of µm.
    - Temperature measurement





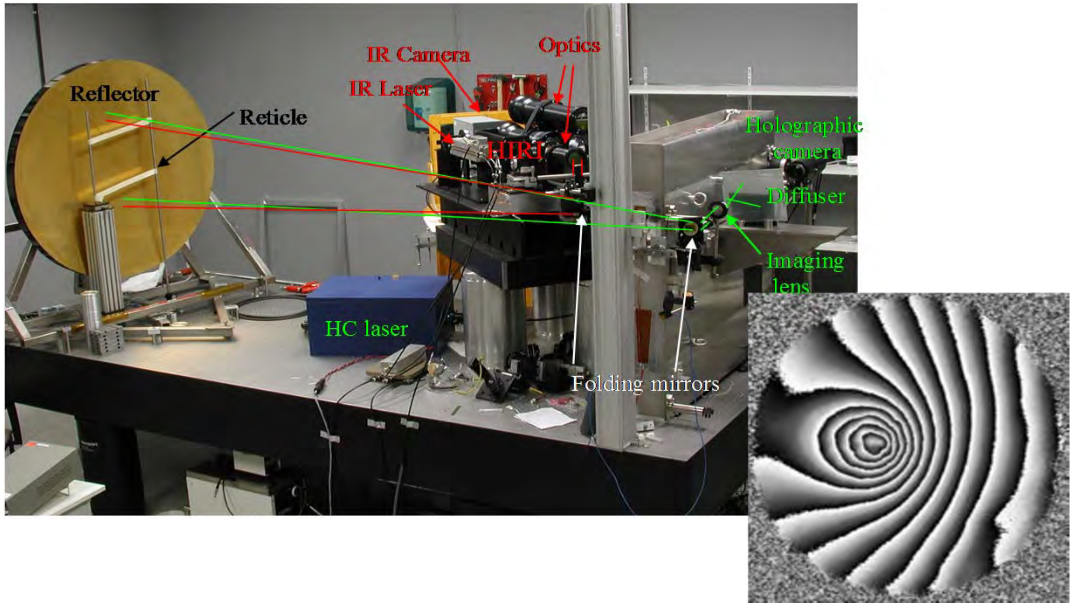




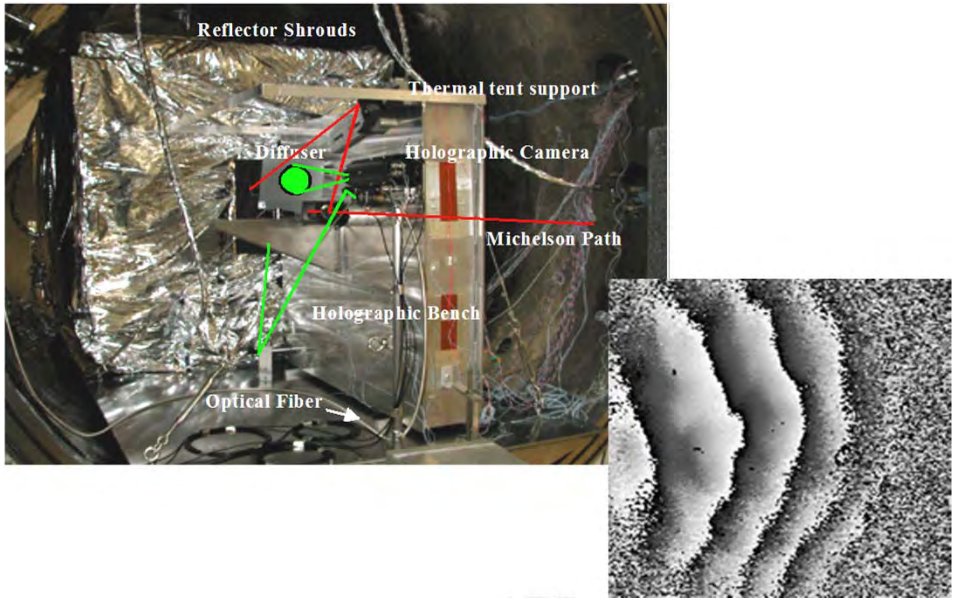
Past projects

- Optical Ground Verification Method
- ESA project (2001-2005)
- Large reflectors
  - CSL : Development of metrology method
    - Holographic interferometry at visible wavelength
    - Out-of-plane deformation : from 10s of nm to 10s of µm.
    - Vacuum-thermal compatibility of measurement technique

Implementation in the lab (measurement OK)

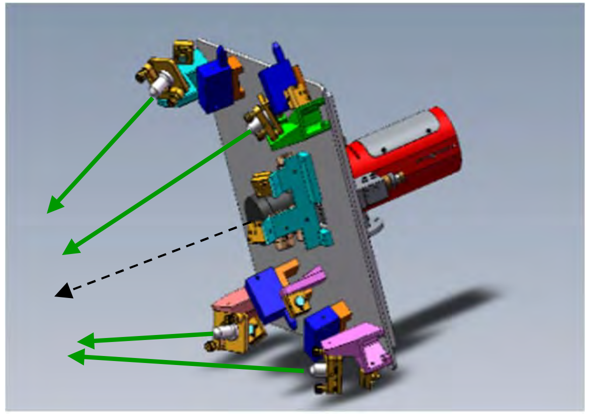


Transfer in vacuum chamber (problem of vibration)

