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HOW TO DESIGN A FULL DISK TELESCOPE FOR SPRING

WORK-PACKAGE (DELIVERABLE NR)

WP8: SOLAR PHYSICS RESEARCH INTEGRATED NETWORK GROUP

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SUMMARY

In this document we describe the general considerations which may lead to a valid full disk telescope design for SPRING. The focus is on the logical order of thoughts starting with the science requirements. During the overall design process certain decisions have to be made. These are discussed in this paper. In the end compromises between feasibility and science requirements will be necessary.

Application of the strategy described in this paper and the detailed design will be presented in subsequent documents.

LIST OF ABBREVIATIONS

ADU	Analog to digital unit
AO	Adaptive Optics
DKIST	Daniel K. Innouye Solar Telescope
EST	European Solar Telescope
FWHM	Full width at half maximum
GONG	Global Oscillation Network Group
MCAO	Multi-Conjugate Adaptive Optics
SPRING	Solar Physics Research Integrated Network Group

1. INTRODUCTION

Solar astronomy started as full disk observations after the invention of the telescope and remained like this until the end of the 19th century. With the ground-breaking solar telescopes at Mt. Wilson the era of high resolution solar physics began with the pioneering works of Hale and others. Full disk observations then were mostly used for monitoring solar activity. Maps of the Sun in white light, H-alpha and CaK were the classical products. Still in the 1970s hand drawn maps were produced and still today these archives are used to investigate properties of the solar cycle.
But most solar physicists were on the quest for ever better spatial resolution which necessarily led to small fields of view. Only few sites on earth could provide the needed good seeing to achieve resolution of better than 1 arcsec over a significant amount of time. With the appearance of Adaptive Optics diffraction limited resolution was in reach and the development of large solar telescopes which can take advantage of this technology made sense. DKIST and the EST-Project are the state of the art telescopes of this kind.
But with Adaptive Optics only a small field of view can be corrected, and the detector resolution also limits the field of view. In the end the largest telescopes (D = 4 m) yield the smallest fields. Even with multi-conjugate adaptive optics (MCAO) the useful field is in the order of 1 arcmin. This corresponds to only about 0.14 percent of the solar disk!
After the discovery of the then called 5-min-oscillations in 1970s it became clear that the Sun is a complex oscillator and that the internal turbulence excites millions of oscillation modes. The fundamental modes refer to the Sun as a whole and provide information about the otherwise inaccessible deep layers of the solar atmosphere. Helioseismology was born.
Suddenly full disk observations were back. But this time not intensity maps but velocity maps were the product. Not spatial resolution but frequency resolution was in the focus. The ambitious requirement of high frequency resolution corresponds to long uninterrupted time sequences and immediately led to the construction of a world-wide network “where the Sun never sets.”
This network exists since more than 20 years and is extremely successful (GONG).

Nevertheless progress does not stop and for the next generation of a helioseismology network new requirements were formulated.
The most important ones are

- GONG works in one spectral line only. The successor network should observe many lines;
- Spatial resolution should be better than in GONG (4k x 4k);
- Time cadence should be considerably less than 1 minute;
- Full Stokes polarimetry should be possible.

In this document we describe the general lines of thoughts which then may lead to a particular design.

2. DETECTOR CONSIDERATIONS AND DESIGN CONSEQUENCES

2.1 Which S/N do we need?

For a possible successor network of GONG which is called SPRING a couple of requirements were formulated. In this document we use only the most important ones:

1. Pixel resolution shall be 0.5 arcsec
2. Doppler sensitivity shall be < 10 ms^{-1}
3. Magnetic sensitivity shall be < 10 G
4. Time resolution shall be < 10 s to 1 min depending on spectral line
5. More than one spectral line shall be observable.

From the designer's point of view everything boils down to measure the number of photoelectrons in a particular pixel of a particular detector. This is the basic signal. But as always there is noise. In order to fulfill the first four requirements the noise must not exceed a certain value.

In this document we shall concentrate on photon noise (shot noise) where the signal to noise ratio (S/N) is proportional to square root of *N*, with *N* the number of photoelectrons.

