THEMIS SPECTROGRAPHS

C. Le Men, 26th of December 2012

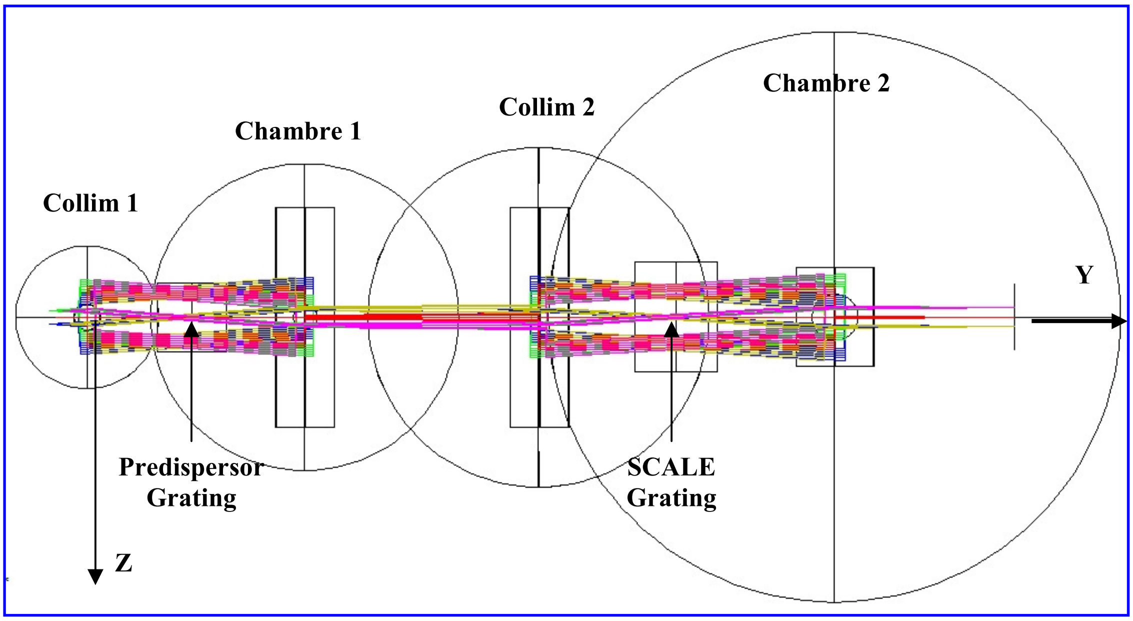


Figure 1 : **Themis Spectrographs TOP VIEW**

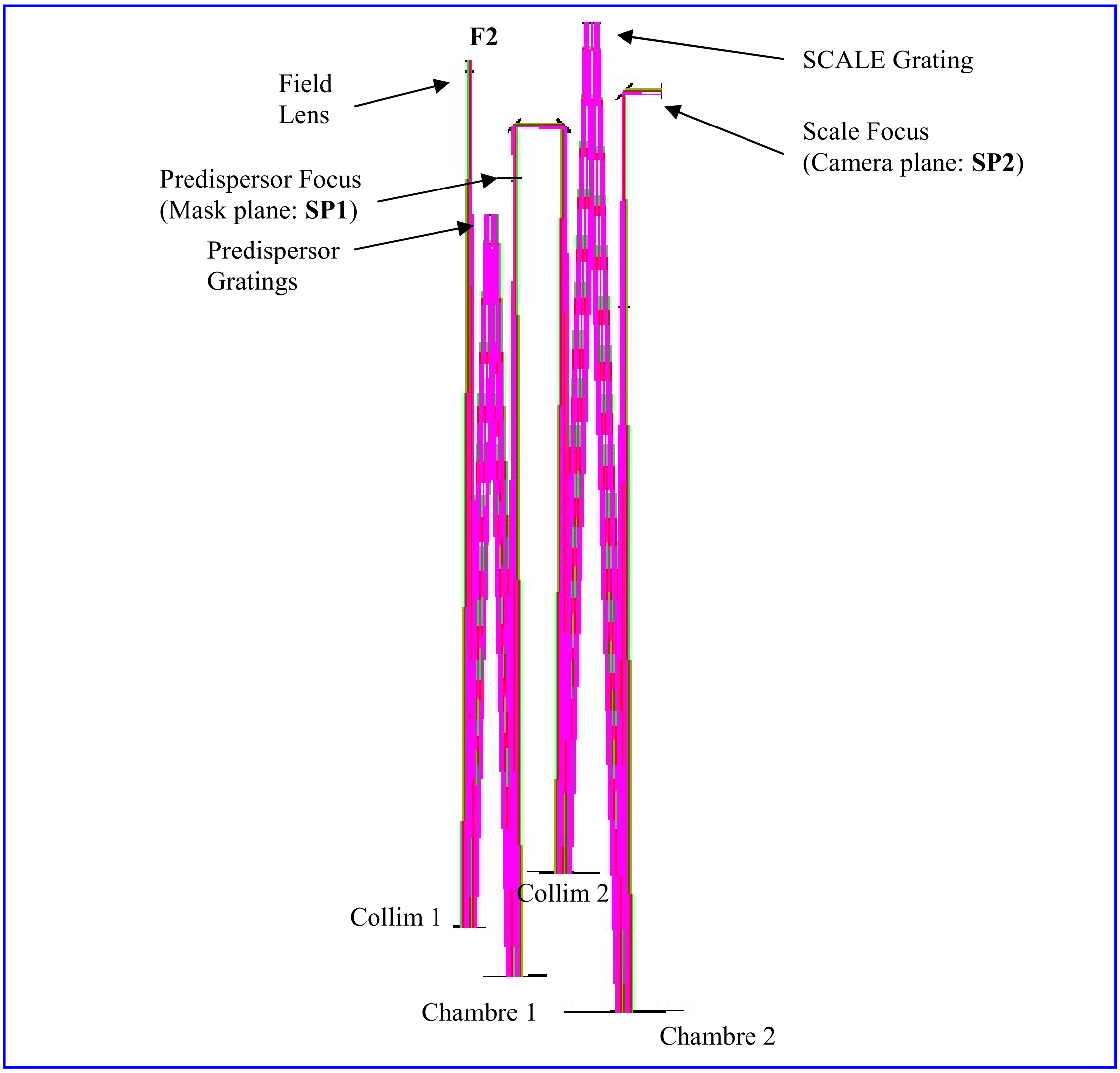


Figure 2 : **Themis Spectrographs SIDE VIEW**

SPECTROGRAPHS:

PREDISPERSOR SPECTROGRAPH:

- F2 focus: F=57750mm @ F/64.2 (0.280 mm /arcsec)

- Collimator 1: F= 7618 mm
  Dia= 260mm

- Grating: 150 gr/mm (a=6.667 μm)
  BLAZE= 2,15º @ order K=1
  DISPERSION along <u>Z axis</u> (see figure 1)

- Chambre 1: F= 7011 mm
  Dia= 420 mm

- SP1 focus: F=53150 mm @ F/59 (0.257mm/arcsec)
  Typical LINEAR DISPERSION: 0.105 mm/A
  "MASK" plane (coef. FIGURE 3)

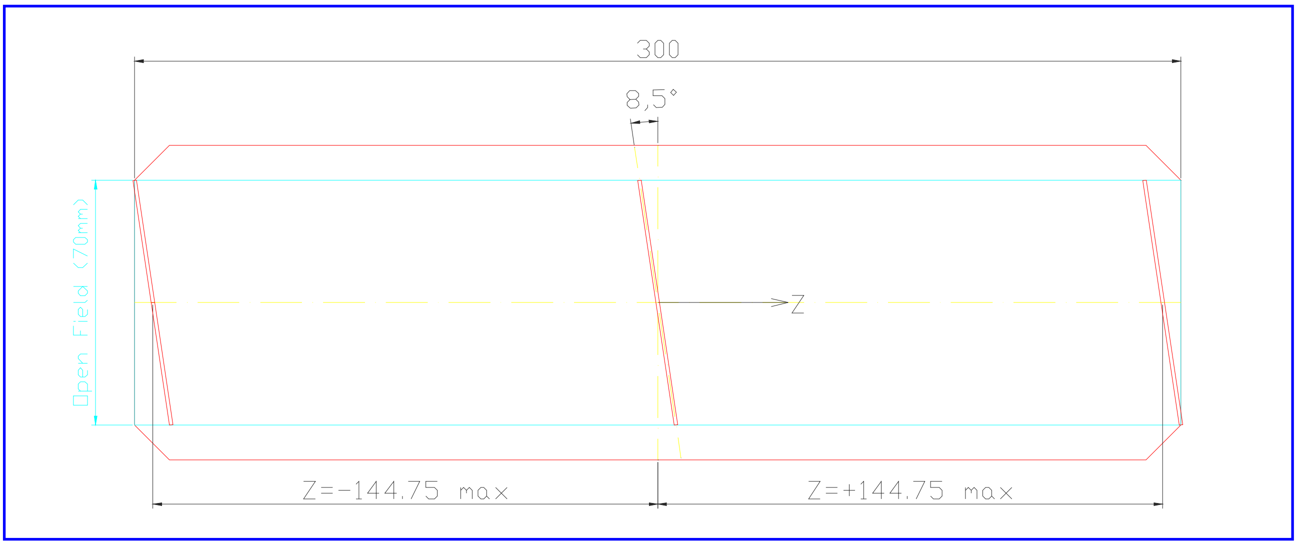


Figure 3 : Predispersor Spectrograph "MASK" plane: TOP-VIEW from the F2 focus

MASK referential

- "Z_{SP1}": Origine @ mask center, positive along Z axis **(range:-144.75 to +144.75mm)**
- "**SP1 Cote**": Origine @ mask right side **(SP1 cote= 150.0 – Z_{SP1})**, used to give "mechanical" cotation in 2D plans **(range: 5.25 to +294.75mm).**

SCALE SPECTROGRAPH:

- Collimator 2: F= 7490 mm
  Dia= 520mm

- Grating: 79 gr/mm (a=12.658 μm)
  BLAZE= 63.433º @ multiple orders
  DISPERSION along <u>Z axis</u> (see figure 1)

- Chambre 2: F= 8437 mm
  Dia= 1040 mm

- SP2 focus: F=59870 mm @ F/66.5 (0.290mm/arcsec) IN LITTROW Mode ($Z_{sp1}=Z_{sp2}=0$)
  (see note on spectrograph magnification)
  Typical LINEAR DISPERSION: 5.408 mm/A (6302A, K=36, Littrow)
  Camera Plane (coef. FIGURE 4)

Note on Scale Spectrograph Magnification:

The magnification factor of such a big scale spectrograph depends not only on mirrors focales, but **also on incident and diffraction angle**. This **magnification factor**, **γ**, is given by:

$$\gamma = \frac{F_{ch}}{F_{col}} \frac{\cos\alpha}{\cos\beta}$$

Where: Fch is the chamber focal length, Fcol is the collimator focal length
α is the incident angle and β the diffraction angle.