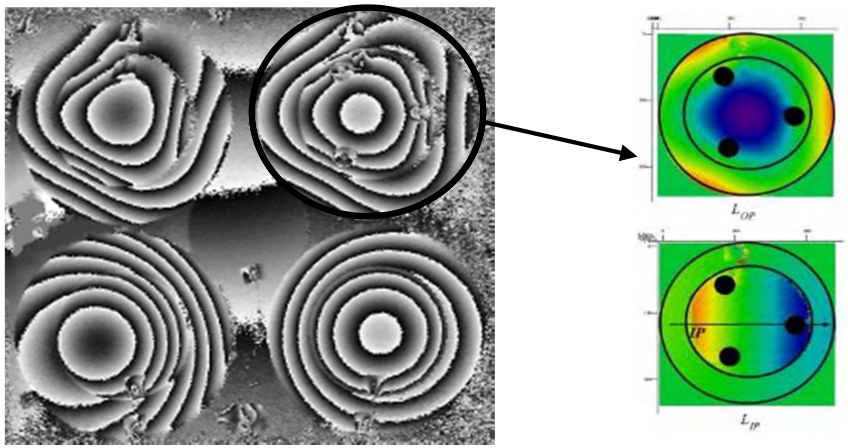


Past projects

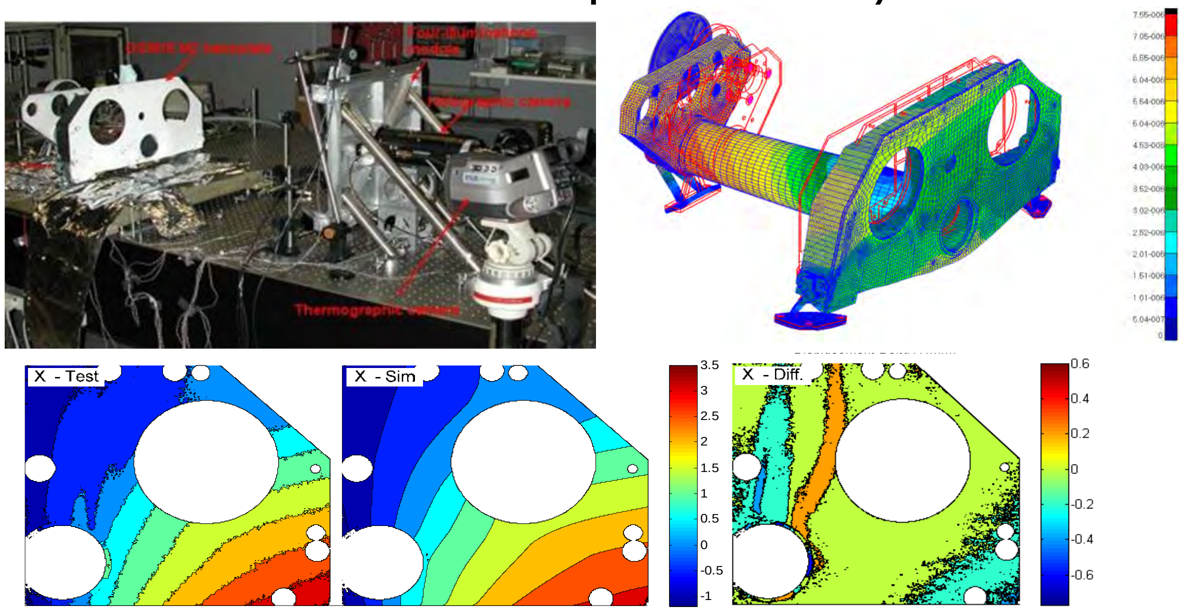
- Thermo-elastic measurement of space structures
- ESA project (2009-2012)
  - Astrium : FEM and test cases
  - CSL: Development of metrology method
    - Holographic interferometry for 3D deformation
    - Measurement campaign



CTE measurement – in and out of plane

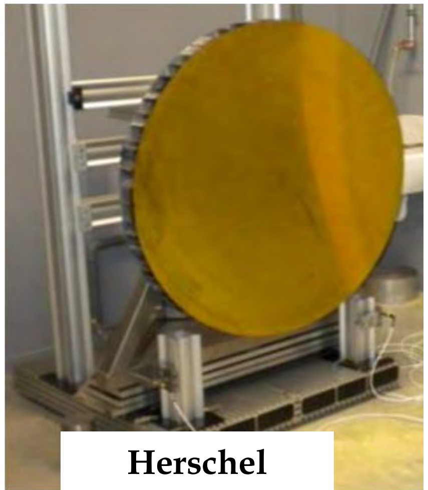


Full 3D deformation – comparison with FEM)



Past projects

- Infrared holographic metrology for aspheric reflectors
- ESA project HOLODIR (2010-2012)
  - Université libre de Bruxelles:
    - Development of holographic processing
  - CSL: Development of metrology method
    - Development of infrared holographic setup in the lab
    - Transfer into vacuum compatible setup
    - Measurement campaign of demonstration reflector



