New Optics for SEPIA- Heterodyne Facility Instrument for the APEX Telescope

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***Abstract* — The design of SEPIA (Swedish ESO PI Instrument for APEX) was driven by the idea of using ALMA receiver cartridges on the APEX telescope. SEPIA was installed at the guest position of the Naismith cabin A, APEX telescope in early 2015. The SEPIA cryostat and optics was designed to accommodate up to 3 ALMA cartridges. In 2017, the APEX facility instrument SHeFI was decommissioned and SEPIA was accepted as its successor. Moving SEPIA from its PI into Facility Instrument position brought additional constrains due to the severe limitations of the available space. That had led to the necessity of complete redesigning of the SEPIA tertiary optics. During February-March 2019, the new tertiary optics was installed in the APEX Cabin A and SEPIA was placed at its final Facility Instrument position. Here, we present the details of the optical design, layout of the optical component placement, the beam alignment technique, the results of the alignment and SEPIA technical commissioning results at the APEX telescope.**

***Index Terms*—Radio astronomy, Radio-wave propagation, Mixers, Receivers, ALMA, APEX, SEPIA Instrument, Gaussian optics.**

I. INTRODUCTION

THE initial idea with the implementation of ALMA cartridge receivers at the APEX telescope was inspired by the interest of the ESO astronomical community to the future observations with Band 5 [1] at ALMA (started in 2018). This idea transformed into the SEPIA [2] (Swedish-ESO PI Instrument for APEX), a mutual project of the GARD, OSO and ESO. SEPIA project was started in the beginning of 2014, and during February 2015 SEPIA was installed and commissioned at the APEX telescope with modified ALMA Band 5 pre-production receiver and updated with ALMA Band 9 [3] in February, 2016. For SEPIA Band 9, GARD provided receiver infrastructure and optics.

SEPIA receiver was designed initially as a PI instrument, dedicated for the installation at guest position of the APEX Nasmyth cabin A and accommodate up to 3 receiving channels, compatible with the ALMA receiving cartridges Bands 5-10. In 2017, the APEX facility instrument SHeFI [4] was decommissioned and SEPIA was accepted as its successor.

Moving SEPIA from its PI into Facility Instrument position brought additional and severe space limitations constrained by the support structure, the facility calibration load unit and requirements for the optical path clearance for the PI instruments, located at the left and right sides of the facility instrument position. That had led to the necessity of the complete redesigning of the SEPIA tertiary optics. The new optics was designed and parts were manufactured in 2018 and SEPIA was installed onto its new position in February-March 2019

II. OPTICS DESIGN

The SEPIA optics design implements frequency-independent illumination of the secondary for all receiving channels with edge taper aiming around -12 dB. To fulfill this condition within the entire working frequency range (159-722GHz) [2], the complete optical path works as a re-imaging system, transferring the image of the secondary onto the aperture of the corrugated horn for each receiver channel. Table I and Fig 1 represent the entire SEPIA illumination path through the Nasmyth and Cassegrain cabins.

The new SEPIA optical design based on the system of equations describing a 2-mirror refocusing optical system [5], derived from the ray transfer matrices for Gaussian beams. The design was performed with the assumption of the mirrors rims sizes of 5 beam waists. The actual optics layout (Fig.2) employs individual active channel mirrors (NMA2-1, NMA2-2, NMA2-3) together with the common active mirror (NMA1). Along with the existing Nasmyth Cabin A tertiary optics, the new optics accommodate the input beams of the SEPIA receiver cartridges to the APEX antenna. Compared to the previous variants of the optical layout, the first common active mirror (NMA1) is located in the vicinity to the Instrument Selection Mirror (NMF1), which allowed to accommodate all elements of the receiver, including the channels' optics in the space inside Flexlink support frame in the middle of the APEX Cabin A, dedicated for the Facility Instrument (Fig.2, Fig.5).