In a monochromator (Z=0, littrow mode), this is not seen because $\alpha=\beta$. But, in our case it is very sensitive to wavelength value, position in SP1 and position in SP2 (the cos changes fastly around 63º).

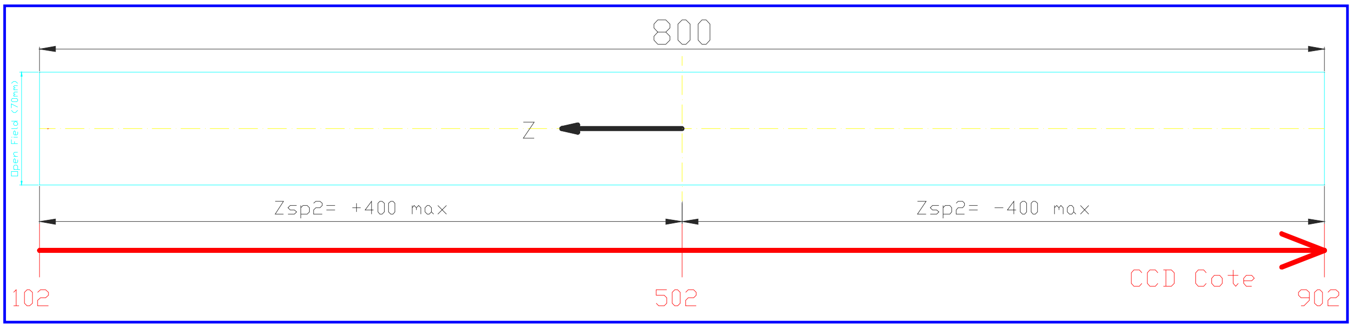


Figure 4 : SCALE Spectrograph "CAMERA" plane: TOP-VIEW <u>from the CCD EXIT</u>

SP2 referential:

- **"Z_{SP2}":** Origine @ SP2 center, positive along Z axis **(range:-400 to +400 mm)**
- **"CCD Cote":** Origine @ SP2 left side **(CCD cote= 502 – Z_{SP2})**, used to give CCD "mechanical" position in exit focus plane **(range: 102 to 902 mm).**

In the SP2 focus plane, spatial scale is of course too big to image directly any camera chip. So, Themis uses re-imaging systems that allow to fit any FIELD between 70 and 180 arcsec on our camera. This set-up also have the advantage to allow correct separation between two spectral ranges on different cameras, **assuming a MINIMUM "spectral" separation of <u>40 mm</u>** between them. The way this is done is shown in figure 5: in such a case one of the spectral range is sent to the upper CCD and the second one to the bottom CCD.

