ESA-INFN contract 4000136905/21/NL/DB

Final Presentation

Hollow Cube Corner Retroeflectors (HCCRs) for In-Orbit PNT

These HCCRs are exposed optics (not internal to satellites), to be observed via Satellite/Lunar Laser Ranging (SLR/LLR).

July 23, 2025

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Outline

- Introduction and Objectives
- Roles of the partners
- HCCR requirements
- Manufacturing of the HCCRs
- Optics metrology
- Qualifications of the HCCRs
- Results, lessons learnt
- Other realizations of HCCRs
- Prospects for further development

Introduction

Optical solid Corner Cube Retro-reflectors (CCR) are often implemented to allow laser tracking of satellites from ground. In order to achieve a measurable return signal, such corner cubes are typically rather large and, as conventional corner cubes are made of glass, also high in mass. A hollow CCR, made of three orthogonal flat mirror surfaces, offers theoretically superior performance and a mass reduction compared to solid CCR's

Objectives

The main objectives of this activity are:

- To design, manufacture and test a hollow CCR for space Positioning, Navigation and Timing (PNT) that can be part of an array assembly.
- To investigate the mass saving potential of a hollow CCR compared to a solid CCR while maintaining a similar performance.

Roles of the partners

- Contractor: **INFN-LNF** (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati), Frascati (Rome), Italy:
  - With ESA: issue harmonized HCCR optical specifications
  - With Media Lario (ML): conception of an HCCR that can be assembled in an array
  - Verify HCCR optical specs; identify independent optics metrology (INRIM, Turin, IT)
  - Qualifications of built HCCRs
  - With ESA/ML: evaluate results and put then in a wider/international context.
- Subco: **Media Lario srl**, Località Pascolo, 23842 Bosisio Parini (LC), Italy:
  - Finalize and detail the mechanical and optical HCCR design. FEM analysis.
  - Manufacture 2 HCCRs to specs exploiting its Repli-formed Optics™ technology
  - In-house optics metrology, get independent confirmation (Astr. Obs. Brera, Merate, IT)
  - Support INFN/ESA in the interpretation of qualifications and in the overall evaluation of results.

Harmonized HCCR Optics Reqs / Quals

- General optical specs:
  - Operating wavelength: 532 and 1064 nm
  - RMS wavefront error ≤ λ/10 at 633 nm
  - Reflectivity ≥ 0.9. Surface micro-roughness ≤ 2nm.
- Optical diameter/aperture: up to 3 inches
- Dihedral Angle Offsets (DAOs, in arcseconds):
  - One “nominal” HCCR with (1.5”, 1.5”, 1.5”) +/- 0.3”
  - Added value: “additional” HCCR with different, larger DAOs (>2.0”)
- TVT range:
  - Widest given manufacturing technology
  - Plus test beyond limit, [-73,+77]C, a 150C range.
- Mechanical qualifications:
  - Sine (up to 20g) and random vibes
  - Shock up to 1000g at high frequency.

Manufacturing: Repli-formed Optics™ concept for HCCRs

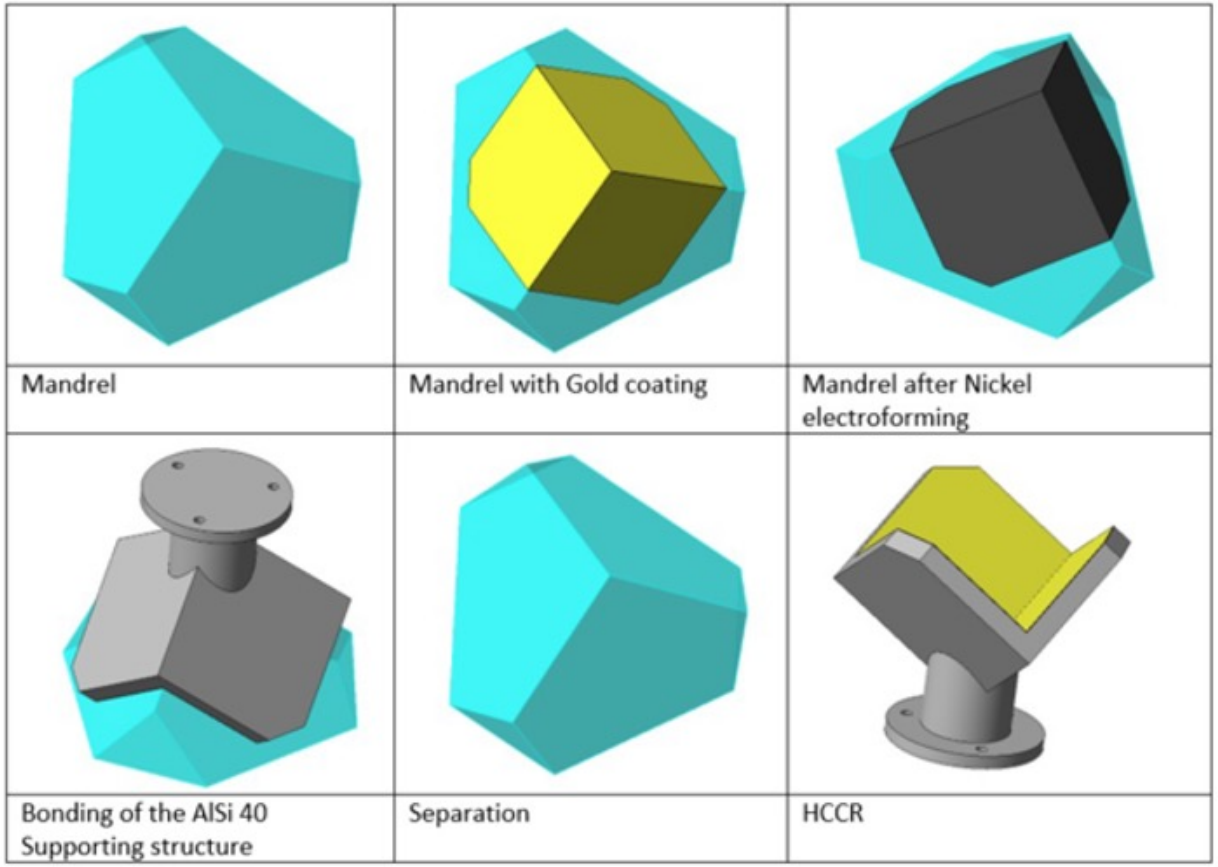
Mandrel = 3” uncoated solid fused silica CCR

The replica technique allows to re-use the mandrel several times, with limited costs and specifically in our case, with the option to tune the HCCR dihedral angles to the desired ones by choosing the mandrel with the requested dihedral angles.

