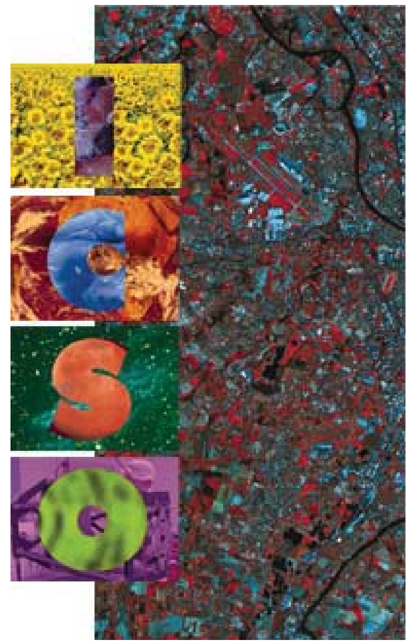
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



Replicated x-ray optics for space applications

René Hudec, Ladislav Pína, Adolf Inneman

International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
105692E · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307880

REPLICATED X-RAY OPTICS FOR SPACE APPLICATIONS

René HUDEC[*1], Ladislav PÍNA[2], Adolf INNEMAN[3]

[1]*Astronomical Institute, Academy of Sciences of the Czech Republic, CZ-25165 Ond ejov, Czech Republic*
[2] *Czech Technical University, Faculty of Nuclear Science, Prague, Czech Republic*
[3]*Center for Advanced X-ray Technologies, Reflex, Prague, Czech Republic*

ABSTRACT *- We report on the program of design and development of X-ray optics for space applications in the Czech Republic. Having more than 30 years background in X-ray optics development for space applications (for use in astronomical X-ray telescopes onboard spacecrafts, before 1989 mostly for Soviet and East European INTERKOSMOS program), we focus nowadays on novel technologies and approaches, thin shell replicated mirrors, as well as studies of light-weight mirrors based on innovative materials such as ceramics. The collaboration includes teams from the Academy of Sciences, Universities, and industry. We will describe and discuss both the history of the development of X-ray optics in the Czech Republic and the developed technologies and approaches (with focus on replication technology) as well as recent activities and developments including our participation on the ESA XEUS mirror technology development based on the Agreement between ESA and Czech Government.*

1. INTRODUCTION

The X-ray optics is a crucial part of most X-ray imaging instruments. The X-ray telescopes with optics achieve much better signal/noise ratio than X-ray experiments without optics - this allows e.g. the detection of faint sources. The use of X-ray optics further allows imaging, precice localization, photometry, spectroscopy, variability studies, and estimation of physical parameters of X-ray emitting regions (temperature, electron density...). The space experiments with X-ray optics are also well suited for monitoring of X-ray sky for variable and transient objects including X-ray novae, X-ray transients, X-ray flares on stars and AGNs, galactic bulge sources, X-ray binaries, SGRs (Soft Gamma Ray Repeaters) and X-ray afterglows of GRBs (Gamma Ray Bursts). The X-ray optics represent an important part of numerous past, recent, and future space projects (EXOSAT, ROSAT, Einstein, Fobos, AXAF, XMM, ABRIXAS, BeppoSAX, ASCA...). In the laboratory, there are numerous applications of the X-ray optics e.g. in plasma physics, laser plasma, biology, crystallography etc. Most of the laboratory applications require superior imaging quality.

2. THE X-RAY OPTICS

The basic division of X-ray optics can be summarized as follows: (1) diffractive optics (Fresnel lenses + pinholes): not useful for space due to small apertures, (2) refractive optics: limited use, not useful for space, (3) reflective optics, based on total reflection (grazing incidence), and (4) reflective optics, based on normal incidence (multilayers). In this paper, we will focus on the reflective optics with the most widely used types listed below.

Wolter optics: The Wolter type optics [Wolt 52] is in wide use in space-borne X-ray astronomical experiments (ROSAT, EXOSAT, Salyut 7, Fobos, XMM, AXAF..). It is based on double reflection on two surfaces (requirement for a superior imaging – the Abbe sine condition). Depending on the combination of surfaces, there are various modifications (Wolter I, II, III types), mostly used is the Wolter I type (paraboloid + hyperboloid).