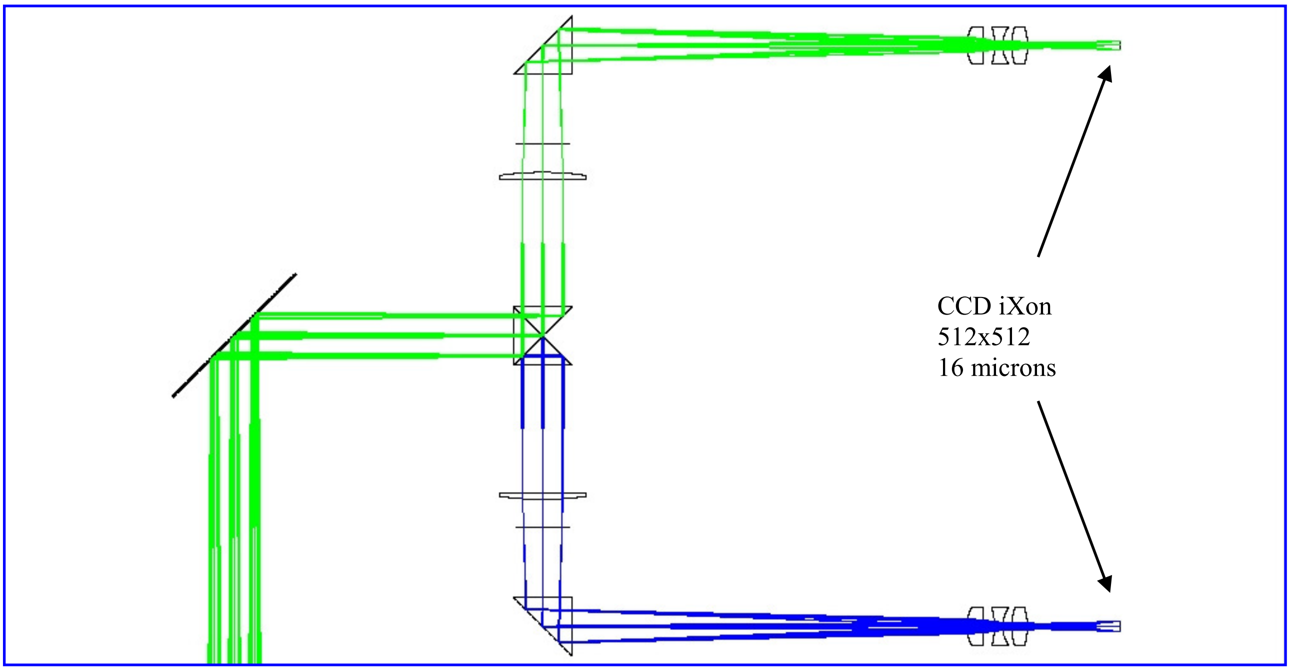
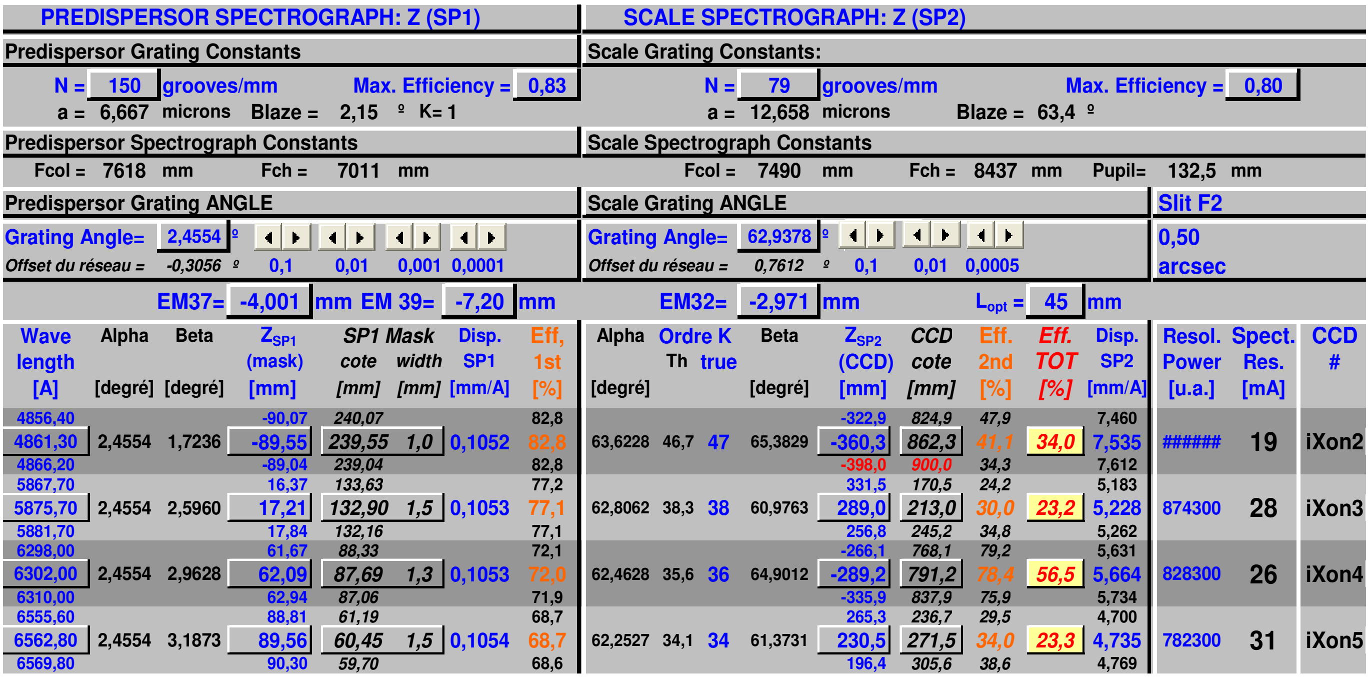


Figure 5 : "CAMERA" plane: RE-IMAGING system (SIDE-VIEW)

“SPECTROGRAPH SIMULATOR”:

An example of a multi-wavelength observation is given in figure 6. This tool allows to compute the best mask (SP1) slits positions and CCD (SP2) positions, assuming all the wavelength ranges are in the best diffraction order of the scale grating.



PREDISPERSOR SPECTROGRAPH: Z (SP1)

Predispersor Grating Constants

N = 150 grooves/mm Max. Efficiency = 0,83

a = 6,667 microns Blaze = 2,15 º K= 1

Predispersor Spectrograph Constants

Fcol = 7618 mm Fch = 7011 mm

Predispersor Grating ANGLE

Grating Angle= 2,4554 º ◀ ▶ ◀ ▶ ◀ ▶ ◀ ▶

Offset du réseau = -0,3056 º 0,1 0,01 0,001 0,0001

EM37= -4,001 mm EM 39= -7,20 mm

SCALE SPECTROGRAPH: Z (SP2)

Scale Grating Constants:

N = 79 grooves/mm Max. Efficiency = 0,80

a = 12,658 microns Blaze = 63,4 º

Scale Spectrograph Constants

Fcol = 7490 mm Fch = 8437 mm Pupil= 132,5 mm

Scale Grating ANGLE

Grating Angle= 62,9378 º ◀ ▶ ◀ ▶ ◀ ▶

Offset du réseau = 0,7612 º 0,1 0,01 0,0005

EM32= -2,971 mm L_{opt} = 45 mm

Slit F2

0,50 arcsec

Wave length [A]	Alpha [degré]	Beta [degré]	Z_{SP1} (mask) [mm]	SP1 Mask cote [mm]	SP1 Mask width [mm]	Disp. SP1 [mm/A]	Eff, 1st [%]	Alpha [degré]	Ordre K Th	Ordre K true	Beta [degré]	Z_{SP2} (CCD) [mm]	CCD cote [mm]	Eff. 2nd [%]	Eff. TOT [%]	Disp. SP2 [mm/A]	Resol. Power [u.a.]	Spect. Res. [mA]	CCD #
4856,40			-90,07	240,07			82,8					-322,9	824,9	47,9		7,460			
4861,30	2,4554	1,7236	-89,55	239,55	1,0	0,1052	82,8	63,6228	46,7	47	65,3829	-360,3	862,3	41,1	34,0	7,535	######	19	iXon2
4866,20			-89,04	239,04			82,8					-398,0	900,0	34,3		7,612			
5867,70			16,37	133,63			77,2					331,5	170,5	24,2		5,183			
5875,70	2,4554	2,5960	17,21	132,90	1,5	0,1053	77,1	62,8062	38,3	38	60,9763	289,0	213,0	30,0	23,2	5,228	874300	28	iXon3
5881,70			17,84	132,16			77,1					256,8	245,2	34,8		5,262			
6298,00			61,67	88,33			72,1					-266,1	768,1	79,2		5,631			
6302,00	2,4554	2,9628	62,09	87,69	1,3	0,1053	72,0	62,4628	35,6	36	64,9012	-289,2	791,2	78,4	56,5	5,664	828300	26	iXon4
6310,00			62,94	87,06			71,9					-335,9	837,9	75,9		5,734			
6555,60			88,81	61,19			68,7					265,3	236,7	29,5		4,700			
6562,80	2,4554	3,1873	89,56	60,45	1,5	0,1054	68,7	62,2527	34,1	34	61,3731	230,5	271,5	34,0	23,3	4,735	782300	31	iXon5
6569,80			90,30	59,70			68,6					196,4	305,6	38,6		4,769			

Figure 6 : **Spectrograph “Simulator” for a 4 wavelength ranges Observation Run**

PREDISPERSOR Spectrograph:

Constants:

N = 150 gr/mm,	grating frequency,
a = 6.667 µm,	grating period,
B = 2.15º,	grating Blaze (blazed @ 500nm)
K = 1,	grating diffraction order.
F_{col} = 7618 mm,	predispersor collimator focal length,
F_{ch} = 7011 mm,	predispersor chamber focal length.

Variables:

θ, teta= 2.4554º,	grating ANGLE (2.4554º in this example) range: Blaze, B +/- 3º (this angle could be adjusted using sets of arrows)
λ [Å],	wavelength range center value in Angstrom (6 values max) (aroung each center value could be defined a range)

OUTPUTs:

α, alpha [º]

grating incident angle: for this case of predispersor spectrograph, the entrance slit position is constant and equal to zero, so that this incident angle is constant and equal to the grating angle teta:

$$\alpha = \theta \quad [\forall \lambda]$$

β, beta [º]

grating diffraction angle, computed from the classical diffraction formula, taking into account our particular algebrical case and signs:

$$\beta = \arcsin\left[\left(\frac{K\lambda}{10^4 a}\right) - \sin\alpha\right]$$

Z_{SP1} [mm],

Mask slit position in the Z_{SP1} referential:

$$Z_{SP1} = F_{ch}\tan(\beta - \theta)$$

SP1 Cote[mm],

Mask slit position in the “mechanical” referential:

$SP1\ Cote = 150 - Z_{SP1}$ if the spectral range is SYMETRICAL aroung center value.

Otherwise, SP1 cote for the center value is computed as the average of both SP1 Cote values defined by the two wavelength range limits.

Mask Width [mm], Sp1 mask Slit width given by the two SP1 cote of wavelength range limits.

Disp_{SP1} [mm/A], **linear dispersion in SP1,** given by:

$$Disp_{SP1} = \frac{K.F_{ch}}{10^4.a.\cos\beta.\cos(\theta-\beta)^2}$$

SCALE Spectrograph:

Constants:

N = 79 gr/mm, grating frequency,

a = 12.658 μm, grating period,

B = 63.433º, grating Blaze

$\mathbf{F_{col}}$ = 7490 mm, scale collimator focal length,

$\mathbf{F_{ch}}$ = 8437 mm, scale chamber focal length.

Variables:

θ, teta= 62.9378º, grating ANGLE (62.9378º in this example) range: Blaze, B +/- 3º (this angle could be adjusted using sets of arrows)

OUTPUTs:

α, alpha [º] grating incident angle: for this case of scale spectrograph, the entrance slit position is wavelength and user dependent, so that this incident angle is NOT constant, and depends on the Z_{SP1} value for each wavelength:

$$\alpha = \theta - \arctan\left(\frac{Z_{SP1}}{F_{col}}\right)$$

Order K, In this scale spectrograph case, the diffraction order is not constant, but wavelength dependent. In order to compute the effective diffraction order of each wavelength range, on first compute a “theorical” real one:

$$K_{th} = \frac{2.a.10^4}{\lambda}\sin(\alpha) \quad (K_{th} \in \Re)$$

And then find the **TRUE diffraction order K_λ** as the closest **entire** value of K_{th}.

β, beta [º] grating diffraction angle, computed from the classical diffraction formula, taking into account our particular algebrical case and signs, AND especially the fact that diffraction order is wavelength dependent:

$$\beta = \arcsin\left[\left(\frac{K_\lambda \lambda}{10^4 a}\right) - \sin\alpha\right]$$

$\mathbf{Z_{SP2}}$ [mm], CCD position in the Z_{SP2} referential:

$$Z_{SP2} = F_{ch}\tan(\theta-\beta)$$

SP2 Cote[mm], CCD position in the “mechanical” referential:

$$SP2\ Cote = 502 - Z_{SP2}$$

Mask Width [mm], Sp1 mask Slit width given by the two SP1 cote of wavelength range limits.

Disp_{SP2} [mm/A], **linear dispersion in SP2,** given by:

$$Disp_{SP2} = \frac{K.F_{ch}}{10^4.a.\cos\beta.\cos(\theta-\beta)^2} + Disp_{SP1}$$

Other parameters, like efficiencies and resolving power are computed, but require a more extensive explanation given in the following paragraphs of this document.