Herschel demo reflector

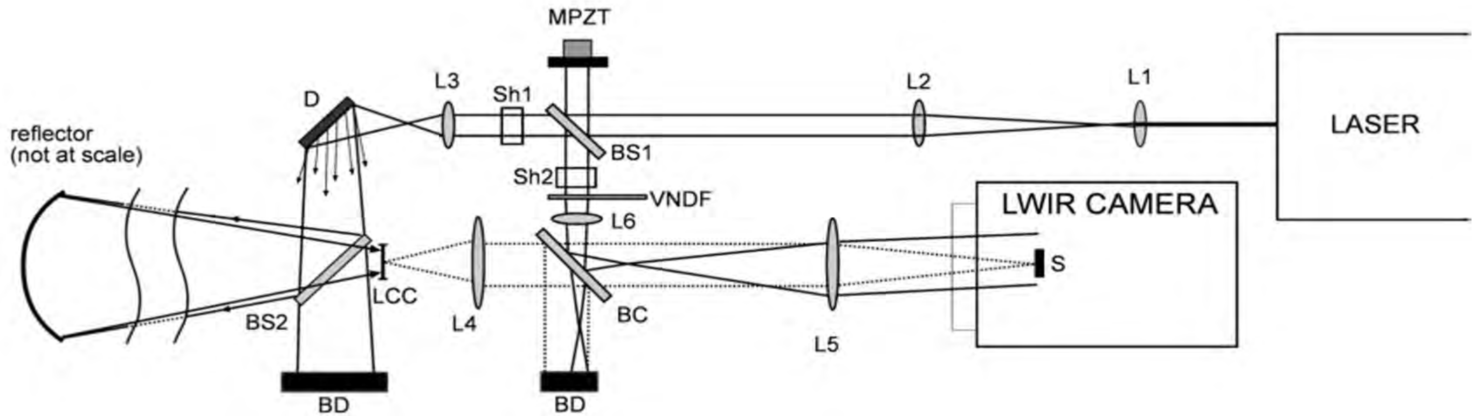
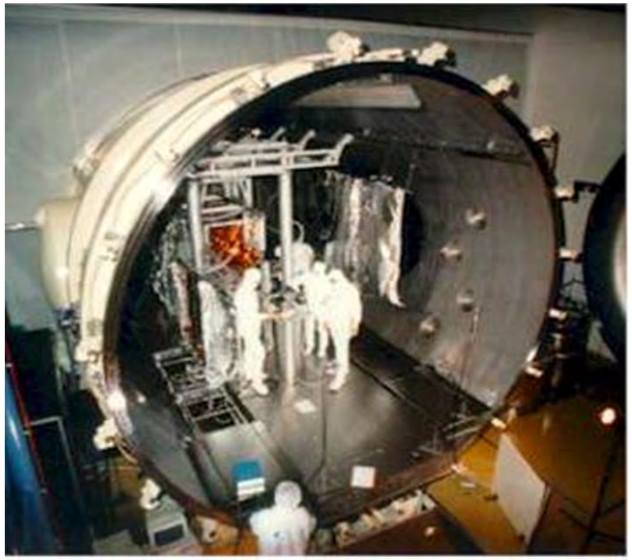
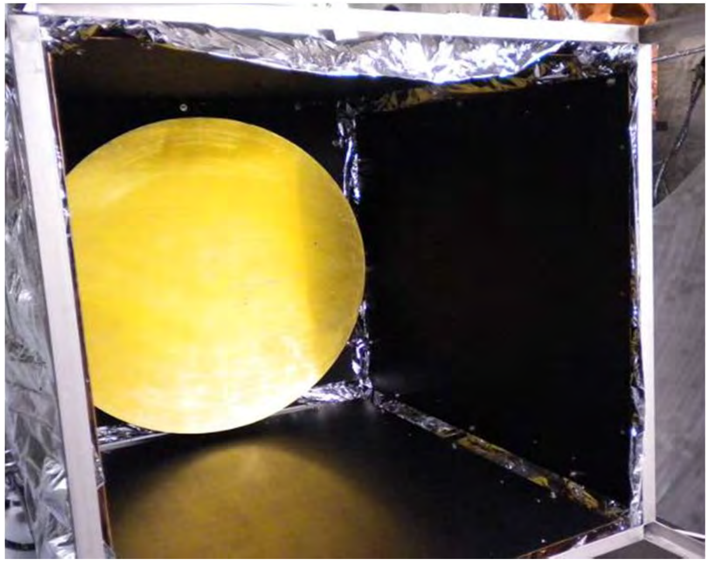


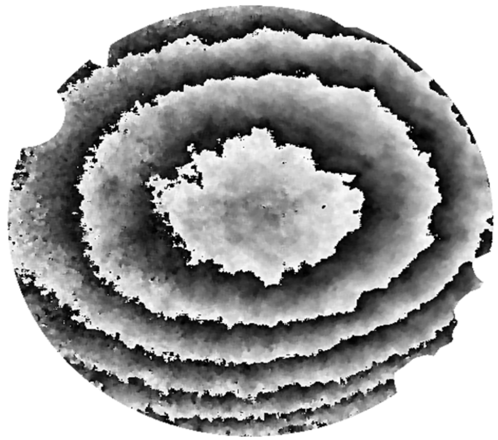
Diagram of the infrared holographic setup