2.2 Which S/N do we get? – Photon flux

The primary signal source is the irradiance in the detector plane

$$N_e(\lambda) = F_{solar}(\lambda) \cdot \Delta\lambda \cdot T_{atm} \cdot T_{instr} \cdot \left(\frac{D_{Tel}}{f}\right)^2 \cdot \Delta t \cdot \frac{\lambda}{hc} \cdot A_{Detector} \cdot Q_e$$

N_e is the number of photoelectrons on the detector

F_{solar} :	Solar irradiance outside the atmosphere measured in $Wm^{-2}nm^{-1}$ (e.g. 1.7 $Wm^{-2}nm^{-1}$ in the visible, see Figure 1)
λ:	Wavelength
$\Delta\lambda$:	Wavelength bandwidth
T_{atm}:	Atmospheric transmission
T_{instr}:	Total transmission of the instrument
D_{Tel}:	Aperture diameter of telescope
f:	Effective focal length
Δt:	Integration time
h:	Planck constant
c:	Speed of light
$A_{Detector}$	Detector (pixel) area
Q_e:	Quantum efficiency of the detector

Note that *f/A* is the f-ratio of the instrument.

***F_{solar}*:**

The solar irradiance is shown in Figure 1.

The integral over wavelength yields the so called solar constant (1364 Wm^{-2})

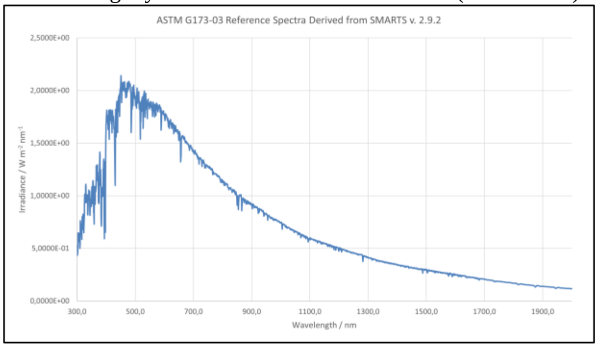

Figure 1: Solar irradiance as a function of wavelength.

***$\Delta\lambda$*:**

The bandwidth in our context is the width of the scanning transmission profile. A typical value is 0.008 nm (80 mÅ)

***T_{atm}*:**

The atmospheric transmission depends on the location (mountain site, sea level side, latitude) and varies with time according to the Sun's elevation.
For our estimations we use the value

$$T_{atm} = 0.8$$

***T_{instr}*:**

The total transmission of the instrument is the product of the transmissions of the individual components and can only be given for the final design.

Here are some typical numbers:

Table 1: Typical transmissions

Component	Transmission
Window (AR coated)	0.95
Mirror	0.9
Interference filter (central wavelength)	0.8
Retarder	0.9
Polarizer	0.5

Etalon	0.04
90:10 beam splitter	0.9

D_{Tel}:

Also the size of the aperture depends on the final design. We estimate it to be in the range 100 mm to 200 mm.

f:

The effective focal length is already determined by the detector size which we assumed to be a fixed choice.

$$f = 4300 \text{ mm}$$

Example

As an example let us assume a system consisting of

- 2 windows
- 5 mirrors
- 2 filters
- 2 retarders
- 1 polarizer
- 1 Etalon
- 1 90:10 beam splitter

We get an estimated transmission

$$T_{instr} = 0.005$$

Now we can estimate the signal assuming the visible wavelength region (600 nm, F_{solar} = 1.7 Wm^{-2}nm^{-1}) for an integration time of 0.1 s, a pixel size of 10 µm, and a quantum efficiency of 0.6:

For a telescope diameter of 200 mm we obtain appr. 3 x 10^4 photoelectrons, and accordingly 7000 photoelectrons for a 100 mm telescope.

Note that these estimations were done with continuum intensity and don't take a line depth into account.

Conclusion: With a single exposure we get a signal to noise ratio due to photon noise ($\sqrt{N_e}$) of about 100 to 200 depending on telescope size.

Kommentiert [MR1]: Wie schätzt Du das Rauschen ab?

