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OPTICAL FAR FIELD DIFFRACTION PATTERN TEST OF LASER RETROREFLECTORS FOR SPACE APPLICATIONS IN AIR AND ISOTHERMAL CONDITIONS AT INFN-LNF

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Abstract

We describe the INFN-LNF standard procedure for the optical Far Field Diffraction Pattern (FFDP) test of cube corner laser retroreflectors (CCRs) for space applications, when these CCRs are in air and in isothermal conditions around $(22 \pm 2)^{\circ}$C. This procedure was developed in 2007 and 2008, using prototype GLONASS CCRs lent to LNF by IPIE of Moscow and a GPS-2 flight model CCR array lent to LNF by the University of Maryland at College Park (all using Al-coated fused silica retroreflectors of 27 mm diameter). This was done in the context of the INFN experiment ETRUSCO[2]. The modeling of FFDP measurements is performed with a commercial software, CodeV by O.R.A. Inc., and it has been cross-checked against two independent software programs developed by other two members of the ILRS "Signal Processing Working Group", D. Arnold and T. Otsubo, finding very good agreement among the three. In summer 2008 this procedure has been validated by performing the FFDP test of the LAGEOS "Sector", an engineering prototype on loan from NASA-GSFC, equipped with 37 uncoated, fused silica retroreflectors of 38 mm diameter. We report test results for the GLONASS and LAGEOS CCRs. Details of the test procedure and CodeV simulations are given for the particular case of the LAGEOS Sector.

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[1] Member of the Signal Processing working group of the International Laser Ranging Service (ILRS).
[2] ETRUSCO (Extra Terrestrial Ranging to Unified Satellite Constellations) is dedicated to characterization and the improvement of the satellite laser ranging of GNSS constellations [1].

FFDP TEST IN AIR AND ISOTHERMAL CONDITIONS

The basic “acceptance” test of the CCR optical performance is the measurement of the absolute angular size and shape of single-CCR FFDP with linearly polarized CW lasers. The conceptual scheme of the optical FFDP circuit is shown in Fig. 1. Our laser beam profiler (by Spiricon) uses a 2 MPixel CCD camera (by PtGrey), readout via Firewire or USB by a PC. FFDPs are acquired with the CCR in air and isothermal conditions. Figure 1 also shows the measured and simulated FFDP of a LAGEOS Sector CCR taken at STP. The absolute angular scale of the circuit is calibrated with the double-slit method to test the consistency of each CCR FFDP with its nominal dihedral angle offsets (DAO). The latter are related to the satellite velocity aberration, which is determined by its orbital altitude (velocity). The FFDP tests of LAGEOS Sector CCRs were done at the “Ex-Virgo” Optics Lab of the LNF with a He-Ne laser (633 nm). We also measure the FFDP intensity relative to the Airy Peak, obtained with optical flats of known reflectivity, as an indicator of the CCR laser return.

FFDP measurements are modeled with CodeV, a software package by Optical Research Associates, Inc. (see http://www.opticalres.com/).

The INFN-LNF CCR FFDP test procedure has been developed in 2007/2008 with GLONASS prototypes and a GPS-2 flight model array lent to LNF by the University of Maryland at College Park, all made by Al-coated fused silica retroreflectors with an hexagonal front face of approximately 27 mm diameter. In summer 2008 this procedure was applied to the FFDP test of the LAGEOS Sector. For the particular case of the LAGEOS Sector, the INFN-LNF FFDP test procedure (LNF-SCF-2008/01**)** is reported in the Appendix 1, while the corresponding CodeV predictions are shown in Appendix 2.

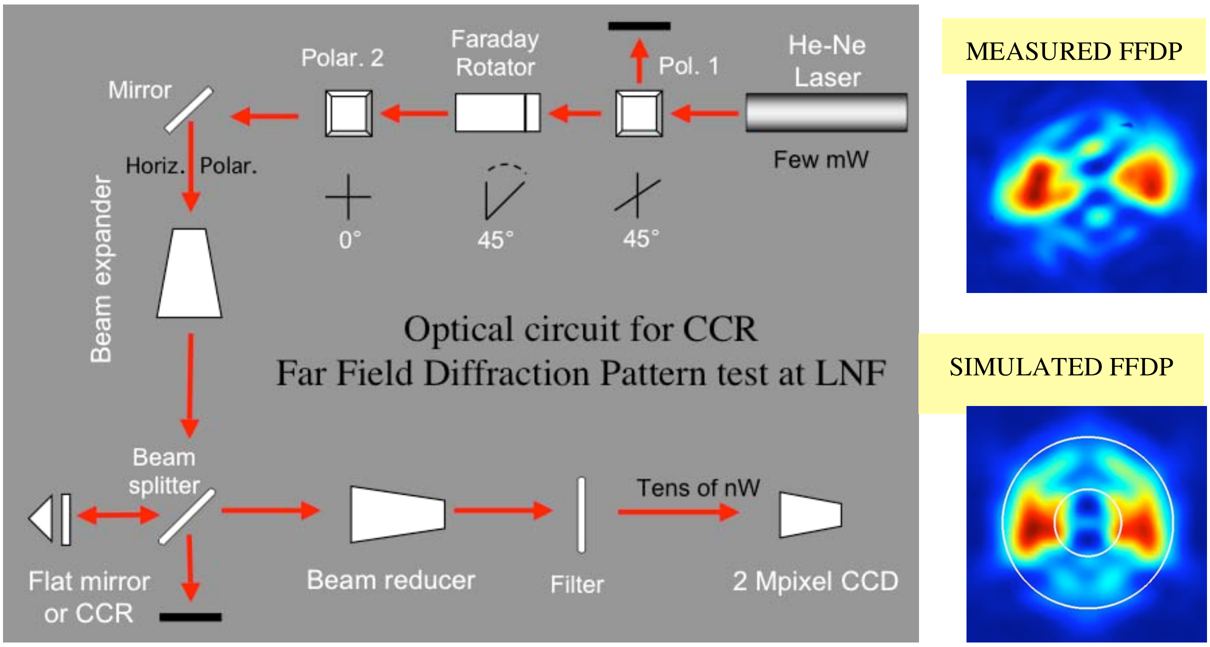


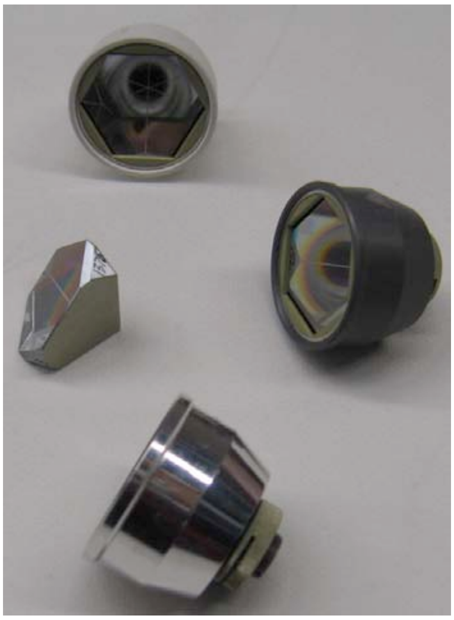
Figure 1 – FFDP optical circuit (left) and FFDPs measured for a LAGEOS Sector CCR (top right) and simulated with CODEV (bottom right). The specs of LAGEOS CCRs are DAO=(+1.25 ± 0.5) arcsec.