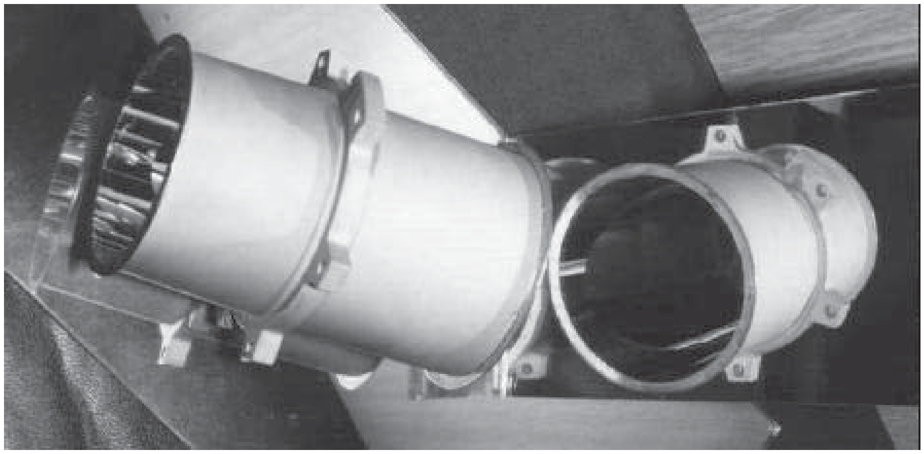


Fig. 1: KORONAS X-ray Wolter mirror, 1979

Double-cone approximation of Wolter optics: The Wolter arrangement surfaces can be approximated by less laborious and hence less expensive conical profiles. These mirrors have lower imaging quality but in many cases larger collecting area since the conical shells can be made very thin. These mirrors usually represent high throughput systems, and can be preferably used in foil telescopes (SODART).

Conical, ellipsoidal and paraboloidal optics: These mirrors with only one reflection find most of their applications in the laboratotry either as collimating or focussing and/or imaging elements.

Kirkpatrick-Baez optics: This configuration is used mostly for experiments not requiring large collecting area (solar, laboratory). Recently, large modules of KB mirrors have been suggested also for stellar X-ray experiments [Gore 98].

Normal incidence optics: This optics requires the multilayer deposition on the mirror surface allowing its use under normal incidence. The use of multilayers results in narrow spectral range, and in the past has been mostly used in solar experiments (TEREK Fobos, TEREK KORONAS...) as well as in laboratory applications.

Lobster-eye optics: This optics has been suggested in 70ies for very wide field X-ray imaging but not yet used in space mostly due to severe manufacturing problems. Recently, the first test modules are available for both the Schmidt as well as for the alternative Angel configurations (Inneman et al., 1999).

The development and manufacture of various types of X-ray optics are heavily affected by manufacturing problems, making their production laborious and hence expensive. The most dominating problems can be summarized as follows: (1) the required microroughness is < 3 nm, in many applications however < 1 nm, (2) the X-ray optics is frequently represented by hollow inner surface, and (3) there are very strict requirements on the slope errors and shape deviations.

3. X-RAY OPTICS IN THE CZECH REPUBLIC

The early stages of the X-ray optics developments in the Czech Republic are closely related to the INTERKOSMOS Space Programme (Soviet and East European equivalent of ESA operated until 1989). All of the X-ray imaging telescopes onboard Soviet spacecrafts were equipped with the Czech X-ray optics (exception: X-ray normal incidence mirrors in the special channel of the TEREK telescopes onboard the Fobos and Koronas spacecrafts). Later on, also the laboratory applications have started. In almost all cases, replicated grazing incidence mirrors of various geometries, types and arrangements have been designed and developed. The replication technology proved to be powerful tool in solving numerous and various different problems and demands.