2.3 Which S/N do we get? – Detector limitation

The S/N of a single measurement depends on the maximum number of photoelectrons a detector can measure. This in turn depends on

- The integration time as long as the full well capacity is not reached.
- The full well capacity of a single pixel. The larger the better.
- The number of bits the signal is translated to. The larger the better

Let us consider the ideal case of near saturation and look on possible detectors. The first scientific requirement in Section 2.1 already limits our choice to 4k x 4k cameras. In addition this camera has to be fast to fulfill science requirement 4 in Section 2.1.

The combination of

- Large (4k x 4k) and
- Fast

almost immediately leads to CMOS detectors rather than CCDs. CMOS detectors read out every single pixel individually. So "blooming" effects are avoided and read out time is much shorter. This is important for large detectors with many pixels. Together with a "global shutter" artefacts which can occur with CCDs are avoided. Whereas in the past CMOS detectors were more "noisy" than CCDs, this has changed during the last years.

Kommentiert [MR2]: Warum?

The demand of a large full well capacity yields a minimum physical pixel size to give "room" to enough photoelectrons. Current technology shows the following characteristics

Pixel size	appr. 10 to 12 µm
Full well capacity	appr. 10^5 photoelectrons
Digitization	16 bit

Here we obtain the first important limitation:
When we observe close to saturation we can expect a photon noise of about 300 photoelectrons ($\sqrt{10^5}$). Due to the digitization this corresponds to appr. 200 ADU yielding a

Kommentiert [MR3]: Wie kommt man auf diese Zahl?

Kommentiert [MR4]: Abkürzung ins Abkürzungsverzeichnis noch eintragen

$$\text{maximum S/N} = (2^{16} / 200) \approx 300$$

for a single measurement of a single pixel.

In Section 2.2 we see that we shall not fill the charge well with a single exposure of 100 ms exposure time. Multiple scans and/or longer integration times will be necessary to obtain a signal to noise ratio of say 500.
The pixel size determines the physical size of the whole detector which than is appr. 50 mm x 50 mm wide. The immediate consequence is the instrument's effective focal length:

$$f_{instr} = \frac{image\ scale\ [\frac{mm}{arcsec}]}{\tan(1\ arcsec)} + \text{margin} \approx 4300\text{ mm}$$

3. SPECTROMETER CONSIDERATIONS AND DESIGN CONSEQUENCES

In Section 2.3 we saw that the instrument must have a focal length of appr. 4300 mm because of science requirement No. 1.

Science requirements No. 4 and No. 5 determine the aperture of the telescope:

3.1 Fabry-Pérot interferometer as imaging spectrometer

The demand for 2D-spectroscopy with high cadence cannot be achieved (easily) with a scanning slit spectrograph. As a result we have to find a solution on the base of a 2D imaging spectrometer. These are interferometers. GONG found a solution by using a Michelson interferometer which matches the particular spectral line used by GONG (Ni 676.8 nm).
When the demand for more than one spectral line comes into play the Michelson approach does not work anymore, and it turns out that only a tuneable Fabry-Pérot type interferometer (FPI) can do the job.

3.2 Which type of mount?

A FPI acts as a resonator. If the gap between the two reflective surfaces is an integer multiple of the wavelength we get constructive interference and therefore transmission. If the angle of incidence changes from normal incidence to a certain angle the “effective” gap becomes larger and therefore the transmission peak is shifted to shorter wavelength. Figure 3 illustrates this. The left panel shows the ray geometry while the right panel shows an example. For the blue transmission curve the angle of incidence was 0.1°. The corresponding blue shift of the transmission peak is 1.3 pm.

Figure 2 shows the blueshift for a particular wavelength as a function of angle of incidence. Note that the blue shift does not depend on the size of the gap between the etalons plates.

By the way: A typical FWHM of a scan profile is 8 pm, a typical step width is 2 pm, and a typical scan is 20 steps long.