While the optical specs of LAGEOS CCRs related to the velocity aberration effect are given in terms of a range of DAO values, for GLONASS CCRs they are given in terms of the (velocity-aberrated) angular distance between the two main peaks/lobes of the FFDP (about 50 μrad or about 5 arc-seconds).

For LAGEOS I (built in the US) and for LAGEOS II (built in Italy) CCR optical tests, including FFDPs and the so-called "range correction", were performed by NASA-GSFC [3][4]. Now INFN-LNF developed FFDP testing capabilities also in Italy.

THE NASA-GSFC LAGEOS SECTOR AND THE GLONASS PROTOTYPES

Three GLONASS CCR prototypes were lent to LNF by IPIE of Moscow for FFDP testing in air and in the SCF space facility [1]. An engineering prototype of LAGEOS, the Sector, built around 1992, was sent to LNF by NASA-GSFC for FFDP testing in air and in the SCF [2]. These loans were the result of a close cooperation of INFN-LNF with ILRS and other international partners, including the University of Maryland at College park, NASA-GSFC and the Smithsonian Astronomical Observatory (SAO). The GLONASS and the Sector prototypes are shown in Fig. 2.



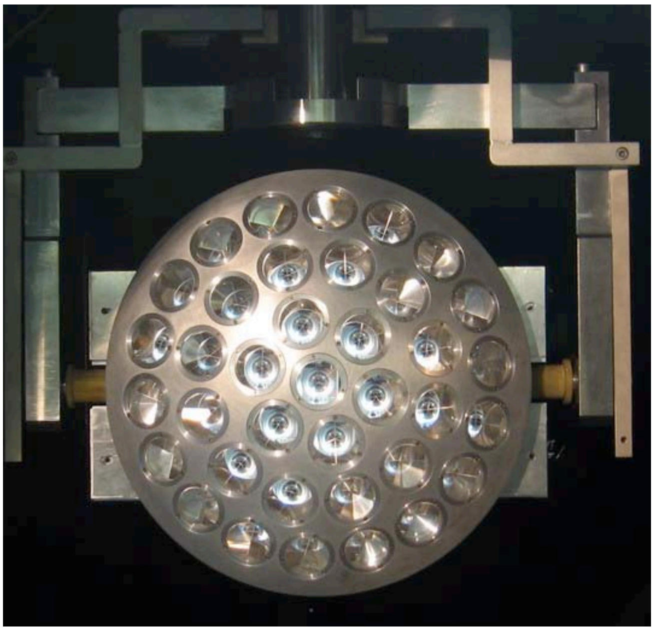


Figure 2 – Photos of three GLONASS (left) and LAGEOS Sector (right) prototypes.

LAGEOS SECTOR FFDP TEST IN AIR AND ISOTHERMAL CONDITIONS

The 37 Sector CCRs were tested at the Optics Lab with a He-Ne laser of 633 nm wavelength according to procedure LNF-SCF-2008/01. The measured Total FFDP angular distance and Total FFDP average intensity are shown in Fig. 3.

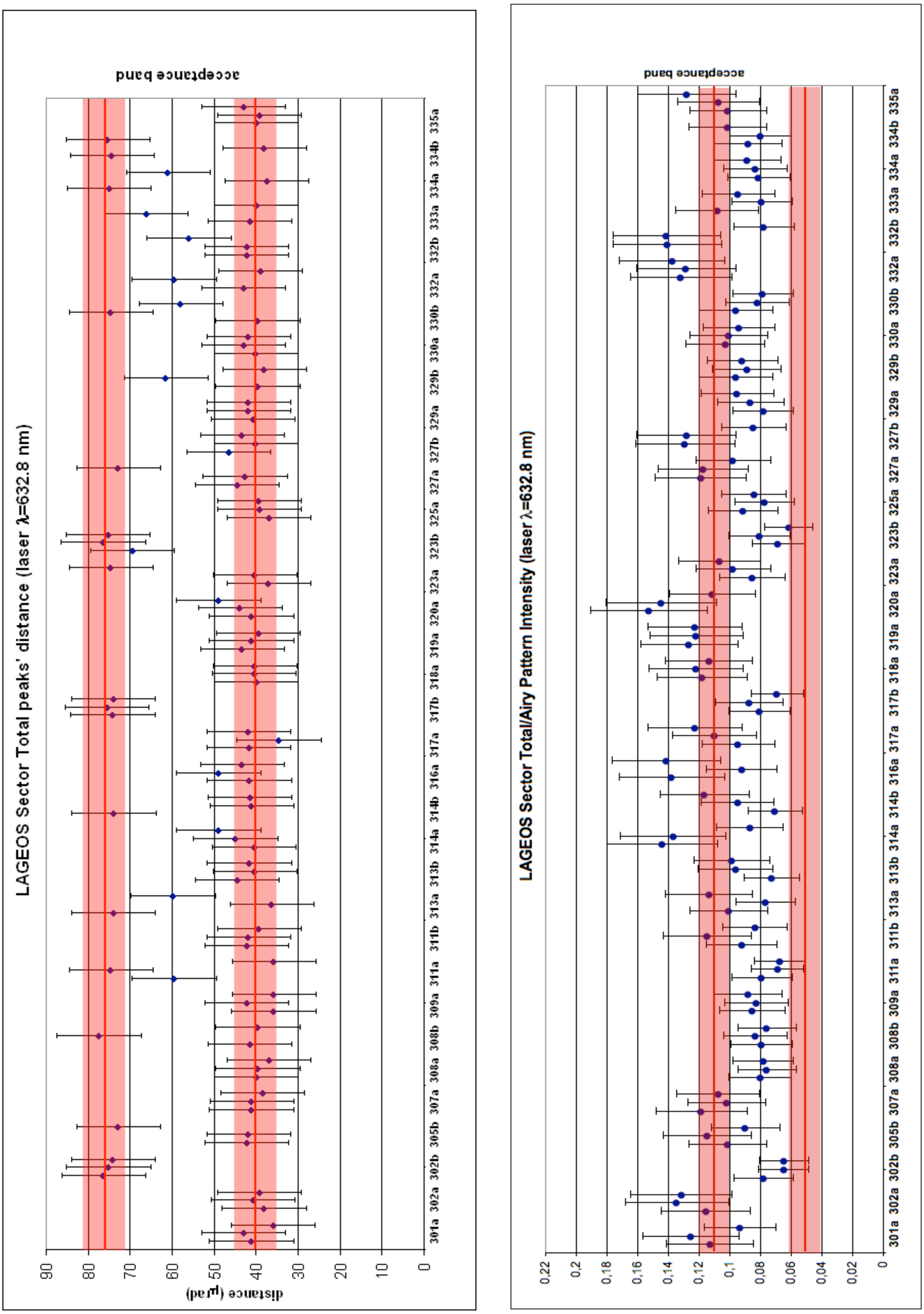


Figure 3 – LAGEOS Sector FFDP test: measured Total FFDP angular distance and Total FFDP average intensity (see Appendix) compared to the CodeV predictions (see Appendix 2).

