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Physics Anecdotes and Personal Recollections (31)

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Earth Observation

Figure 1 shows an application of modern remote sensing, where the earth's surface has to be optically observed and recorded. To this purpose the instrument's carrier, either an airplane or a satellite, is equipped with an optical system, described by its focal length *F* and F-Number *F#*, together with a 1D-CCD array of *N* pixels. Both airplane and satellite move perpendicular to the sensor line, and flight speed and the readout time of the CCD are adjusted so that the earth surface it seamlessly covered line by line (Pushbroom method). Let's assume that the same CCD sensor with N = 30,000 pixels and a pixel size of 7 μm is used in both cases, and that we ask for optical systems with a $F\#$ = 4 due to radiometrical reasons. In both cases a ground pixel should be 25 cm, which corresponds to a swath width of 7.5 km.

Figure 3: Herschel telescope with EP diameter of 3 m. On the left a Leica laser tracker for interferometric testing

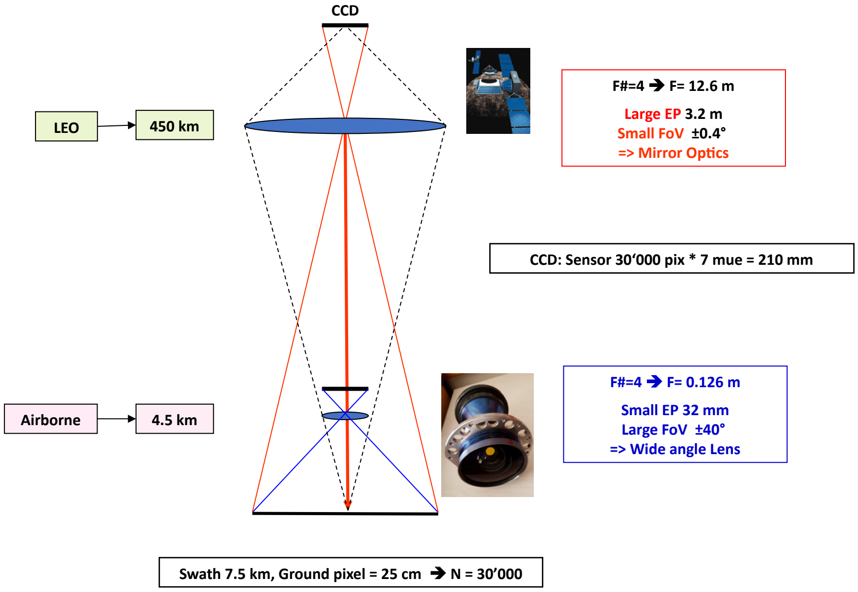

Figure 1: Earth observation with a small wideangle lens or a large mirror telescope

Then for a flight altitude of 4.5 km of the airplane, an optical system with a focal length of 12.6 cm, a diameter of the Entrance Pupil (EP) of 31.5 mm, and a large field of view of ± 40° is required. If the same task with the same sensor has to be performed from the satellite orbiting at an altitude of 450 km, one would need an optical system with a focal length of 12.6 m, an EP diameter of 3.15 m, but a very small field of view of only ± 0.47°. The consequence is that the large field specification in the case of an airplane carrier can only be fulfilled by a wide-angle lens optic (Figure 2), while in the case of the satellite the large dimensions of the EP require a mirror system (Figure 3).

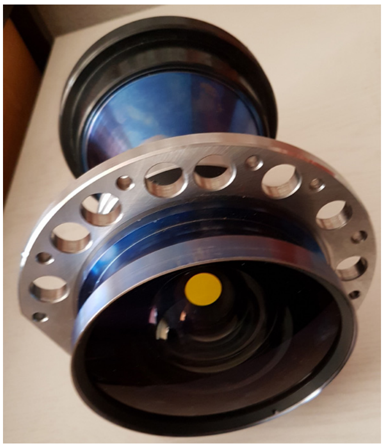

Figure 2: Wide angle lens. The yellow spot indicates the entrance pupil at large field angle

Catadioptric Systems

Permanent efforts were undertaken in history to bridge the gap between both extreme optical layouts, i.e. to look for compact mirror systems with larger field of view. It is clear that then compensation elements must be added to e.g. a normal Cassegrain telescope with a large concave prime mirror M1 and a smaller convex mirror M2 to correct the field dependant spherical, comatic and astigmatic aberrations and also the field distortion.