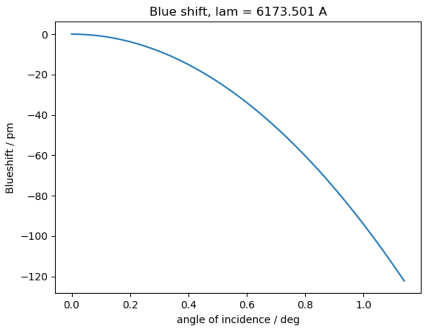

Figure 2: Blue shift as a function of wavelength and angle of incidence

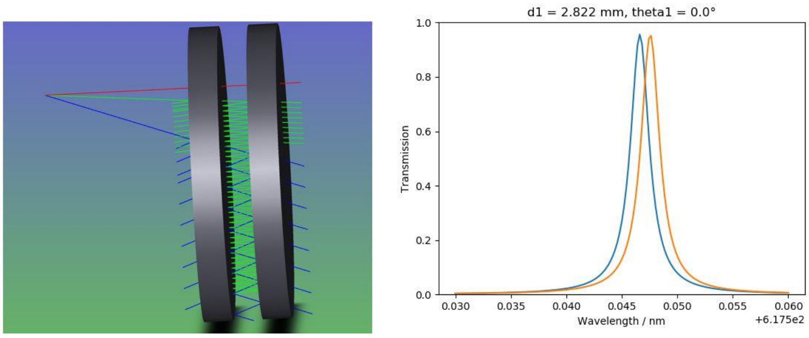

Figure 3: Interference change with angle of incidence

There are two principle ways to set up the etalons:

3.2.1 The telecentric mount:

Here the etalons are mounted close to the focus, and the pupil is in infinity (Telecentricity). This has the following consequences:

- The etalon has to have the same diameter as the image of the FOV.
- Each point in the field gets light which passed different parts of the etalons.
- Each point in the field gets light of a ray cone which covers a certain range of incident angles. So the effective transmission profile is the result of an overlap of many profiles with different transmission maxima. In the end the profile is broadened.

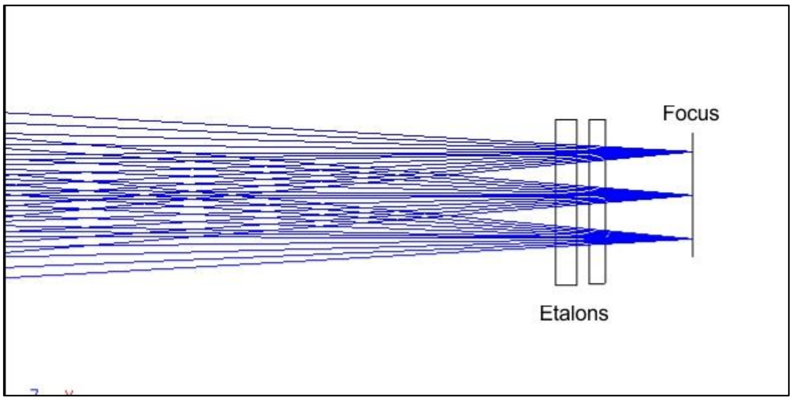

Figure 4: Etalons in telecentric mount

The broadening of the transmission profile depends on the ray cone angle and therefore on the f-ratio at the focus

$$tan(cone\ angle) = \frac{D_{Telescope}}{f}$$

If we want to keep the angle of incidence smaller than say 0.2°, the cone angle has to be smaller than 0.4° yielding a f-ratio of larger than 150.

That means we need a relay optic consisting of a magnifying part to produce the desired f-ratio for the etalon, and a demagnifying part to yield the desired image scale on the science detector..

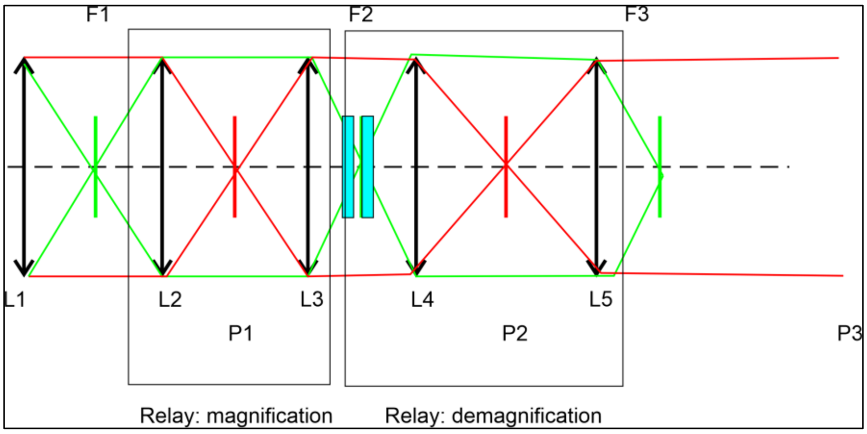

Figure 5: Scheme for a telecentric setup (not to scale). Green: Object imaging, red: Pupil imaging.