SP1 and SP2 EFFICIENCIES:

The typical efficiency curve of the **predispersor grating** is given in figure 7-a hereafter. This curve is computed for a theoretical maximum efficiency value (here 83%) at the blazed wavelength (5000A) AND is relative to coating reflectivity (meaning that it DOESN'T take into account the spectrograph optics transmission and reflectivity).

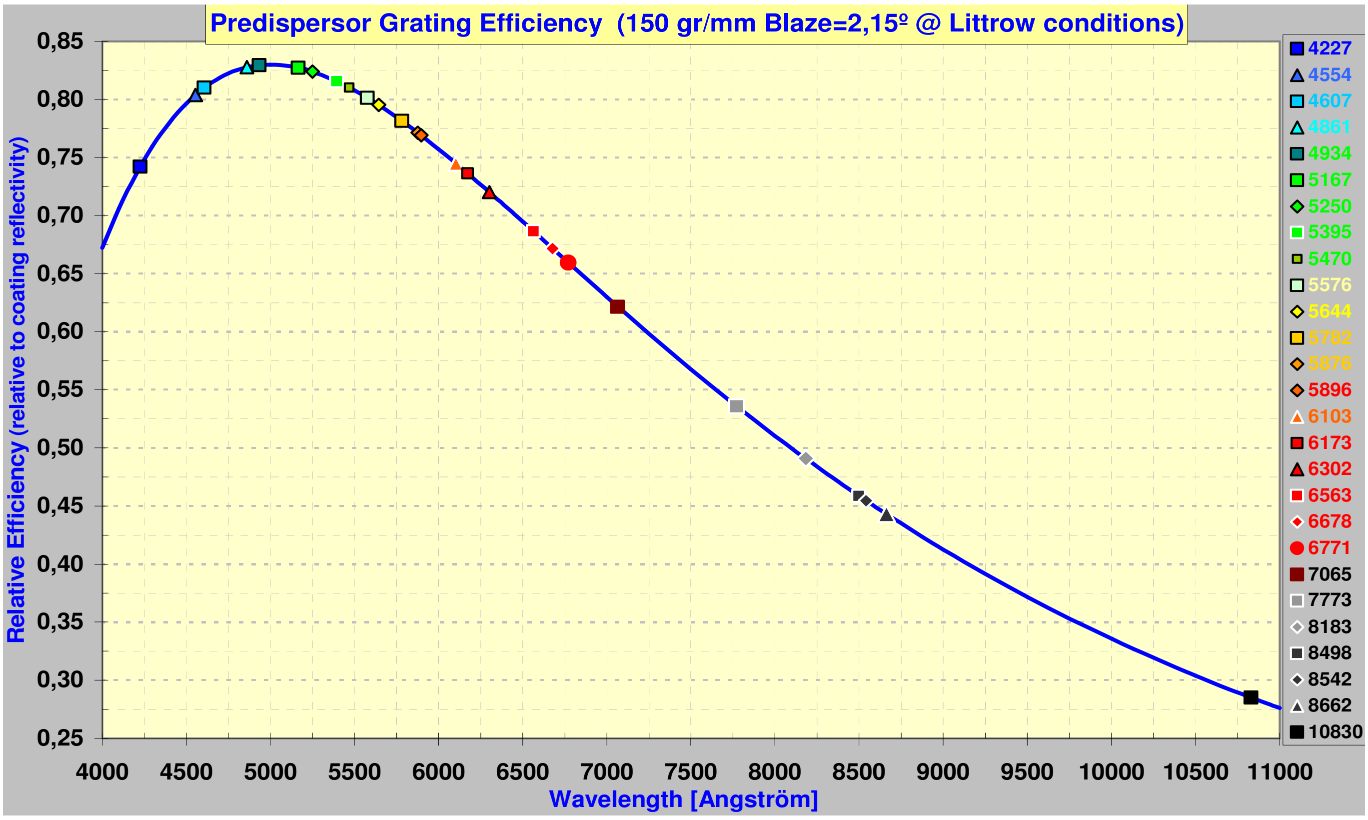


Figure 7-a : **Predispersor "VISIBLE" Grating Efficiency**

The efficiency **Eff$_{SP1}$** in [%] of the predispersor grating is given by:

$$Eff_{SP1}[\%] = 100.eff_{\max}.\left[\frac{\sin X}{X}\right]^2 \quad with\ X = 10^4.a.\pi.\cos Blaze\left(\frac{\sin(\alpha - Blaze) + \sin(\beta - Blaze)}{\lambda}\right)$$

where **eff$_{max}$** is the maximum efficiency (0.83 here) at blaze wavelength (5000A).

It could be seen that efficiency drops quickly after 6600 A. To improve transmission in the Infrared, Themis also have a "infrared" predispersor grating, which efficiency curve is given in figure 7-b.