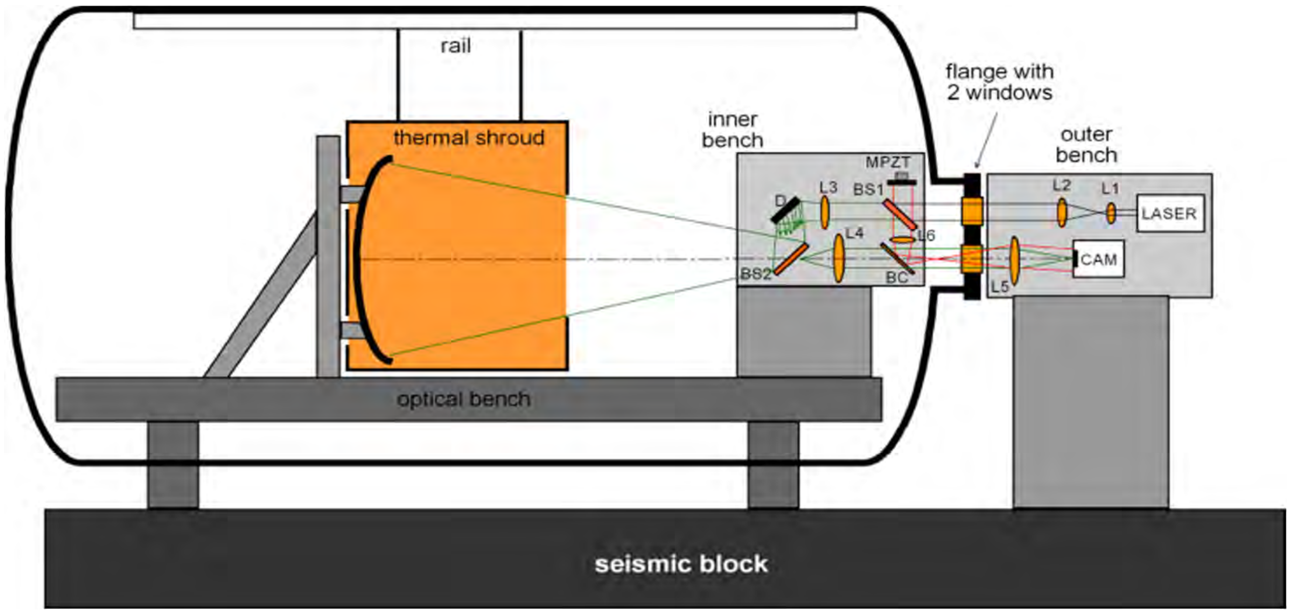
Diameter: 1.1 m
Focal Length: 1.58 m

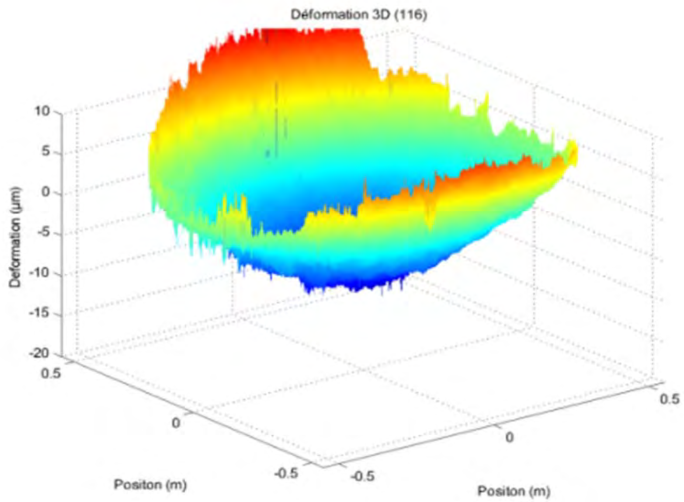
Holodir results under vacuum







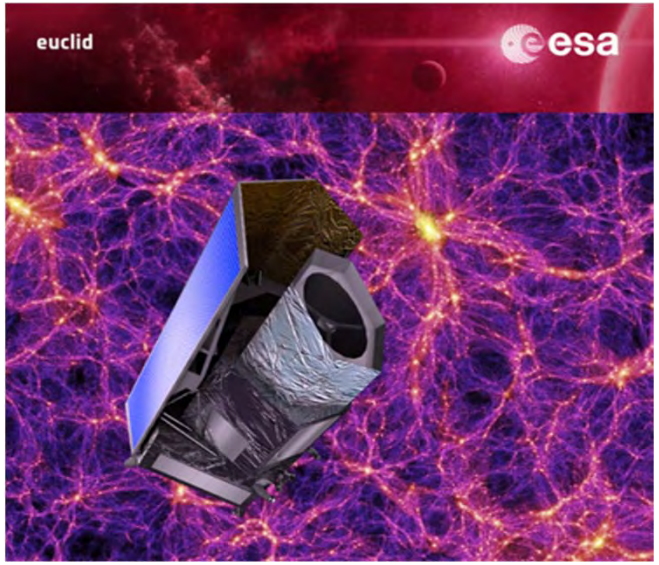




Georges, M., et al., "Digital Holographic Interferometry with CO2 lasers and diffuse illumination applied to large space reflectors metrology" (invited), Appl.Opt. 52(1), A102-A116 (2013)