Nightvision Instrument

This is visualized by the nightvison system BIG35 of Leica (Figure 4), developed in the 90s of the last century, and in use until today worldwide. Its main components are an optical telescope of two spherical mirrors and a light amplifier placed in the image plane to increase the incident light intensity by a factor 10^4. Its display screen is observed by two eyepieces. The focal length is 75 mm, $F\#$ = 1 and the full field is about 13.6°. This large field is only possible by inserting two correction groups, first by both large entry lenses acting similar as a Schmidt plate of weak optical power, and second by an objective of two cemented lenses to correct the chromatic and the remaining field aberrations. The MTF functions in Figure 4b show that the objective performs nearly diffraction-limited up to 70 lp/mm within the full field of view.

Large Field optical systems in Astronomy

Technical advances in astronomy are leading to ever larger image sensors and thus enable optical telescopes with larg-

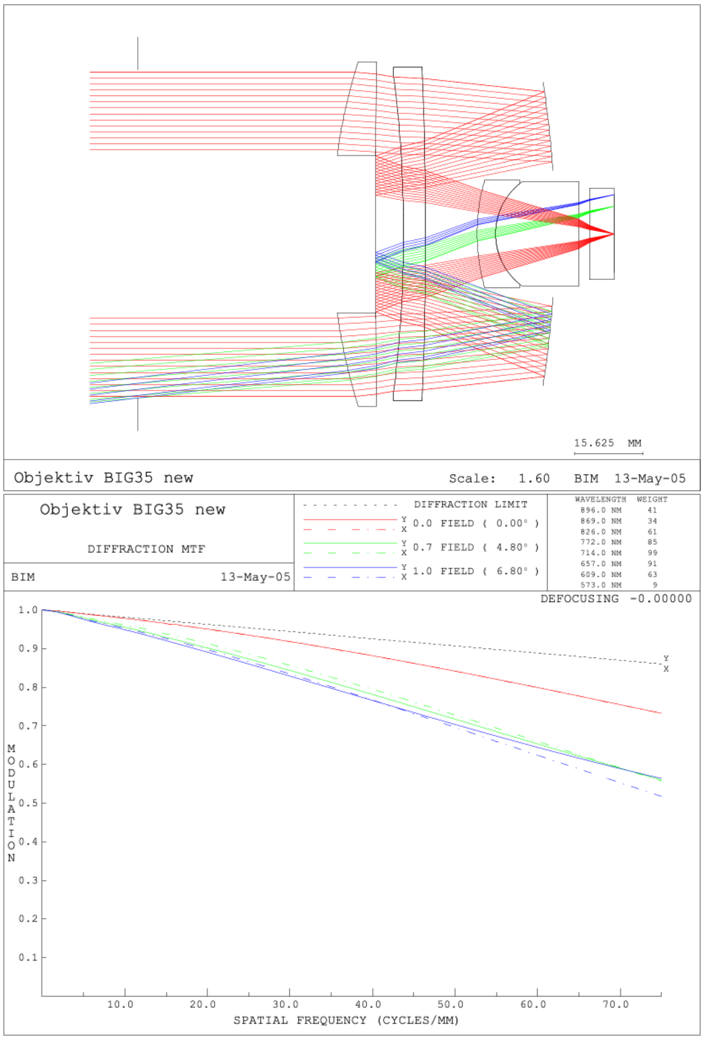

Figure 4: Catadioptric design of the Leica nightvision instrument BIG35.

er fields of view. As shown before, the greater wide-angle capability requires more design effort, especially if the telescopes must still be very fast with $F\# = 1$ and as compact as possible for stability reasons. Then the number of large mirror elements at the EP side, i.e. at the input-side, could be increased to three mirror elements, all mirrors are aspherical, and additional lens elements must be placed near to the sensor plane to correct the aberrations at larger field angles.

The Vera C. Rubin Observatory

This is impressively demonstrated by the *Vera C. Rubin Observatory*[1] (Figure 5). The telescope will be located on the 2682 m high El Peñón summit of Cerro Pachón in northern Chile. The Rubin Observatory differs from other telescopes of this size due to its *large field of view diameter* of 3.5°. It is expected to detect around 10 billion stars and 10 billion galaxies. Scientific goals are the measurement of weak gravitational lenses to find dark energy and dark matter; the mapping of small objects in the solar system, in particular near-Earth asteroids and objects from the Kuiper Belt; the observation of short-lived events such as novae and supernovae and the mapping of the Milky Way[2].