The procedure LNF-SCF-2008/01 states that:

- “The shape of the Total FFDP contains the main quantitative information of the test”
- “The acceptance of the FFDP test is based on the comparison of the measured distance and the distance evaluated with CodeV, taking into account their respective uncertainties”.

For DAOs above the specs range (‘acceptance band’) the FFPD maintains two distinctive, separated, main peaks/lobes of energy, preferentially located in the in the horizontal region. For DAOs at the lower bound of the ‘acceptance band’ (0.75”) a third additional peak of energy is present in the central region of the FFDP between the two main peaks/lobes with energy higher than the other two. If DAOs are below the specs range, only the third central peak remains. This is a very distinctive feature, which allows to detect DAOs below specs.

Failure of the test occurs for significant deviations from:

- The distance predicted by CodeV
- The configuration of two main peaks/lobes of energy with the appearance of a central 3rd peak of intensity much larger that the two horizontal peaks/lobes and up to the disappearance of the two horizontal peaks
- Any other major change of FFDP shape.

All the Sector CCRs are within DAO specifications, since the FFDP distance is always within specs and because no CCR showed a third central peak of significant intensity consistent with DAO<0.75”. Further details of this work can be found in Ref. [5].

FFDP TEST OF THE GLONASS PROTOTYPES IN AIR AND ISOTHERMAL CONDITIONS

The GLONASS FFDP tests reported in this section were carried out with the optical circuit of the SCF experimental apparatus, equipped with a 532 nm Nd-Yg laser. This was done in order to compare with the similar measurements performed by IPIE in Moscow at the same wavelength. The total FFDP of the GLONASS CCR with polished Al case measured by INFN-LNF and by IPIE are shown in Fig. 4 and 5, respectively.

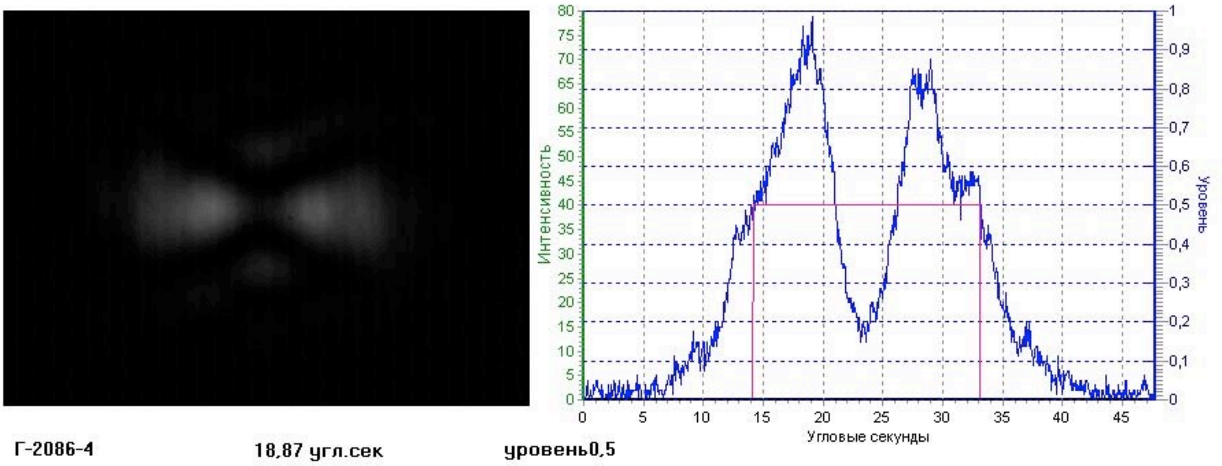


Figure 4 – Total FFDP angular distance measured by IPIE in arc-seconds.

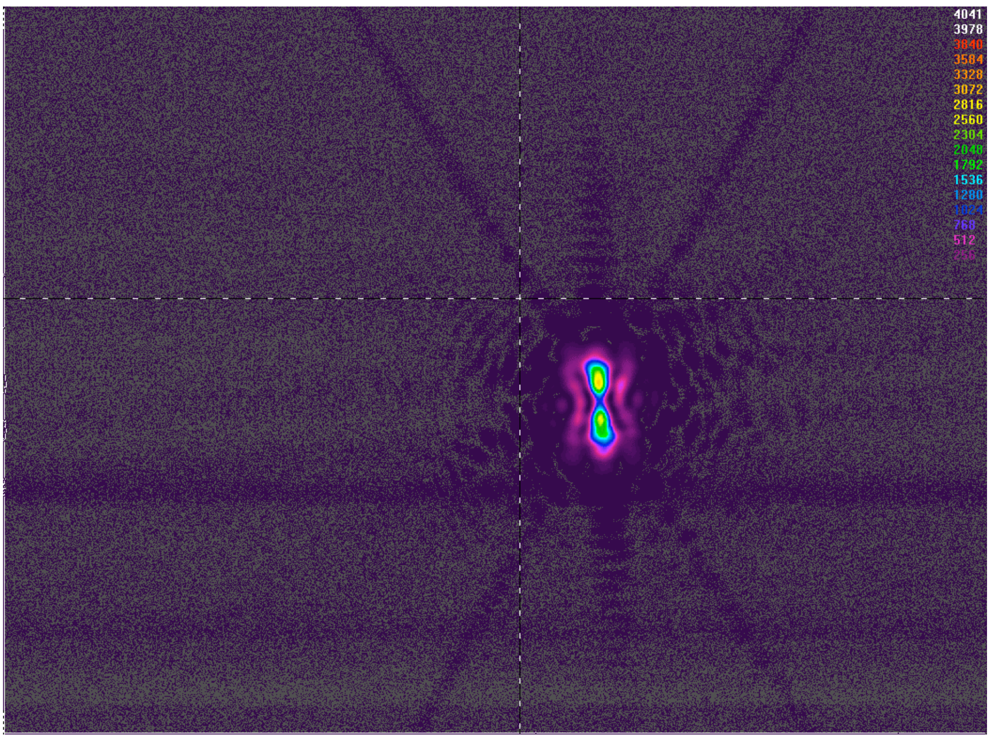


Figure 5 – Total FFDP measured by INFN-LNF.

The peak distance measured by IPIE, about 50 μrad agrees with the one measured by INFN-LNF, 50 μrad. The two FFDP shapes are also consistent.

The total FFDP of the GLONASS CCR with grey case measured by INFN-LNF and by IPIE are shown in Fig. 6 and 7 respectively.