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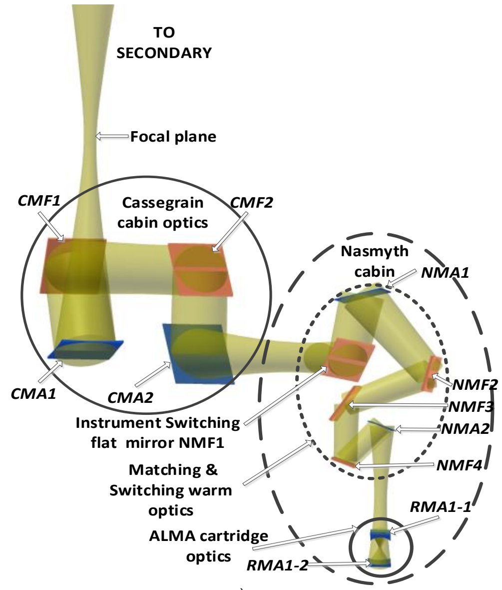

Fig. 1. The 3D CAD model of the total SEPIA optics path.

TABLE I
SEPIA TOTAL OPTICS LAYOUT

	Element's Tag	Distance (mm)	Focal distance (mm)	
	Cassegran cabin optics			Common optical path
	Focal plane	5882.86*	-	
	CMA1	750 (6632.86)**	700	
	CMF1	361.86	Fold Instrument Selection Mirror	
	CMF2	1838.14	Fold Mirror	
	CMA2	300 (2500)**	1800	
		1764.2	Fold Mirror	
	Nasmyth cabin warm optics			
	NMF1	400	Fold Mirror	
Modified optics layout	NMA1	234.30 (2398.5)**	760	
	NMF2	369.23	Fold Mirror	
	NMF3	304.34	Fold Mirror	
	NMF4	205.18	Fold Channel Selection Mirror	
	NMA2-1 NMA2-2 NMA2-3	234.85 (1055.77)**	295.66	Individual channel optical path
	Receiver position 1 Cold optics ALMA Band5			
	RMA1-1	500	67.192	
	RMA2-1	140	32.756	
	Horn1	60.05	(60.17/9.0)***	
	Receiver position 2 Cold optics ALMA Band7****			
	RMA1-2	498	60	
	RMA2-2	133.78	30.41	
	Horn2	52.04	(20.46/6.9)***	
	Receiver position 3 Cold optics ALMA Band9			
	RMA1-3	446.2	39.41	
	RMA2-3	95.9	24.86	
	Horn3	44.48	(15.72/5.07)***	

*- distance from the telescope secondary mirror
**- unfolded distance between active mirrors
***- horn's parameters (slant length/ aperture diameter)
****- cartridge optics designed in GARD, compatible with the existing Band 7 ALMA front-end optics

The flat Channel Selection Mirror (NMF4) is used to switch between the bands. Each frequency band has individual adjustable active mirror (NMA2-1, NMA2-2, NMA2-3) and a set of mirrors that form common optical path. As a consequence of the space constraint, we had to use several additional flat mirrors (NMF2, NMF3, NMF4) to fold the beam inside the allocated space. The picture (Fig.5) shows actual placement of the SEPIA in the APEX Cabin A.