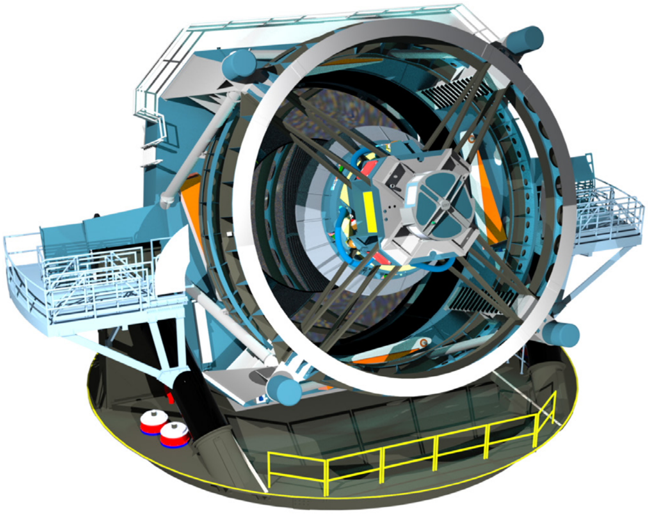

Figure 5: Rubin Telescope

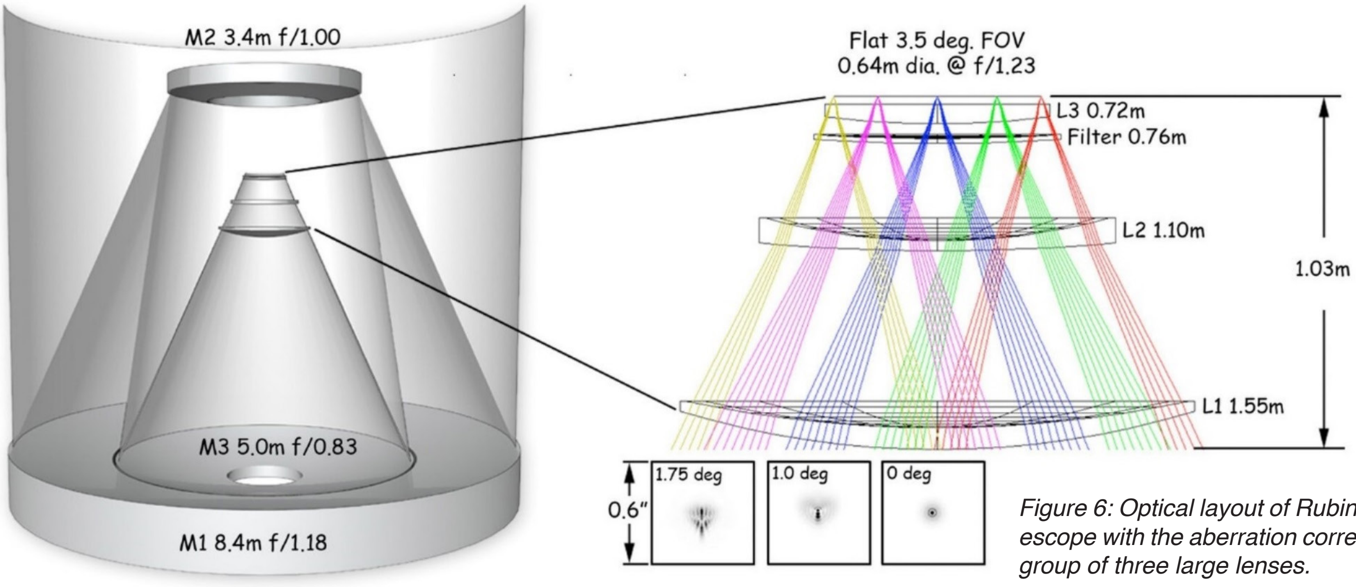

Figure 6: Optical layout of Rubin telescope with the aberration corrector group of three large lenses.