Trade-offs performed to select:

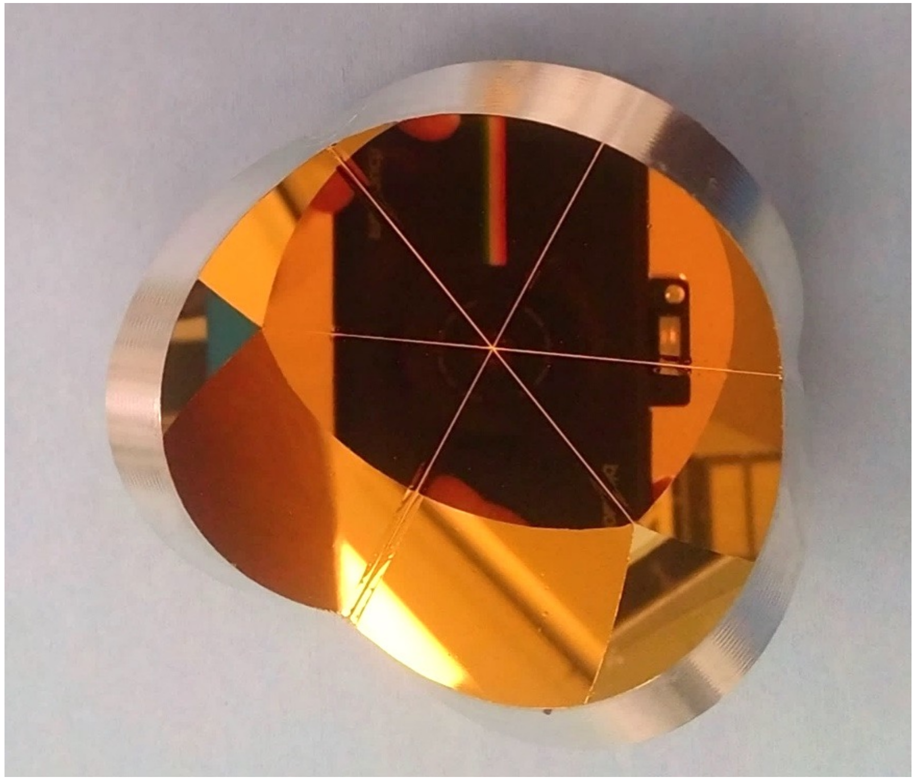
- **Geometry of HCCR mech. structure**
- **Material of backing structure**
- **Adhesive with low CTE, shrinkage and viscosity**

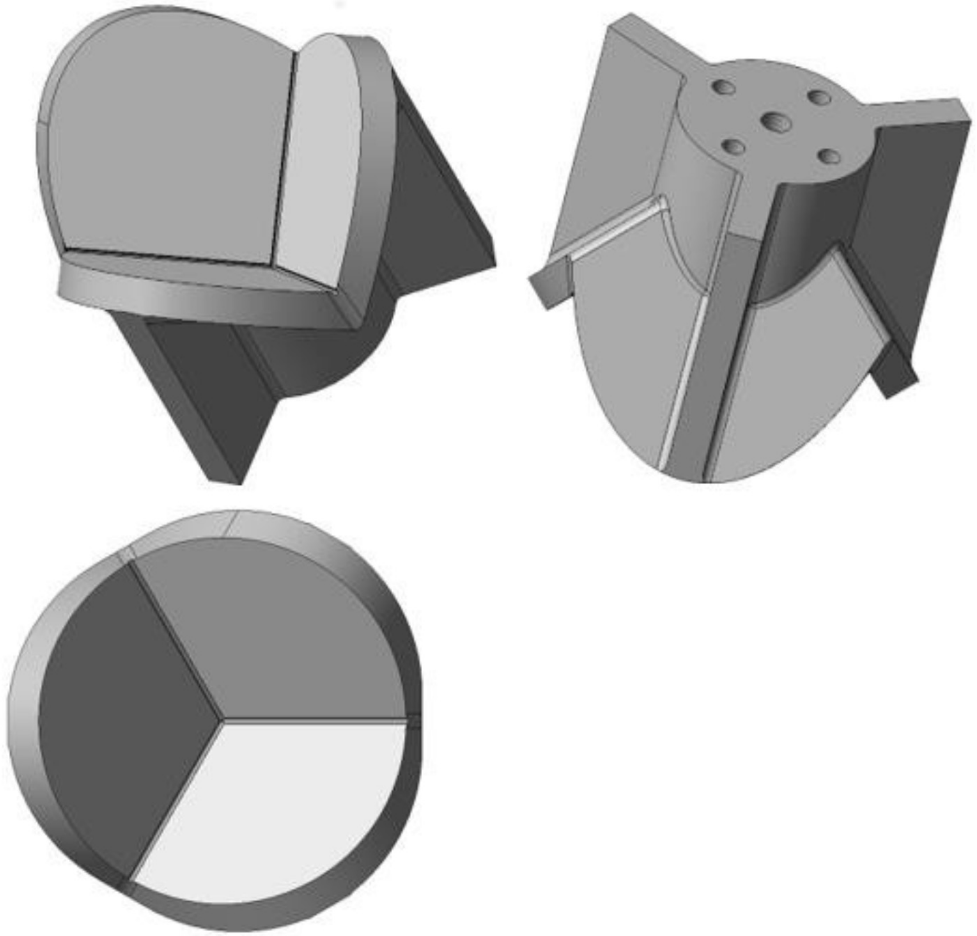
PROCESS CONCEPT based on the repliforming



Manufactured HCCRs (2.8 inch diam.)