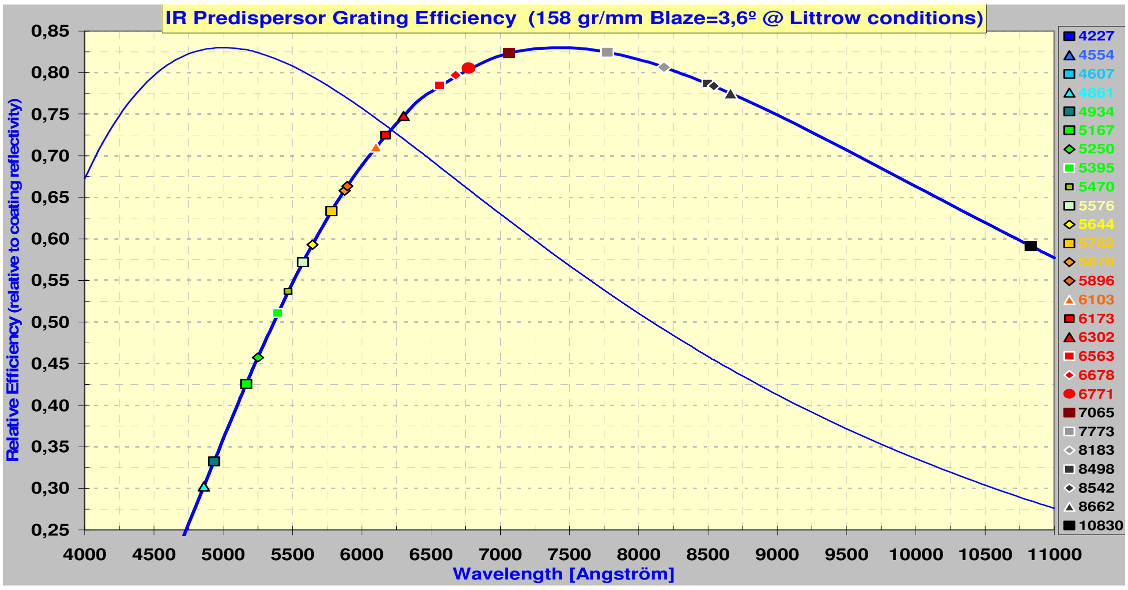


Figure 7-b : **Predispersor "INFRARED" Grating Efficiency**

The typical efficiency curve of the **scale grating** is given in figure 8 hereafter. This curve is computed for a theoretical maximum efficiency value (here 80%) AND is relative to coating reflectivity (meaning that it DOESN'T take into account the spectrograph optics transmission and reflectivity). This curve is now dependent on diffraction order, so that wavelength efficiency could STRONGLY vary INTO a single diffraction order, as shown in that figure (look at Hα in the order 35 or 34: efficiency 35% !, also have a look at the typical Mg lines: 5167,5173 and 5183A which efficiency in the 44th order drops from 72% for the first line to 56% for the third one !). These curves are given for $Z_{SP1}=0$ et $Z_{SP2}=0$.

