Optical Compressive Sensing (CS) Technologies for Space Applications

ESA Contract No. 4000116422/15/NL/BJ/gp

Final Presentation

Alexandre Pollini

Division System, CSEM SA

ESTEC, 13 Septembre 2018

Project

- Objectives:
  1. Investigate and assess the **potential of using CS technologies in future optical instruments** for several space applications, and to compare them with traditional systems.
  2. **Design a CS based optical system** (at elegant breadboard level) targeting a specific space application and aiming at a **significant advantage** with respect to the resources required at instrument level as **compared to a traditional counterpart**.

Numerically:

A. > **5% improvement** on compression ratio, processing time and PSNR.

B. > **40% reduction** of system's mass, power and volume

- Optical systems for **EO and SSE** to be assessed include: optical cameras, spectrometers, hyperspectral imagers, attitude sensors and 3D cameras.
- The final result is the **detailed design** and the EBB **development roadmap** of an optical CS based multispectral imager for EO

Study Flow

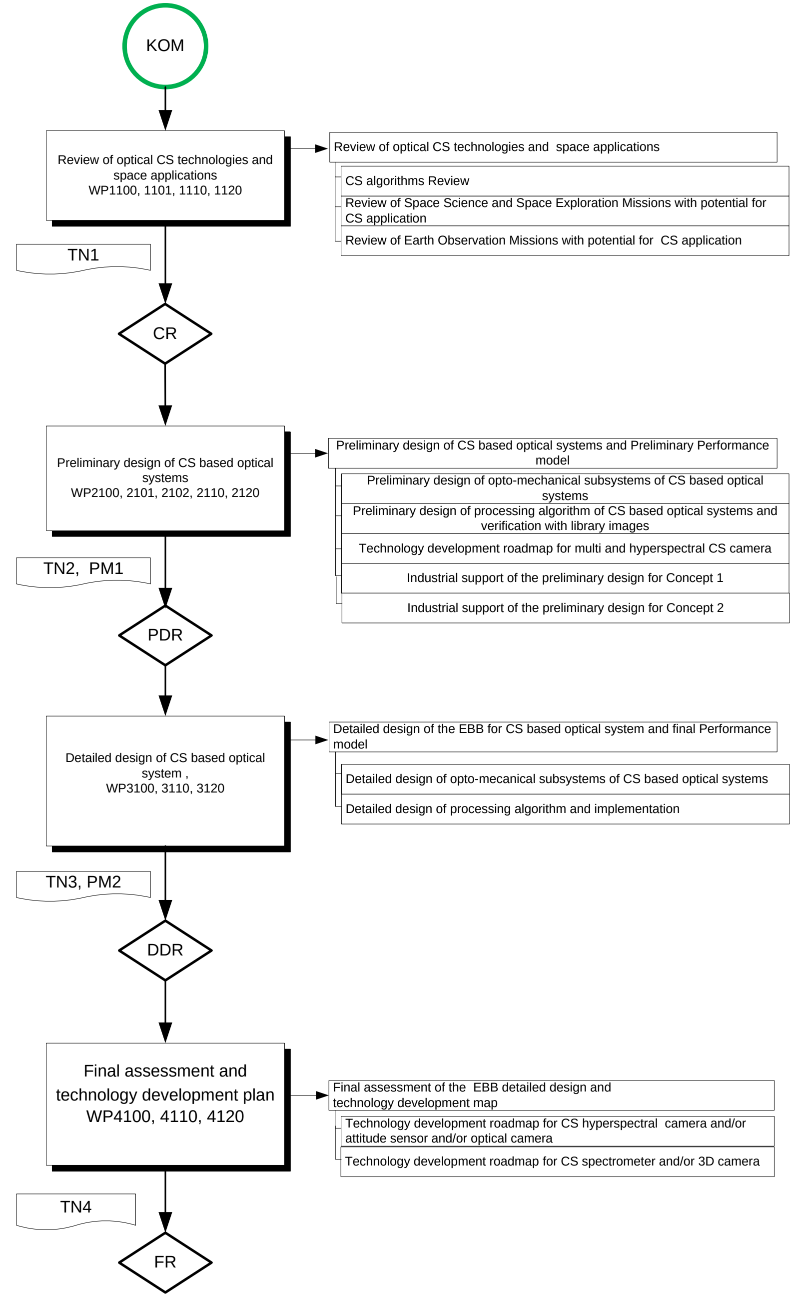
- **Task 1**:
  CS tech./Applications
- **Task 2**:
  Preliminary design
- **Task 3**:
  Detailed design
- **Task 4**:
  Assessment, roadmap

Task 1
Review of optical CS technologies and space applications

Task 2
Preliminary design of CS based optical systems

Task 3
Detailed design of CS based optical system

Task 4
Final assessment and technology development plan



Instruments review

- Large set of instruments and applications
  - Land and geology survey, cartography, vegetation monitoring, etc.
    Involve surface imaging with very high spatial resolution
  - Detection of aerosol and trace gases in the atmosphere.
    Relatively low spatial resolution, atmospheric limbs scanning
  - LiDARs
  - Imagers
  - Laser Altimeters
  - Imaging spectrometers (slitless spectrographs, IR and thermal IR systems, FTS)
  - Spot spectrometers
  - X-ray spectrometers
- **50-60 instruments reviewed** !
- 1st selection down to 11 instruments according to:
  low resolution detector ?, faster spectral measurement ?, big data set ?, signal sparsity ?
- For analysis, used as additional hardware (if needed) off-the-shelf features of DMD (spatial modulation) and PRISM+stepper motor (Spectral modulation)