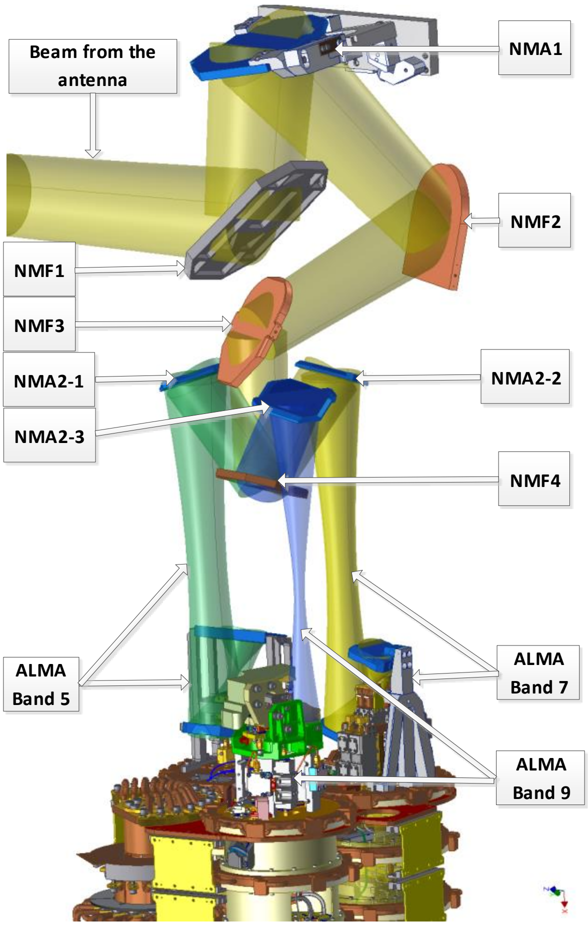

Fig. 2. The 3D CAD model of the new layout of the SEPIA instrument at the Facility Instrument position. NMF1-Switcing mirror between PI and SEPIA instruments; NMA1 – active adjustable refocusing mirror, NMF4 - Channel switching mirror; NMA2-1, NMA2-2, NMA2-3- Individual channel refocusing mirrors NMA2; ("ALMA Band 5"; "ALMA Band 7"; "ALMA Band 9")- ALMA receiving cartridges.

Verification of the optical system using the GRASP program [6], confirmed the required parameters of the illumination system, (Fig3,4) As a feed, Gaussian beam, matched with the horn parameters was implemented. Special attention was paid to the level of cross-polarization losses and optical distortions in the optical system, generated by reflections from off-axis mirrors. Compare with the initial layout, modified optical system employed mirrors with smaller F/D parameters, and large incidence angles; it was a compromise, allowed to compact optical layout. Estimation was made with the Murphy formulas [7] (1), (2), based on the parameters of the beam radii at the mirror (w_{beam}), the focal length (f), and incidence angle (i).

$$P_{cross-pol} = {}^{1}\!/_{8} \cdot \left({}^{w_{beam}}\!/_{f}\right)^{2} \cdot \tan^{2} i \qquad (1)$$

$$P_{distortion} = {}^{1}\!/_{4} \cdot \left({}^{w_{beam}}\!/_{f}\right)^{2} \cdot \tan^{2} i \qquad (2)$$

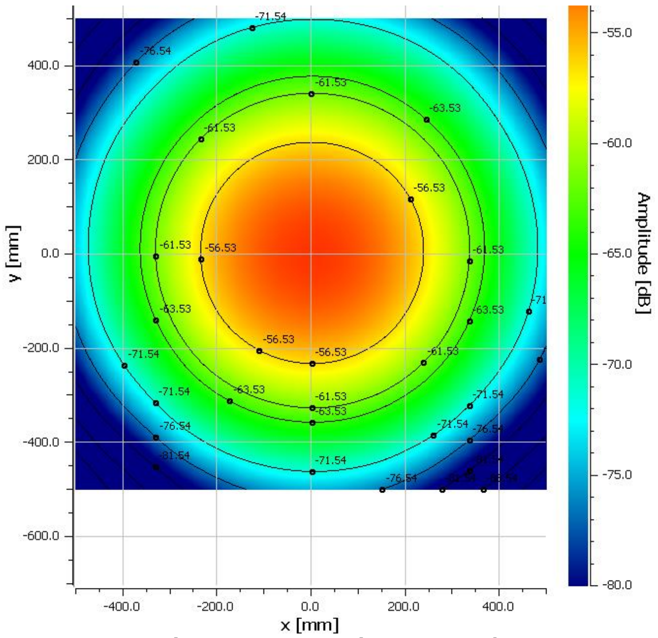

Fig. 3. GRASP simulation 163GHz, Co-pol component at the APEX secondary mirror.

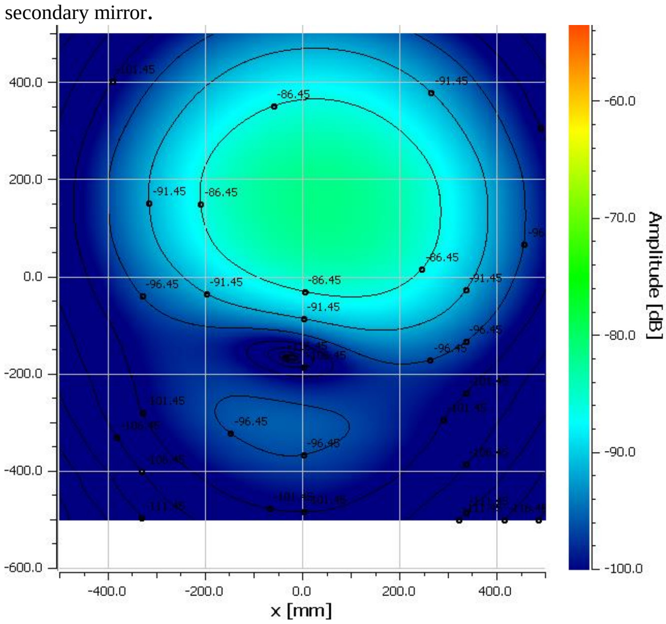

Fig. 4. GRASP simulation 163GHz, X-pol component at the APEX secondary mirror.