Media Lario



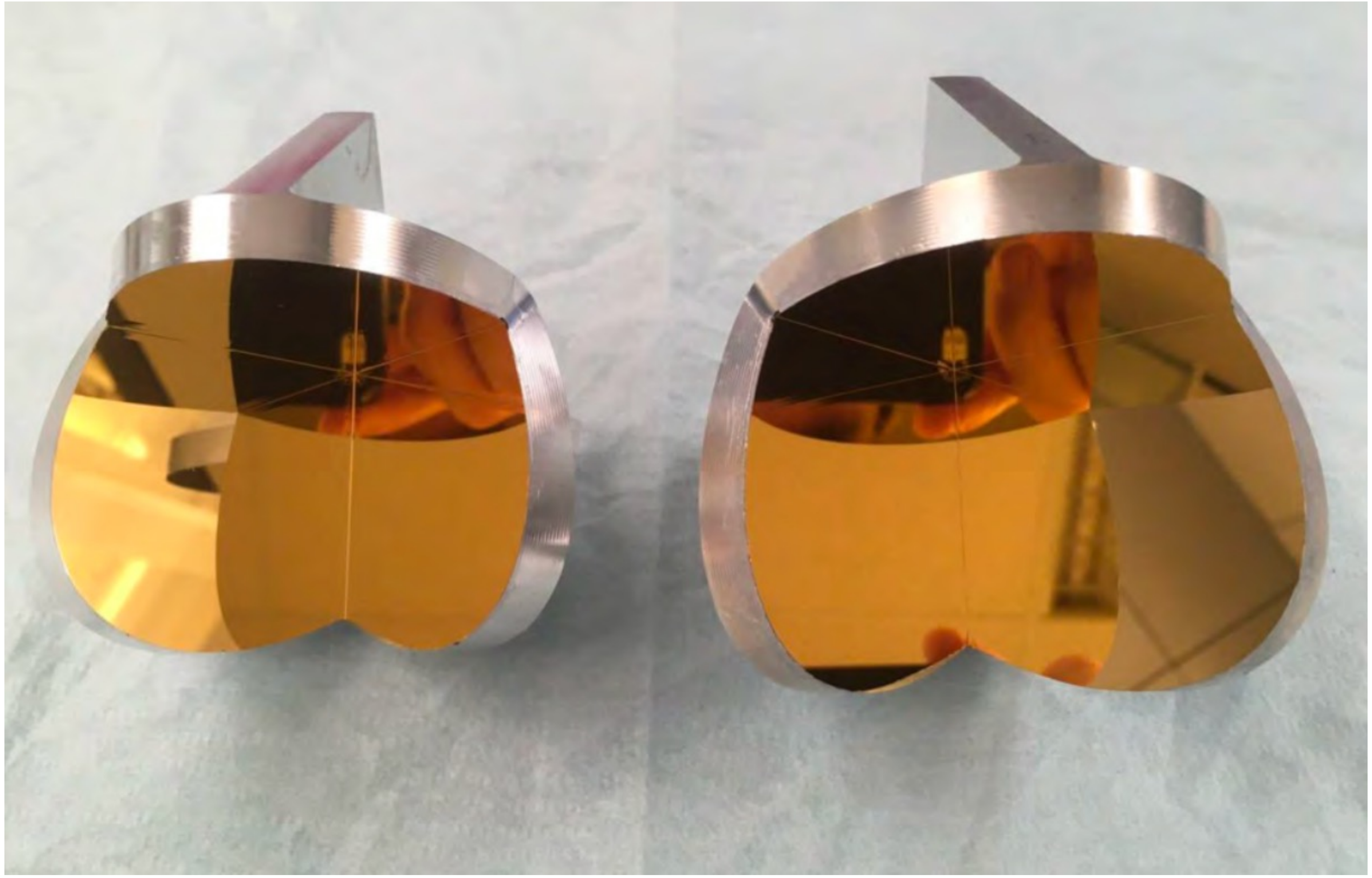


Two manufactured HCCRs (2.8 inch diam.)

Measured DAOs

Nominal HCCR:
DAOs = **(1.3”, 1.3”, 1.7”)**
Additional HCCR:
DAOs = **(2.9”, 2.4”, 2.5”)**

Masses:
~300 gr



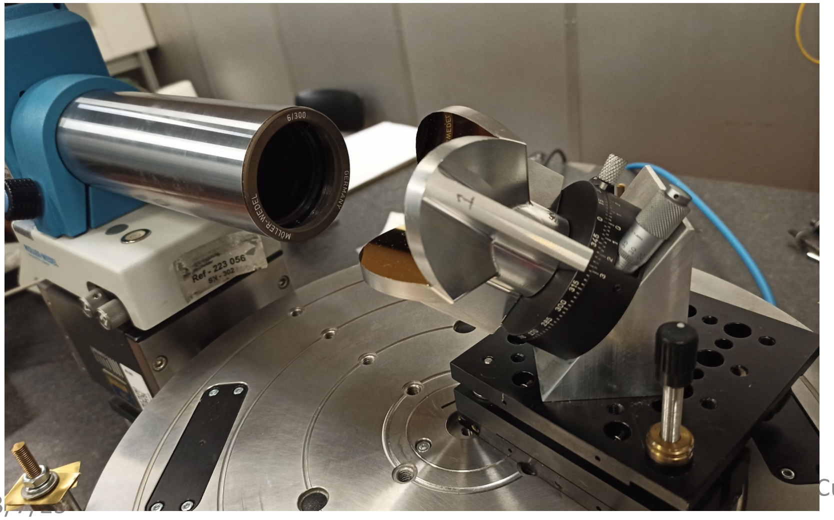
Requirements verified during manufacturing and their verification methods.

Table 4 Requirements vs. proposed verification methods

Specification			**Verification**	
ID	**Description**	**Value**	**Verif.**	**Method**
Mechanical Interface Req.				
M1	The flatness of the HCCR interface	see drawings	T	CMM
Optical Interface Req.				
M2	The useful optical area	75 mm aperture	T	Interferometer FoV
Performance Requirements				
Mechanical Performance Req.				
M3	The mirrors dimensions with tolerances	as per drawings	T	CMM
M4	Single mirror surface error	< 63 nm RMS	T	Interferometry
M-49	The surface reflection coefficient	>90%	T	Reflectance Spectrometry
Surface finish and contamination				
M-50	The mirrors surface micro-roughness	<2 nm RMS	T	WLI

Optics (Laser) Metrology: Fizeau interferometer and Autocollimator

- 4D interferometer at ML, confirmed with a Zygo at Astronom. Observ. of Brera in Merate. Full 2.8-inch diam. measured.
- **INRIM**, Istituto Nazionale di Ricerca Metrologica in Turin: independent verification using an autocollimator and a very accurate rotation table (left figure). Central part of 1 inch of each face measured.
- Reasonable agreement for two DAOs. Very different geometric coverage may explain difference in DAO of faces 1-2. But this difference may also indicate a potential systematic effect, present also in the comparison of measured and simulated Far Field Diffraction Patterns.