- 1969 first considerations started
- 1970 first X-ray mirror produced (Wolter 1, 50 mm)
- 1971 Wolter 1, 80 mm
- 1976 Wolter 1, 115 mm
- 1979 first mirrors flown in space (two Wolter 1, 50 mm, Vertikal 9 rocket)
- 1980 Vertikal 11 rocket (two Wolter 1, 50 mm)
- 1981 first large Wolter 1 mirror (240 mm)
- 1981 Salyut 7 orbital station, RT- 4M stellar X-ray telescope (Wolter 240 mm, double nested objective)
- 1985 applications for plasma physics, EH 17 mm, PP 20 mm
- 1987 first high quality X-ray foils for foil mirror X-ray telescope (SODART)
- 1988 Fobos 1 Mars probe, TEREK X-Ray solar telescope
- 1989 KORONAS I X-Ray mirror, Wolter 80 mm
- 1990 first micromirror (aperture less than 1 mm)
- 1993 collaboration with SAO, USA, WF X-Ray optics started
- 1996 first Lobster Eye test module produced, Schmidt geometry
- 1997 Lobster Eye Angel geometry project started
- 1999 first Lobster Eye test module produced, Angel geometry

Total number of X-ray mirrors produced: more than 50
Total number of mirrors flown in space: 8
Total spacecrafts with Czech X-ray optics: 4
Total number of space experiments with Czech X-ray optics onboard: 8

Fig. 2: Mirror shells of the Salyut 7 X-ray mirror assembly, 1981

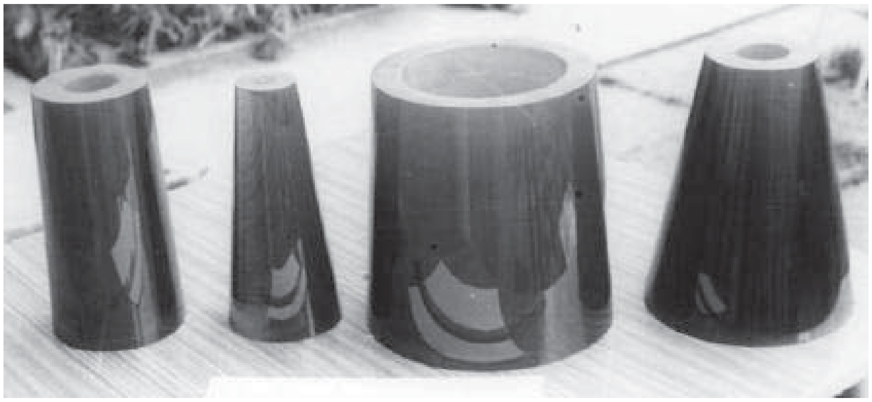


Fig. 3: Mandrels of the double-nested X-ray Wolter 1 mirror, Salyut 7, aperture 240 mm

