The Ultimate High Resolution View of the Sun: the SOLARNET Mission

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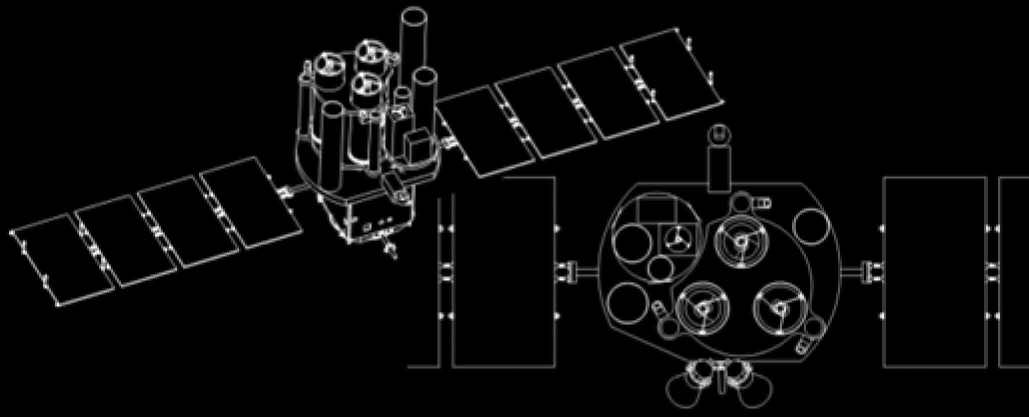
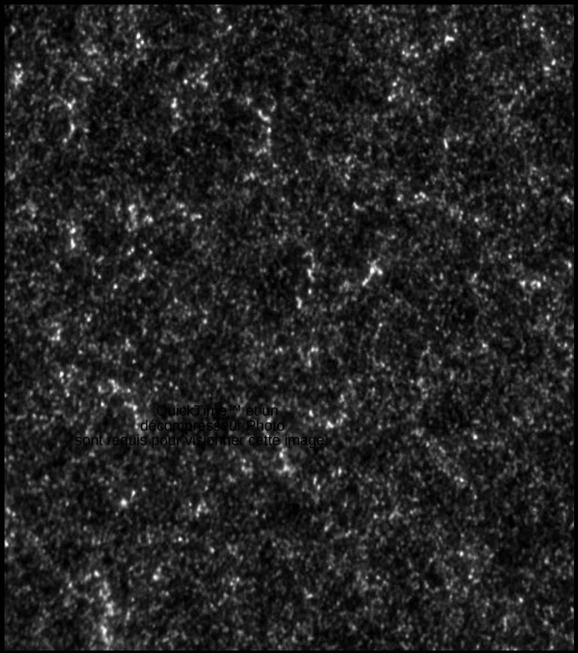


SOHO: a very complete Observatory

- SOHO, the Solar & Heliospheric Observatory, is a unique combination of coronagraphs, spectrographs, multi-wavelengths coronal imagers (EIT), and helioseismology instruments, in particular MDI (Michelson Doppler Imager).
- SOHO, however, is limited in spatial resolution and lacks UV and FUV (Far UV) imaging.
- But, combined to other satellites, in particular to Yohkoh and TRACE, we have, then, the performing tools to study the energetic phenomena from the photosphere to the corona and, most important, through the structuring / plasma confining Transition Zone.

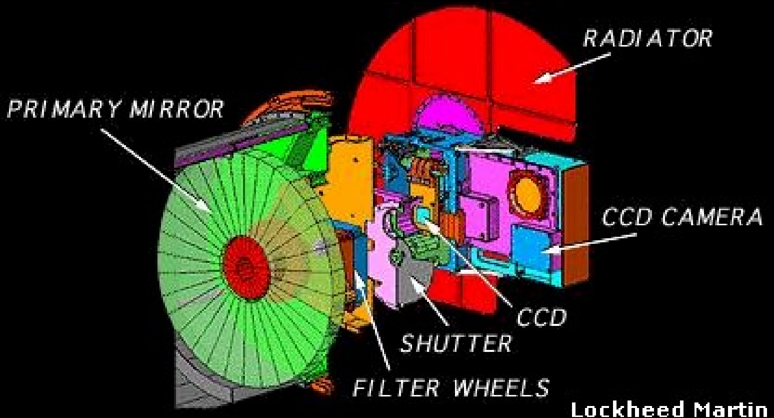
TRACE — A Small Explorer

- Wavelengths: 171Å FeIX, 195Å FeXII, 284Å FeXV, 1216Å Lyα, 1550Å CIV, 1600Å Tmin continuum
- Spatial resolution: 1"
- Temporal resolution: < 1s; 5s nominal
- Exposure time: 2 ms to 260 s
- FOV: 8.5 x 8.5 arc minutes



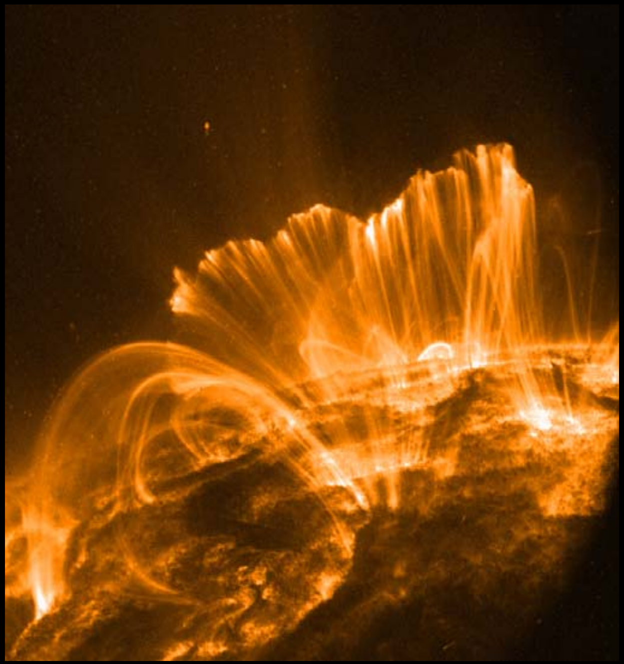
TRACE high spatial and temporal resolutions and XUV & FUV WAVELENGTHS are complement-
ary to SOHO

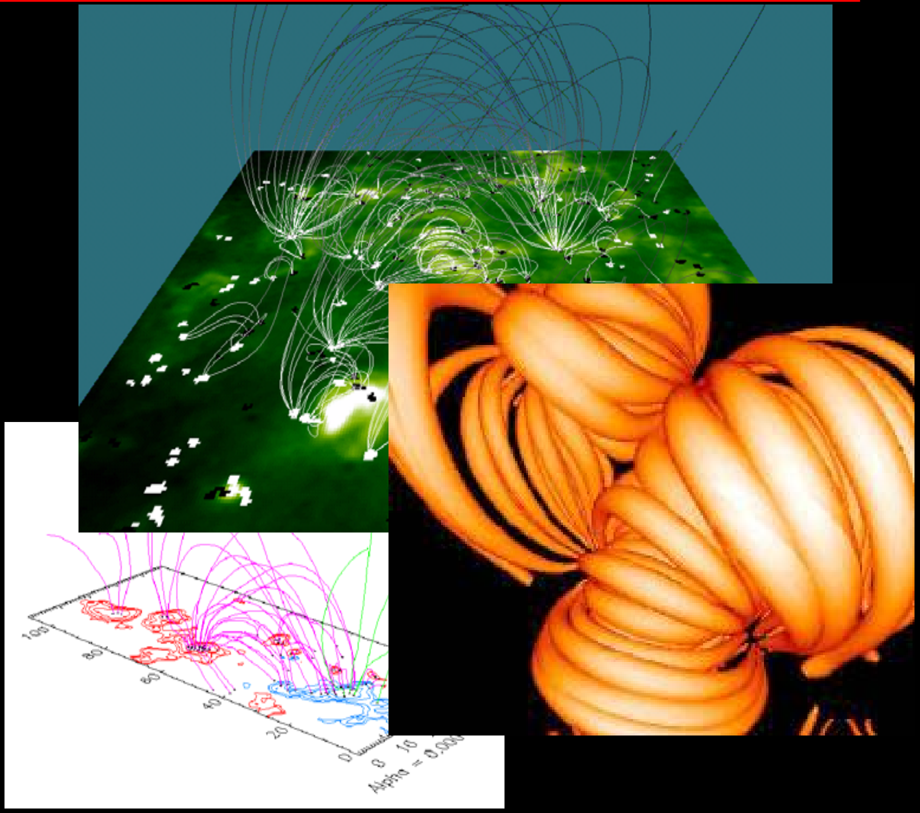
IMPORTANCE OF CHROMOSPHERIC & TRANSITION ZONE IMAGING



Lockheed Martin

Why Do We Need High Resolution?





- **The Sun is not simple (e.g. TRACE λ171Å, Fe IX) but NEAR so that the physical scale of the underlying processes can be observed.**
- **Complex phenomena (loops, sunspots, magnetic reconnection, granulation, etc.) are the result of a strong magnetic structuring that will only be addressed by very high resolution and long and continuous observations.**

Modeling magnetic fields extension in the chromophere, transition zone and corona is now possible, although complex, but this will gain enormously from higher resolu-tion and atmospheric height sampling.

The Structured "Spaghetti" Solar Atm.

A complex, dynamic, magnetically dominated environment, driven by the convective, turbulent solar interior.

Eruption & CME: relation?

This simple question, *in appearance*, is yet without a definitive answer despite the current observing means (probably because the Transition Zone and inner corona are not observed?)

TRACE

SOHO – LASCO

Imaging and spectroscopy are complementary THROUGHOUT the solar atmosphere

This is high resolution spectroscopy (HRTS 1978) which first showed the need for very Very High Spatial Resolution (<< 0.1")

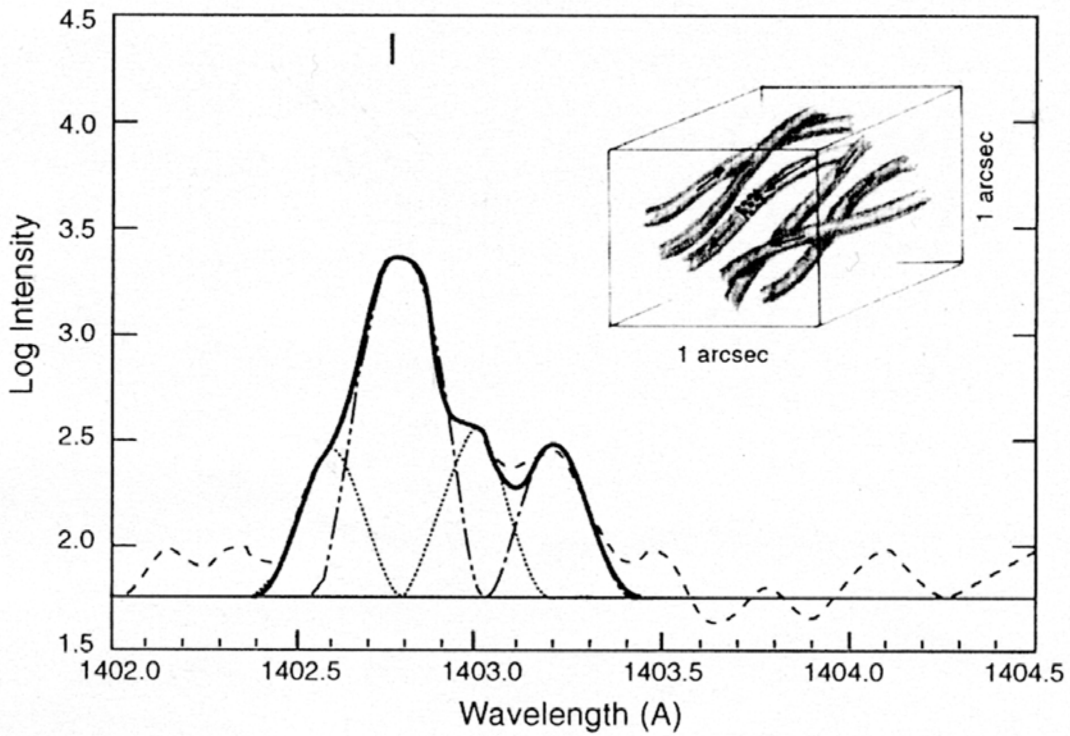


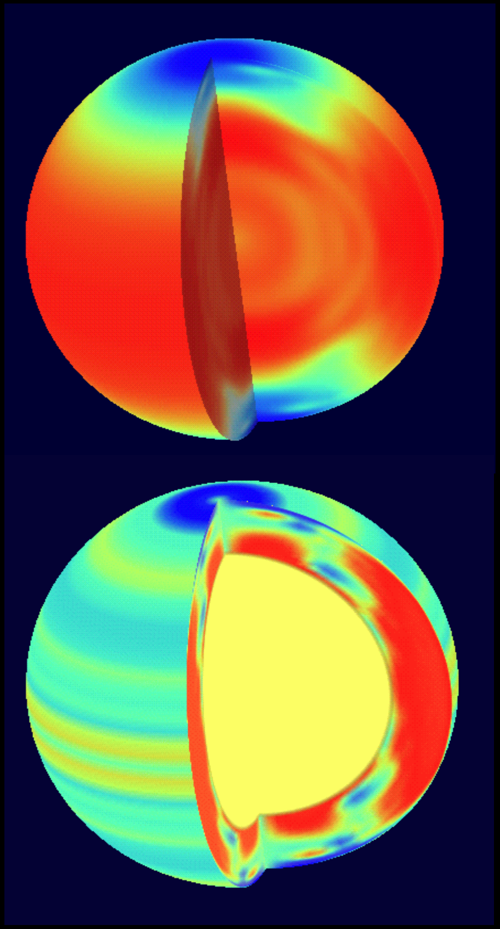
Figure 6. A complex 1402 Å profile observed with HRTS on 13 February 1978 (the 1393 Å line shows similar features). The profiles represents the emission from a 1 × 1 arc sec area on the Sun and have been fitted with Gaussian line components (solid line) and each line component is indicated. The raw data is the dashed line. Inserted is a cartoon of a possible explanation of the observed profiles.

Fine Structure
Brekke, 1999

Filling Factor
<1% (<0.1%?)

UV & FUV

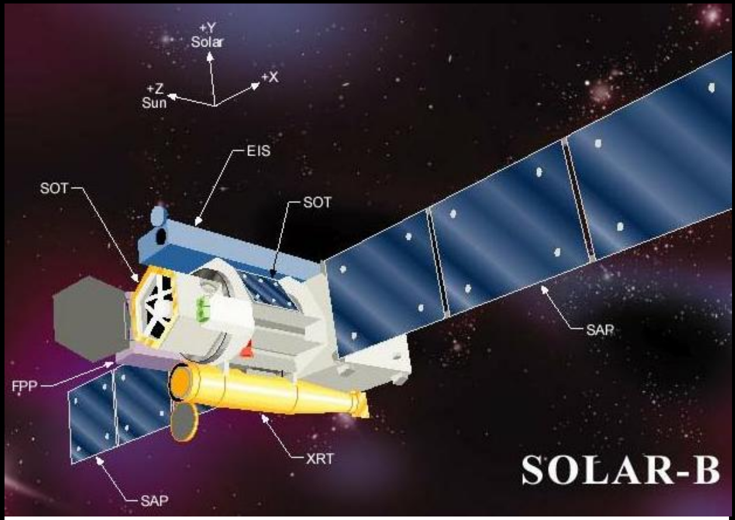
SOHO success is also Helioseismology and the solar internal structure and dynamo

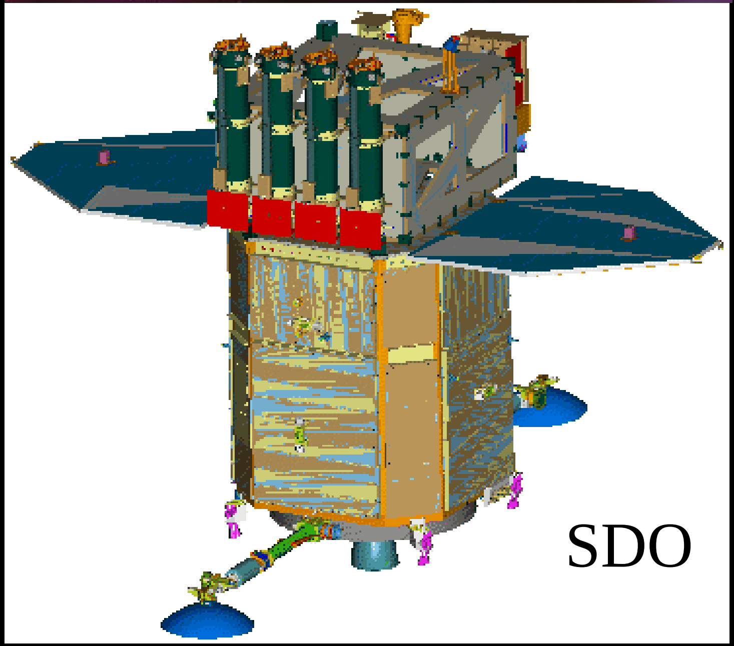


RED *Fast Rotation*
BLUE *Slower Rotation*

What after SOHO & TRACE?