Our simulations using GRASP physical optics software package (Fig.4, 5) confirm that the integral level of the cross-polarization losses along the entire optical system, from the horn to the secondary mirror, which included 6 active mirrors and 4 flat mirrors was less than -23 dB.

III. Optics fabrication, Alignment and Installation

The entire SEPIA optics unit was built at GARD workshop in house. Before shipping the optics to the telescope, all optical components were pre-aligned in the lab using a laser placed at the optical central axis. To facilitate the laser-assisted alignment the mirror's surfaces was additionally polished at their central area to provide sufficient reflectivity. During the alignment procedure, the laser was placed in the position of the axis of the input beam. for each respective frequency channel. The pre-aligned optics unit then was shipped and installed at the telescope.

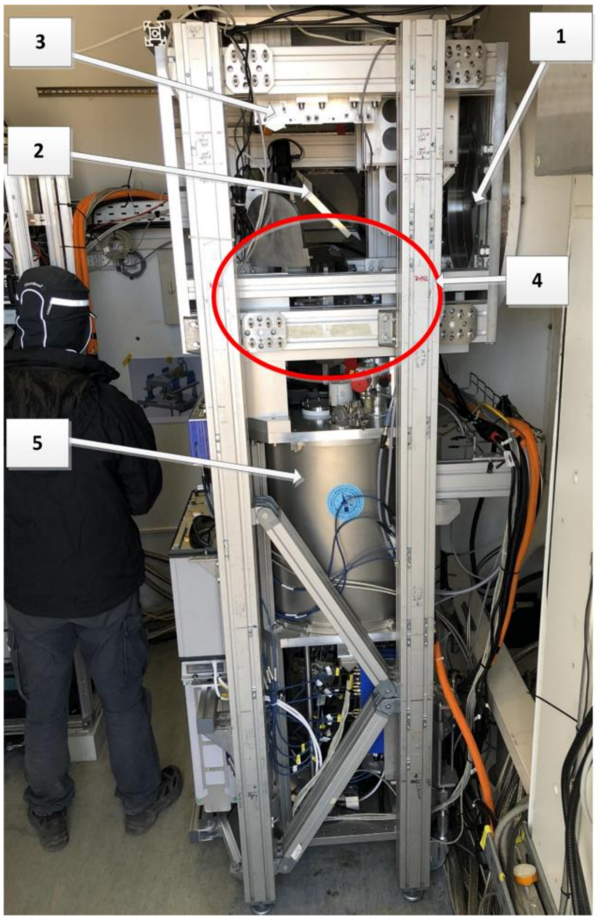

Fig. 5. SEPIA receiver installed in the central position;1- Nasmyth flange, Cabin A; 2- Instrument Selection Mirror (PI or Facility Instrument);3- SEPIA Active Top mirror support bracket; 4- SEPIA New Optics; 5- SEPIA Receiver.

Total alignment and installation procedure at the telescope included 3 steps. At the first step (Fig. 6) the laser was installed in the Cabin A Nasmyth tube (the position of the input beam axis). A position sensitive device (PSB) was attached to the SEPIA optics unit frame using temporary mechanical centering and alignment structures and the entire optics frame was aligned using the laser beam as a reference while placing the PSD in the three firmly arranged positions along the optical axis of the input beam inside the optics unit as depicted in the Fig. 6. Using the PSD sensor installed in these different positions and iterative adjustment of the entire optics frame, we achieved alignment accuracy at the level of a fraction of millimeter.