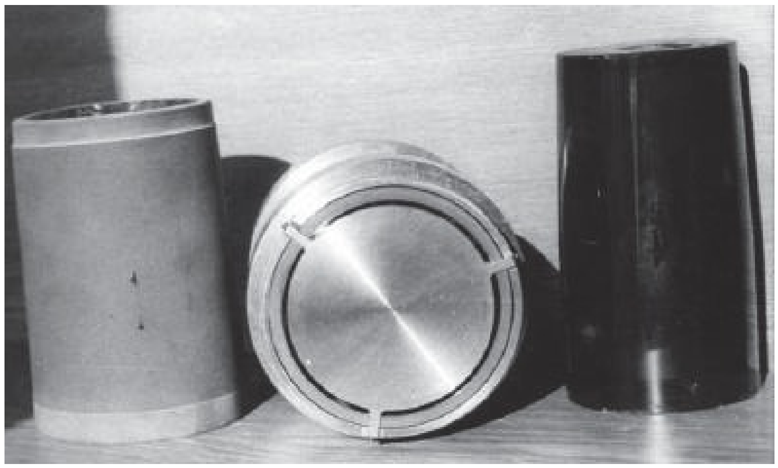


Fig. 4: Fobos 1 X-ray mirror, 1988

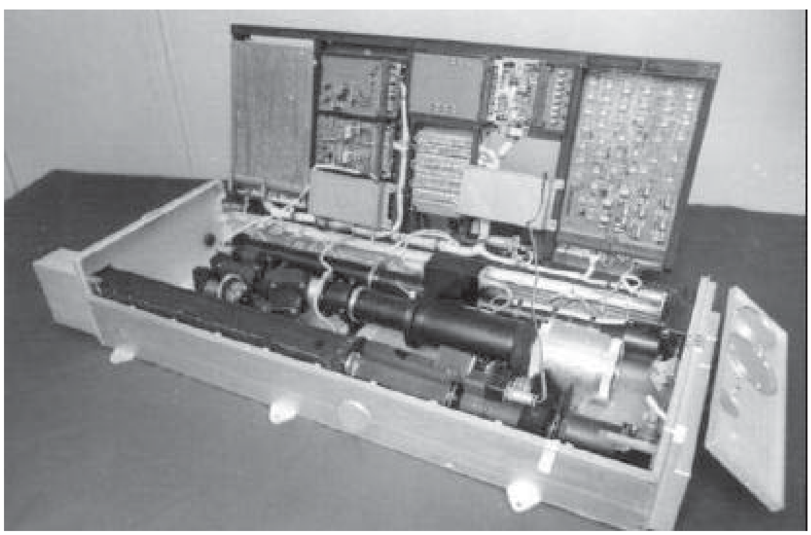


Fig. 5: TEREK X-ray telescope and coronagraph, Fobos 1 spacecraft, 1988

3.1 Technologies

The mirrors have been produced by various replication technologies:

- 1970 Heavy Replica Technology: heavy electroforming of X-ray mirror shells from polished glass masters, wall thickness 5-10 mm

- 1978 Replica Epoxy Technology tested: epoxy replication of gold evaporated glass masters
- 1980 Replica Epoxy Electroforming Technology: thin electroformed shells reinforced by epoxy
- 1981 as above but carbon fibre filling involved
- 1982 super-thin test Wolter shells for hight throughput telescopes
- 1983 flat master replication: production of X-ray reflecting foils for foil X-ray telescopes (SODART, RENTGEN SPEKTR GAMA)
- 1990 first micromirrors (aperture ~ 1 mm) produced
- 1993 first double - sided replicated flats for Lobster telescopes of Schmidt type
- 1998 first replication of Angel geometry Lobster Eye cells

3.2 Replication

The idea of replica technology is to create a perfect copy of a negative shaped master and of smooth surfaces. This is very suitable if the negative shape is easier to be produced. The two main advantages of the replication in X-ray optics design and construction are as follows: (1) the negative shapes are usually easier to be produced, and (2) the produced shells may be much thinner than is possible with classical technologies (important for light-weight high throughput nested arrays). The replication by electroforming has been used in the Czech Republic for development and production of X-ray mirrors since 1967. Since then, the technology has been further developed and modified. A number of modifications exist, meeting different demands. The replication is perfectly suitable for the production of X-ray grazing incidence optics since external surfaces can be much easily grinded and polished than inner cavities (especially in the case of small apertures). The masters are of high quality optical glass, glass ceramics or metals. It should be noted that the replication technology in X-ray optics is applied by different groups in various different modifications.

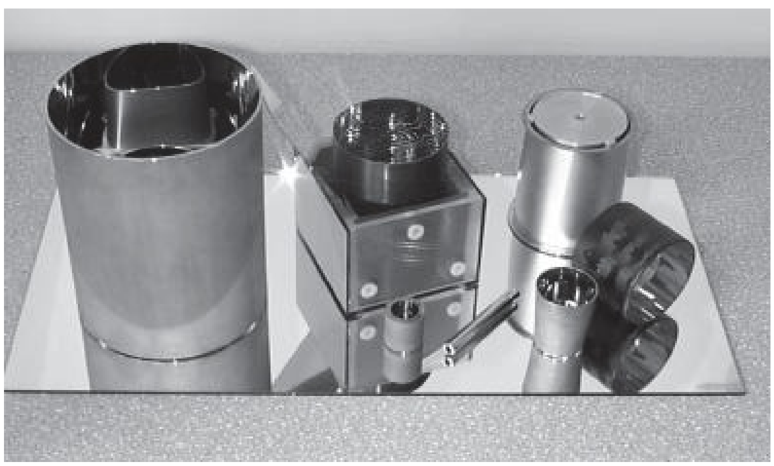


Fig. 6: Replicated grazing incidence X-ray optics

3.3 Characteristics

The basic characteristics of by electroforming replicated X-ray mirrors can be summarized as follows. Reflecting surfaces: electroformed Ni, or electroformed Au, or evaporated/sputtered Au. Other materials are also possible as well as additional coatings. External surface-structure: metallic (Ni), or CF/epoxy, or sandwich. Parameters: the mirrors are polychromatic from 10 keV to optical wavelengths. They have a high reflectivity, up to 90% depending on the wavelength and the grazing angle (e.g. 60% at 0.83 nm and 1 deg incidence angle). The mirrors have smooth surfaces analogous to surfaces of masters. Thickness uniformity is of order of 2%. Additional technologies: multilayers may also be applied to achieve better energy coverage (hard X-rays up to 100 keV). Superpolishing and/or surface quality improvements by lacquer coating are also possible.