- SOLAR-B, STEREO, SDO and the 1m Chinese Solar Space Telescope (SST), have no or limited high spatial, spectral and temporal resolutions in the UV, FUV and EUV to follow and understand the evolution of chromospheric and coronal structures (SDO spatial resolution is limited to 1.4"; SOLAR-B 0.2").
- On ground, major Observatories (NSST 1m, GREGOR 1.5m, BBSO 1.6m, ATST 4m) are aiming at very high resolution (by use of Adaptive Optics) ↓ **0.1"** **(but in optically thick visible lines)**.





Towards Very High Resolution

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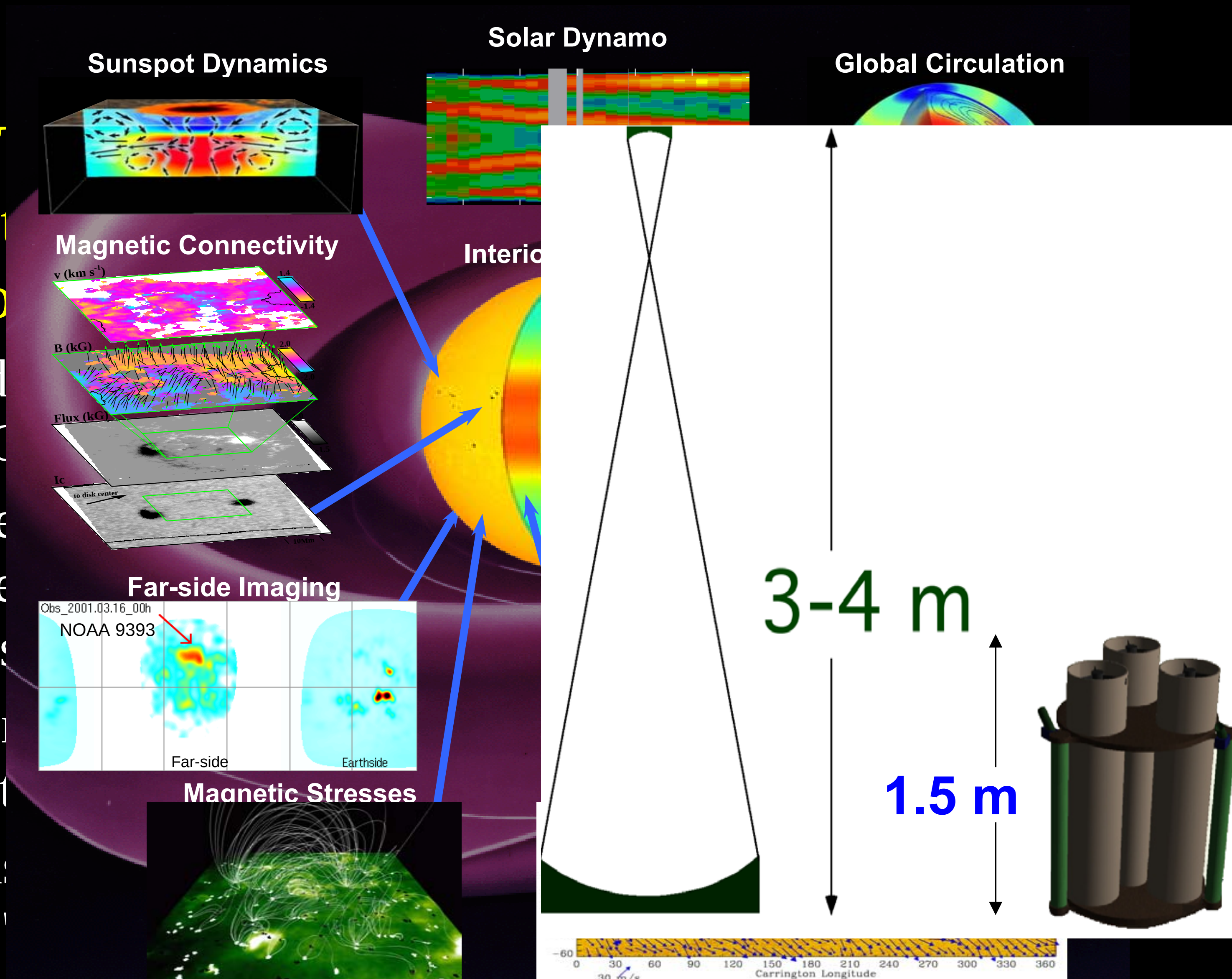
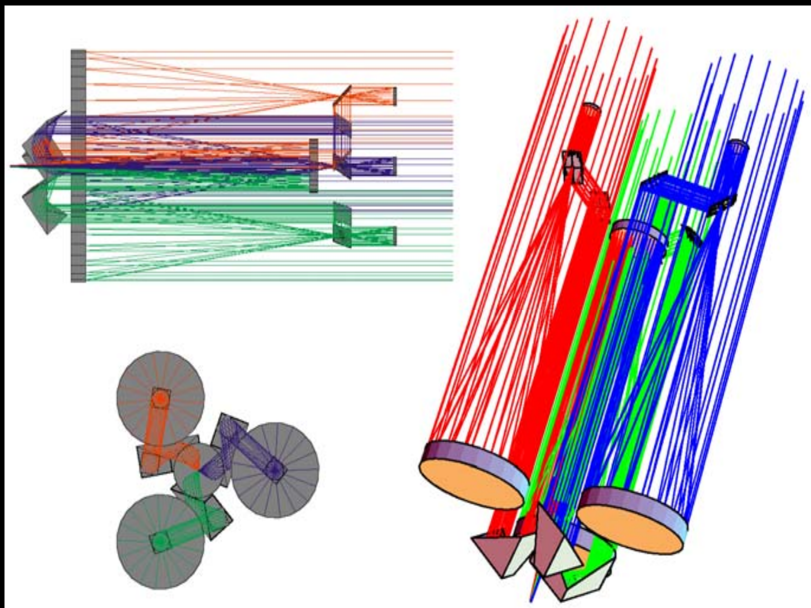
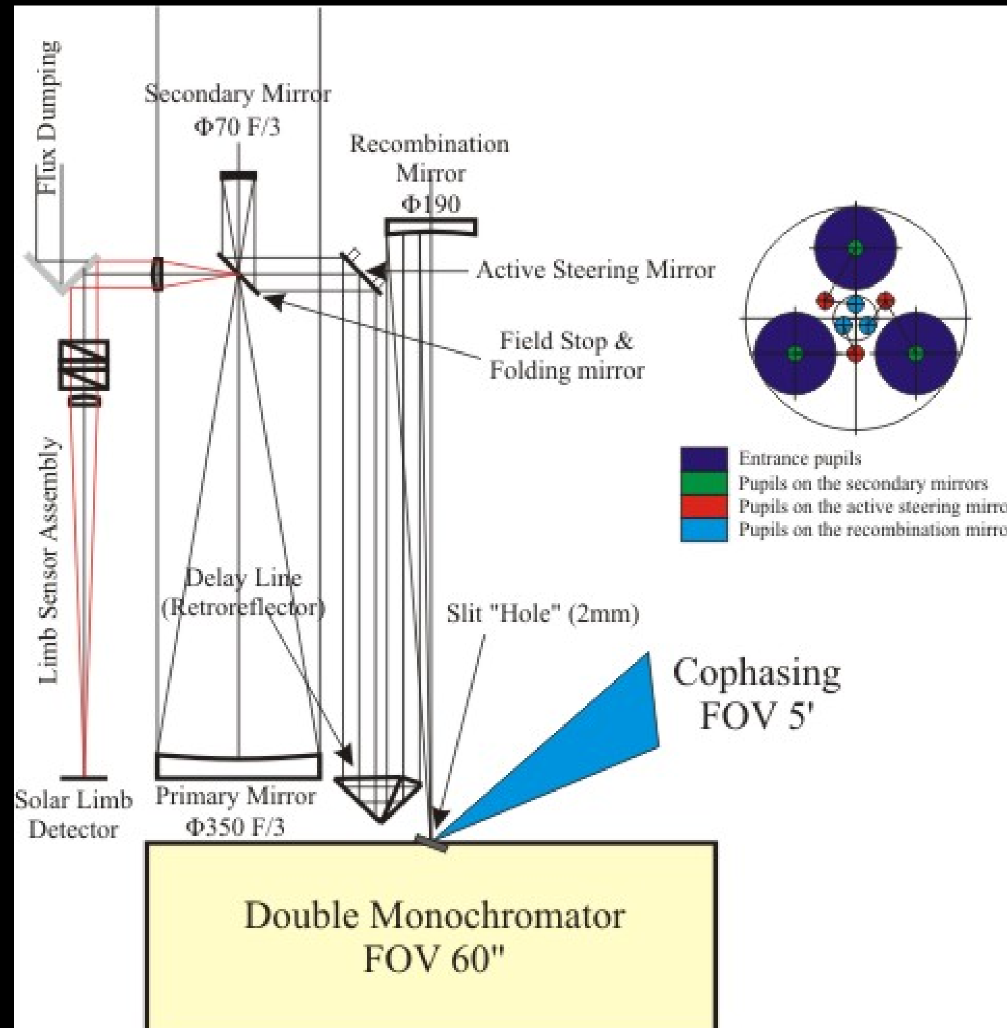


SOLARNET is a unique concept of direct interferometric imaging on an extended FOV



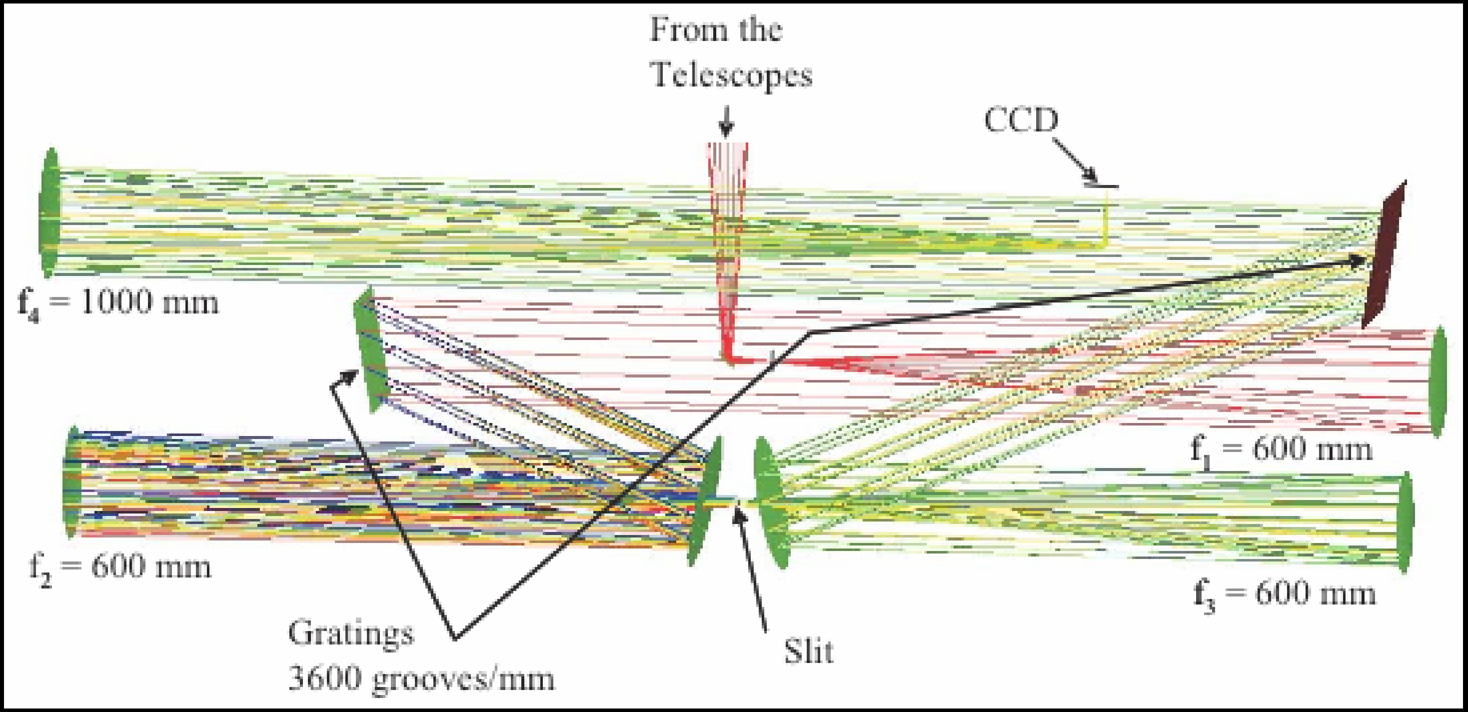
- Compact Configuration: 3 telescopes of Ø350mm on 1m
- Spatial Resolution of 0.025” (20–30km on the Sun)
- Multi-wavelengths spectral imaging λ110–400nm with a subtractive double monochromateur FUV & UV (coupled to an IFTS ⬇ 0.01nm)



SOLARNET Spectro-Imaging

Subtractive Double Monochromator FUV & UV

Improved design for the Subtractive Double Monochromator. The parabolic mirrors work on their axis (thanks to the central obscuration of the reconstituted beam). The DM spectral resolution is **0.1 nm on the 40" FOV**. An added Fabry Perot or an IFTS would then allow higher spectral resolutions (e.g. **0.005-0.01 nm**)



Requirements for a Working Large FOV Interferometric Design

- Demonstrate reliable image reconstruction on a significant FOV
- Demonstrate high quality cophasing and limited aberrations for long time integration
- Design a focal instrument capable of Physics:
  - 2D: images and velocities (Dopplergrams)
  - Large accessible spectral domain (FUV – UV – Near UV)
  - High spectral resolution (line ratios: temperatures and densities)