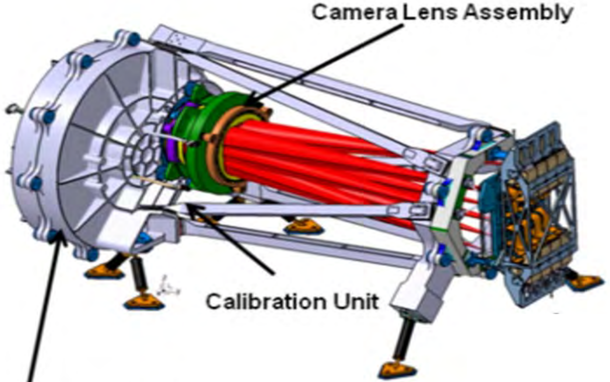
Current projects

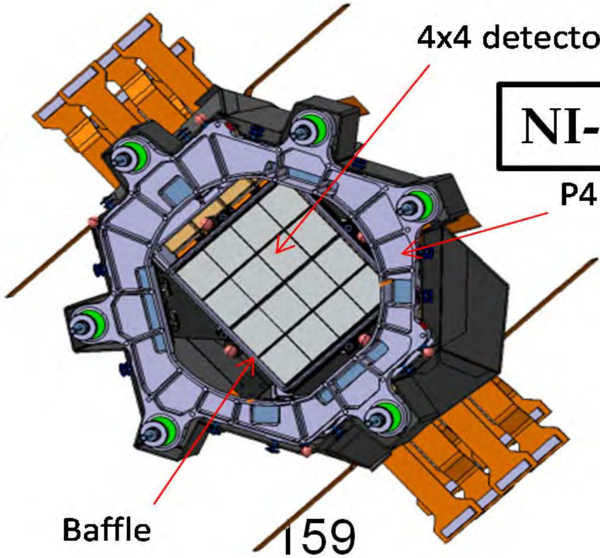
- Thermo-elastic measurement of space structures
- EUCLID project (2013-2017)
  - LAM (Marseille): provides test case (NI-DS)
    - Mosaic of 4x4 detectors
    - Including mechanical assembly
  - CSL: Development of metrology method
    - Holographic interferometry in infrared
    - Measurement campaign



LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

NISP





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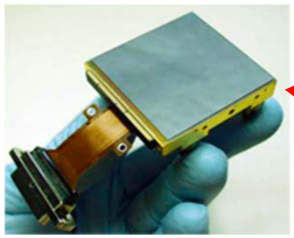
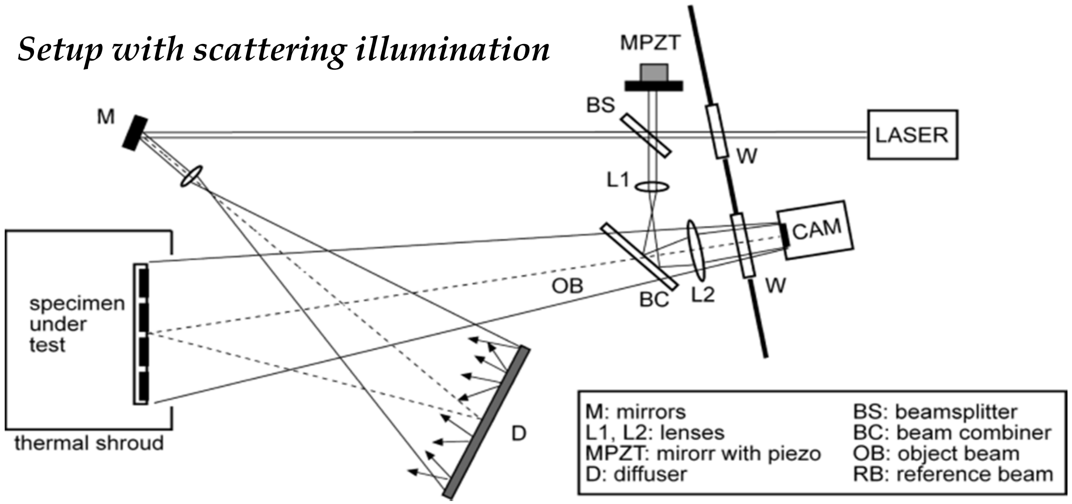
STM	STM	STM	STM
STM	STM	MUX	FM
STM	STM	FM	MUX