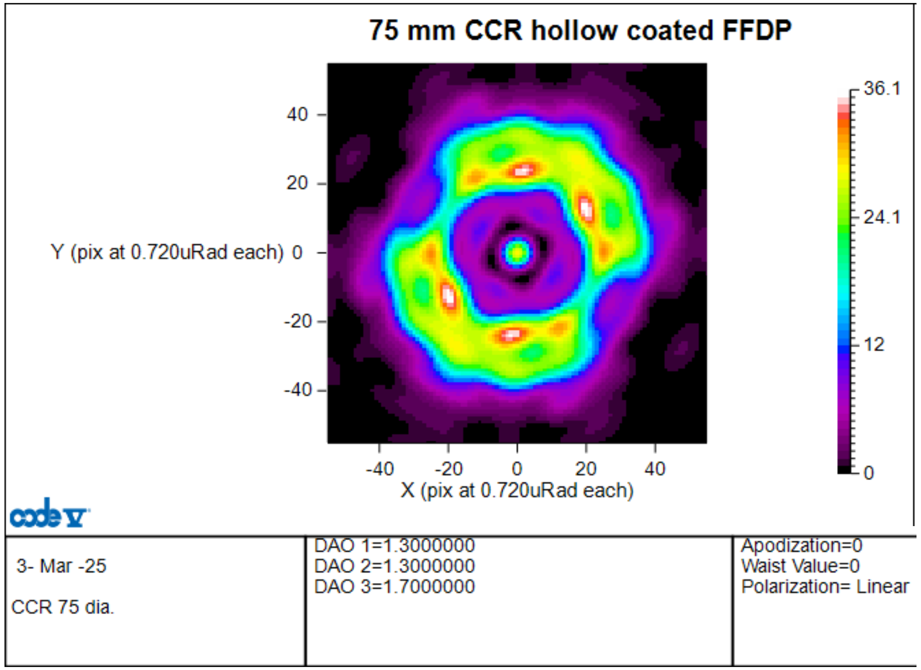


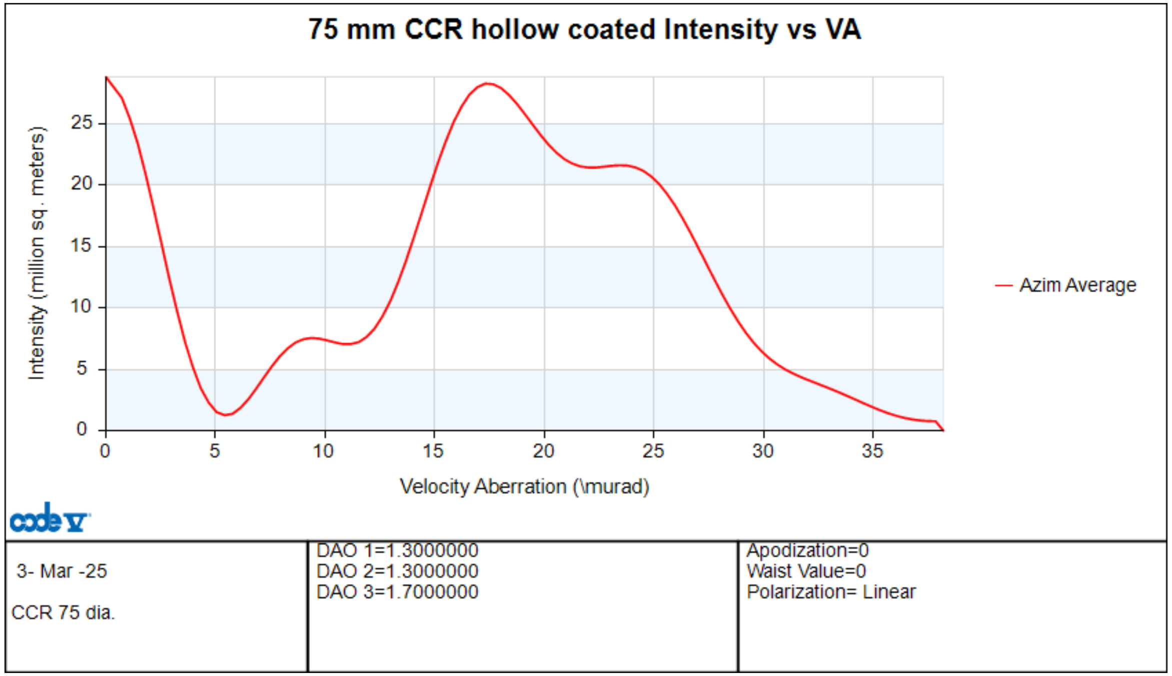
Measured Dihedral Angle Offsets (DAOs) of “nominal” HCCR with requested DAOs = **(1.5”, 1.5”, 1.5”) ± 0.3”**

Faces	Media Lario	STD Dev [Arcsec]	INRIM	STD Dev [Arcsec]
1-2	90° + 1.3”	0.1	90° + 0.6”	0.05
2-3	90° + 1.3”	0.1	90° + 1.3”	0.05
3-1	90° + 1.7”	0.1	90° + 1.4”	0.04

Far Field Diffraction Patterns (FFDPs)

Nominal HCCR: DAOs = **(1.3”, 1.3”, 1.7”)**

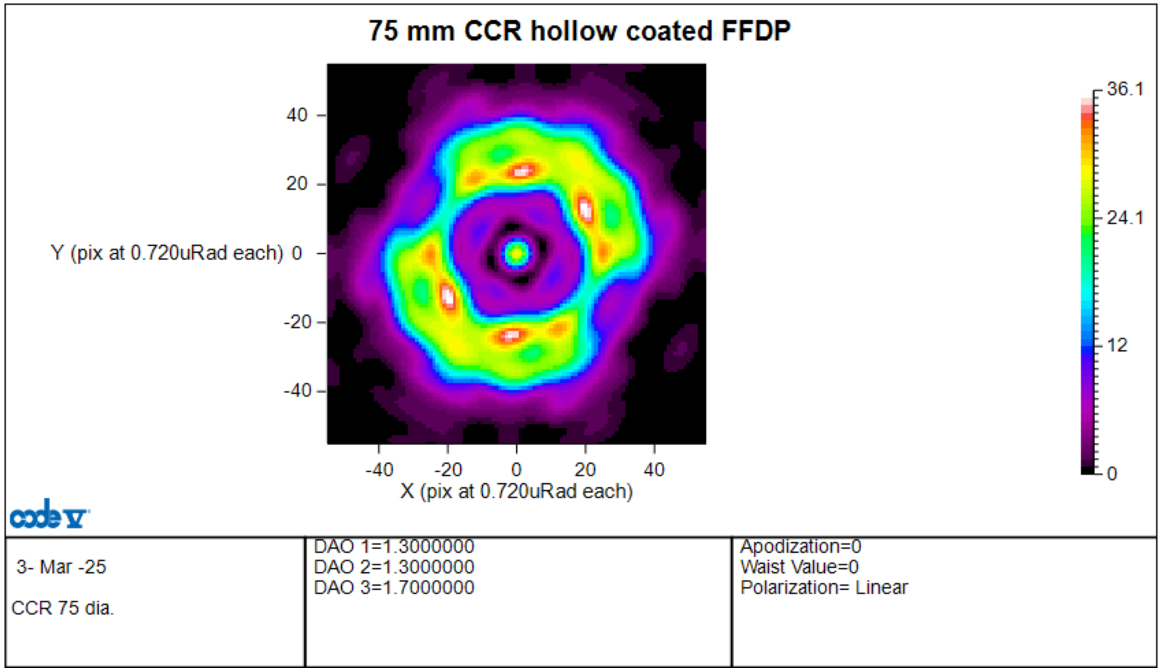


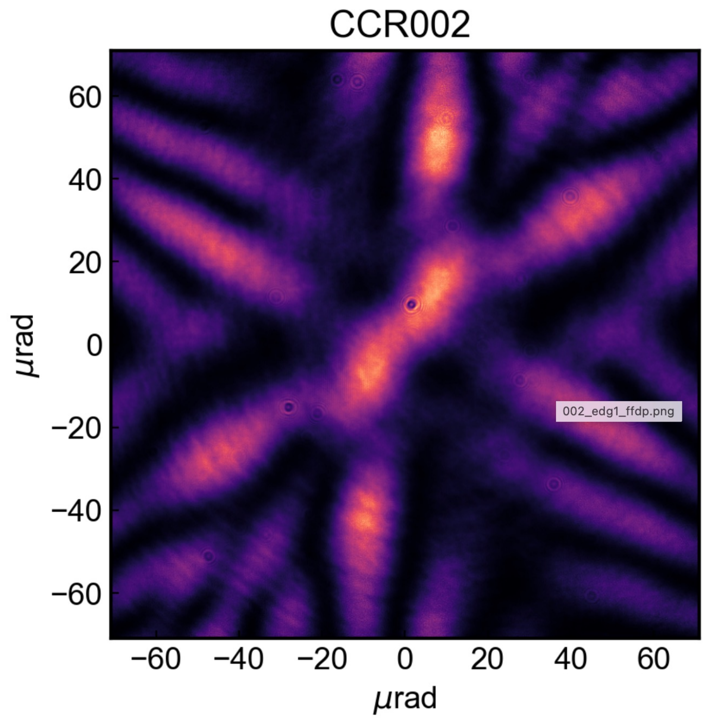


Far Field Diffraction Patterns (FFDPs)