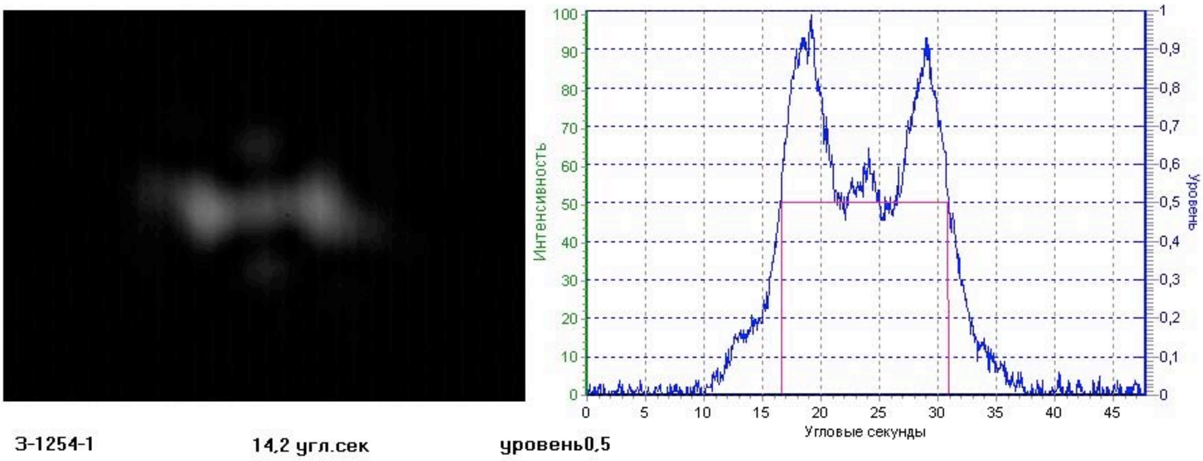


Figure 6 – Total FFDP angular distance measured by IPIE in arc-seconds.

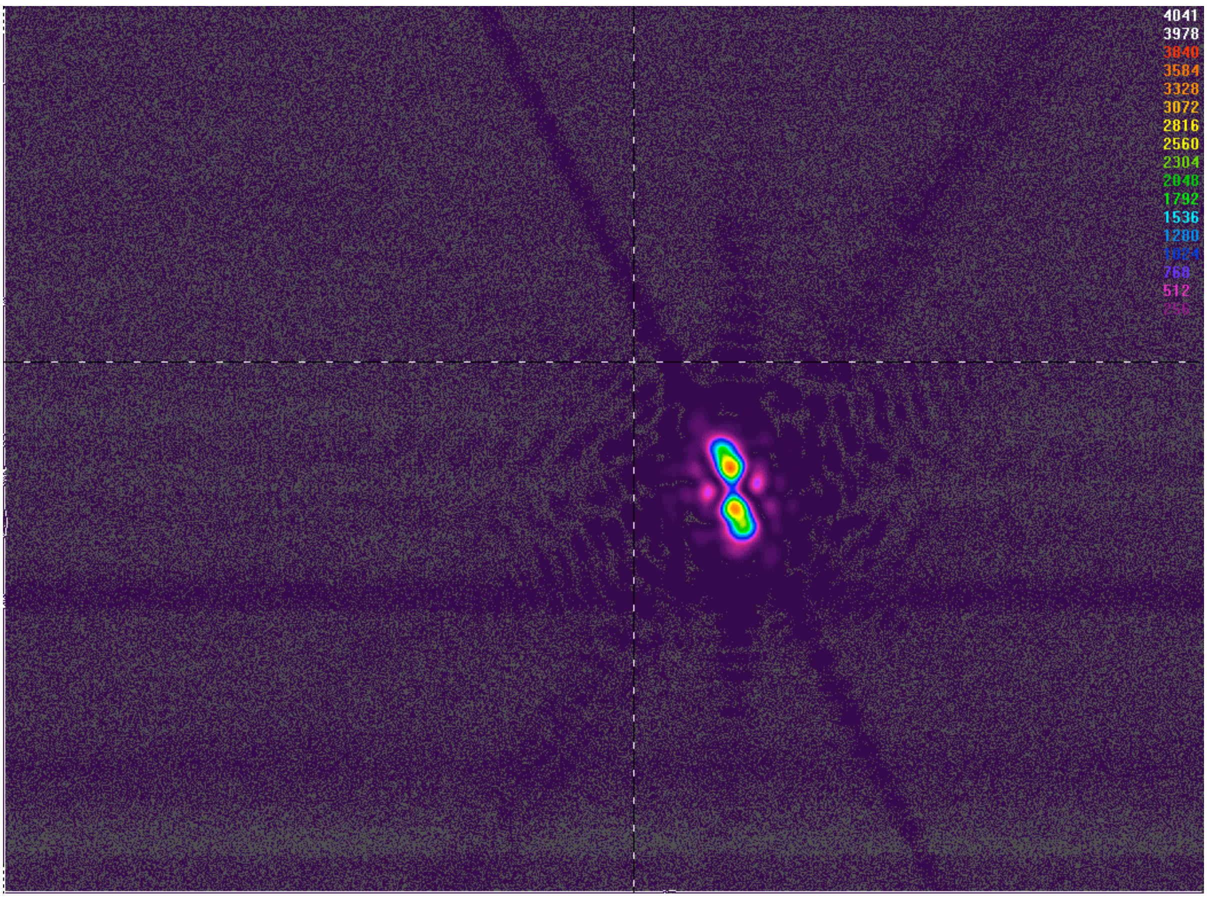


Figure 7 – Total FFDP measured by INFN-LNF.

The peak distance measured by IPIE, about 50 μrad agrees with the one measured by INFN-LNF, 49 μrad. The two FFDP shapes are also consistent.

The total FFDP of the GLONASS CCR with white case measured by INFN-LNF and by IPIE are shown in Fig. 8 and 9 respectively.

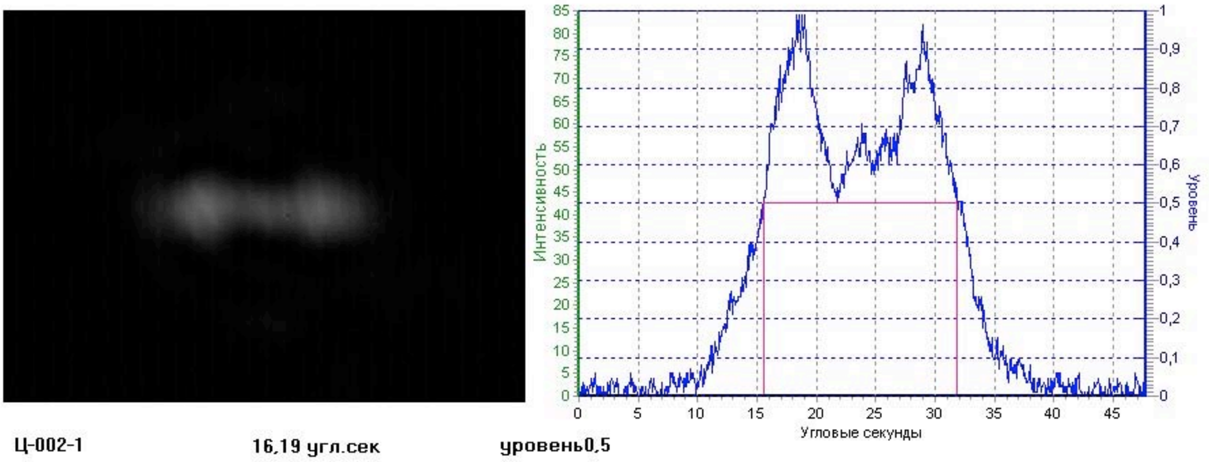


Figure 8 – Total FFDP angular distance measured by IPIE in arc-seconds.