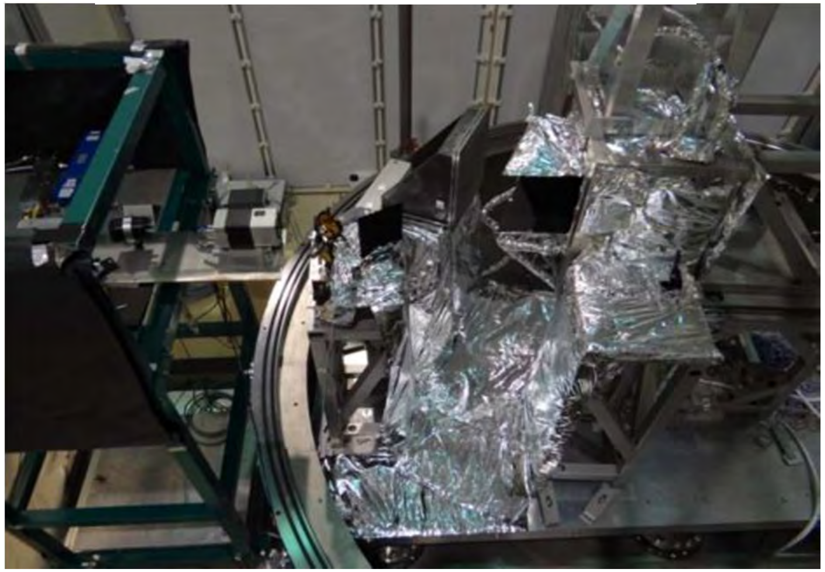
Current projects

- EUCLID setup and results

Setup with scattering illumination

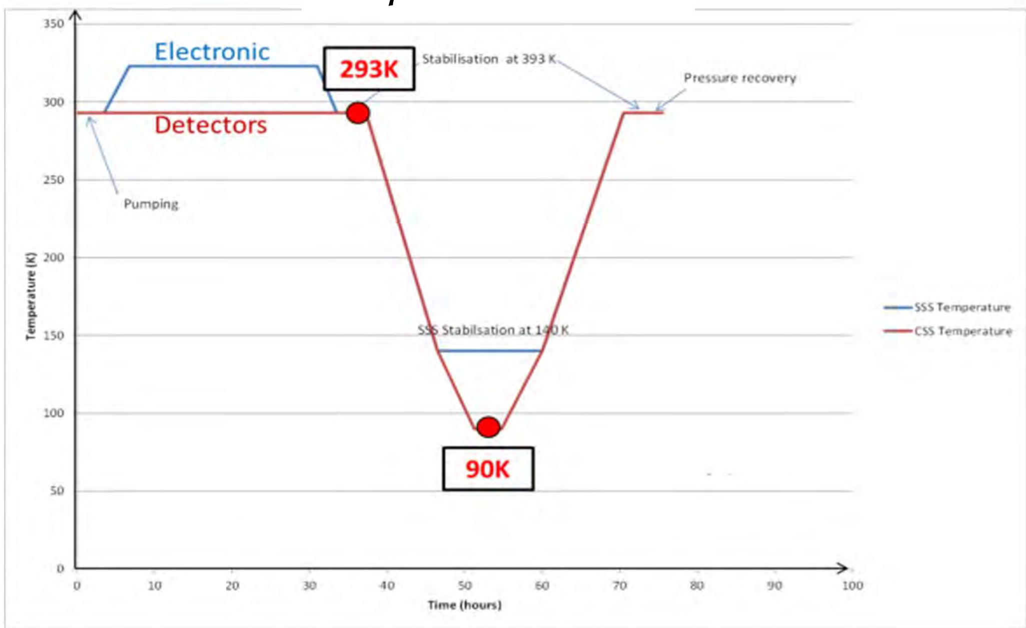


Implementation in vacuum chamber

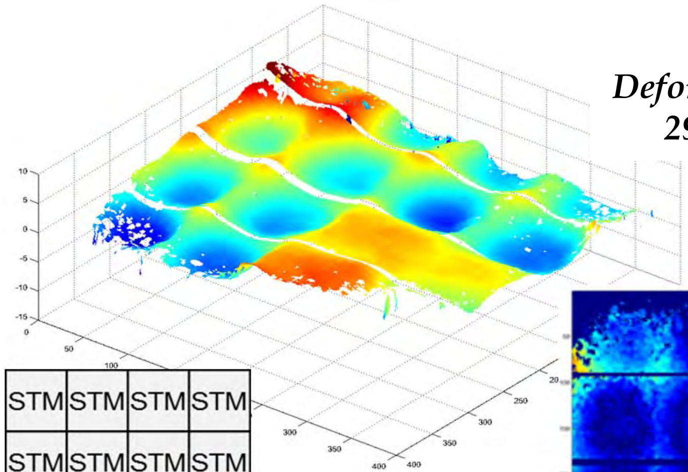


Vandenrijt, J., et al., Opt. Eng 55(12), 121723 (2016)