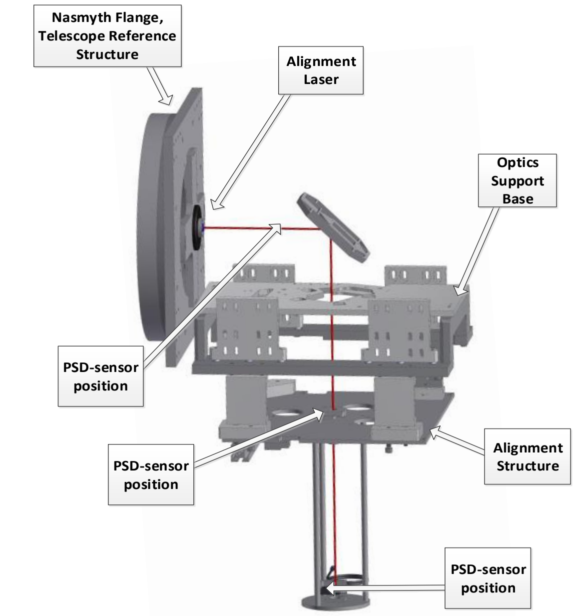

Fig. 6. Laser alignment during the optics installation at the telescope. Step1.

At the second step (Fig. 7), after the Optics unit frame was installed and aligned, the optics components that was temporary removed could be integrated back into the Optics unit, and its alignment verified, and if necessary, corrected using the laser with procedure similar to what we used in the lab and as shown in the Fig. 7.

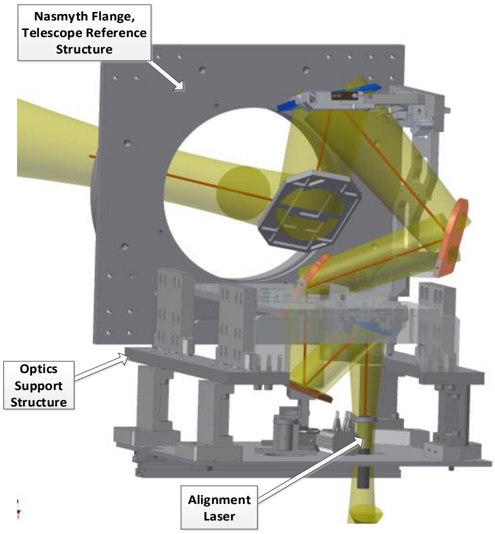

Fig. 7. Installation procedure at telescope. Step2

At the third step, the SEPIA receiver was attached to the new Optics unit. Using a cold load (77K) and a warm load (300K), the RF beams of the Band 5 (SEPIA180) and the Band 9 (SEPIA660) was then checked and fine-tuned with the individual channel adjustable mirrors NMA2 for best pointing.

IV. Commissioning

In the spring of 2019, the installation of the new optics and the SEPIA receiver were completed and commissioning was conducted via set of verification observations with the SEPIA receiver installed into the Facility Instrument position.

The *SiO* maser observation of *R Dor* at 171 GHz was used for the SEPIA180 verification procedure [8]. The *SiO* maser emission is essentially a point source and thus the map depicts the beam shape. Results of observation (Fig. 8, Fig. 9) demonstrated good quality beam shape down to 2% (below 2% the noise starts to show up). The contour levels start at 2% and end at 20% of peak value at the center. The (Fig. 9) show the radial cross-section of the beam pattern for the same data with the Bessel beam fit for illumination tapering of -14 dB. The half power beam width (FHPBW) at 171 GHz estimated as 36.5 ± 0.5 arcsec, which is close to expected value.

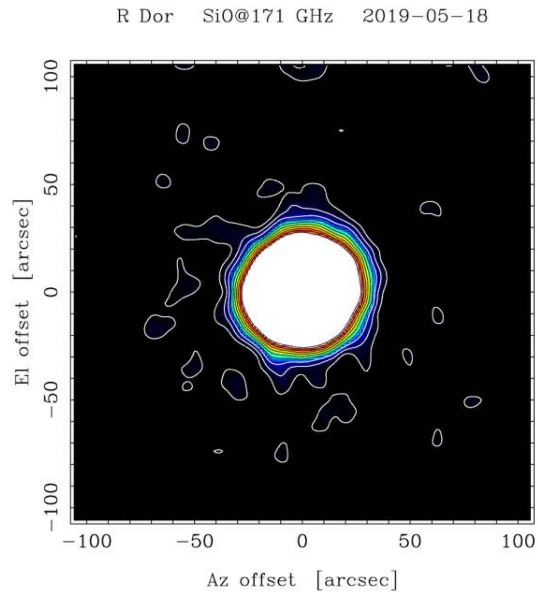

Fig. 8. SEPIA facility instrument position, SEPIA180 tests observation [8]. Beam map at 171 GHz (*SiO* J=4-3 v=2 maser) toward the star R Dor.