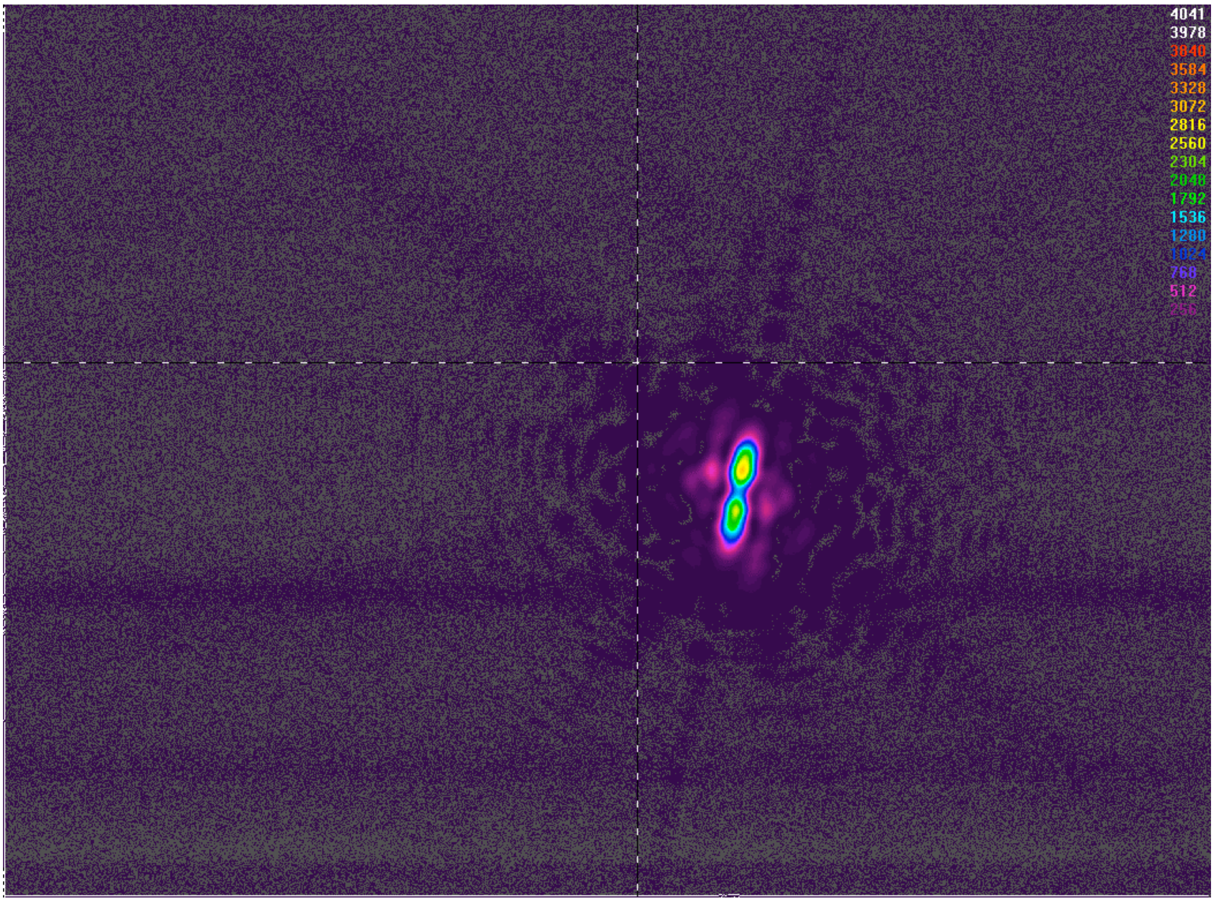


Figure 9 – Total FFDP measured by INFN-LNF.

The peak distance measured by IPIE, about 50 μrad agrees with the one measured by INFN-LNF, 44 μrad, within errors (see Appendix 1). The FFDP shapes are also consistent.

INFN-LNF measurements are consistent with IPIE measurements taken with procedure LNF-SCF-2008/01.

COMPARISON OF INFN-LNF CODEV SIMULATIONS WITH TWO INDEPENDENT CALCULATIONS

We checked our FFDP modeling against two independent software programs developed by two members of the Signal Processing Working Group of the ILRS, D. Arnold (SAO) and T. Otsubo. In the following we present a selection of these comparisons.

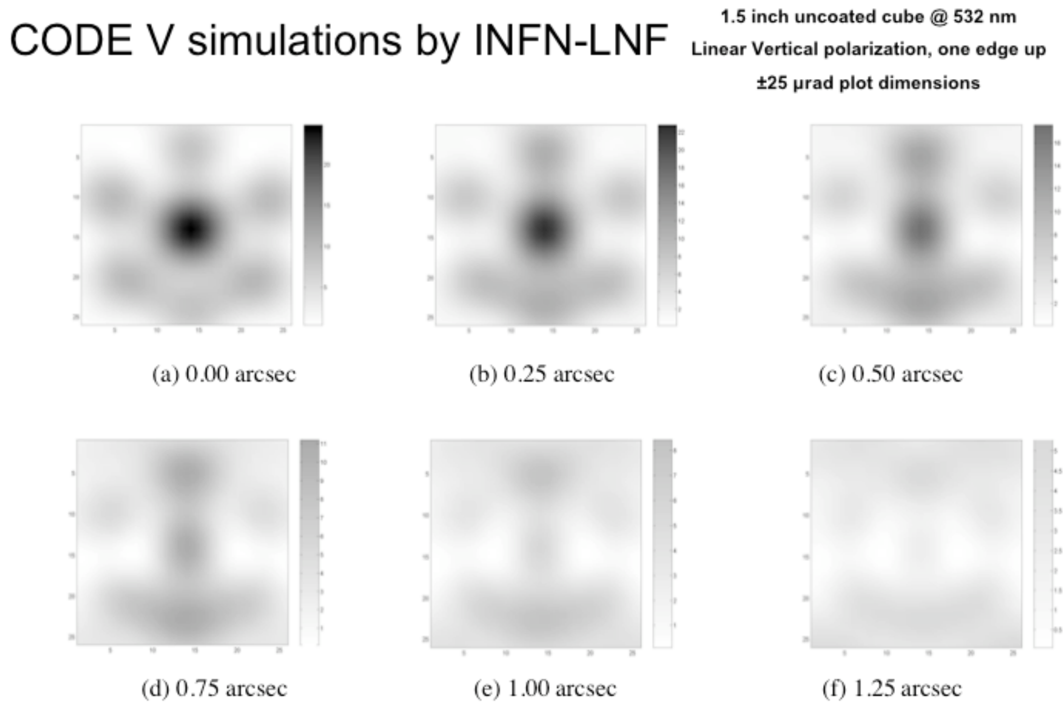


Figure 10 – FFDP simulation with CodeV by INFN-LNF.