2D Optical Aperture Synthesis

Optimum coverage of the (u,v) plane => 3 pupils

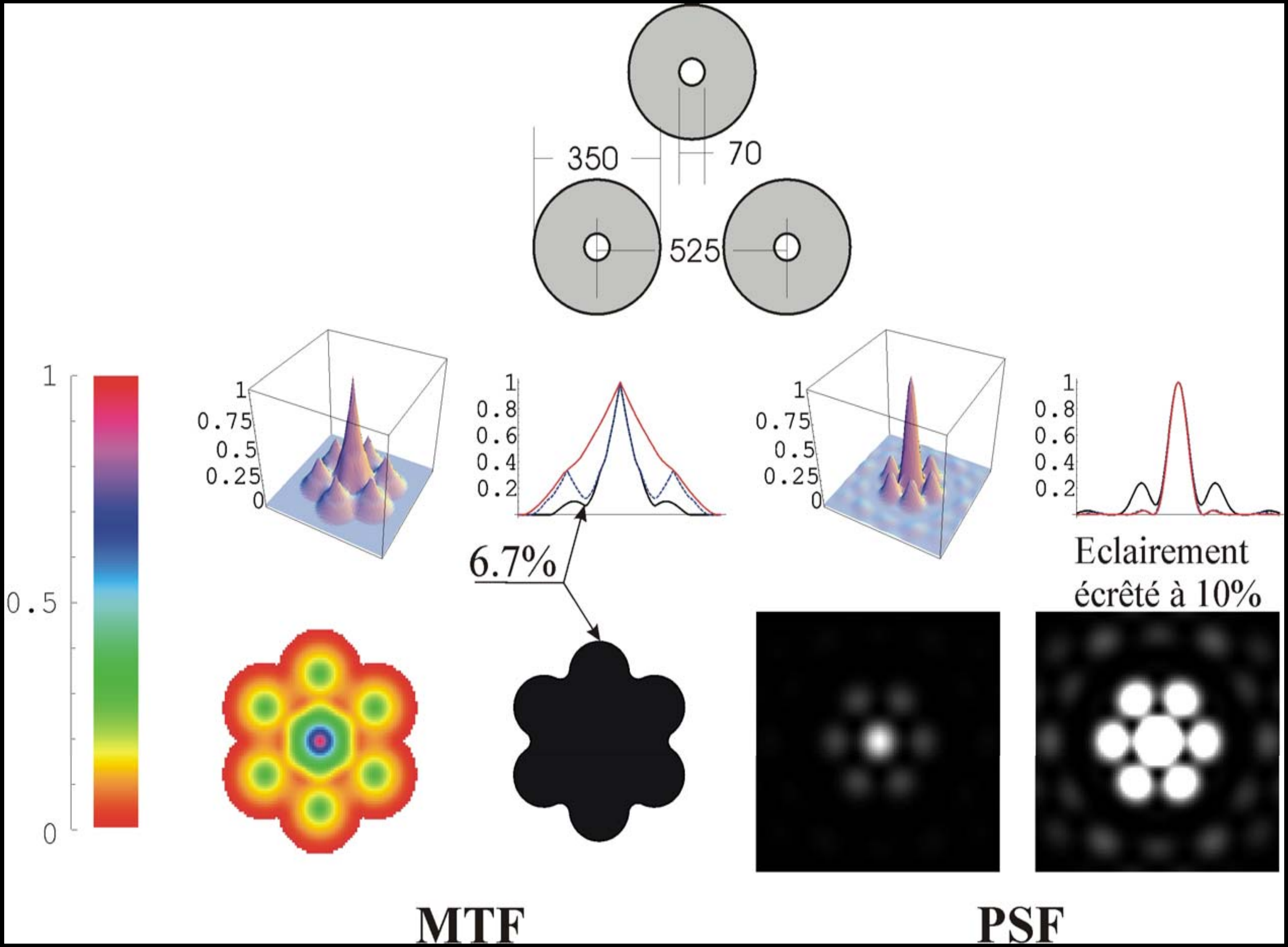
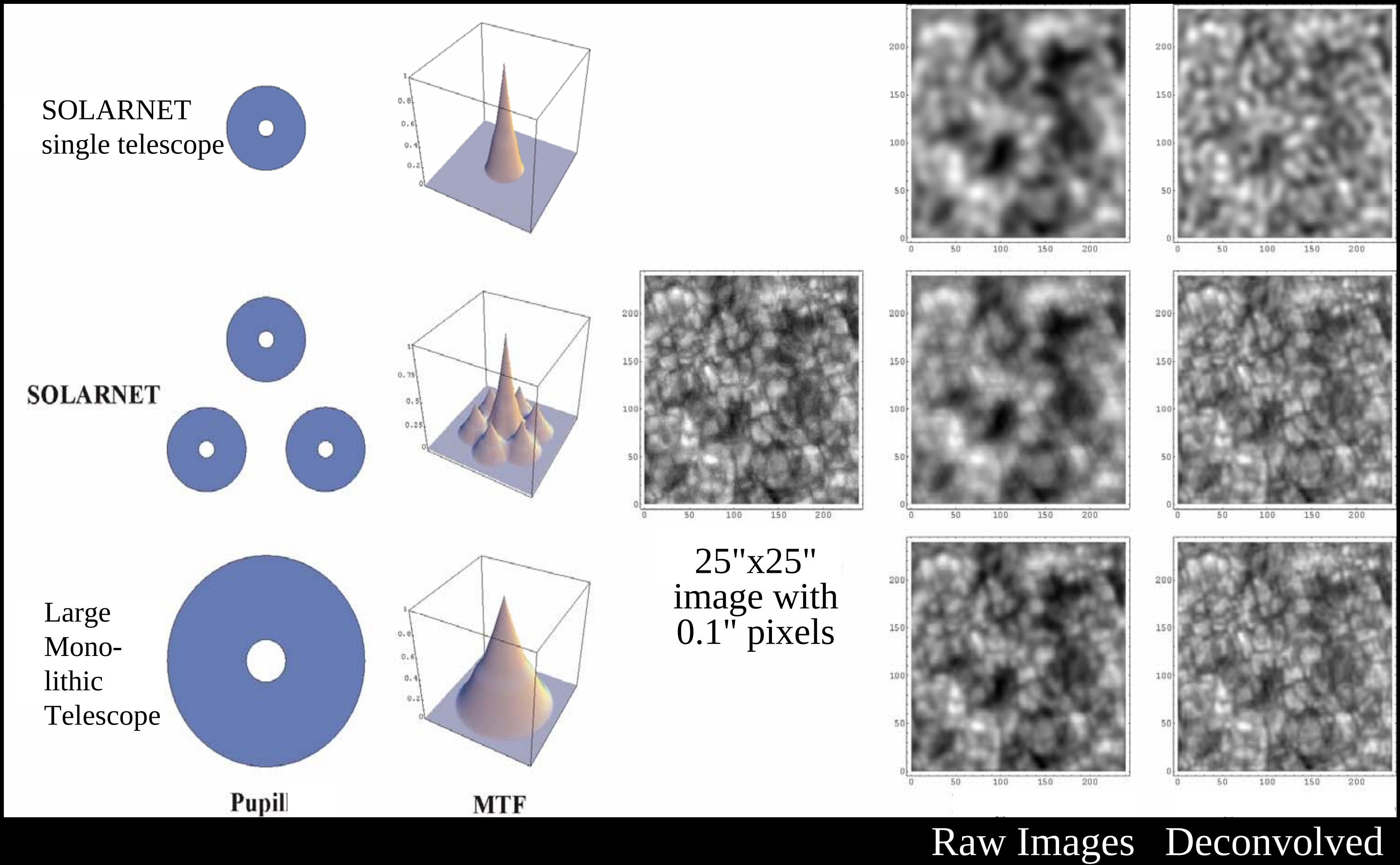
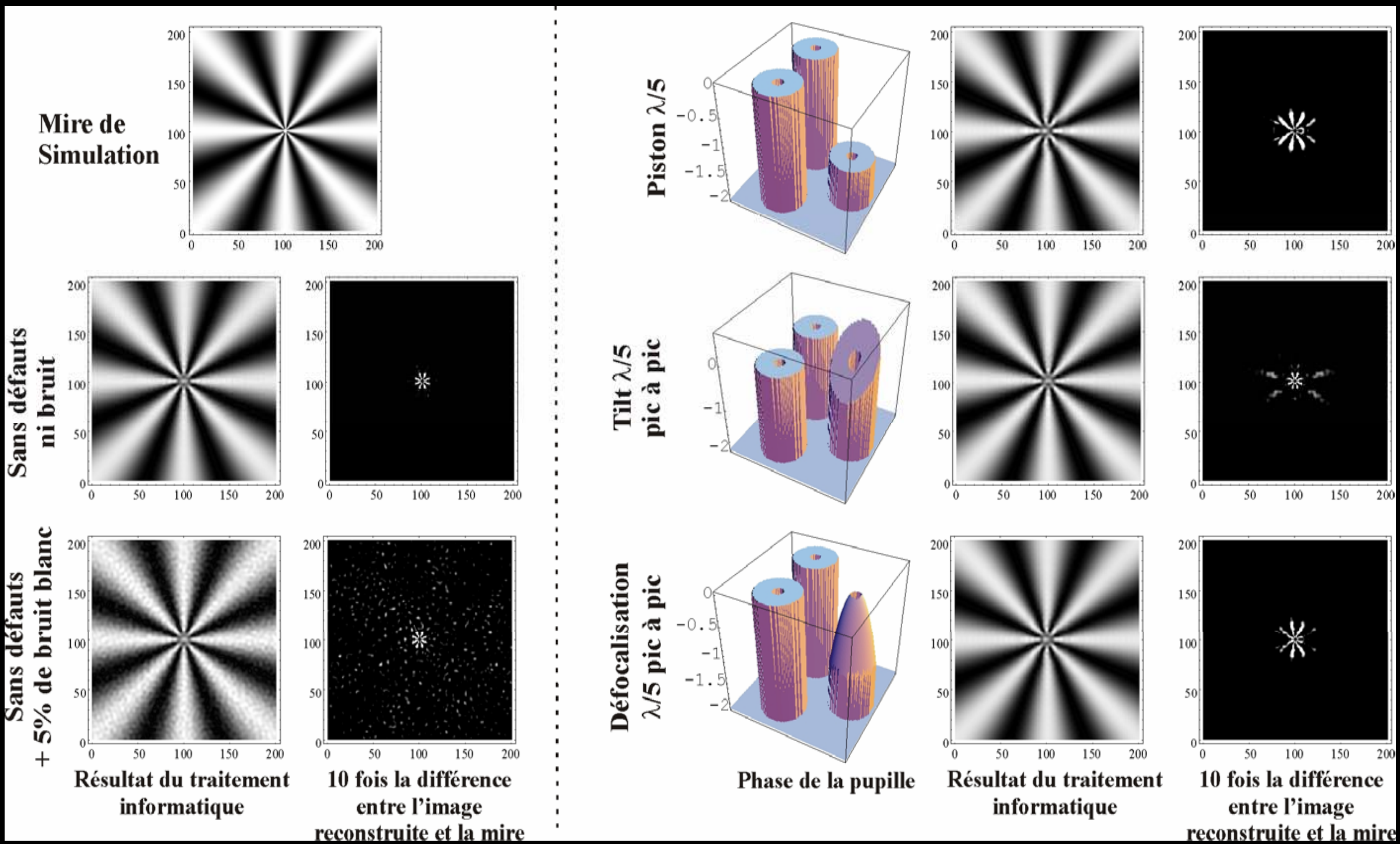


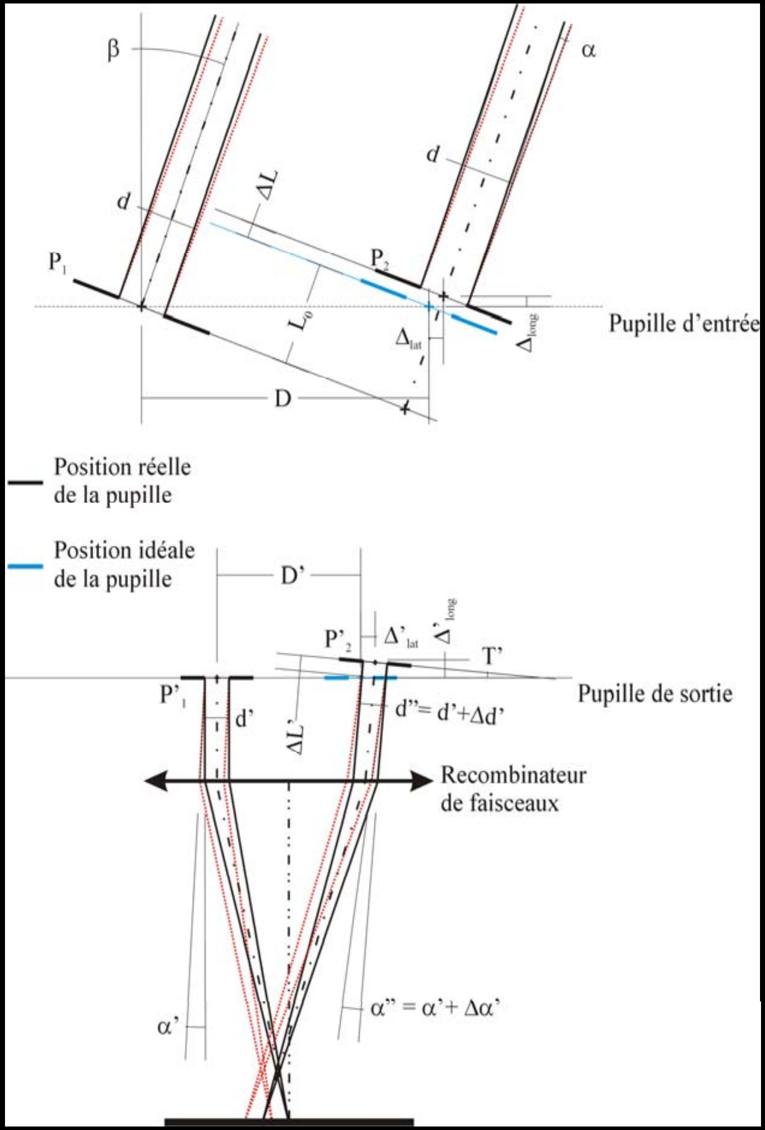
Image Reconstruction with 3 Telescopes



"Perfect" Cophasing: Phase, Tilt & Focusing Errors



Recombination Errors Linked to OAS



Without rotation, 2 effects:

- Piston (FOV dependent) :

$$\delta(\alpha) \approx \frac{\Delta G_\alpha}{G_\alpha}.D.\alpha + \left(G_\alpha.\Delta'_{lat} - \Delta_{lat}\right).\alpha - \left(G_\alpha{}^2\Delta'_{long} - \Delta_{long}\right).\frac{\alpha^2}{2}$$

- Tilt:

$$T(\alpha) \approx \Delta G_\alpha.\alpha$$

With rotation:

$$T_{pup}(\alpha) \approx \sqrt{2}G_\alpha.\alpha.\theta_{pup}$$

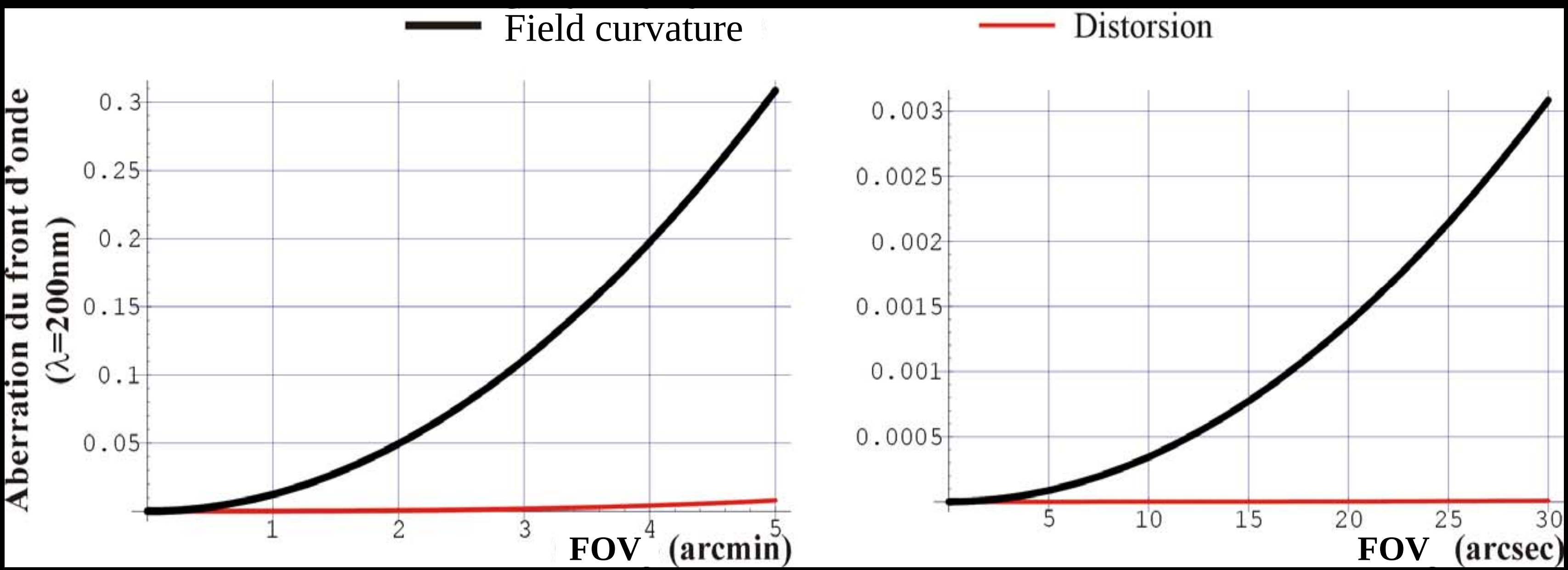
Telescopes' Optical Aberrations

Marsenne telescopes ➢ Distorsion and field curvature

$$W_{220} = \frac{d}{16N_f}(G_\alpha - 1)\alpha^2 \quad \text{Courbure de champ}$$