3.4 Advantages of the replication

The replicated X-ray mirrors have numerous advantages which can be summarized as follows.

- Wide variety of geometries is possible: Wolter I, II and III systems, conical, ellipsoidal, paraboloidal, flats etc.
- Light-weight and thin shells are possible. This is important for high throughput X-ray optics (nested arrays with many shells) and for space applications in general.
- Multiple replication of identical elements is possible, minimizing the price of final mirrors.
- There is no need to grind and to polish small inner cavities - negative shapes are to be polished
- There are almost no aperture limits including both very small (below 1 mm) and very large (more than 500 mm) apertures
- There is large number of various applications
- The surfaces are resistant to space and/or laboratory environment (cleaning possible, no heat degradation)
- The replicated Au surfaces are more smooth than evaporated surfaces

3.5 Summary of X-ray astronomical mirrors produced

Approximately 50 mirrors have been produced between 1970 and 1999 as well as numerous tests for technology purposes: (1) Wolter 1 mirrors for space applications, apertures 40 to 240 mm. They have been used onboard satellites as imaging elements in X-ray solar and stellar telescopes, (2) Bent foil mirrors/flats foils. X-ray reflecting foils produced from float glass masters with sizes up to 300 x 400 mm. Thickness homogenity better than 2%. Wide range of foil thickness from a few microns up to 1 mm. Designed for the SODART foil X-ray telescope and analogous projects, (3) Lobster-eye wide-field X-ray optics, Schmidt geometry, size of the flats from 23 x 23 mm to 80 x 100 mm, and (4) Lobster-eye wide-field X-ray optics, Angel geometry, various test modules, a/L (aperture/length) ratios of about 50. The replication technology has also been applied in numerous ground-based and laboratory applications such as PP (paraboloid-paraboloid) microscopes, aperture 20 mm, EH (ellipsoid-hyperboloid) Wolter microscopes, aperture 17 mm, conical, ellipsoidal, paraboloidal mirrors, micromirrors of conical, ellipsoidal, and paraboloidal profiles, foils including those for foil X-ray telescopes, as well as flat and bent mirrors.

4. RECENT AND FUTURE PROJECTS

The widely used Wolter objectives have a very limited FOV (typically of order of 1 degree or less) so they are suitable for pointed observations but not for monitoring and surveys. The wide-field X-ray optics has been suggested in 70ies by Schmidt (orthogonal stacks of reflectors) [Schm 75] and by Angel (array of square cells) [Ange 79] but has not been constructed yet. With this type of reflective X-ray optics, up to 180 deg FOV may be achieved. The difficult production of LE lenses has caused the significant delay between their theoretical description and their construction and real use. The possible solution is offered recently by the replication technology. Recently, the first Lobster-eye X-ray telescope prototypes have been successfully finished. The prototype of Schmidt geometry represents one module and consists of two perpendicular arrays of double-sided X-ray reflecting flats (36 and 42 double-sided flats 100 x 80 mm each). The flats are 0.3 mm thick and gold-coated. The focal distance is 400 mm from the midplane. The FOV of one module is about 6.5 degrees. More such modules may create an array with substantially larger FOV. Advanced Schmidt modules based on 0.1 mm glass gold-coated plates separated by only 0.3 mm have been also developed and tested.