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[1] https://rubinobservatory.org/

[2] Vera Rubin, whose career began in the 1960s, faced a lot of barriers simply because she was a woman. She balanced her work with raising children at a time when most women just didn't do that. She persisted in studying science when her male advisors told her she shouldn't. And she insisted on observing at facilities that had never allowed women to observe there before. Her strength in overcoming these challenges is admirable on its own, but Vera worked even harder to help other women navigate what was, during her career, a very male-dominated field. https://rubinobservatory.org/explore/vera-rubin

The telescope consists of three large mirrors. The parabolic primary mirror ***M1*** has a diameter of 8.4 m and includes as inner zone the tertiary mirror ***M3*** with a diameter of 5.0 m. Above ***M1/M3*** is the secondary mirror ***M2*** with a diameter of 3.4 m. A three-lens corrector sits in front of it. The largest lens has a diameter of 1.55 m (Figure 6). The folding concept and the single piece construction of ***M1*** and ***M3*** lead to a very compact and stable system. Various color filters can be inserted into the lens corrector in order to examine certain spectra from near ultraviolet to near infrared with wavelengths in the range of 0.3 to 1 μm. The optics is 'fast', i.e. with $F\# = 1.23$. Using ***M1*** as entrance pupil leads to focal length $F = 8.4$ m / 1.23 = 10.36 m. The detector format employs a mosaic of 21 "rafts" of 3 × 3 CCDs with 4 kpixels, providing a total of about 3.2 Gpixels. With a pixel size of 10 μm, the diameter of the detector field is 5 rafts or 634 mm, corresponding to a FoV of 3.5°. The spatial resolution is (10 μm / F) = 1 μrad or 0.2 arcsec. The camera includes a filter-changing mechanism and shutter. It is the largest digital camera ever planned, weighting around 2.8 tons, but measuring only 3 m in length and 1.6 m in diameter.

Vera Rubin, American astronomer who established the presence of dark matter in galaxies, measures spectra in the 1970s.

Photo courtesy of Vera Rubin © 2000 American Museum of Natural History.

The Rubin telescope generates raw data volumes of up to 30 Tbytes per night and around 6000 Tbytes per year. This volume of data can only be effectively analyzed with the help of automated data processing pipelines. Thereby new CCD images are compared with archived photos of the same sky position within 60 seconds of observation. The pipeline includes supercomputing centers in the US and France which will produce updates of calibrated data sets on a daily and yearly basis. An excellent summary of concept, design and scientific goals of LSST is presented in [3]

Measurement Problems

However, the larger field of view also requires more data processing efforts. Modern telescopes measure permanently the incoming wavefront to deform the surface of a small mirror element for wavefront compensation. The algorithm must be extended with larger field of view to compensate the longer optical pathways through the atmosphere. Another reason for more processing effort is that wide-angle telescopes register more new types of optical distortions resulting from fleets of mini-satellites, which are increasingly corrupting the sensitive measurements.

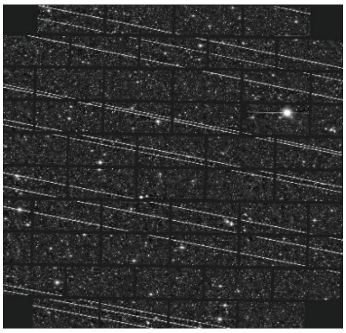

Figure 7: Traces of a satellite flotilla

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[3] R. Ansari and C. Doux, "Vera Rubin Observatory and LSST", *Europhysics News*, **55**/5, 2024, Special Issue: "Probing the Universe". DOI: *https://doi.org/10.1051/epn/2024511*

Impact of Satellite Flotillas on Astronomical Observations

The plans of commercial operators to cover space with an armada of satellites (Figure 7) are threatening to science. Astronomy is striving to produce sensitive telescopes with sophisticated technology and great effort, with which it can then gain knowledge beyond anything previously imagined. Instead, it now runs the risk of being unnecessarily concerned with the detection of artifacts and their elimination. While the visual distortions can be removed by image processing, the main problems are that the bright reflections lead to saturation, crosstalk and blooming effects on the very sensitive CCD sensors and lower their performance. It is difficult to find political solutions since the space above a state territory is not part of the territory, i.e. it is free territory for personal interests. Here, the community of states should try to find solutions similar to the regulations of sovereignty on the seas. Proposed means such as painting the satellites black is surely not a convincing solution in the infrared spectrum [1].

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[1] *https://www.lsst.org/content/lsst-statement-regarding-increased-deployment-satellite-constellations*