N_f : Ouverture du miroir primaire de l'afocal

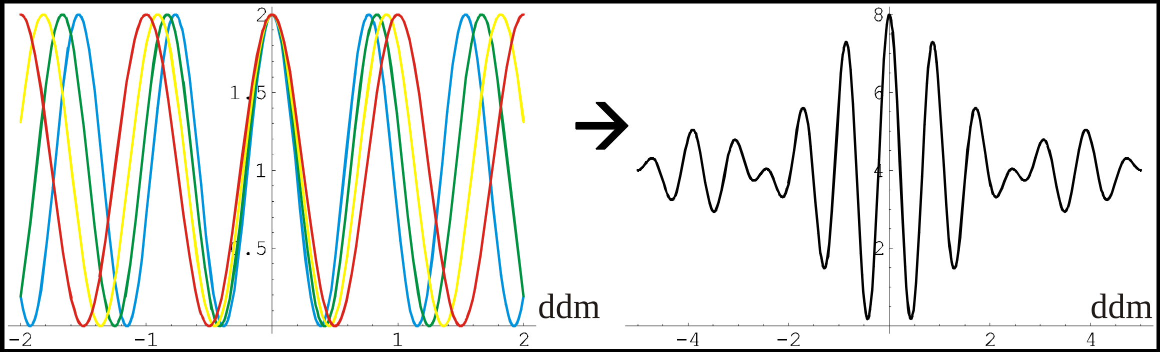
$$W_{311} = \frac{d}{8}(G_\alpha + 3)(1 - G_\alpha)\alpha^3 \quad \textit{Distorsion}$$

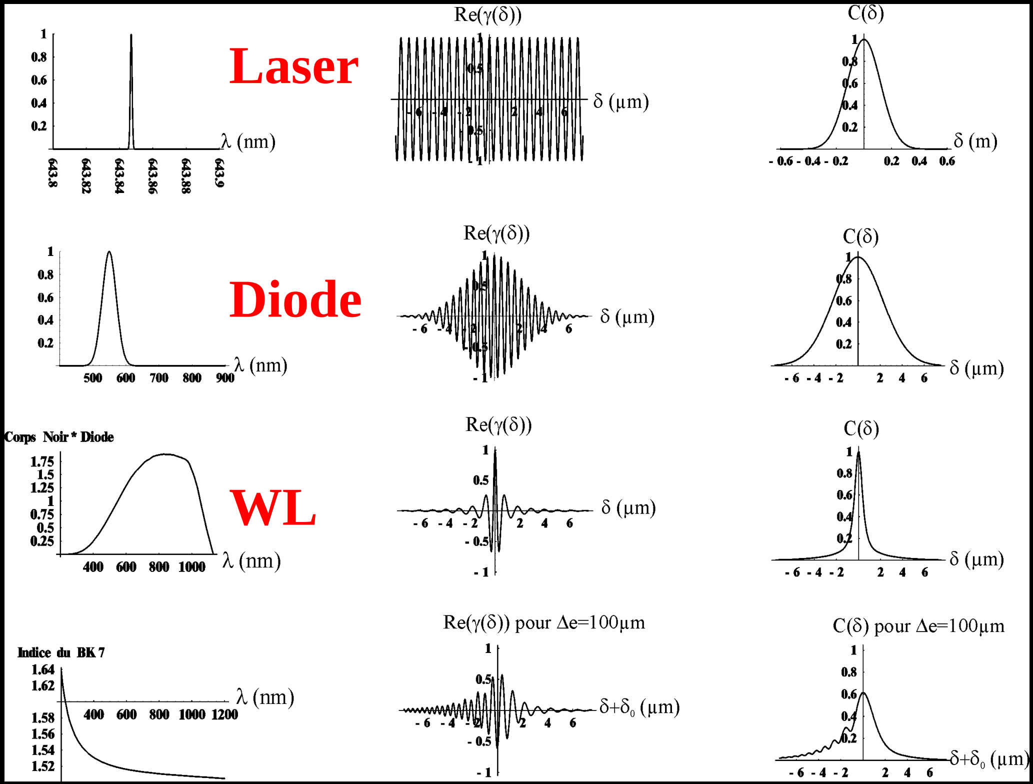


Tolerances Analysis (for λ/10)

Parameter	Maximum Error (formula)	Value for SOLARNET $\lambda = 200nm$, $G_\alpha = -5$, $\alpha_{max} = 2.10^{-4} rad$	Value for the SOLARNET breadboard $\lambda = 550nm$, $d = 60mm$, $G_\alpha = -10$, $\alpha_{max} = 2.10^{-4} rad$
Δ_{lat} (mm)	$\Delta_{lat} = \frac{\lambda}{N.\alpha_{max}}$	0.1	0.27
Δ'_{lat} (mm)	$\Delta'_{lat} = \frac{\lambda}{N.G_\alpha.\alpha_{max}}$	0.02	0.027
Δ_{long} (mm)	$\Delta_{long} = \frac{2.\lambda}{N.\alpha^2_{max}}$	1000	2750
Δ'_{long} (mm)	$\Delta'_{long} = \frac{2.\lambda}{N.G_\alpha{}^2.\alpha^2_{max}}$	40	27.5
ΔG_α piston	$\Delta G_\alpha = \frac{G_\alpha.\lambda}{N.D.\alpha_{max}}$	0.0010	0.031
ΔG_α tilt	$\Delta G_\alpha = \frac{G_\alpha.\lambda}{N.d.\alpha_{max}}$	0.0015	0.046
θ_{pup} (°)	$\frac{\lambda}{\sqrt{2}.d.\alpha_{max}N} \times \frac{180}{\pi}$	0.012° = 0'45''	0.186° = 11'
Distorsion	$W_{311} = \frac{d}{8}(G_\alpha + 3)(1 - G_\alpha)\alpha^3_{max}$	$2.1\ 10^{-5}\ \lambda$	$3.6\ 10^{-4}\ \lambda$ (Zemax calculation)
Field Curvuture	$W_{220} = \frac{d}{16N_f}(G_\alpha - 1)\alpha^2_{max}$	$8.7\ 10^{-3}\ \lambda$	$3.4\ 10^{-3}\ \lambda$ (Zemax calculation)

Temporal Coherence



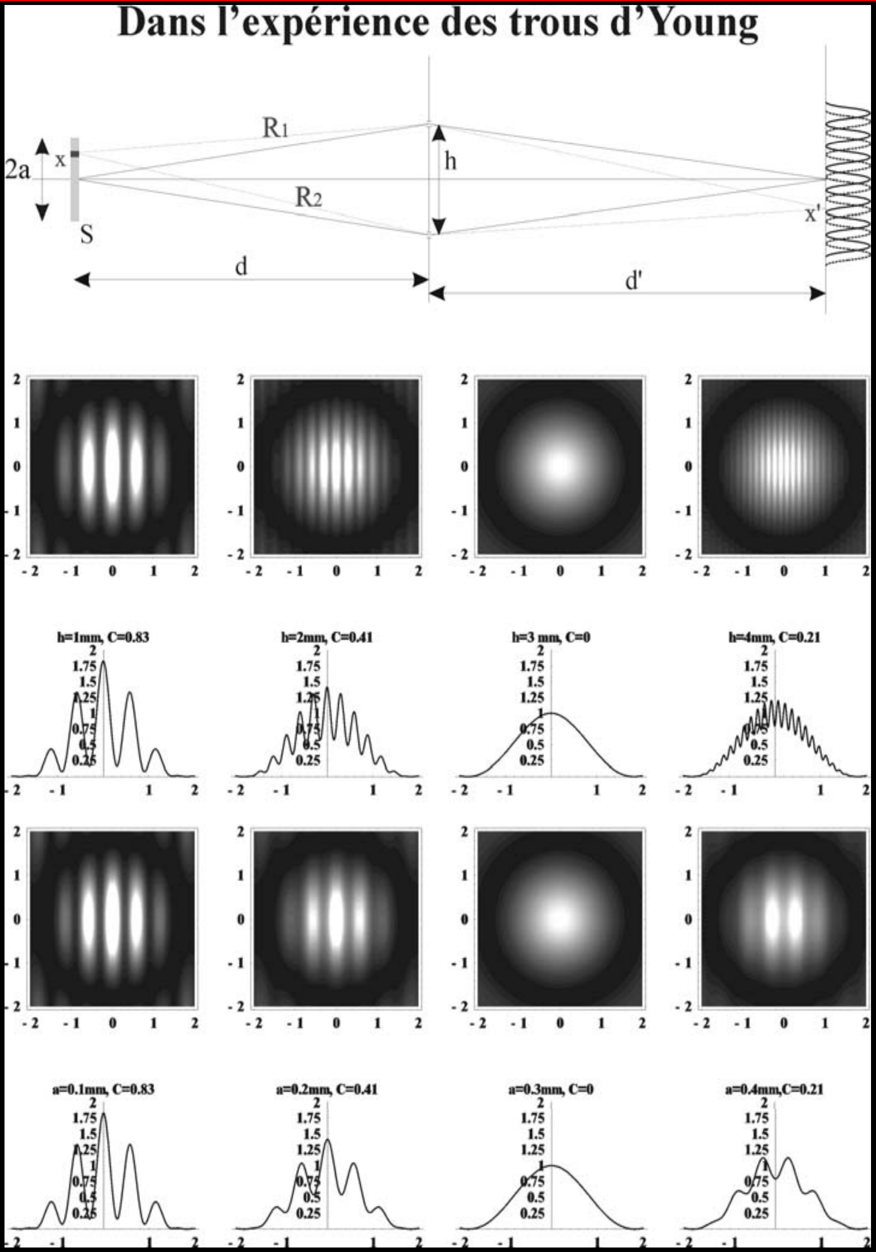


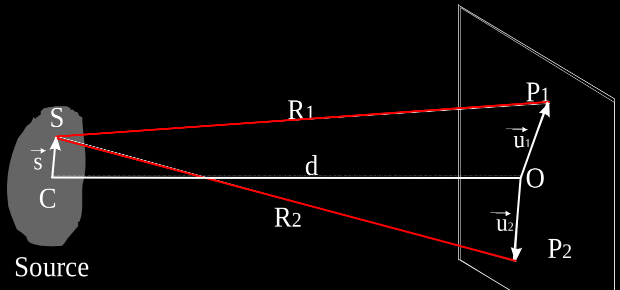
- **Monochromatic light : alignment but no simple identification of the central fringe**
- **Solution: large spectral bandpass**
- **But problem if differ-ential aberration (uneven glass thicknesses)**

Spatial Coherence

As a function of the distance h

As a function of the source size



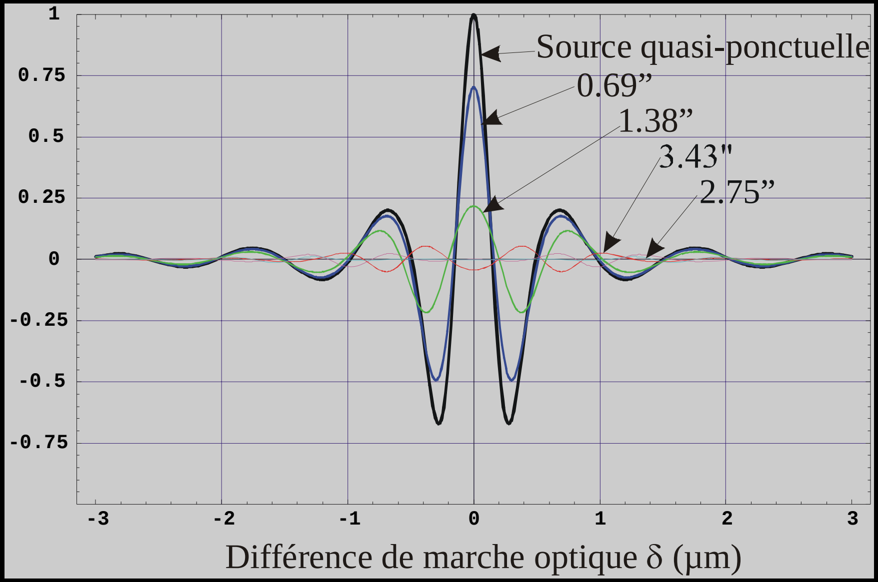


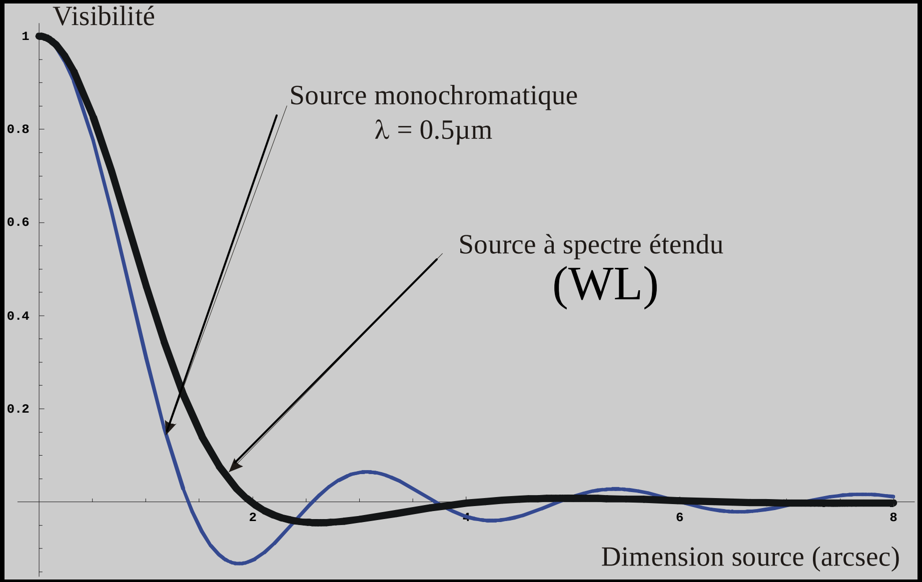
- To achieve a decent (> 1 %) contrast (visibility) the FOV needs to be reduced

Coherence and SOLARNET

Coherence, spatial and temporal:
(no polarization)

$$\gamma(h,\delta) = \frac{\iiint_S L(\alpha,\beta,\sigma) e^{i2\pi\sigma h\alpha} e^{i2\pi\sigma\delta}\, d\alpha\, d\beta\, d\sigma}{\iiint_S L(\alpha,\beta,\sigma)\, d\alpha\, d\beta\, d\sigma}$$





Contrast as a function of the source size (in arcsec)

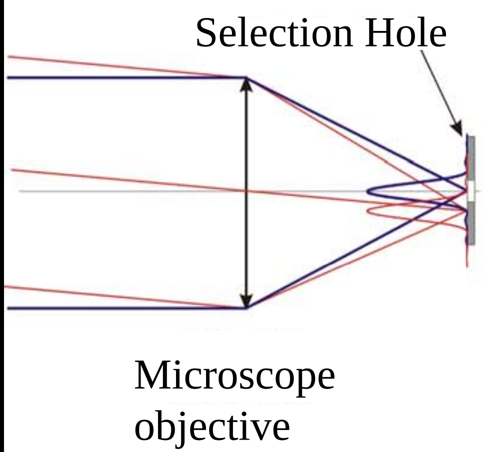
Contrast as a function of the spectral content and size (")

Phase Measure → Spatial Filtering

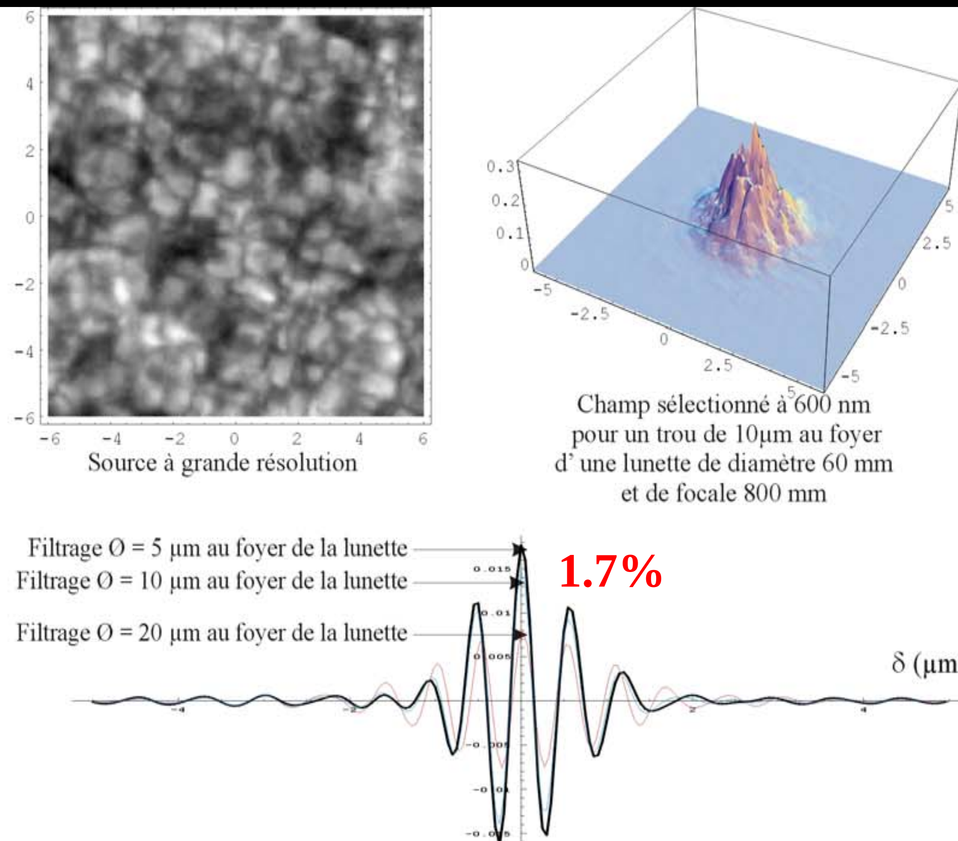
With an <u>extented source</u>

➢ **a <u>spatial filtering</u> is required to measure a <u>proper contrast</u>**

<u>Principle of a Spatial Filtering</u>

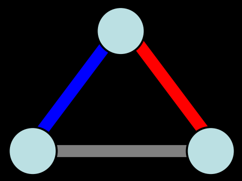


Simulation of the interference figure in the case of a solar type image (granulation – not WL)