Figure 5 shows the principle:

L1: Telescope
F1: first focus with original f-ratio
L2: Collimator1 : Collimates object beam, images pupil
P1: Intermediate pupil
L3: Reimager with long focal length to produce an image with the desired f-ratio. Telecentric beam because the pupil is imaged to infinity
L4: Collimator 2: Collimates object beam, makes another pupil P2
L5: Reimager

If we assume a telescope aperture of say 200 mm we end up with a focal length for F2 of 30000 mm and a solar image with a diameter of about 300 mm. In the telecentric configuration the etalon has roughly the same diameter as the f/150 image, in other words it is very large.

We see the disadvantages:

- Extremely long relay optics
- Too large etalons

and conclude: Telecentric mount does not work for small telescopes and/or large FOV.

3.2.2 The collimated mount

The complimentary setup is the one where the etalon is placed at a pupil position. Since in most cases the telescope aperture is much larger than the available etalon diameter a relay optic is necessary to produce a suitable pupil size.

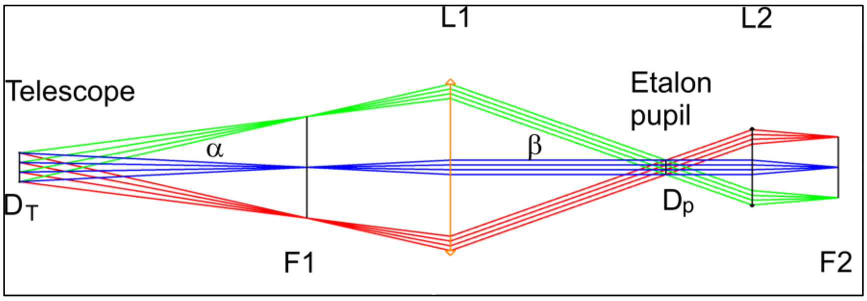

Figure 6: Scheme for collimated mount

Figure 6 shows the scheme:

A telescope wth aperture D_T observes with a field angle α. A collimator L1 produces a pupil with diameter D_p . Here the etalons will be placed. The lens L2 reimages the object in focus F2.

As can be seen from Figure 6 every image point gets light from the whole etalon diameter. The angle of incidence on the etalon β is given by

$$\beta = \alpha \, \frac{D_T}{D_p}$$

I.e. a smaller pupil increases the angle of incidence und thus the blue shift of the transmission profile.

In our case the FOV is 0.56° (the solar disk plus some margin), i.e. α = 0.28°. Assuming a 200 mm telescope and a 70 mm etalon (which is a “typical” diameter) we obtain β = 0.8°. From Figure 2 it is obvious that this angle of incidence is much too large. It would lead to appr. 40 more scan steps to cover the blue shift. I.e. the cadence would be three times longer than with vertical incidence.

We conclude: The collimated mount is a good candidate for a setup which has to be compact but the ratio D_T / D_p should be as small as possible.

4. GENERAL TELESCOPE CONSIDERATIONS

In this Section we discuss possible telescope designs based on the assumption that we need 200 mm aperture and 4300 mm focal length.

In the considerations we have to include that we need space in front of the science focus to accommodate field stop, filter wheel, polarization optics, beam splitters. So the back focal length has to be in the order of 1000 mm.

4.1 Refractor

A straight forward consideration would lead to a 200 mm aperture f/21.5 refractor. The advantages are:

- Simple
- No central obscuration
- Proven concept (There are several classical refractors used for full disk imaging)

But these instruments are not compact (f = 4300 mm), and therefore not very well suited for a system which should operate in a compact enclosure. A number of folding mirrors would be needed which make the design unnecessarily complex.

We therefore did not follow this line further.

4.2 Two mirror telescopes

There are two classes of 2-mirror-telescopes: The Gregorian and the Cassegrain. The Gregorian telescope has two concave mirrors and a real focus between the primary and the secondary. See Figure 7.