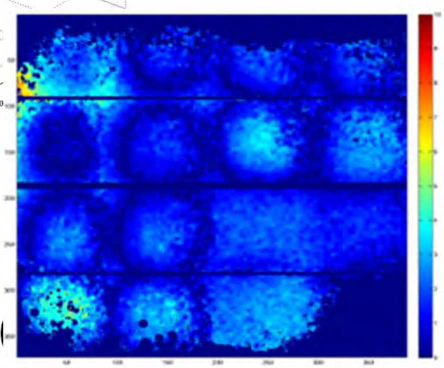
Temperature variation



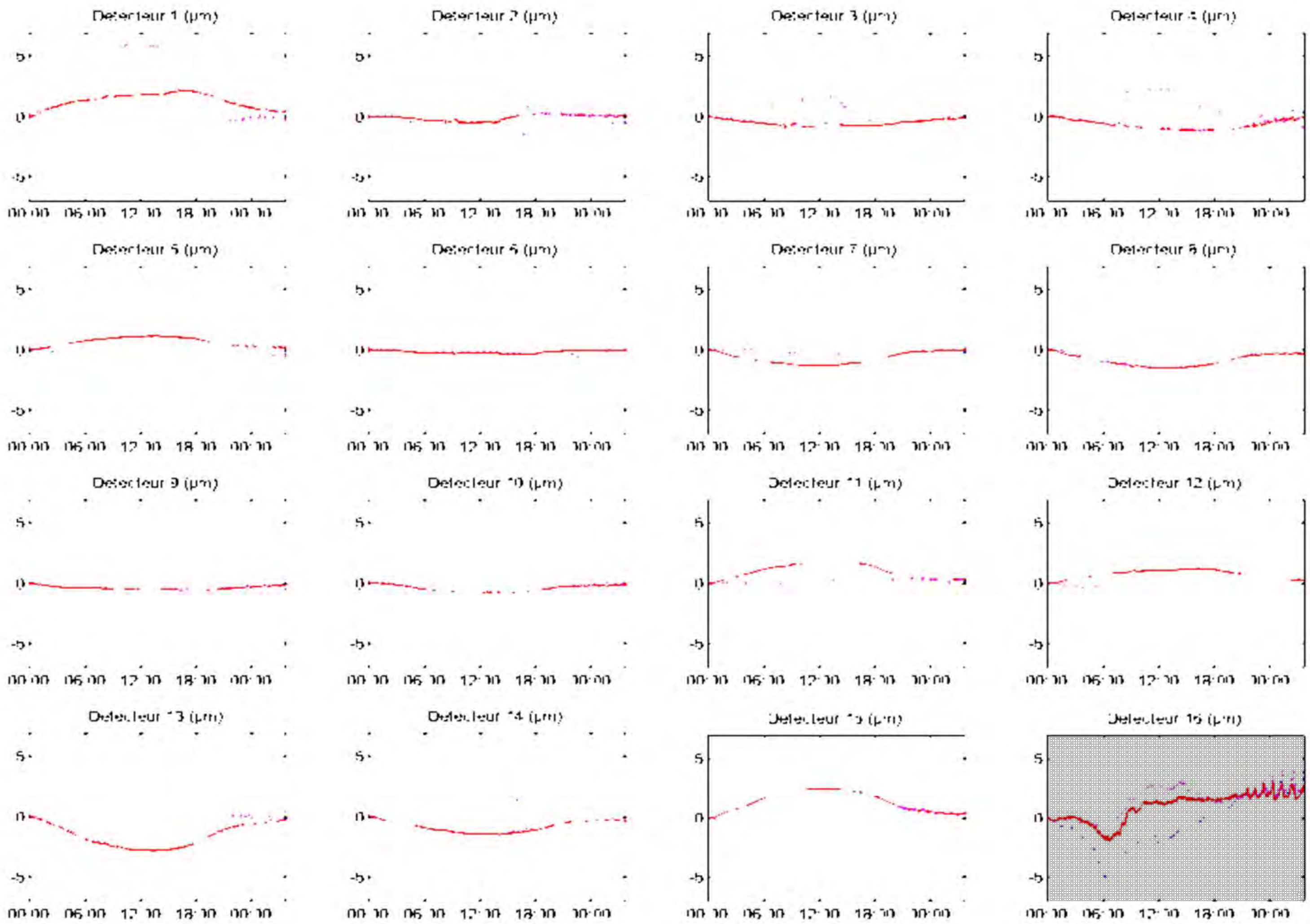
Deformation between 293 K and 90 K



STM	STM	STM	STM
STM	STM	STM	STM
STM	STM	MUX	FM
STM	STM	FM	MUX



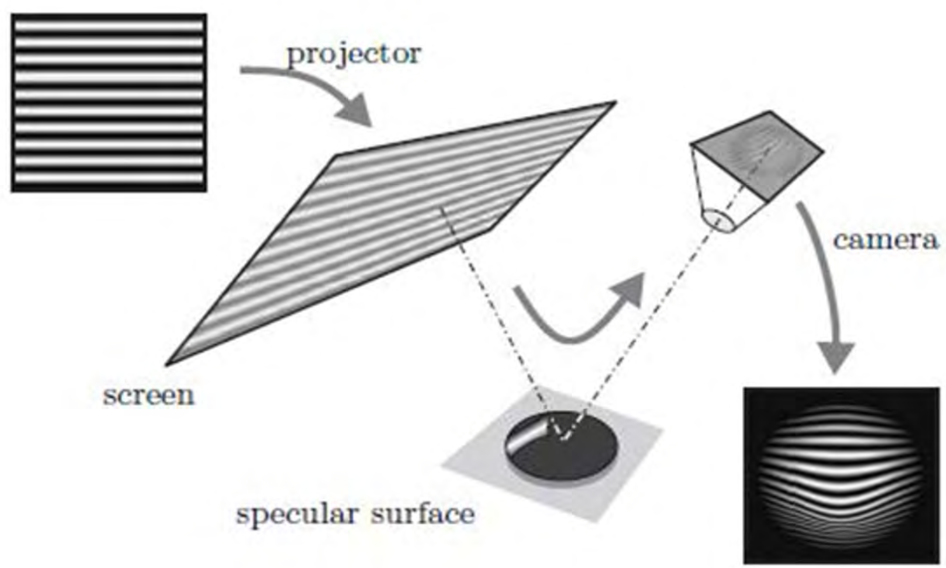
- EUCLID results
  - Rigid body motions of each detector (piston/rotation)