Reference FOV and Spatial Filtering

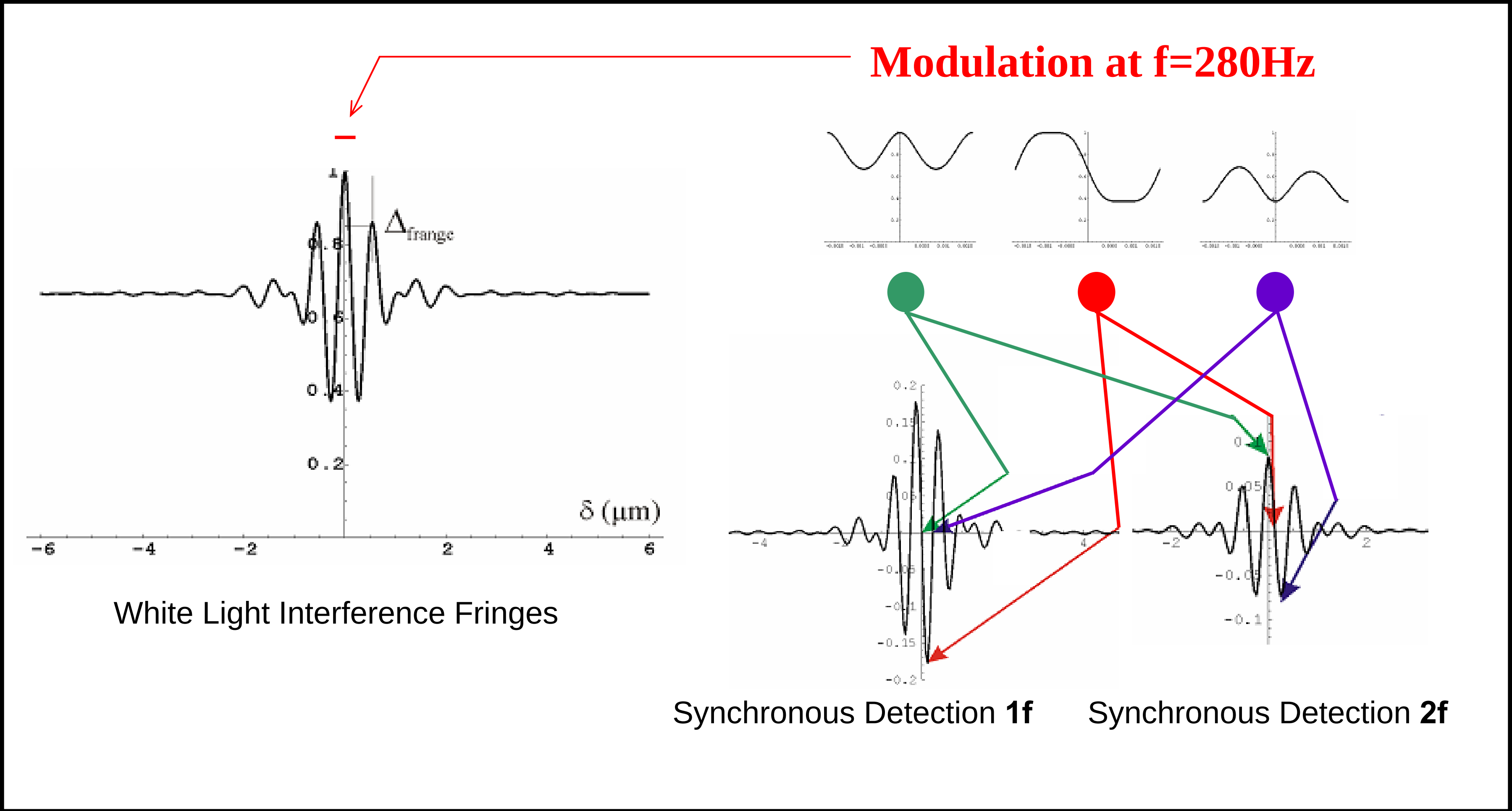
Extreme single wavelength example of source in the reduced FOV after filtering



A small decentering of the reference field α (α small) in the baseline direction will produce a biais in the WLF absolute nulling OPD position of **$\delta \sim h\alpha$**.
When centered, the contrast is maximum on the 3 interferometers.

Principle of the Phase Measure

- Technique: use of 2 synchronous detections
  - Measure of the fluctuations of the phase
  - Research of the central fringe, OPD zero (nulling)

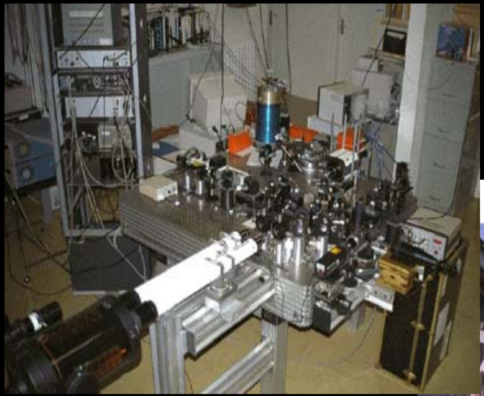


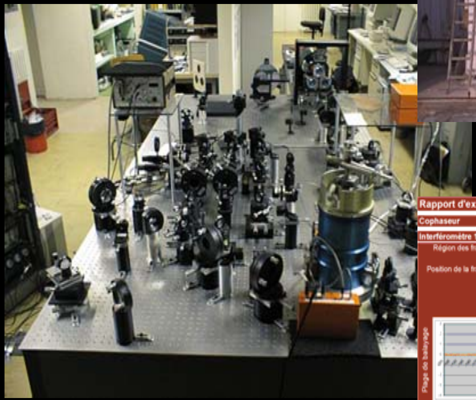
White Light Interference Fringes

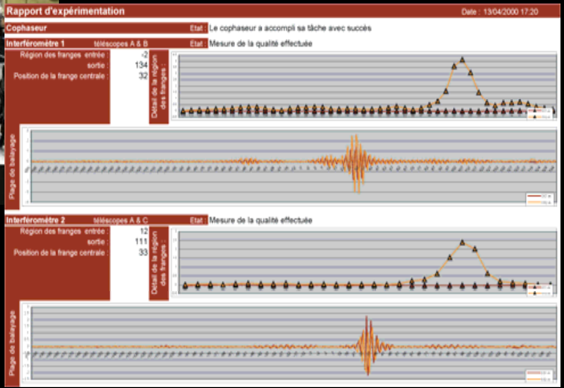
Synchronous Detection **1f**   Synchronous Detection **2f**

Attainments & Results since 1994

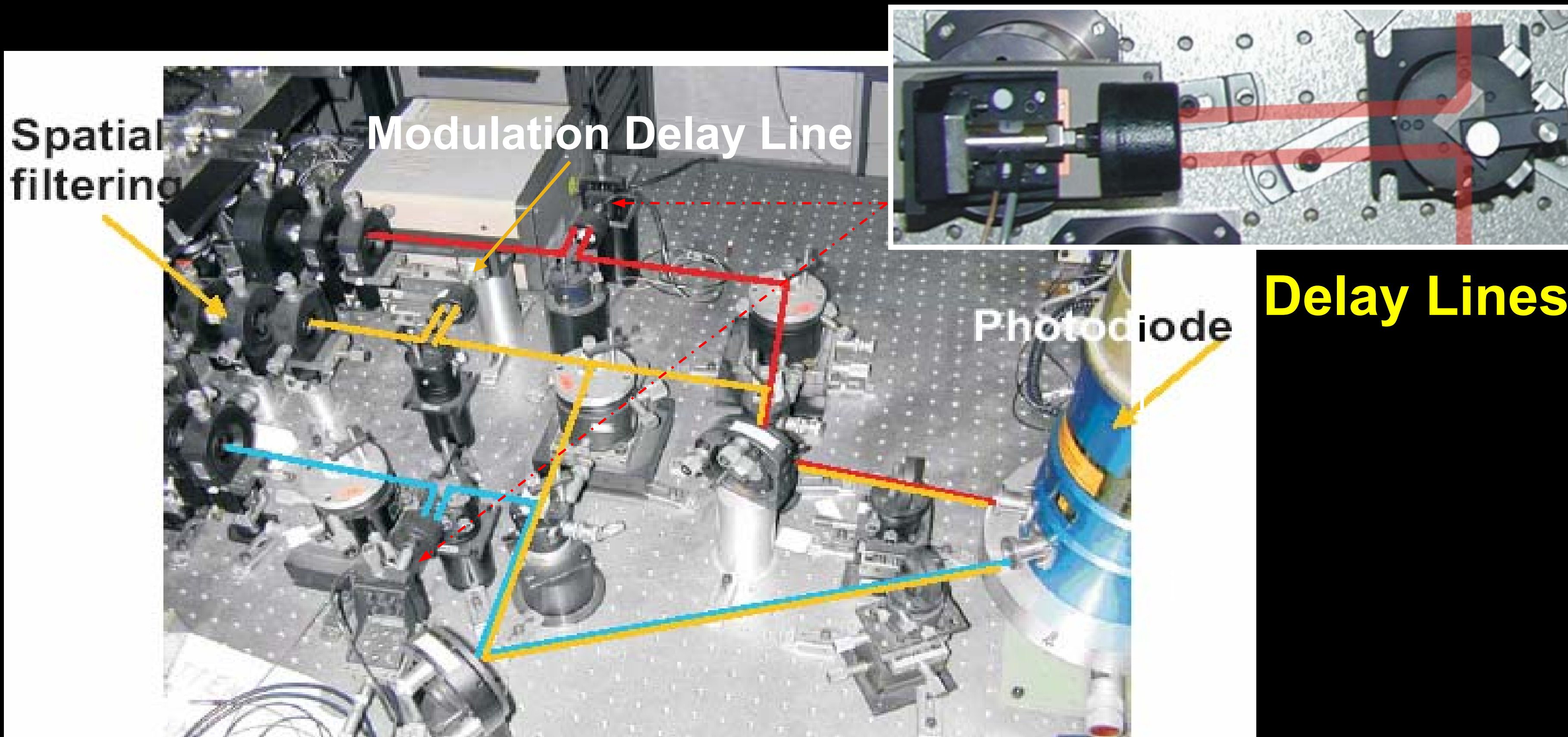
- Direct cophasing at **λ/300** of two telescopes on an extended laboratory source in **94**
- Fringes and cophasing at **λ/140** on the **Sun** and λ/220 on stars and Planets (Jupiter, Mars) in **95** and 96 (Obs. Meudon)
- Stabilities up to **λ/1000** on solar like flux and λ/100 on mag. 10 stars (OAST 2 - **1997**)
- **2000**: acquisition, control and imaging with the 3 telescopes cophased breadboard (laboratory setup) with measured stabilities > **λ/300**!







Cophasing in Practice



SOLARNET's phase measure white-light interferometers

Recombination (in pupil plane on a 1mm^2 diode) of the 3 beams in 2 of the reference interferometers after spatial filtering

Fringes Acquisition and Phasing

Rapport d'expérimentation Date : 13/04/2000 17:20

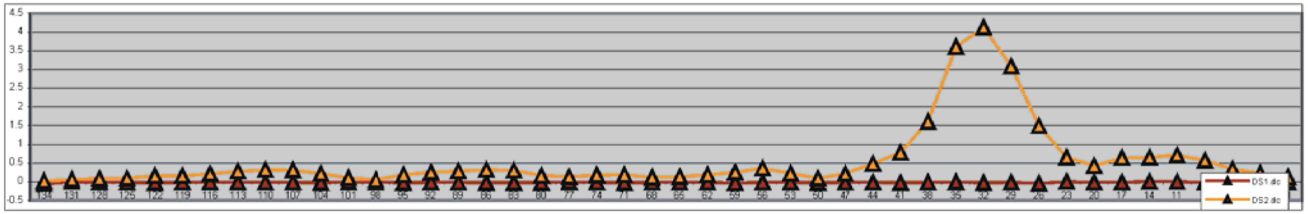
f
2f

Cophaseur Etat : Le cophaseur a accompli sa tâche avec succès

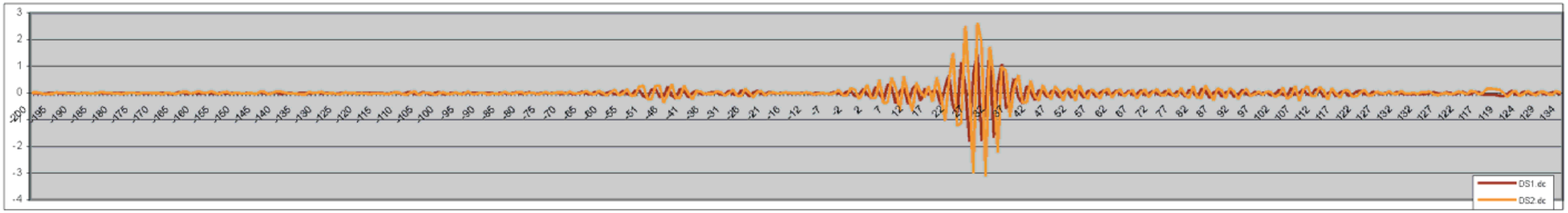
Interféromètre 1 téléscopes A & B Etat : Mesure de la qualité effectuée

Région des franges entrée : -2
sortie : 134
Position de la frange centrale : 32

Détail de la région des franges :



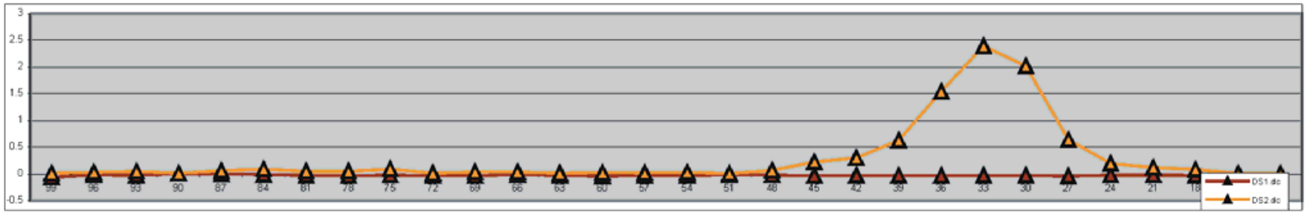
Plage de balayage



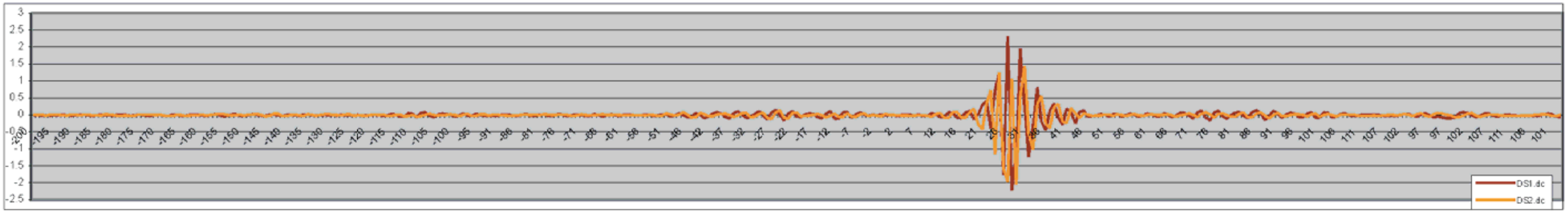
Interféromètre 2 téléscopes A & C Etat : Mesure de la qualité effectuée