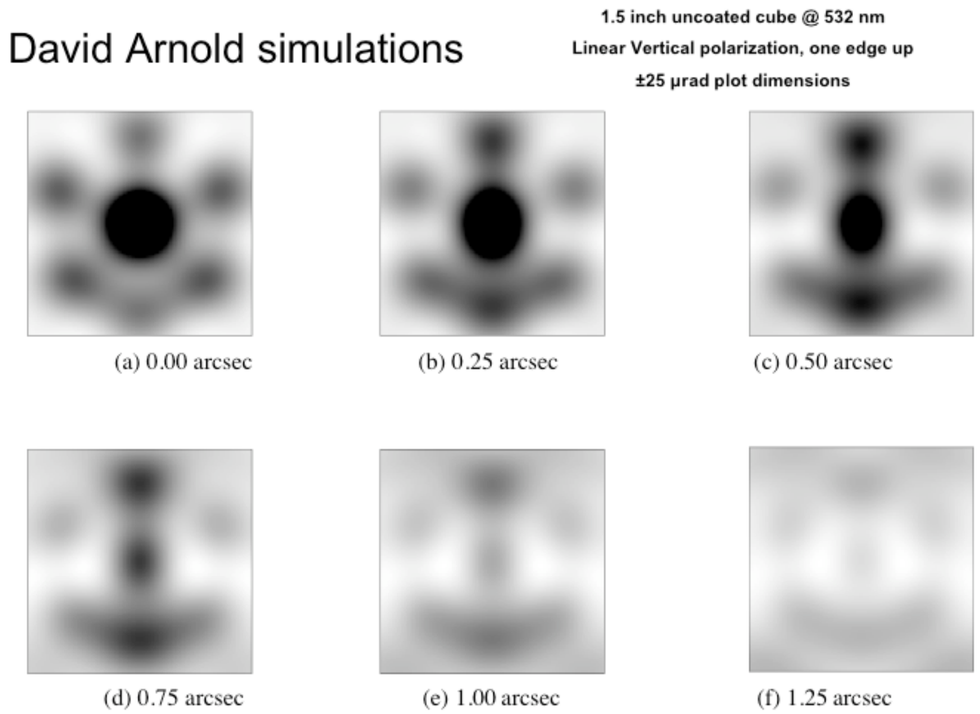


Figure 11 – FFDP simulation by D. Arnold.

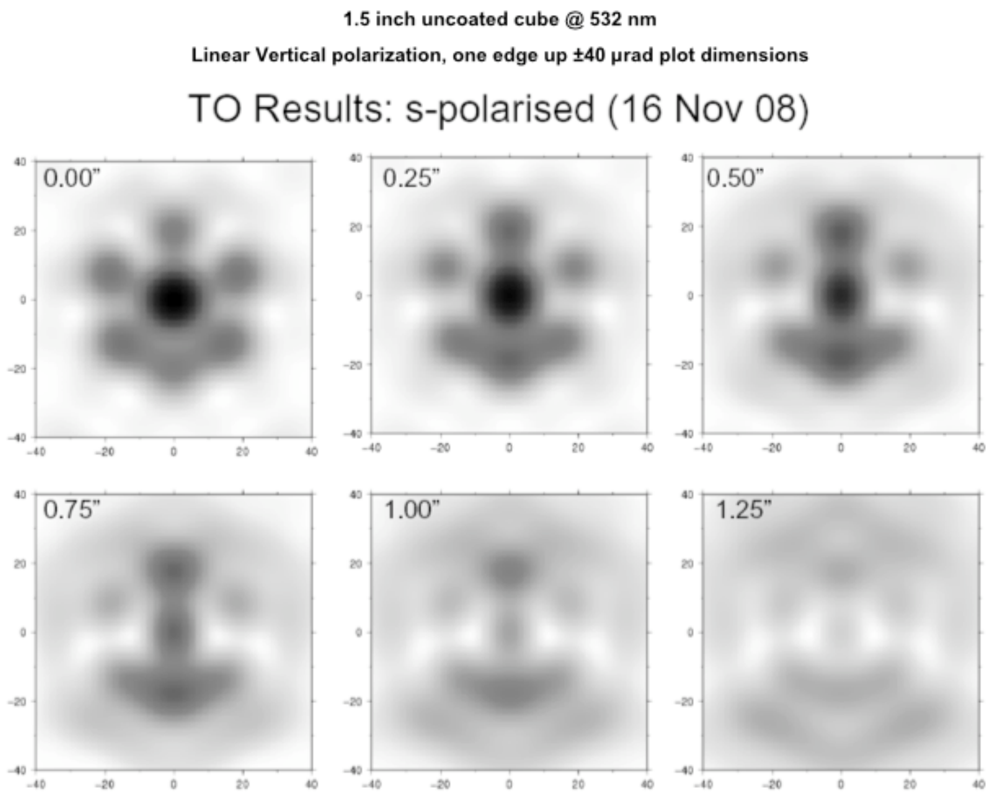
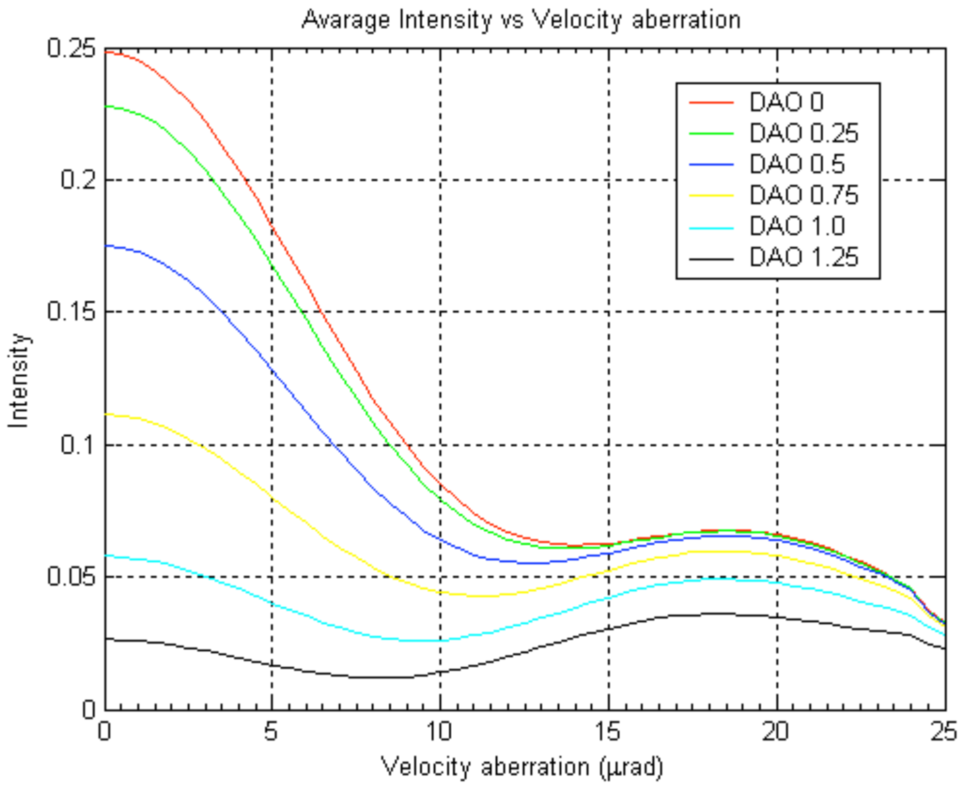