For the Angel geometry, numerous square cells of very small size (about 1x1 mm or less at lengths of order of tens of mm) are to be produced. This is much more difficult than the Schmidt arrangement mentioned above. Nevertheless, the recent results indicate that this demand can be also solved by modified innovative replication technology [Inne 99]. Various test Angel LE modules have been produced so far such as a linear module with 47 cells of 2.5 x 2.5 mm 120 mm long, f = 1.3 m, and a L-shaped module with 2 x 18 cells, dimensions and f as above, surface microroughness 0.8 nm. An advanced LE Angel test module is in development as a 2D module with 96 x 96 = 9 216 cells 2.5 x 2.5 mm, 120 mm long, f = 1.3 m.

The LE X-ray telescopes are extremely important since the discovery of X-ray afterglows of Gamma Ray Burst (GRBs) sources in 1997. The expected rate of GRBs is 1 per day, however the theoretical prediction assumes larger beaming angle in X-rays if compared with gamma rays, hence the actual rate of X-ray afterglows is expected to be substantially larger (nearly 10 x or even more) than the rate of GRBs, hence about 10 X-ray afterglows are expected daily. The sensitivity of LE telescopes is sufficient enough to detect the recently discovered X-ray GRB afterglows. It should be also noted that the localization accuracy of the LE telescopes is of order of 1 arcmin, substantially exceeding the recent localization accuracy of most gamma ray instruments (2 deg and more). It is hence obvious that the LE telescopes are expected to provide a substantial contribution to the science and statistics of GRBs. The additional science of LE X-ray telescopes includes supernova explosions, high energy binary sources, AGNs, blazars, X-ray novae, X-ray transients etc.

The further activities involve the participation on the ESA XEUS project where first test mirror shell has been produced based on replication technology. Within this project, various innovative technologies will be studied and developed such as light-weight ceramics replication and the use of amorfous and glossy metals.

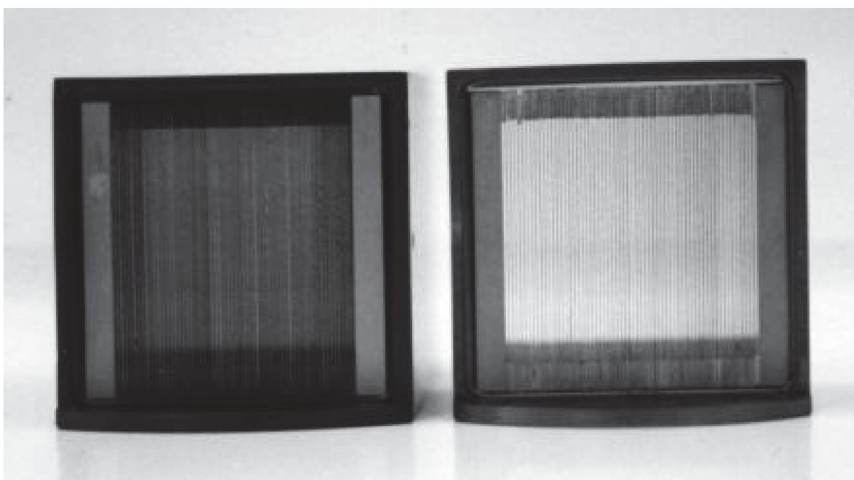


Fig. 7: Lobster-Eye telescope prototype, advanced Schmidt arrangement (23 x 23 mm plates with 0.3 mm spacing).

5. DISCUSSION

The (replicated) grazing incidence X-ray optics shows some advantages if compared with other types of X-ray imaging and focussing elements which can be summarized as follows [Hude 99]: (1) wide energy range (no narrow window), (2) large collecting area, (3) resistant to heat and other environment influences, (4) high reflectivity, over 90% depending on the grazing angle, and (5) wide field systems are possible. The grazing incidence X-ray optics is in use within space experiments already for 30 years. Despite of this, some innovative types of the X-ray mirrors are still in the development phase. Moreover, the requirements for future missions are much higher than for those in the past so new and innovative technologies are necessary. The future of astronomical grazing incidence X-ray optics can be briefly summarized as follows:

- segmented large aperture mirors (e.g. XEUS)
- high throughput optics/very thin shells
- wide field imaging systems, FOV >> 1 deg
- better surface quality (< 1 nm), reduced slope errors, arcsec angular resolution, new technologies
- better spectral coverage – multilayers, imaging in hard X-rays up to 100 keV

For laboratory applications, improved imaging quality and superior angular resolution (X-ray microscopes) are required.