Région des franges entrée : 12
sortie : 111
Position de la frange centrale : 33

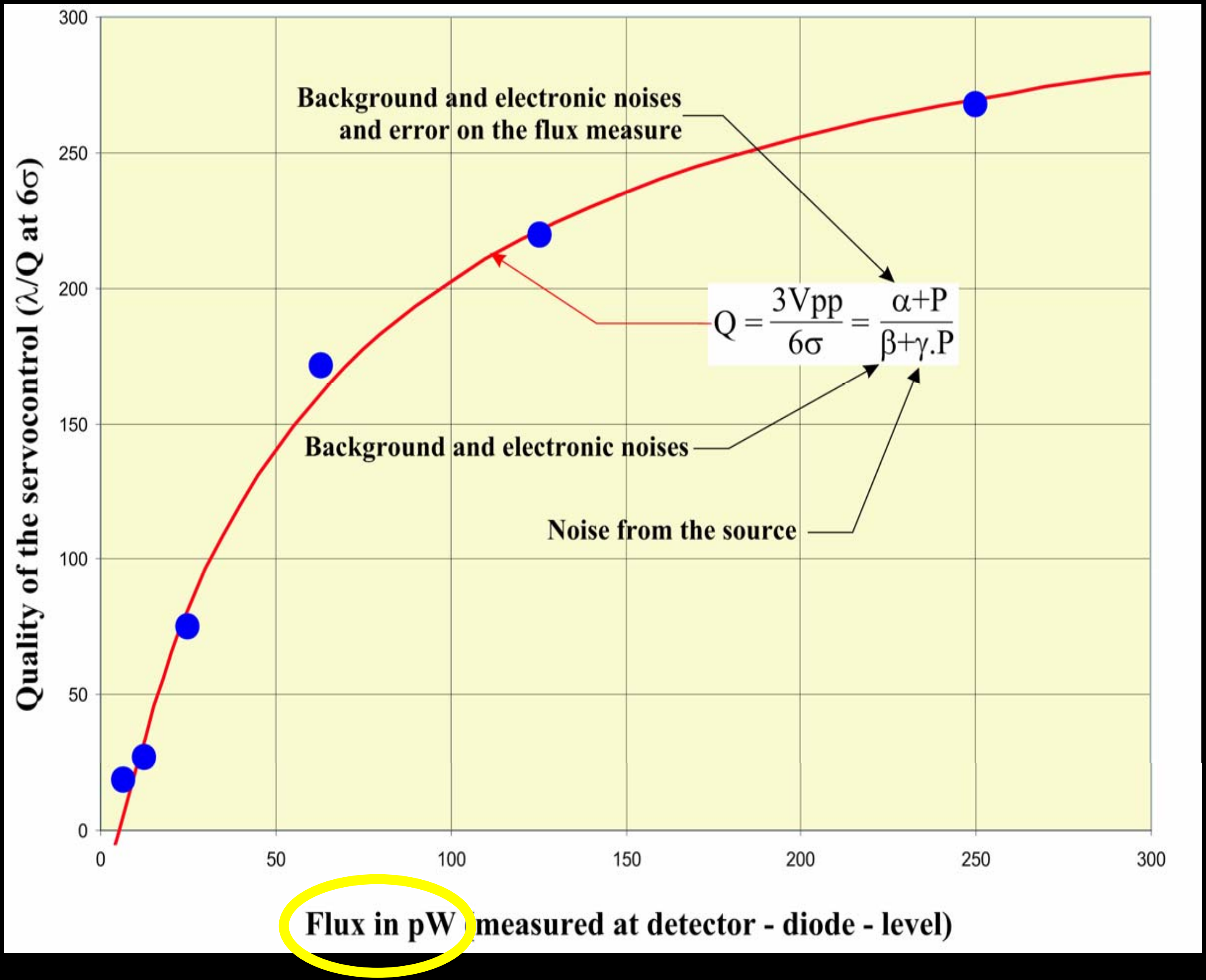
Détail de la région des franges :



Plage de balayage



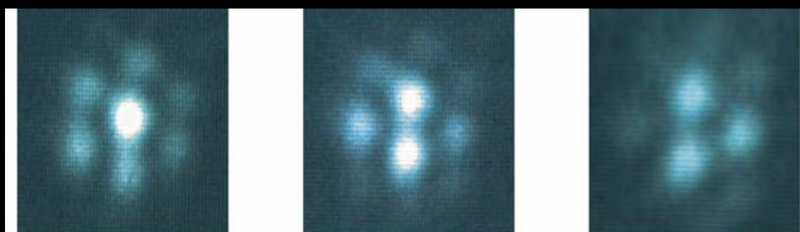
Cophasing Quality



Stabilized Imaging with the 3 Beams

Interferences (limited FOV)

Laser Diode

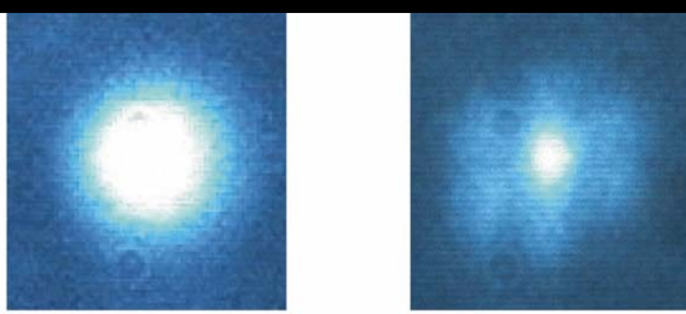


Piston partiellement corrigé piston < $\lambda/10$

Erreur de piston sur un des faisceaux de $\lambda/2$

Erreur de piston $-\lambda/3$ sur un des faisceaux et de $\lambda/3$ sur un deuxième

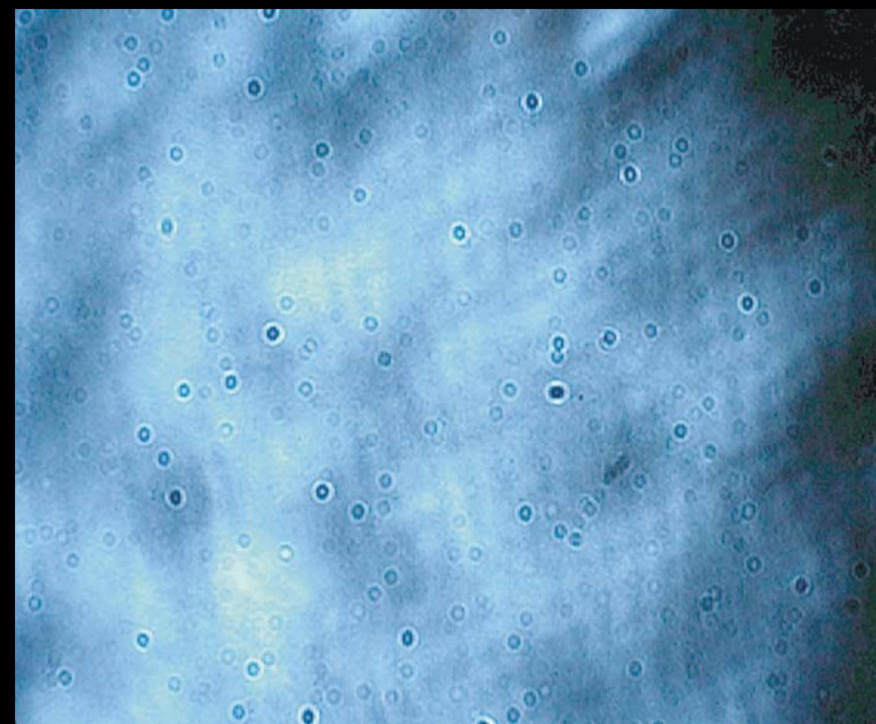
White Light



Tache de diffraction de SOLARNET lorsque les faisceaux sont déphasés

Tache de diffraction de SOLARNET lorsque les faisceaux sont parfaitement en phase

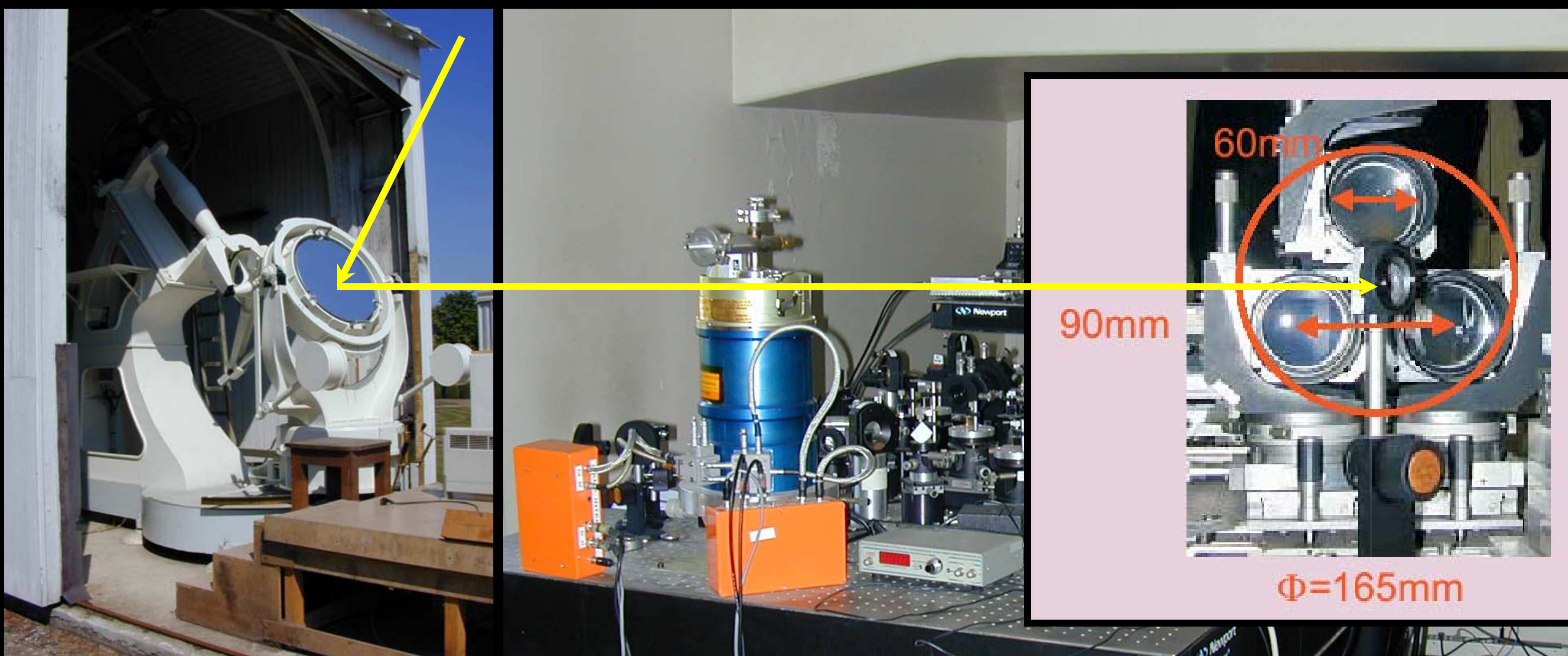
White Light Fringes (extended FOV)



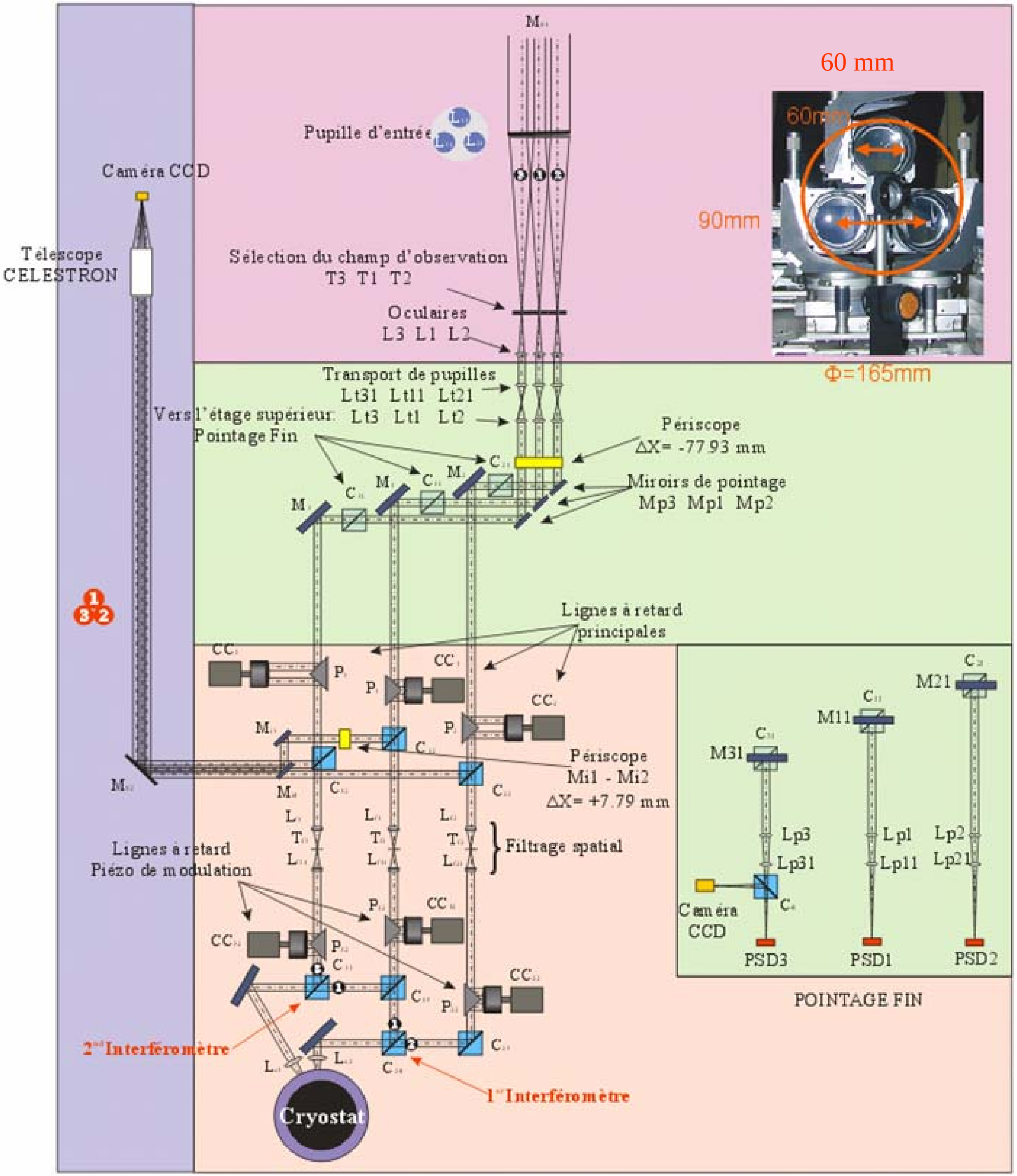
3 telescopes stabilized image (holographic diffuser screen)

SOLARNET R&D Program: Demonstrate Concept and Performances on a Representative Breadboard

- Cophasing & direct imaging in laboratory in 98–2000 (measured λ/300 phasing)
- Adaptation to direct solar observations at Meudon Observatory (Grand Sidérostat de Foucault) in 2001–2002; completion of fine pointing ongoing (0.1" goal); first images before spring, and with SDM (0.1 nm spectral resolution) next summer.