Vandenrijt, J., et al., Opt. Eng 55(12), 121723 (2016)

Future (prospective ideas)

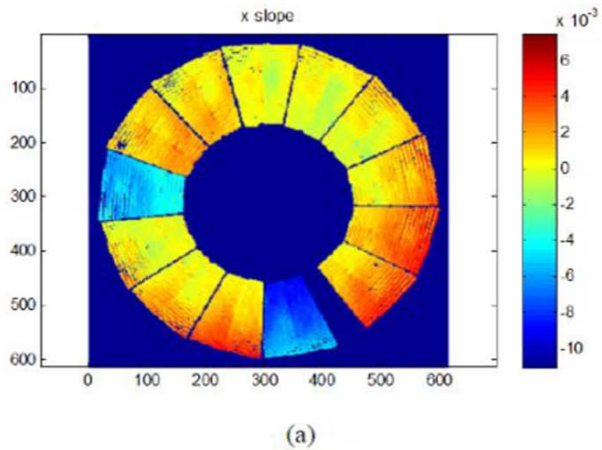
- Develop **deflectometry** for testing space optics under **vacuum-test** facilities
- Principle of deflectometry
  - Observe fringe pattern of projector through the specular surface under test
  - Deviation of fringe pattern is related to shape
  - Insensitive to vibration (unlike interferometric methods)
  - Larger dynamic range



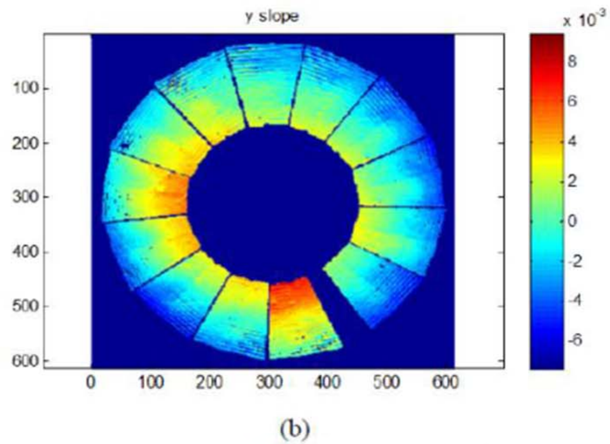
Knauer *et al,* Proc. SPIE **5457** (2004).

Future (prospective ideas)

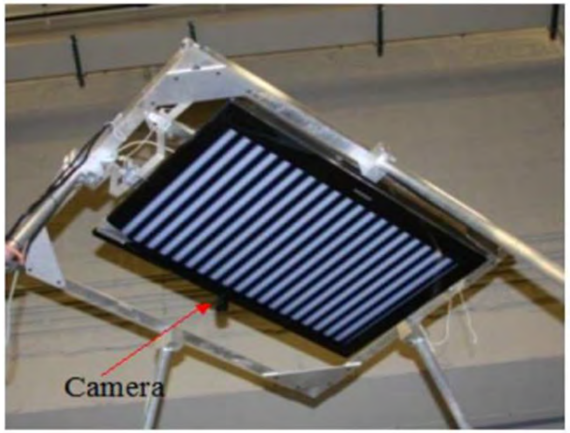
- Deflectometry applications
  - Segmented/deployable concentrators or aspherics

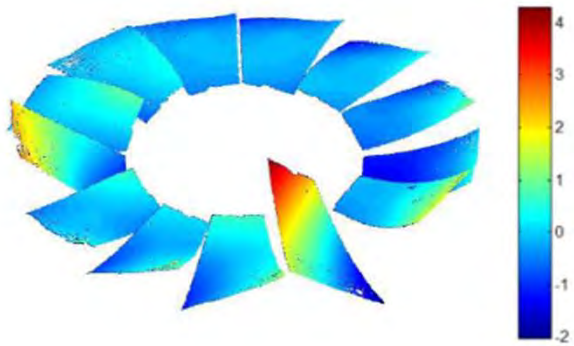


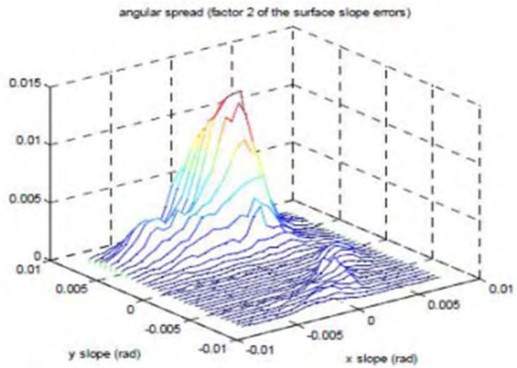
(a)



(b)







Ref. L. Wang, et. al. Proc. of SPIE vol 7652 76521H-1 (2010)

College of Optical Sciences