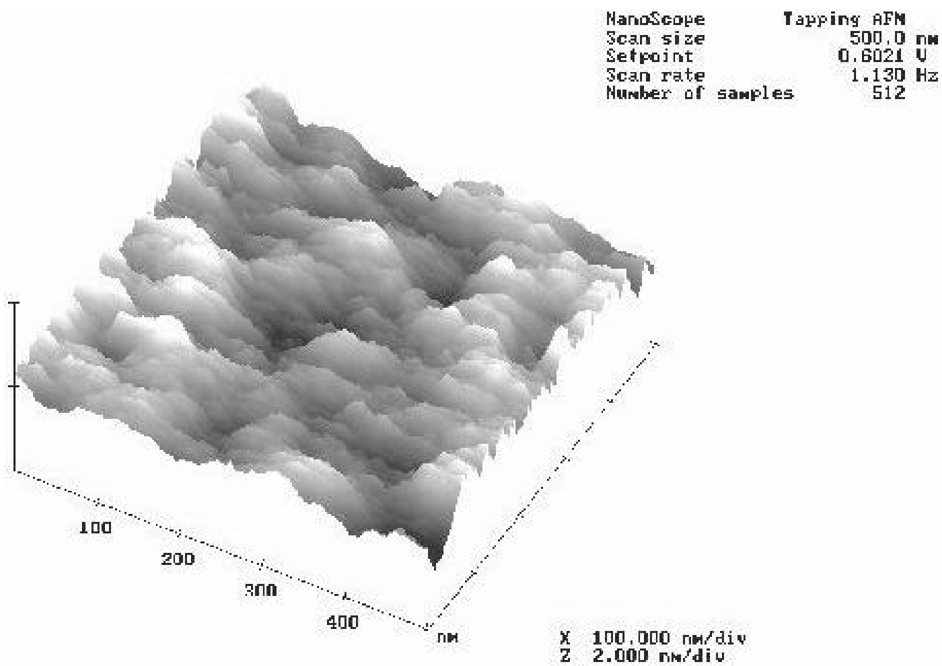


Fig. 8: Tapping AFM images of the sample of replicated surface taken in the test facility of the Astronomical Institute in Brera, Italy – the resulting microroughness RMS is 0.3 nm.

These needs require innovative technologies for the future:

- superpolishing: to achieve superior angular resolution and high efficiency
- application and/or replication of multilayers: to achieve a better spectral coverage (for hard X-rays, up to 100 keV)
- improving the surface quality: to achieve superior angular resolution and high efficiency
- innovative measuring techniques
- very large apertures: to achieve high detection sensitivity
- very wide-field of view systems: to achieve WF X-ray monitoring of the sky
- very large collecting areas: to achieve high sensitivity

ACKNOWLEDGEMENTS

The development of double-sided reflecting flats was supported by the US-Czech Science and Technology Project 1993-1997 (Harvard-Smithsonian Center for Astrophysics, Cambridge, MA USA, Astronomical Institute Ondrejov, CR and Czech Technical University, Faculty of Nuclear Engineering Prague CR). The development of the Angel type Lobster eye X-ray optics was supported by the Grant Agency of the Czech Republic, grant 106/97/1223. The development of future innovative X-ray telescopes is supported by the grant 105/99/1546 provided by the Grant Agency of the Czech Republic. The Reflex Prague acknowledges the support provided by the Ministry of Industry and Trade of of the Czech Republic within the Project FB-C3/29 „Centre of advanced X-ray technologies“.

REFERENCES

[Wolt 52] H. Wolter, *Ann. Der Phys.* **10**, 94, 1952.

[Gore 98] P. Gorenstein: *Proc. Symposium X-ray surveys*, Potsdam, 1998.

[Schm 75] W. K. H. Schmidt, *Nucl. Instr. Methods*, **127**, 285-292, 1975.

[Ange 76] J. R. P. Angel, *ApJ*, **233**, 364-373, 1979.

[Inne 99] A. Inneman, R. Hudec, L. Pina and P. Gorenstein: *SPIE Proc. Vol.* 3766, 72, 1999.

[Hude 99] R. Hudec, L. Pina, A. Inneman, *SPIE Proc. Vol.* 3766, 62, 1999.