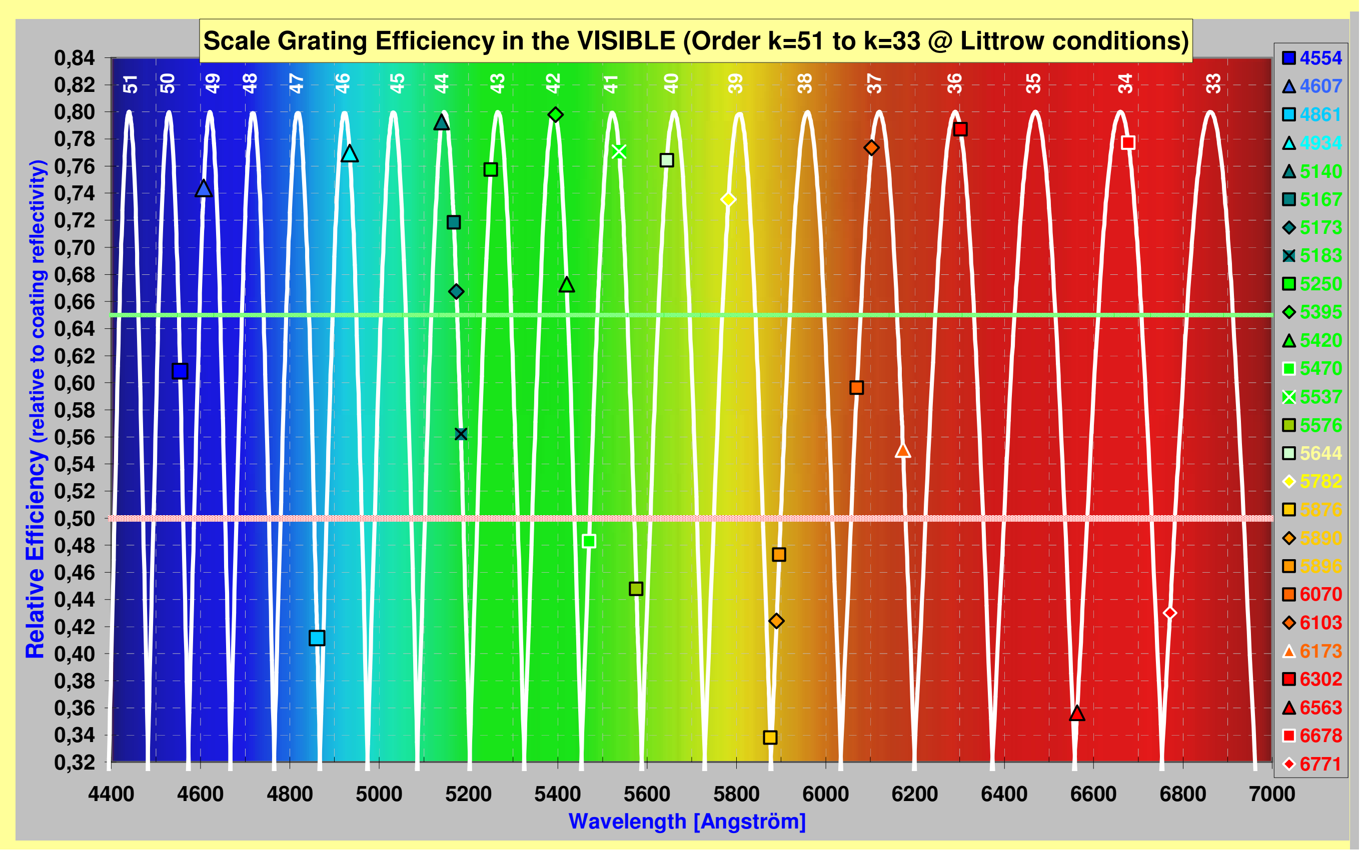


Figure 8 : **SCALE Spectrograph Grating Efficiency**

The efficiency $\mathbf{Eff_{SP2}}$ in [%] of the scale grating is given by:

$$Eff_{SP2}[\%]=100.eff_{\max}.\left[\frac{\sin X}{X}\right]^2 \quad with\ X=10^4.a.\pi.\cos Blaze\left(\frac{\sin(\alpha-Blaze)+\sin(\beta-Blaze)}{\lambda}\right)$$

where $\mathbf{eff_{max}}$ is the maximum efficiency (0.80 here).

TOTAL EFFICIENCY: (see Figure 6)

Eff. Tot [%], Total Efficiency is then the product of predispersor and scale efficiencies.

Resolving Power and Resolution:

RP, Resolving Power gives the **INTRINSIC spectral resolving power** of the spectrograph at The desired wavelength. Intrinsic meaning that, the correct definition of that resolving power DOESN'T take into account the entrance and exit slits EFFECTS. It depends on grating incidence and refraction angle, but ALSO on the projected size of the pupil on the grating.

$$RP = 10^7 . \left(\frac{width\_pupil}{\cos\theta} \right) \left(\frac{\sin\alpha + \sin\beta}{\lambda} \right)$$

Where **width_pupil** is the pupil diameter on the scale grating (**132.5 mm** here)
In the figure 6, the Resolving Power is rounded to a closest hundredth.

$\Delta\lambda_i$ [mÅ], INTRINSIC spectral resolution (**not computed in the figure 6**) is directly given from the Resolving Power (with a factor 1000 to scale it in mA):

$$\Delta\lambda_i = 10^3 . \left(\frac{\lambda}{RP} \right)$$

As a example, in the observation Run detailled in figure 6, intrinsic resolution for the 4 wavelength values IS:
4861.3 A RP= 1082300 and **$\Delta\lambda_i$** = 4.5 mÅ
5875.7 A RP= 875100 and **$\Delta\lambda_i$** = 6.7 mÅ
6302.0 A RP= 829000 and **$\Delta\lambda_i$** = 7.6 mÅ
6562.8 A RP= 783000 and **$\Delta\lambda_i$** = 8.4 mÅ
Now, the REAL spectral resolution SHOULD take into account the entrance slit effect, and Also the exit slit effect (which in our case could be the pixel spectral resolution):

$\Delta\lambda$ [mÅ], FINAL spectral resolution (**given in figure 6**) is directly given from the Resolving Power and the equivalent spectral width of the entrance slit (with a factor 1000 to scale it in mA):

$$\Delta\lambda = 10^3 . \sqrt{ \left(\frac{\lambda}{RP} \right)^2 + \left(\frac{Slit_{F2} . Scale_{F2}}{Disp_{SP2}} \right)^2 + \Delta\lambda^2_{pixel} }$$

Where ***$Slit_{F2}$*** is F2 Slit Width in **arcsec**,
$Scale_{F2}$ is the spatial scale in F2 in **mm/arcsec** (0.28mm/arcsec here)
$\Delta\lambda_{pixel}$ is the pixel spectral resolution in **mA**

In figure 6, we don't take into account the pixel spectral resolution because it depends on the magnification factor that we are going to use between the spectral and the camera planes. In that condition, one can show the great difference between intrinsic resolution **$\Delta\lambda_i$** and total resolution **$\Delta\lambda$** for a **0.5 arcsec Slit**:
4861.3 A RP= 1082300 and **$\Delta\lambda_i$** = 4.5 mÅ BUT **$\Delta\lambda$** = 19 mÅ
5875.7 A RP= 875100 and **$\Delta\lambda_i$** = 6.7 mÅ BUT **$\Delta\lambda$** = 27 mÅ
6302.0 A RP= 829000 and **$\Delta\lambda_i$** = 7.6 mÅ BUT **$\Delta\lambda$** = 25 mÅ
6562.8 A RP= 783000 and **$\Delta\lambda_i$** = 8.4 mÅ BUT **$\Delta\lambda$** = 30 mÅ
yielding to a "Real Resolving Power" close to 400000.
Or for a **0.1 arcsec Slit**:
4861.3 A RP= 1082300 and **$\Delta\lambda_i$** = 4.5 mÅ BUT **$\Delta\lambda$** = 6 mÅ
5875.7 A RP= 875100 and **$\Delta\lambda_i$** = 6.7 mÅ BUT **$\Delta\lambda$** = 9 mÅ
6302.0 A RP= 829000 and **$\Delta\lambda_i$** = 7.6 mÅ BUT **$\Delta\lambda$** = 9 mÅ
6562.8 A RP= 783000 and **$\Delta\lambda_i$** = 8.4 mÅ BUT **$\Delta\lambda$** = 10 mÅ
showing that Themis spectrograhs resolution is DRIVEN by the ENTRANCE slit width.