Nominal HCCR: DAOs = **(1.3”, 1.3”, 1.7”)**

Reasonable shape agreement

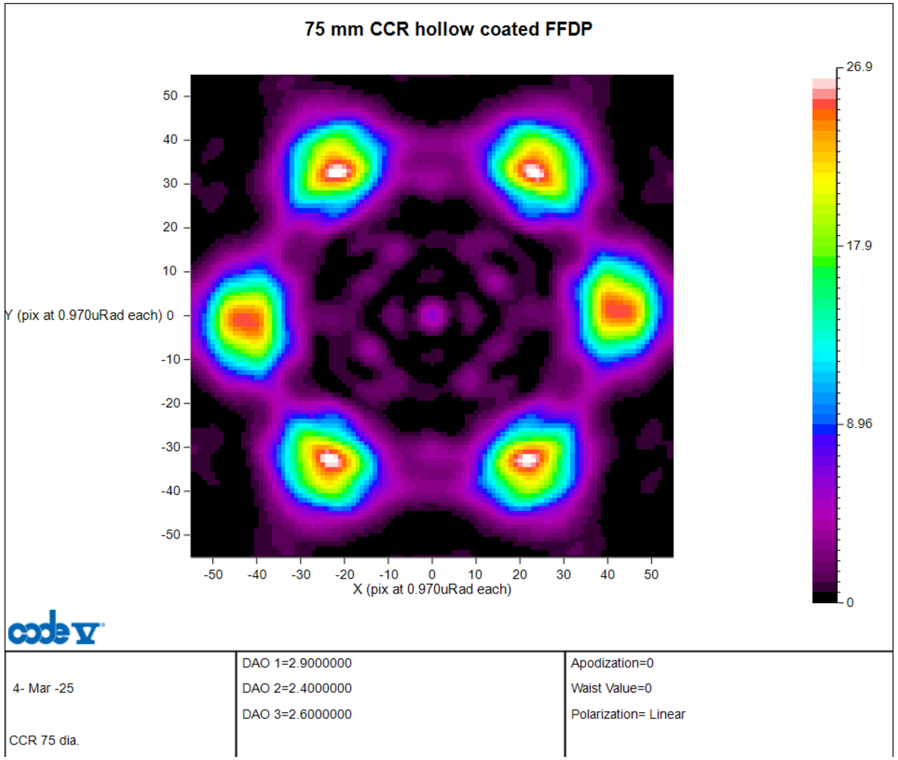


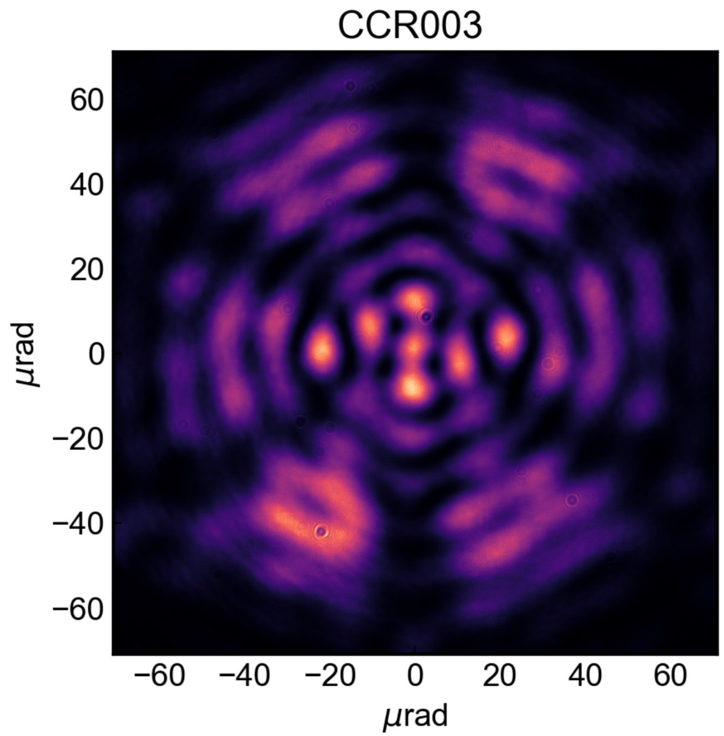


Far Field Diffraction Patterns (FFDPs)

Additional HCCR: DAOs = **(2.9”, 2.4”, 2.5”)**

Reasonable shape agreement





HCCR Mechanical Qualifications

Sine vibrations

Frequency	Level
(5 – 21) Hz	11 mm (0 – peak)
(21 – 60) Hz	20 g (0 – peak)
(60 – 100) Hz	6 g (0 – peak)

Random vibrations

Location	Duration	Levels
Equipment located on “external” panel [a] or with unknown location	Vertical [b] 2.5 min/axis	(20 – 100) Hz +3 dB/octave (100 – 300) Hz PSD(M) [c] = 0.12 g^2/Hz x (M + 20 kg)/(M + 1 kg) (300 – 2000) Hz -5 dB/octave
	Lateral [b] 2.5 min/axis	(20 – 100) Hz +3 dB/octave (100 – 300) Hz PSD(M) [c] = 0.05 g^2/Hz x (M + 20 kg)/(M + 1 kg) (300 – 2000) Hz -5 dB/octave

Shock

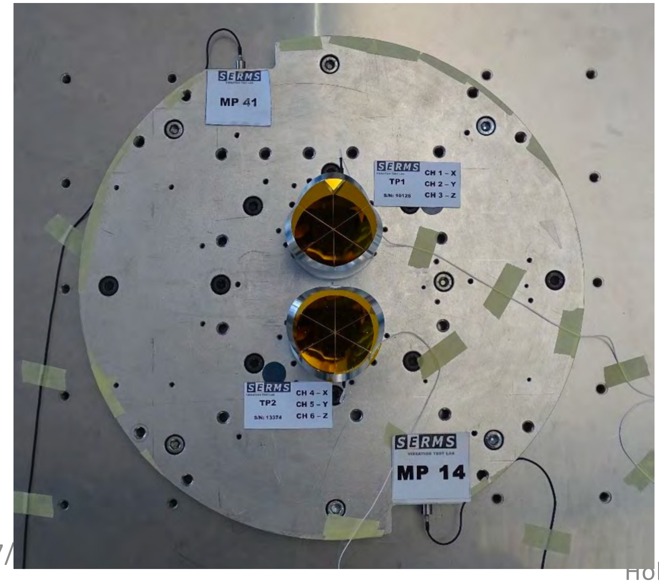
The hollow CCR shall be able to withstand without degradation the following shock specification applicable independently to each axes X, Y and Z:

SRS with Q=10

100 Hz	10g
2000 Hz	1000g
10000 Hz	1000g

Results, lessons learnt

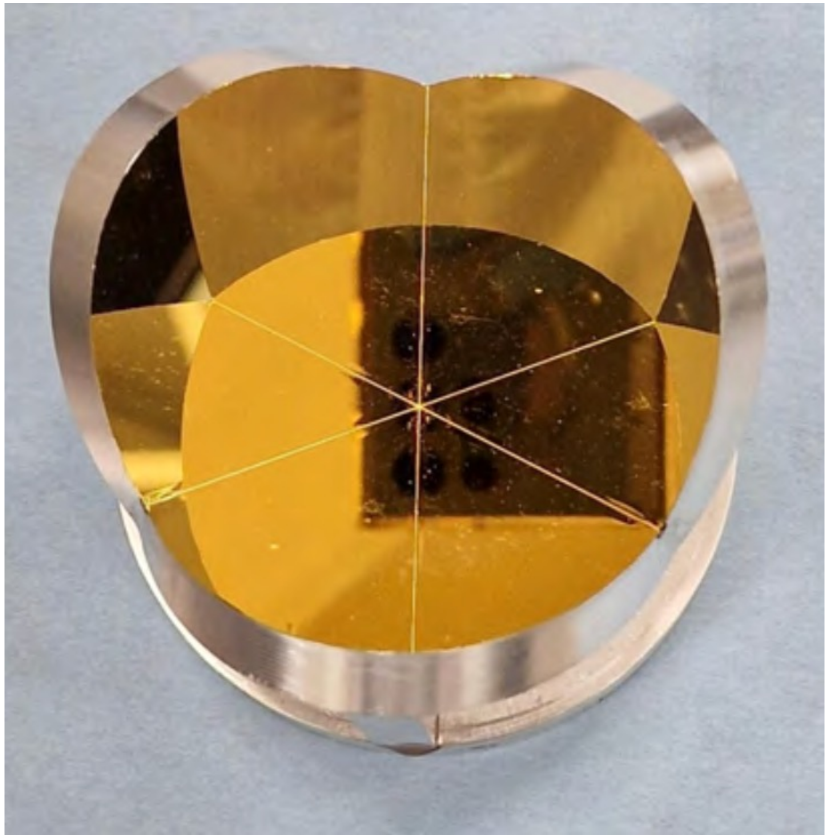
- HCCRs shown no damage after the mechanical test. The pass-fail criteria exposed the sensitivity of the optical performances to the torque applied to the M6 fixing screw at the base of the HCCRs.
- To pass a torque >6 Nm is required. But then DAOs are severely modified (see table) and the optical performance FFDP is destroyed.
- Nominal performance required a 0.3 Nm torque.
- The HCCR mechanical design needs to be modified accordingly.



Face Pairs #	23/09/24 [Arcsec]	13/03/25 Torque > 6 Nm [Arcsec]	13/03/25 No Torque [Arcsec]	13/03/25 0.3 Nm Torque [Arcsec]
1-2	**2.9**	-16.8	4.1	**2.7**
2-3	**2.4**	-10.5	3.5	**2.2**
3-1	**2.6**	-17.7	4.0	**2.6**

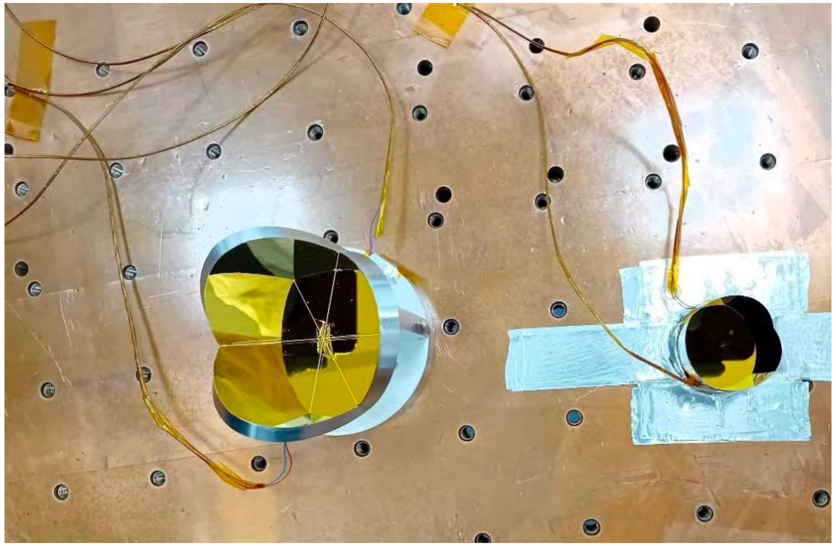
HCCR TVT Qualifications

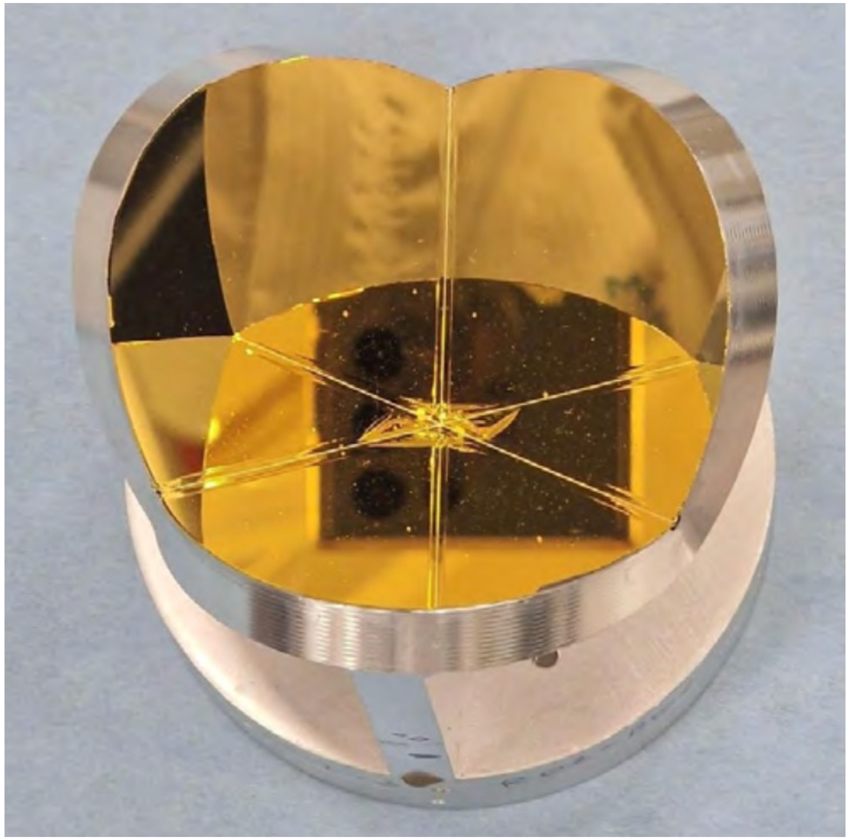
- HCCR with DAOs = **(1.3”, 1.3”, 1.7”)**
- 4 Thermal Cycles [-60,+50]°C.
- 4 Thermal Cycles [-70,+60]°C.
- Limited delamination along the edges. Delamination does not affect the wavefront error of the HCCR, the optical performance.



HCCR TVT Qualifications

- HCCR with DAOs = **(2.9”, 2.4”, 2.5”)**
- 4 Thermal Cycles [-73,+77]°C.
- Delamination in the inner part creates deformations on HCCR surface.





Results, lessons learnt

1) Reason for delamination can be related to air trapped in the glue developed during the gluing process after the centrifugation.
2) Media Lario believes that this unwanted effect is not a limit of their Repli-formed Optics™ technology, at least in the TVT range [-70,+60] C.
3) The delamination is rather an event that happened specifically for this application, for the reason n. 1 above.

Conclusions (1)

- The project has demonstrated that an HCCR can be produced using the Repli-forming™ method. This process offers several significant advantages over traditional methods, including faster production times, reduced costs, and improved angular precision, but a few challenges have been found.
- Validating the 0.3 arcsecond accuracy of DAOs has required an independent metrological validation (by the INRIM metrology institute of Turin, IT). A higher multiplicity of HCCR prototypes with independent metrological confirmation is needed before making this technology usable for applications such as satellite PNT.
- Earth-Moon distance measurements are not accessible until an HCCR with 4 inch diameter can be realized (2.8 inches was produced).