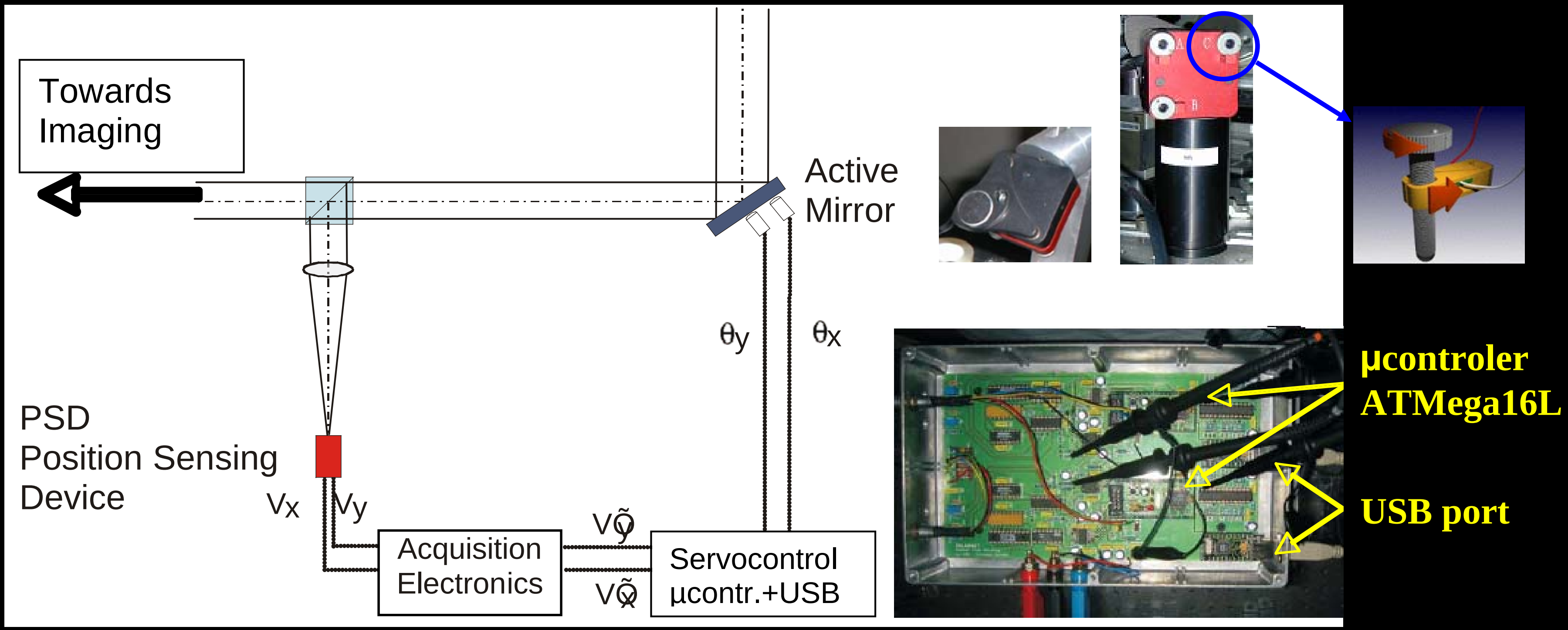
SOLARNET Breadboard: more than 150 optics and detectors!



Breadboard at Meudon

- True image reconstruction with a real solar extended source
- Test on the Sun, in white light, of the spatial filtering cophasing method, its principle and performances
- Require minimum fine pointing at 1 tenth of an Airy Disk, $\lambda/10$ (and servo-controlled guiding of the "Grand Sidérostat")

Fine Pointing of the Breadboard



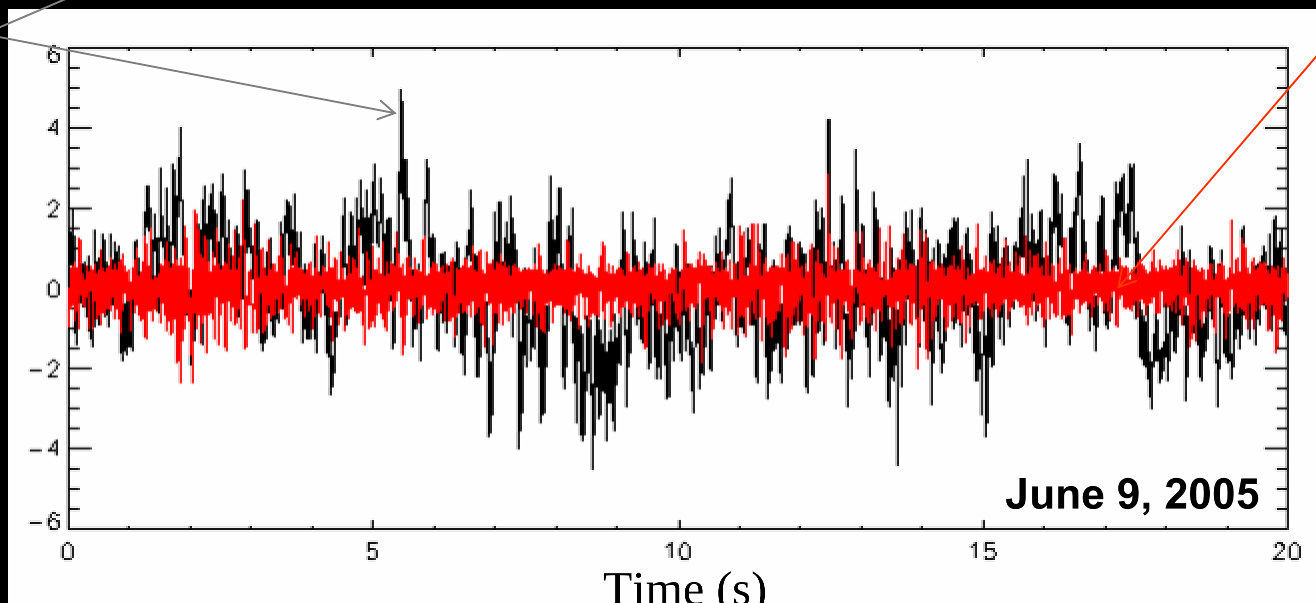
- 3 actives mirrors with 2 active x-y piezoelectrics (orthogonal mount) are numerically servo-controlled in real time by 6 microcontrolers (ATMega16L) and 6 USB communication ports (1 per piezoelectric) through a LabView 7 interface

Solar Pointing Preliminary Results

Without correction: **σ = 1.2"**

(r_0 ~ 4 cm)

With correction: **σ = 0.2"**



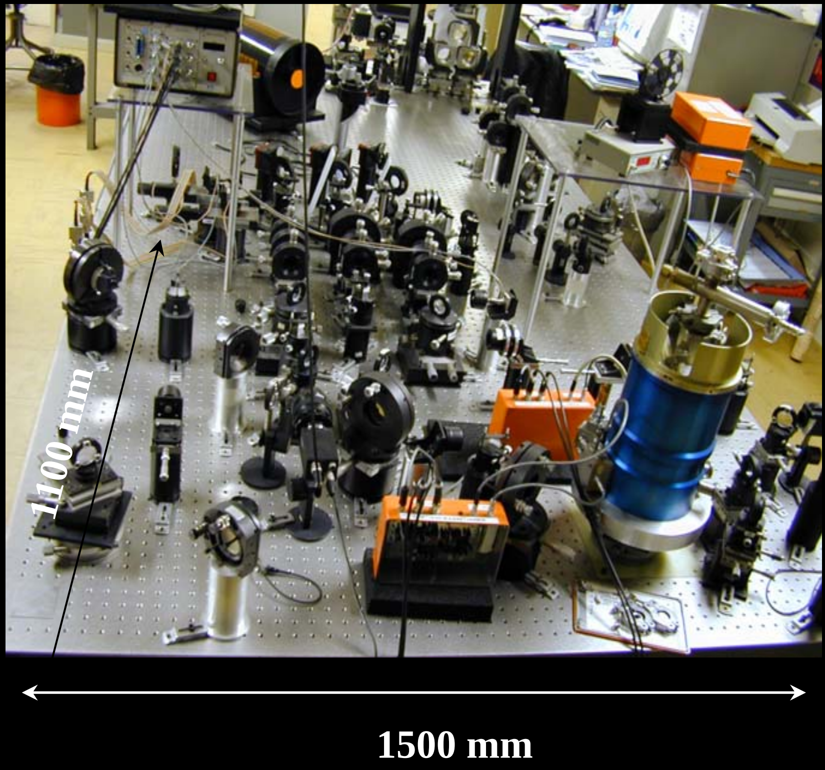
Optimization to **0.1 arcsec** (λ/15) can be achieved:

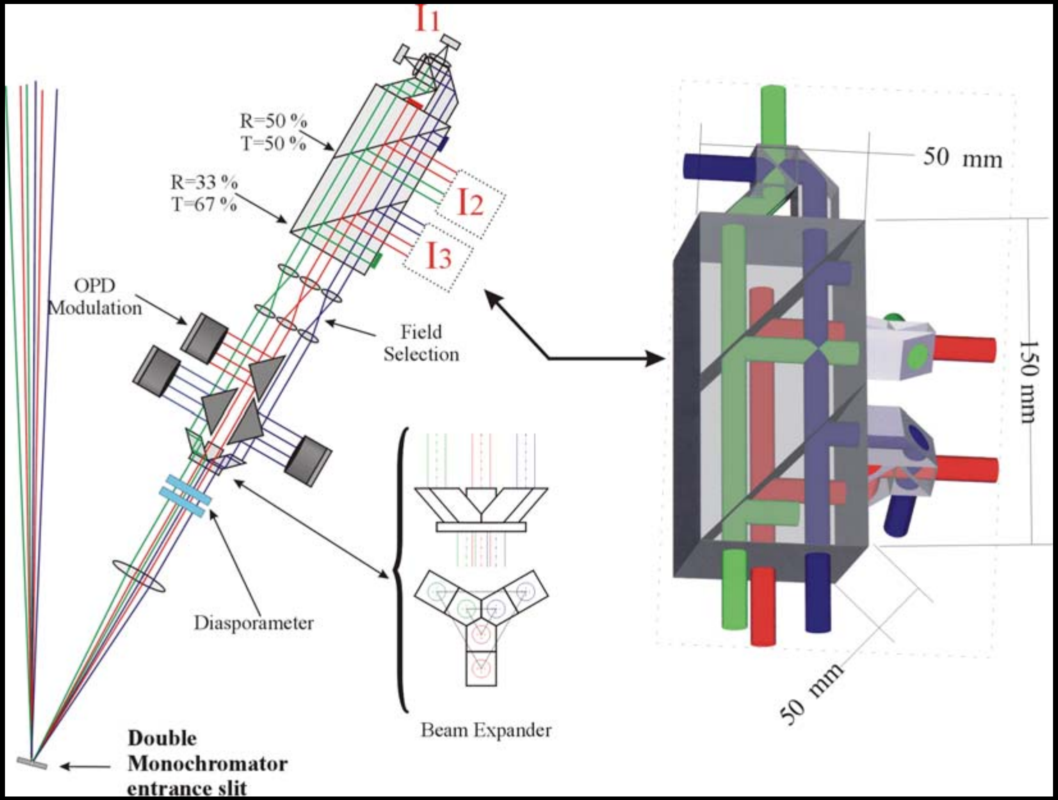
ΔW(σ = 0.2'') = 60 nm (**λ / 8**)

- Remapping the pupil on the active mirror
- Suppressing constant drift in guiding declination (servo-controlled frequency variator)
- Resizing properly the sunspot on the PSD using the zoom
- Optimizing the servo-control parameters (non-linear gain, offset, etc.)
- Reducing magnification from 10 to 5 (mirror dynamics of 80''/s rather than 40''/s)

Miniaturization of the Reference Interferometers (Phase Measure)

From a breadboard more than a meter long…



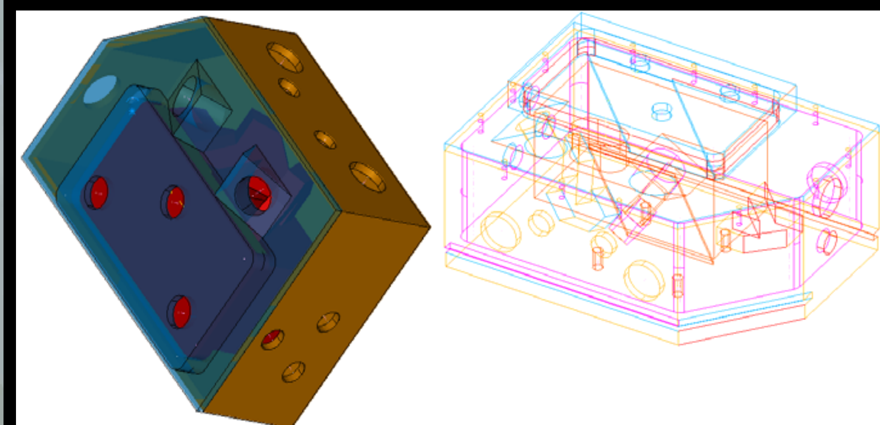


… to a 15 centimeters block!

The Interferometric Binding Block of 3 Reference Interferometers

- It has been designed and realized

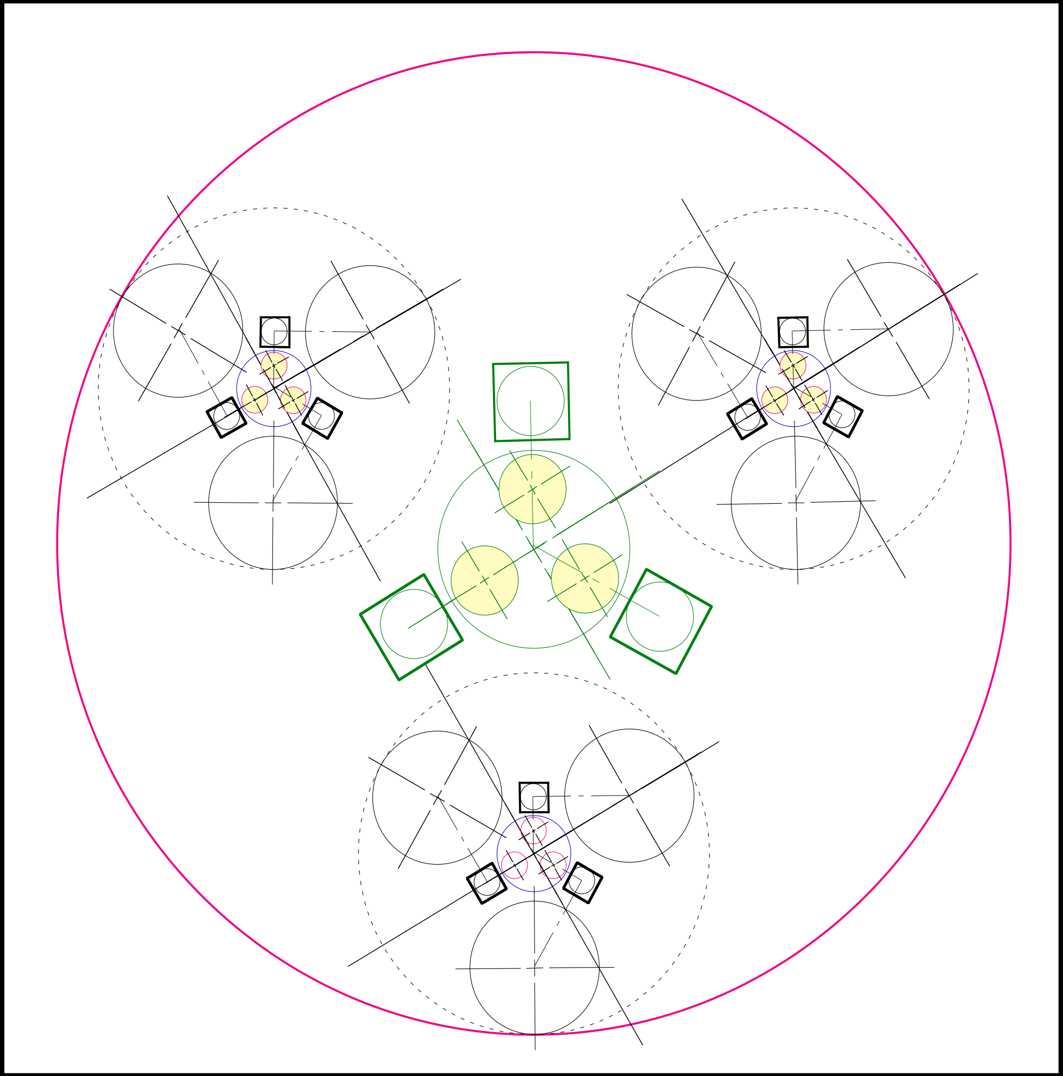
- Molecular binding
- 15 Homosil prisms to sub-μm & sub-arcsec precision



- Invar support designed (IDEAS modeling: 0.8 MPA and 2" for ± 5° tolerance) and under realization (tests this automn)

3 x 3 Telescopes on Ground? At Hanlé?