Figure 12 – FFDP simulation by T. Otsubo.

All above simulations have been performed for an uncoated, 1.5 inch (38.1 mm diameter) CCR with three equal DAO values ranging from 0.00" to 1.25" in the same laser illumination conditions: linear vertical polarization, one vertical edge and constant (ie, not Gaussian) laser intensity over the CCR aperture.

FDDPs shown in Fig. 10, 11, and 12 are plotted with different intensity grey-scales, but they have the same detailed angular shape. We checked the intensity values, which are also consistent among the three sets of simulations. Figure 13 shows another more detailed comparison between the INFN-LNF simulations and D. Arnold simulations. The agreement among the three analysts of the SPWG is remarkable.



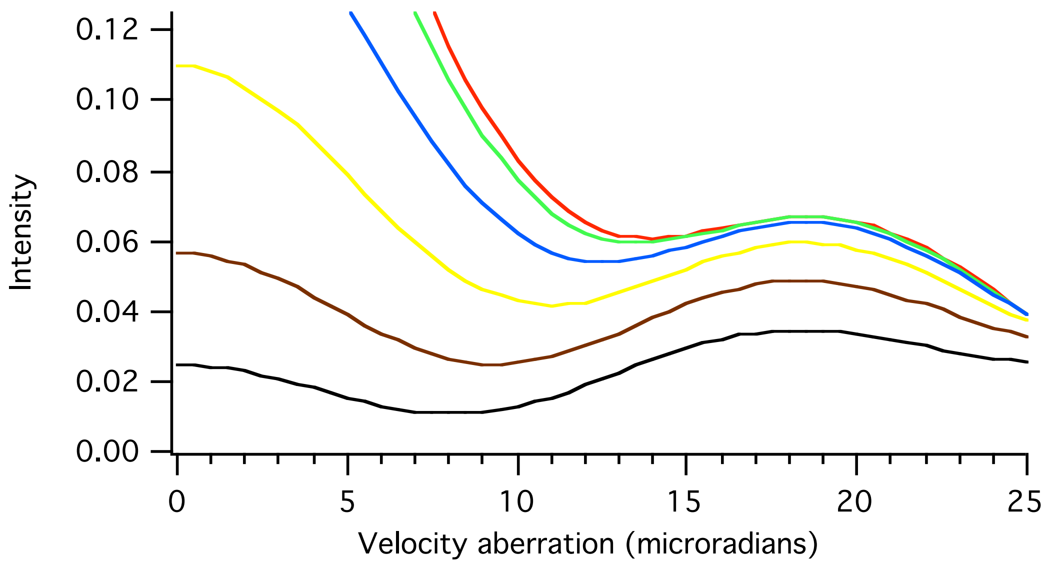


Figure 13 – Plot of the FFDP average intensity vs. velocity aberration for several dihedral angle offsets. The values are averaged around circles of increasing radius (velocity aberration) in the far field pattern. The average energy decreases as the dihedral angle offset increases. The top plot is a simulation with CodeV by INFN-LNF; the bottom plot is a simulation by D. Arnold. Note that in the INFN-LNF plot the DAO = 1.0” curve corresponds to the brown color curve for Arnold.

On the following we show a series of figures representing the intensity of the patterns along a circle of 19 μrad of distance from the center of the pattern. Intensities are always referred to the Airy pattern. The azimuth angle is measured counter-clockwise from the +X axis (pointing to the right).

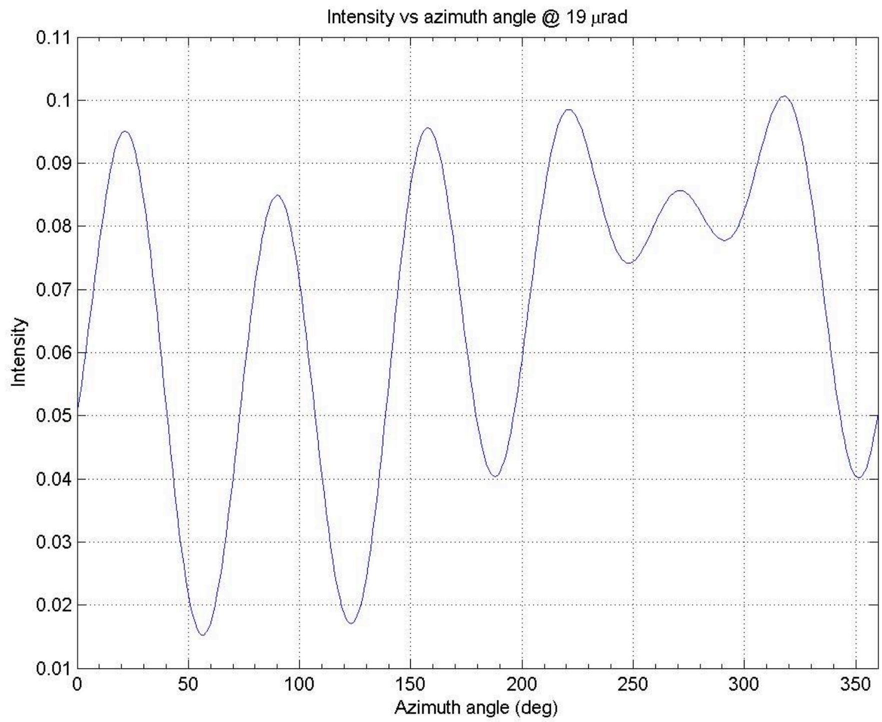


Figure 14 – CodeV simulation for DAO = 0 arcsec.