Conclusions (2)

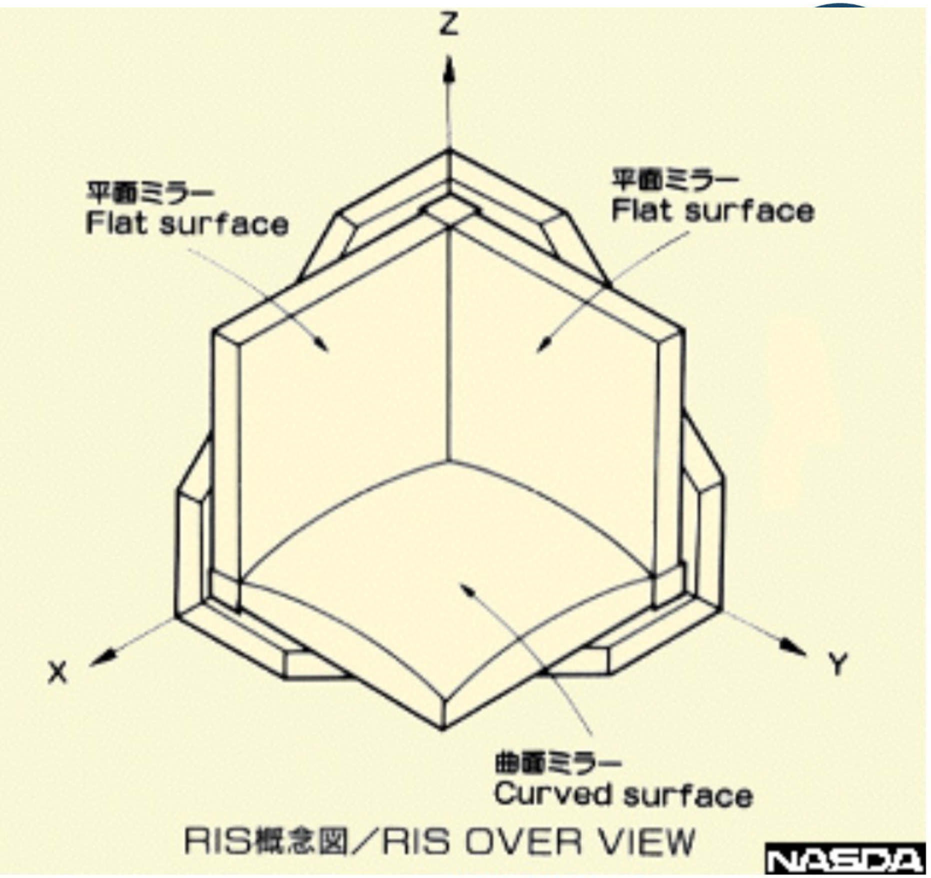
- The mechanical stability of the realized HCCRs needs to be improved by modifying the base of the optics and the design of the interface to the s/c. Specifically, the mechanical interface should be developed not to introduce mechanical strain on the reflecting mirrors.
- Finally, the lunar thermal environment is not within reach of the Repli-forming™ technology, but less challenging space environments should be proposed.
- HCCRs of large diameter continue to be very challenging.
- For the mass-saving potential: see final slides and in particular slide 27.

Other HCCR realizations: first, HCCRs used inside satellites

- **PLX Inc in the USA** sells commercial HCCRs up to 5 inch diameters, made with a proprietary technology (including ‘glue-like’ bonding from what we tested). Outside the US it sells only HCCRs with DAO = 3 x 0.0”. About 12-13 years ago we tested extensively an HCCR of 1.5 inch diameter in realistic space solar-thermo-vacuum conditions (equivalent of many GNSS orbits) for ASI, for potential application to Galileo FOC3. But the HCCR was deformed in an anelastic way. Option discarded quickly in favor of the solid CCR technology currently chosen for G2G.
- PLX HCCRs have been successfully deployed for missions to Mars and Venus, in optics systems located inside satellites and for internal alignment purposes. As far as we know they have not been used as optics exposed to outer space for Satellite/Lunar Laser Ranging.
- An example in EU is MTG, which uses a large HCCR made by **TSESO in France**, manufactured under contract with ESA.
- Of course these HCCRs passed the mechanical qualifications for their space missions, and TVac qualifications as well.
- But they operate in benign thermal environments since they are NOT space-exposed.

Other HCCR realizations: ADEOS-1

- ADvanced Earth Observing Satellite 1 (ADEOS-1) "MIDORI", of JAXA. launched in August 1996. Lasted 1 year, of 3 foreseen
- The [Retroreflector In-Space (RIS)]() is a single hollow corner cube structure with an effective diameter of 50 cm. A spherical mirror with a very small curvature is used for one of the three mirrors forming the corner cube, to optimize the ground pattern of the beam reflected by RIS on ADEOS-1, which moves with a velocity of 7 km per second. In the RIS experiment a infrared laser beam is transmitted from a ground station, reflected by RIS, and received back at the ground station. The absorption of the intervening atmosphere is measured in the round-trip optical path. The column contents and the vertical profiles of atmospheric trace species are obtained from the measured spectra.
- On the ILRS website there are **no Satellite Laser Ranging data.**



Courtesy of JAXA/EORC

HCCRs for Tianqin, LLR, Queqiao-1

- Two Chinese papers on 100mm and 170mm HCCRs made with the **HCB** (Hydroxide-catalysis bonding) technology.
- For the 100mm (below), see the four-step fabrication: solid CCR is *green; g*lass panels of the hollow CCR are *transparent;* glass block used to bond is *blue*. ‘i’ and ‘ii’ are the bonding surfaces.

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Research in Astronomy and Astrophysics

Manufacture of a hollow corner cube retroreflector for next generation of lunar laser ranging

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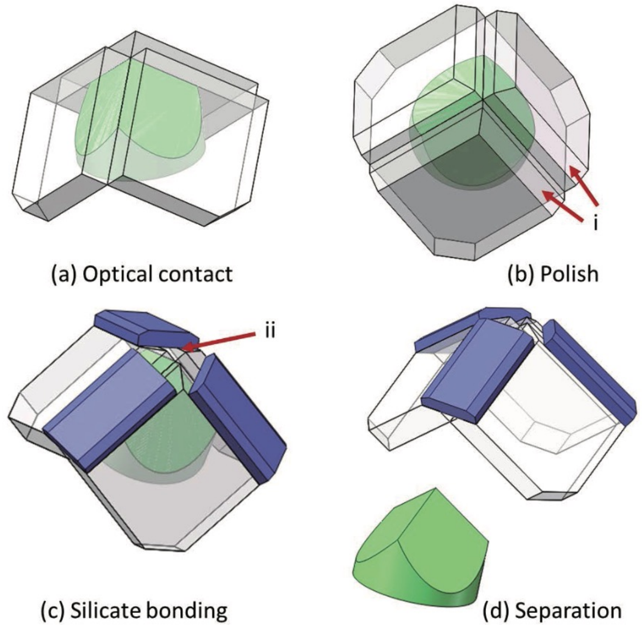

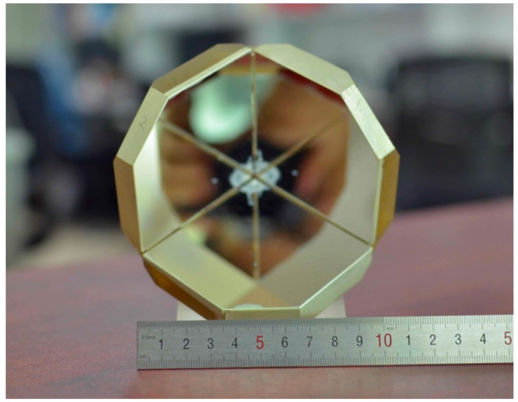

Fig. 3 A prototype hollow CCR with 100-mm aperture.