This is useful to put a field stop there. This principle is used in larger solar telescopes with small field of view to reduce the heat load. For full disk application this feature is not needed. Because of the intermediate focus the distance between primary and secondary mirror is larger than in the alternative case, the Cassegrain.

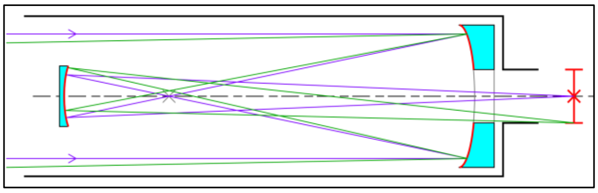

Figure 7: Gregorian telescope (By Krishnavedala - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=34874191)

The Cassegrain telescope has a convex secondary mirror and no intermediate focus. This makes the telescope shorter and more compact than the Gregorian. See Figure 8.

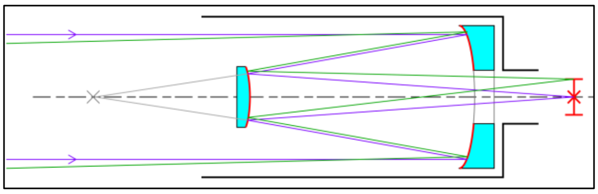

Figure 8: Cassegrain telescope (By Krishnavedala - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=34884711)

Given these advantage we prefer the Cassegrain type. An example is shown in Figure 9.

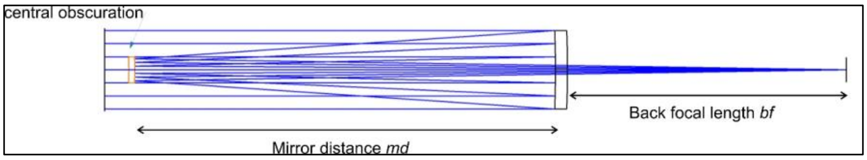

Figure 9: Example for a Cassegrain design

But there are some constraints:

We already fixed the focal length (4300 mm). In addition we need a certain space behind the primary (back focal length), we also want to keep the central obscuration small, which depends on the distance between the primary and the secondary mirror.

These parameters are not independent from each other and determine the focal lengths for the primary and the secondary mirror.

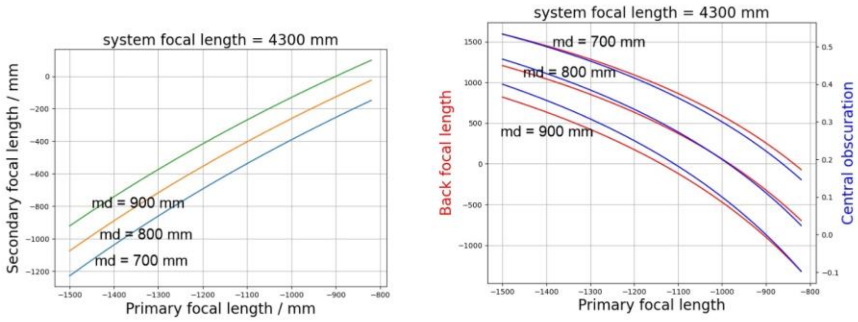

Figure 10: Relations between Cassegrain design parameters. *md* is the distance between primary and secondary mirror. The aperture diameter is 130 mm

In Figure 10 one can see how different parameters affect the design.

Let us assume we need a back focal length of 1000 mm. We can achieve that with a mirror separation (*md*) of 800 mm or 700 mm. In both cases the central obscuration will be appr. 40% (diameter). For *md* = 800 mm we obtain a primary focal length of appr -1380 mm (right panel of Figure 10). For the secondary focal length we get appr. 850 mm.

With these numbers we have a design to start with.

Because of the rather large back focal length the central obscuration will also be large. This is a crucial point in the design consideration: We have to find a compromise between back focal length, central obscuration, total length of the telescope, and the overall complexity:

If we want a central obscuration of say 25% and keep *md* = 800 mm we need a focal length for the primary of -1030 mm (right panel) and a focal length for the secondary of appr. 350 mm.

Then the back focal length is only 160 mm. The comparison is shown in Figure 11.