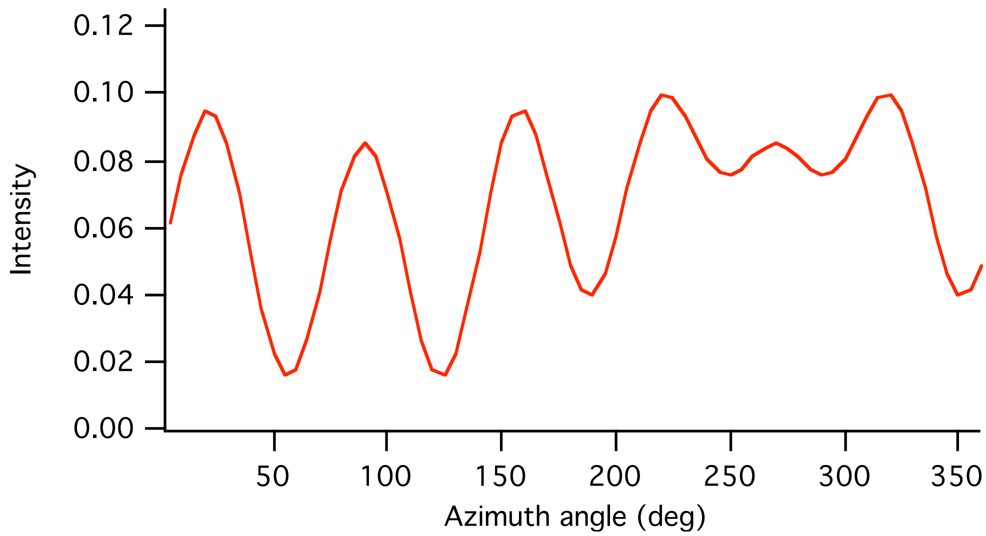


Figure 15. D. Arnold's simulation for DAO = 0 arcsec.

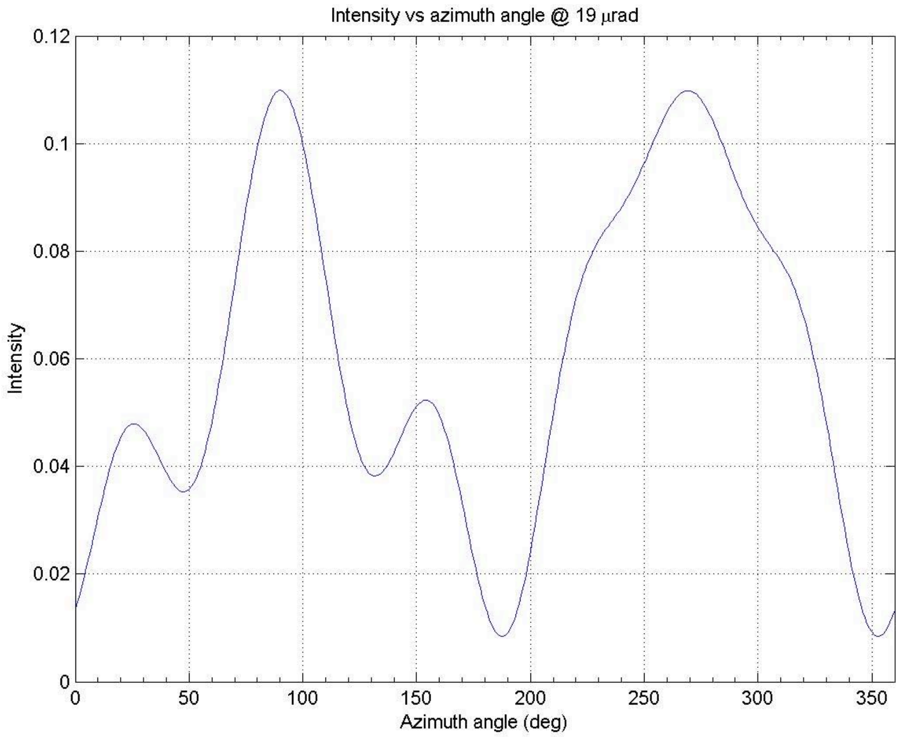


Figure 16 – CodeV simulation for DAO = 0.75 arcsec.

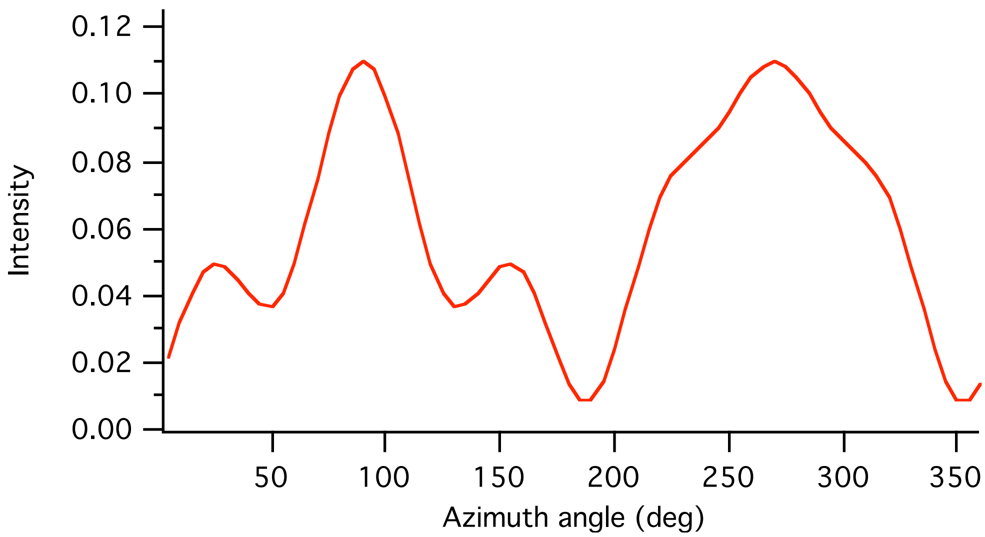


Figure 17. David Arnold's simulation for DAO = 0.75 arcsec.

Acknowledgments

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References

[1] S. Dell'Agnello, G. O. Delle Monache, D. G. Currie, R. Vittori, et al, *ETRUSCO: Extra Terrestrial Ranging to Unified Satellite COnstellations*, INFN-LNF Report LNF-07/8(IR).

[2] A. Bosco, C. Cantone, S. Dell'Agnello, G. O. Delle Monache, et al, *Probing Gravity in NEOs with High-Accuracy Laser-Ranged Test Masses*, Int. Jou. Mod. Phys. D, Vol. 16, No. 12A (2007) 2271-2285.

[3] M. W. Fitzmaurice, P. O. Minott, J. B. Abshire, H. E. Rowe, *Prelaunch Optical Testing of the Laser Geodynamic Satellite*, NASA-GSFC Technical Paper, 1976.

[4] P. O. Minott, T. W. Zagwodzki, T. Varghese, and M. Seldon, *Prelaunch Optical Characterization of the Laser Geodynamic Satellite (LAGEOS 2),* NASA Technical Paper 3400, September 1993.

[5] S. Gentile, Bachelor Thesis, University of Tor Vergata, Ingegneria Modelli e Sistemi, Rome, November 20, 2008 (unpublished); Thesis Advisors: G. Bellettini, R. March, S. Dell'Agnello.