HCCRs for Tianqin, LLR, Queqiao-1

- Two Chinese papers on 100mm and 170mm HCCRs made with the **HCB** (Hydroxide-catalysis bonding) technology.
- For the 100mm: TVT done, 18.5 cycles (~5 days).

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Research in Astronomy and Astrophysics

Manufacture of a hollow corner cube retroreflector for next generation of lunar laser ranging

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Table 2 Dihedral angle measured for the master CCR and hollow CCR before and after the thermal test. All values are reported in units of arcsec. The values in parentheses correspond to the angle across the beam stop (Burke et al. 2005).

		Angle 1	Angle 2	Angle 3
Master CCR		0.27	0.31	0.39
Hollow CCR (before)		0.5	0.8	1.9
Hollow CCR (after)	Six Measurements	0.38	(1.17)	1.98
		0.42	(1.30)	1.99
		(0.14)	0.92	2.22
		(0.26)	1.11	2.04
		0.43	0.90	(2.59)
		0.32	1.09	(2.16)
	Average	0.39	1.00	2.06

HCCR for LLR and Queqiao-1

- Two Chinese papers on 100mm and 170mm HCCRs manufactured with the **HCB** (Hydroxide-catalysis bonding) technology.
- In the case of 170mm two autocollimators are used to fix the 3rd face.
- My (SD) personal communications with Chinese researchers: the 170mm HCCR has been deployed on the lunar relay satellite Queqiao-1 of CNSA (launched in 2018), in a halo orbit around L2.
- **But it has never been observed by lasers.**

Chin. Phys. B Vol. 27, No. 10 (2018) 100701

Development of a 170-mm hollow corner cube retroreflector for the future lunar laser ranging*

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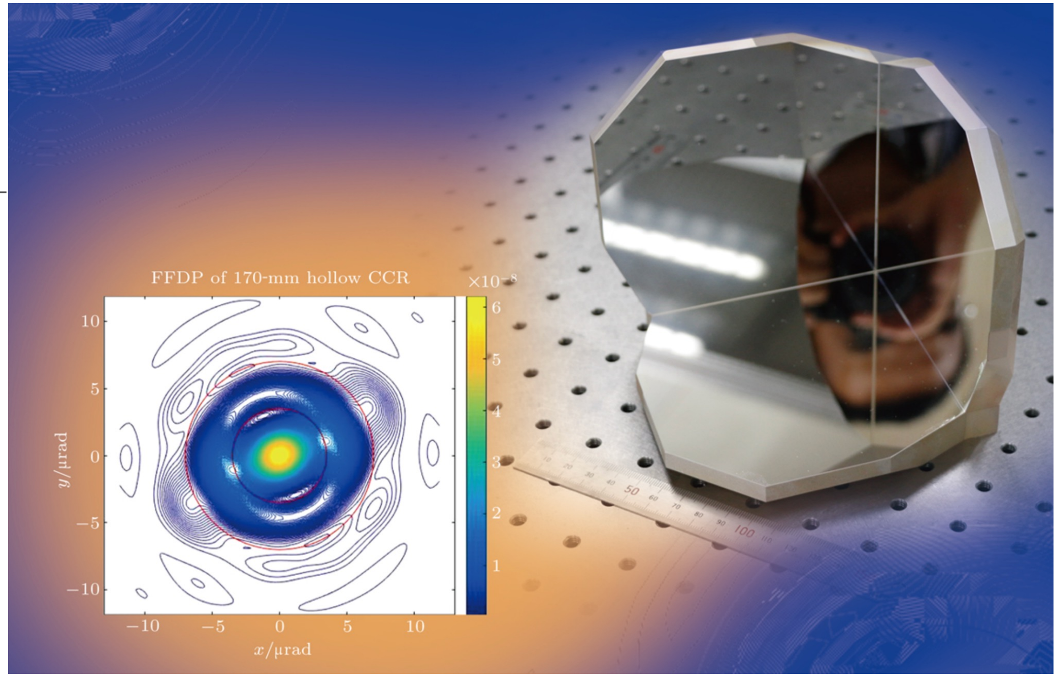

Prospects for further development

- To our knowledge (INFN's) there are no HCCRs that operate/d in space.
  But this knowledge should of course be constantly verified / challenged.
- If a single good-working HCCR is realized, then solutions to build arrays can be found. Basic one: mount multiple HCCRs on a base plate.

- Mass-saving seems an attractive advantage for single HCCRs, which is the natural choice for Lunar Laser Ranging, with diameters ≥ 100mm. In fact, a single solid CCR of 100mm has a naked mass of ~600 gr. Its support frame may have a similar mass.
- Also note:
  - Chinese papers do not quote a mass of their prototypes of single, large HCCRs; why?
  - Their 170mm HCCR was never observed in Moon orbits.

Prospects for further development

- When building arrays, typically of H/CCRs with diameters much smaller than 100mm (4 inches), ½ inch to 1, 1.3, 1.5 inches, the total mass-saving advantage may not be clear. Some arguments:
  - The solid CCR mass decreases quickly with the 3rd power of the diameter. A solid ½ inch CCR has a mass of ~1 gr
  - The mass of the same diameter HCCR may not scale down like that
  - Smaller, naked solid CCRs can be all integrated (for example glued) on the same mechanical frame
  - It depends on the number N of H/CCRs needed for a given space orbit/destination
  - Given how HCCRs are being designed/realized now, the array mass would be:
    - (Single HCCR mass) x N + (Baseplate mass)
- To assess the mass-saving potential for the case of an array, a careful, maybe dedicated, trade-off has to be performed.

Prospects for further development

- Realizing a good-working single HCCR remains the challenge.
- Optical challenge: with this project, and from other HCCR realizations, one can see that there are technically viable solutions. DAO accuracy 0.3” is difficult by doable, and not the real problem.
- Mechanical challenge: yes, still a challenge. This project did not give the desired mechanical stability, but this may be overcome with a focused study/work.
- TVac challenge: the full space environment seems the ’brick wall’ that affected:
  - ADEOS-1
  - PLX commercial 1.5 inch (ASI-INFN testing)
  - Queqiao-1
  - This project.

Prospects for further development

- What strategy for a potential, further HCCR development?
- Include more than one HCCR technology (not too many, but >1):
  - Media Lario (evolution / improvement)
  - TSESO (new dedicated product?)
  - …
  - Take existing commercial HCCRs (typically DAO = 3 x 0.0”, different diameters) and just expose it/them to realistic space qualifications. If these are passed, then evaluate with makes the scaling of the diameter and variation(s) of the DAOs.
  - We tested a commercial one, that we call “HCCR Benjamin”, <u>1.5 inch only,</u> from Newport that passed:
    - the TVTs with HCCRs of this project
    - plus a recent TVT [-140,+140]C, 4 cycles
    - More severe low T test is underway.