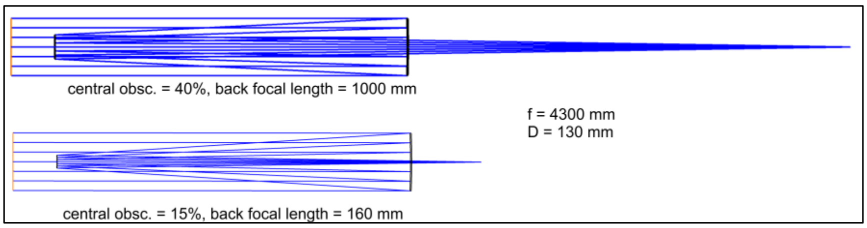

Figure 11: Trade-off between back focal length and central obscuration

So:
A smaller central obscuration leads to an unpractical short back focal length. This in turn requires an additional relay optics to yield the desired back focal length.

This relay optic can also be used to produce a suitable pupil for the etalon(s). We end up with a "classical design" as shown in Figure 6 as the basic scheme.

Even with a pupil diameter as small as 50 mm we need a collimator (L1) with 1000 mm focal length. Figure 12 shows a (unfolded) design using lenses rather than mirrors for the relay optic. It is very long.

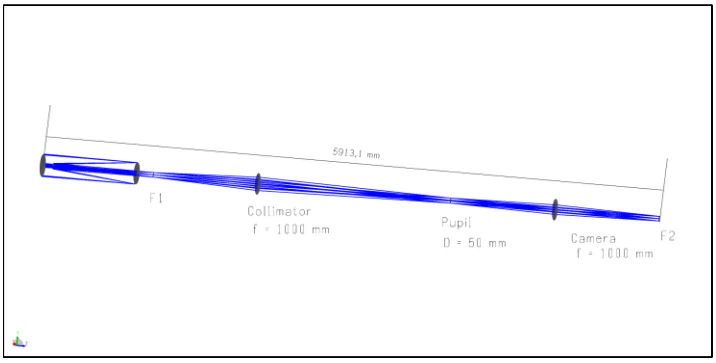

Figure 12: Design with small central obscuration and 50 mm pupil

The design in Figure 12 combines a small central obscuration with a long back focal length and a pupil with a diameter $D_{pupil} = D_{Telescope} / 4$

We summarize the properties of this "classical" design:

Advantage:

- „Normal" central obscuration
- Long back focal length
- Easily accessable pupil
- Large aperture (can be 200 mm and more)

Disadvantage:

- Long physical length, i.e. compact only when folded.
- Small pupil and therefore large blue shift (angle of incidence on the etalon at the solar limb = 1°)
- Etalons have to be mounted vertically (Gravitation issue)

5. CONCLUSION

In this document we described the logical way to a telescope design which possibly matches the science requirements.

It turns out that we have to find a compromise between five main parameters as shown in Figure 13.

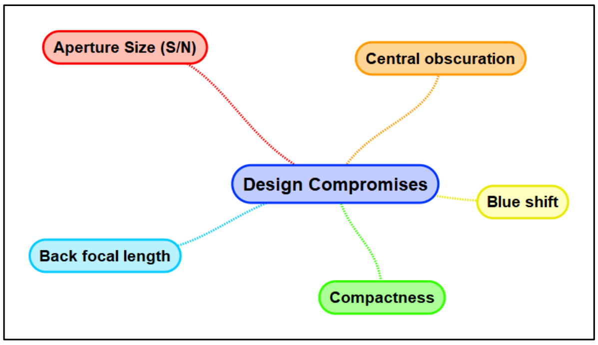

Figure 13: Compromise relations

Kommentiert [MR5]: back focal length -> Back focal length; alle anderen Ausdrücke in der Graphik fangen auch mit Großbuchstaben an.

Several designs are possible but at some point decisions have to be made. Certain weights have to be assigned to certain parameters.

We finally decided to focus on

- a small blue shift in order to increase the cadence
- Compactness following the classical engineering rule “the best part is no part”
- a comfortable back focal length to accommodate the back end instruments

as a consequence we would accept

- a rather large central obscuration (Dip in the MTF)
- a maximum telescope aperture of 120 mm (Photon noise , see Section 2.2)

These decisions led to the final design which will be described in a subsequent document.

LIST OF REFERENCED DOCUMENTS

ANNEXES (IF APPLICABLE)