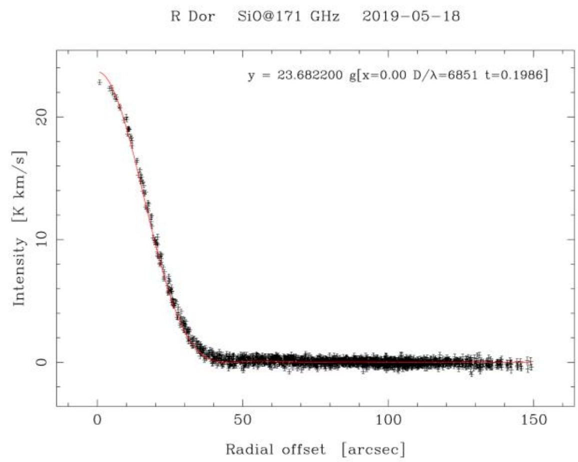

Fig.8. SEPIA facility instrument position, SEPIA180 tests observation [8]. Beam pattern (Fig.7) radial cross-section. Solid line-Bessel fit for the -14dB edge taper illumination.

In addition, the SEPIA180 Neptune measurements at 208 GHz confirmed the value of the antenna efficiency, and found to be consistent and close to the results of previous years. The SEPIA660 passed similar verification procedure [8], based on the source *VX Sgr* water line observation as depicted in Fig. 10,

Fig. 11.

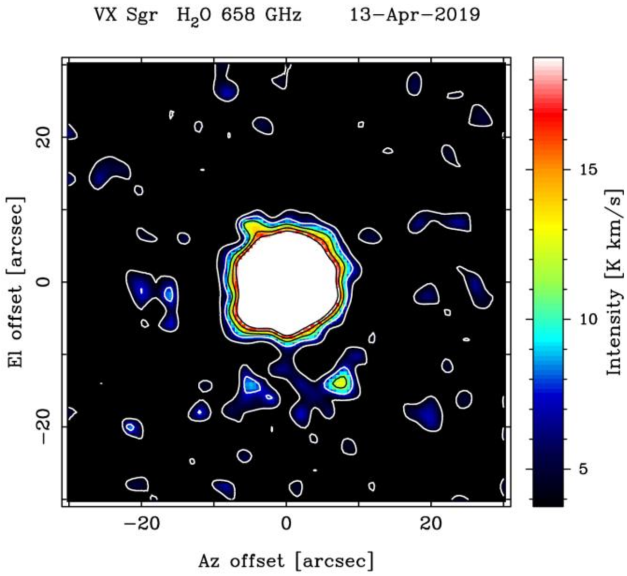

Fig. 9. SEPIA facility instrument position, SEPIA660 tests observation [8].

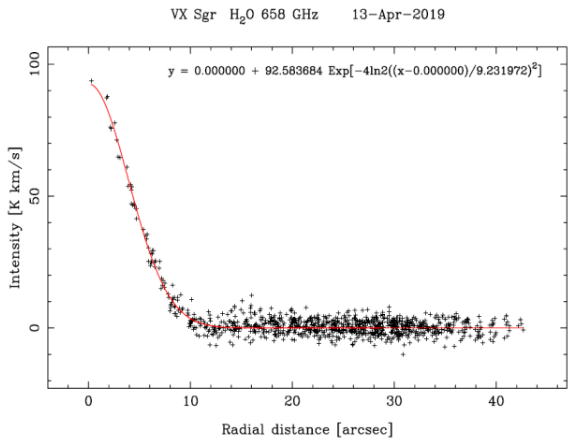

Fig. 10. SEPIA facility instrument position, SEPIA660 tests observation [8]. Beam pattern (Fig.9) radial cross-section. Solid line-Bessel fit for the -14dB edge taper illumination

V. Conclusion

At the time of writing this manuscript, the SEPIA receiver is fully operational, commissioned and actively used for observations with its both bands, the SEPIA180 and SEPIA660.

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