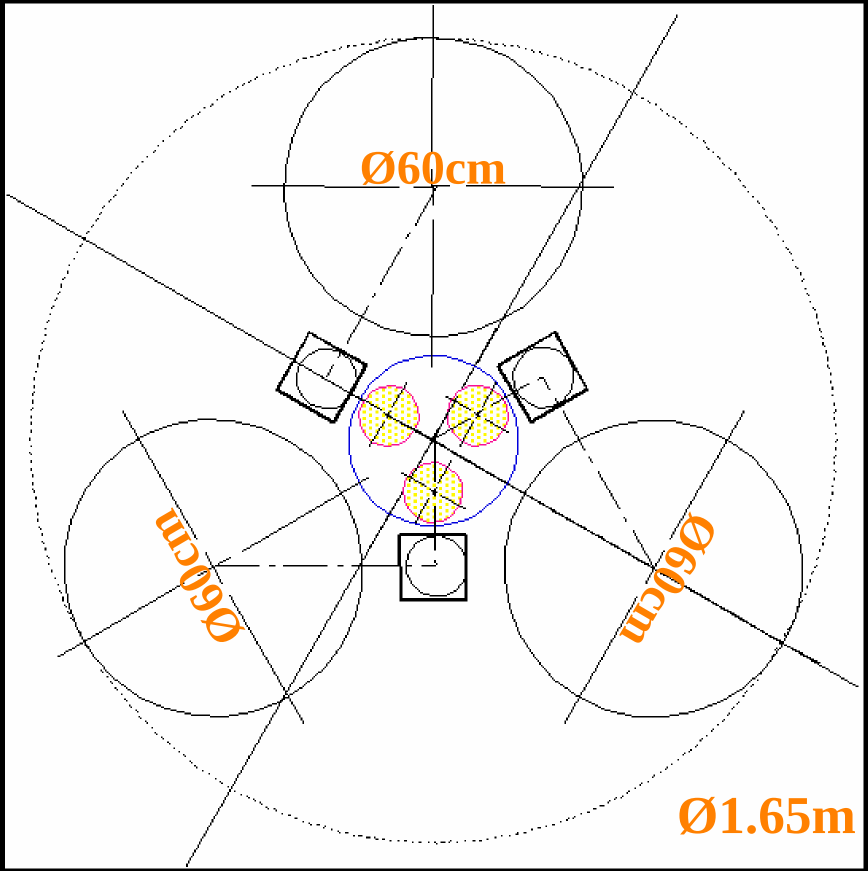
YES, "easy" with the 3T binding blocks

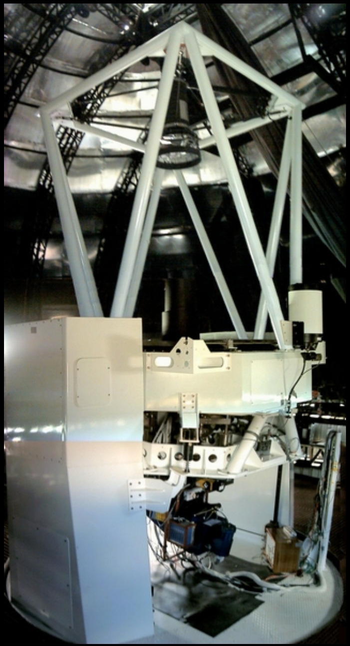


With small Ø40 cm telescopes, this 9-telescopes configuration provides an equivalent telescope of Ø2.5m diameter

- **Recombination of the telescopes by active optics (interferometry)**
- **Perfect wavefront at individual telescope level by simple 64 elements Adaptative Optics (adapted to 4–5 cm isoplanatic coherence patch)**

Hanlé optimized 3 x 60 cm 1.65 m Interferometric Imaging Telescope





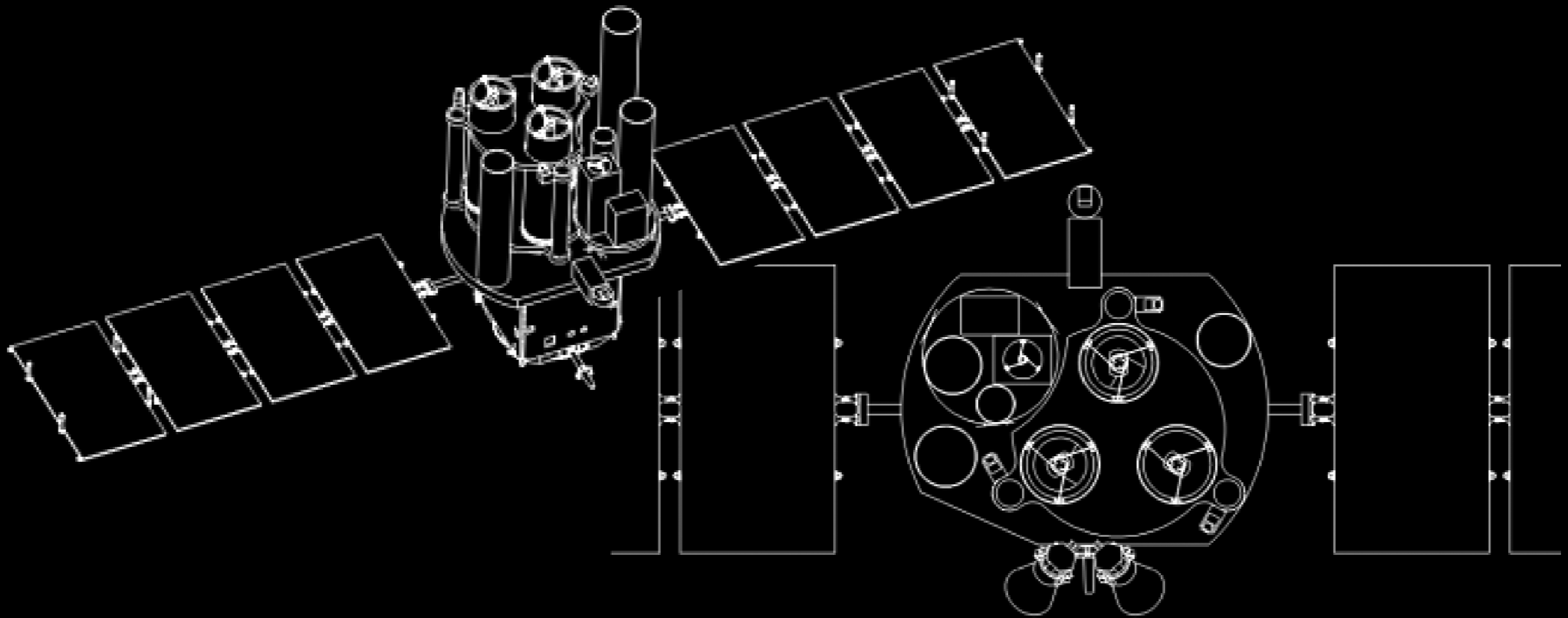
A simple and compact mount, comparable to Hanlé's HCT (open structure, open dome) is readily feasible for HSIT & instruments

Hanlé good seeing in the 8–10 cm range allows to use 64 elements adaptive optics with 60 cm telescopes

1.65m Hanlé Solar Interferometric Telescope (HSIT) would be world largest before ATST with PERMANENT < 0.1" RESOLUTION

A mission around SOLARNET

on the ALCATEL/CNES PROTEUS platform



- **SOLARNET (Ø1.7m x 1.8m) on the 1m^3 PROTEUS platform**
- **The baseplate of PROTEUS platform is optimized for SOLARNET (form, mass, dimensions, rigidity)**
- **A smaller pointed platform of Ø60 cm (ESA Hexapod – 6 linear actuators) is used for the Sun-centered instruments (helio, coronographs)**
- **350 kg payload** ⬇ **complete set of complementary instruments: UV & EUV spectrographs, EUV & X-ray imagers, etc**

Satellite & launch:

- EuRockot – 880 kg, Plesetsk (62.7°)
- Polar Sun-synchronous orbit, 6:00–18:00, 1000 km
  ⬇ **No eclipses: Helioseismology & evolution**
- 3-axis stabilized pointing : 1"/15 seconds — 5"/15 min
- Band-X, Kiruna (or Svalbard) : **large telemetry of 3 Mbps**

SOLARNET Mission Profile

Scientific Objectives	Solar imaging, spectro-imaging, helioseismology and Solar activity: • Spectroscopy and imaging at very high spatial and temporal resolution • Helioseismology, resolved and global oscillations, g-modes (diameter oscillations) • Solar variability, influence of the Sun on the climate, Space weather (Lyman Alpha imaging)
Payload	8 Instruments and adaptation totaling **430 kg** and consuming **350 W** power (with thermal control included) Solar Instrumentation – Imagers and Spectrometers: – SOLARNET Ø1 m interferometer with its UV spectro-imager system (UVIS) – EUV Imager and Spectrometer (MAGRITTE, SPECTRE) – X-Ray/EUV Imager Oscillations and Solar Variability Package (on Sage III type Hexapod) – OVIM-MOF (resolved velocity oscillations and magnetographs) – NSSOT [UV-original-PICARD] (oscillations, g-modes, solar shape & absolute diameter measure) – DORADE (solar constant, global and resolved intensity oscillations – Ultraviolet and Visible Light Coronograph 1.1–2.6 Solar radius Space Weather – NG-SWAN Full sky Lyman Alpha imager
Launcher	• Dedicated launch with **EuRockot** launch mass **880 kg** (including 50 kg of dispenser mass) • Nominal launch from Plesetsk (62.7°) well situated (high latitude) for an injection on a polar orbit • **Non-eclipsing 6:00-18:00 polar orbit 1000 km height**
Spacecraft	• Design lifetime = 2 y, consumables sized for 6 y (extended mission) • Total satellite mass = **830 kg** • Main S/C bus (with payload): 300 cm x Ø170 cm • 3-axis stabilized • Pointing stability better than 1 arcsec/15 seconds and 5 arcsec/15 min • Deployable Solar arrays (no rotation) of 800 W (4 m^2) • 2 S-band antennae for TC • X-band LGAs, omni coverage, for TM • 1 ground antenna at Kiruna (or Svalbard) compatible with permanent **3 Mbps** telemetry)

SOLARNET Possible Model Payload

Instrument	Measurement	Specifications	Mass kg	Size cm x cm x cm	Power Watt	Telemetry kb/s
SOLARNET and the Ultraviolet Imaging System	Very high resolution disk and limb imaging and spectroscopy	UV and FUV spectroheliograms between CIII 117.5 nm and the MgII lines 280 nm	**100** **40**	**Ø110 x 140** **20 x 30 x 70**	**60** **60**	**20** **1 200**
EUV Imager and Spectrometer	Imaging and diagnostics of TR and corona	EUV emission lines	**40**	**Ø32 x 180 (Telescope Ø25)**	**30**	**400**
X-ray / EUV Imager	Coronal imaging	He and Fe Ion lines	**30**	**Ø28 x 140 (Telescope Ø20)**	**30**	**400**
Ultraviolet and Visible Light Coronograph °	Imaging and diagnostics of the corona	Coated mirror coronograph CCD detector	**25**	**Ø20 x 80 (Telescope Ø12)**	**15**	**100**
OVIM (Oscillations, Visible-light Imager & Magnetograph) °	High-res. disk imaging and polarimetry	Na D1 Na D2	**38**	**Ø30 x 120 (Telescope Ø25)**	**30**	**400**
NSSOT (New Solar Shape & Oscillations Telescope) [non-degraded UV PICARD]°	Precise diameter measurement, oscillations, and full Sun imaging	230 nm cont. Ly α 160 nm cont. 548 nm	**25**	**25 x 30 x 70 (Telescope Ø12)**	**30**	**400**
New Generation DIARAD/VIRGO °	Radiometers for Solar constant and Intensity Oscillations	UV, Visible and IR light	**25**	**20 x 30 x 40**	**25**	**1**
New Generation SWAN	H Lyman α Solar activity	Sky Ly α imaging with Hydrogen cell (5° x 5° FOV)	**7**	**18 x 17 x 36**	**12**	**10**
TOTAL			**330**	**Ø170 x 180**	**292**	**2931**

Conclusions & Perspectives

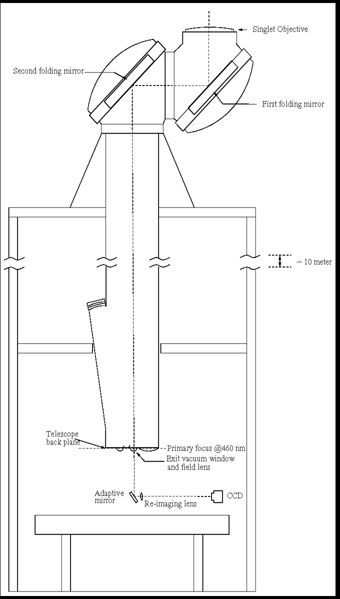
- In complement to SDO, SOLAR-B & TESIS/CORONAS we propose SOLARNET, an ambitious High Resolution, Multi-wavelengths, Solar Observatory, half-way before the ESA Solar Orbiter (resolution > 150 km, 0.2", limited telemetry) *(first observations in 2018… for a launch in 2015*)
- Imaging and spectroscopy, at high resolution in the UV, FUV and EUV, in the chromosphere, transition zone and corona, are necessary to understand the magnetic structuration in the dynamic solar atmosphere, the Flares and CMEs, and address dissipating structures, reconnection and heating
- Resources, instruments and scientific interests do exist in Europe, India and China, and small payloads like SMESE, NSSOT (UV-Non-Degraded PICARD), DYNAMICS (Ex-NgGOLF) can (and should) be accommodated on the SOLARNET platform
- Next CNES mission (micro or mini) should be decided end of 2006 or 2007

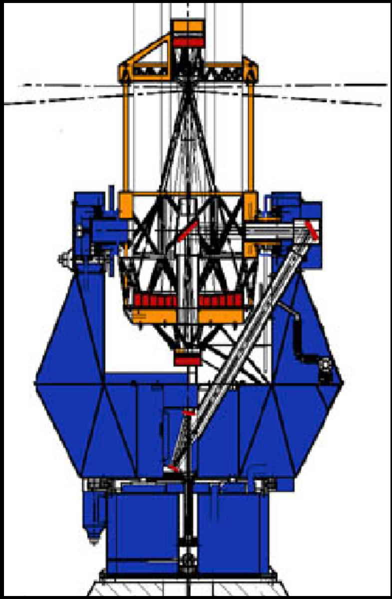
And we can certainly envisage to start, in parallel and rapidly, since technologies are available and tested, a ground solar interferometric telescope with unique capabilities, to be implemented, with appropriate instrumentation, at Hanlé site

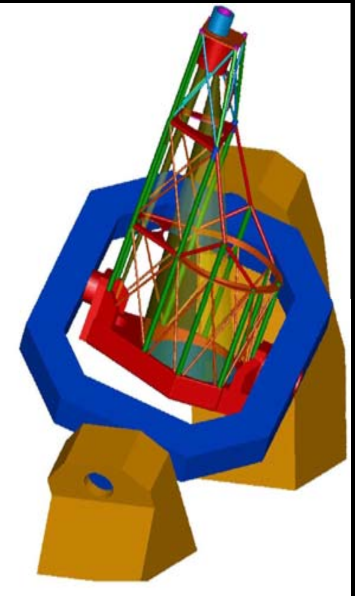
France (Germany, Italy, Belgium), India and China have the competences and interests to complement SDO and bring, in 2012, these UV, FUV, EUV & helioseismology HR observations


Thank you!

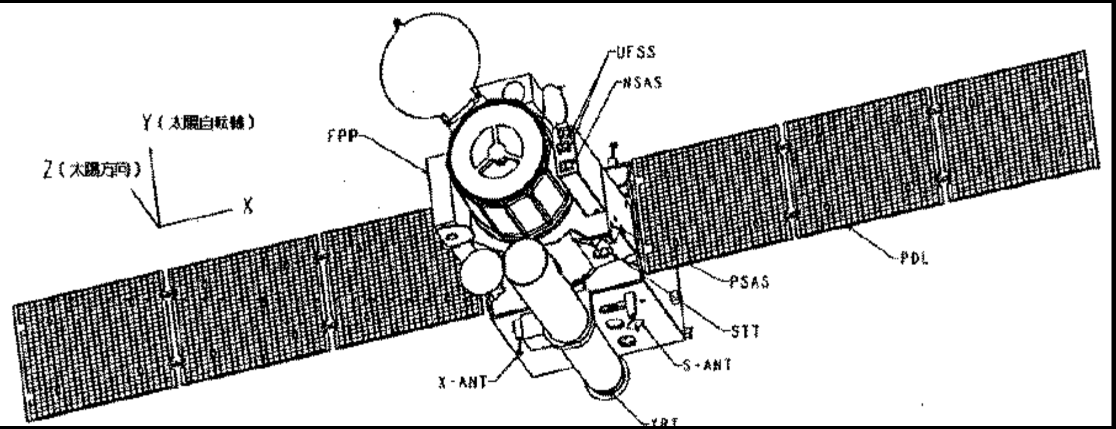
Scientific Context — Ground & Space







- NSST: Ø 0.9 m
  (THEMIS: Ø 0.9 m)
- GREGOR: Ø 1.5 m
- ATST: Ø 4 m



- SOLAR B: 0.5 m
  (visible: 390–660 nm)