Tool to proceed with 2nd down-selection: Figure Of Merit

- FOMs proposed:

$$FOM_1 = 8 \cdot \left(\frac{1}{m} + \frac{1}{V} + \frac{1}{E}\right) + \left(PSNR + \frac{1}{R} + \frac{1}{T}\right)$$

$$FOM_2 = A \cdot \left(\frac{1}{m} + \frac{1}{V} + \frac{1}{E}\right) + B \cdot \left(\frac{1}{R} + \frac{1}{T^*}\right) + C \cdot SNR + D \cdot \frac{1}{r}$$

- Change motivations:
  1. Large disparity of instruments → better use relative figures between standard and CS versions
  2. Factors in FOM1 and 2 hardly available for all instruments (litterature, IP)
  3. PSNR/SNR → requires original dataset

$$= A \cdot \left(\frac{1}{\frac{\Delta m}{m} + \frac{\Delta V}{V} + \frac{\Delta E}{E}}\right) + B \cdot \left(\frac{AfterCompressionBit_{pixel\ (PAN)}}{NBit_{pixel}(PAN) \cdot 0.25} + \frac{1}{MaxSpectralBand} \sum_{1}^{MaxSpectralBand} \frac{AfterCompressionBit_{pixel}}{NBit_{pixel} \cdot 0.25 \cdot 0.25}\right) +$$

$$C \cdot (\frac{Nb\ of\ Colon \cdot Nb\ of\ Row\ (PAN)}{Raw\ image\ size\ (PAN)} + \frac{1}{MaxSpectralBand} \sum_{1}^{MaxSpectralBand} \frac{Nb\ of\ Colon \cdot Nb\ of\ Row}{Raw\ image\ size}$$

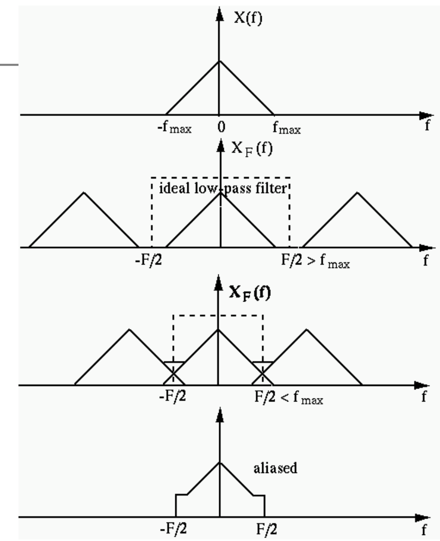
FOM application

Instrument	FOM
EO1: Worldview3	A x 2.7+ B x 7.3 + C x 17.8
EO2: SLSTR	A x 0.919 + B x 20 + C x 2
EO3: FCI (VIS-NIR)	A x 5.38 + B x 20 + C x 9.2
EO4: FCI (IR)	A x 10.8 + B x 20 + C x 3.2
EO5: MIPAS	A x 5.2 + B x 20 + C x 2
SSE1: IMP	A x 0.12 + B x 15.3 + C x 31
SSE2: CRISM	A x 0.49 + B x 2.86 + C x 18.9
SSE3: PFS	A x 0.532 + B x 10 + C x 2
SSE4: FREND	A x 0.09 + B x 8 + C x 2

- FOM's factors:
  1. «A» proportional to delta SWaP figures
  2. «B» factor proportional to compression efficiency and processing resources needs
  3. «C» factor proportional to Focal Plane Array size

- Selection of FCI and MIPAS
- Performance Model application
  - **FCI** estimated Compression Ratio: 2-12, Power Saving: 75-89%
  - **MIPAS** estimated Compression Ratio: 0.1-1, Power Saving: 21-81%
- → both large instruments: no saving on size and weight as defined mostly by telescope CS implementation allows **dataset reduction + higher resolution + power saving**

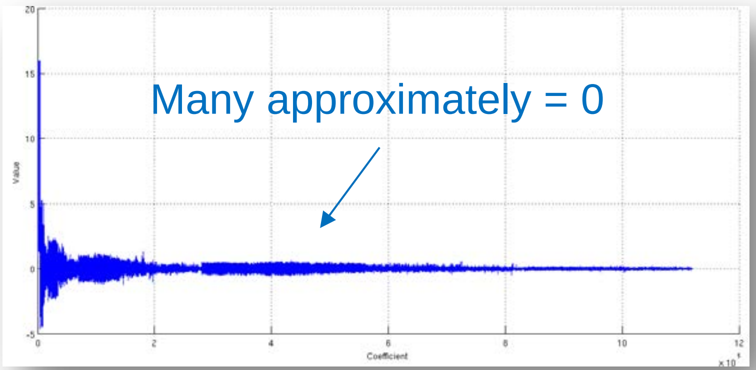
Would CS change the world ?



- Compression conventional limit is determined by the Shannon-Nyquist-Whittaker sampling theory
- Compressive sensing
  - Relies on signal's structure
  - Know structure → signal can be reconstructed using sampling rate <<< Nyquist rate.

Coefficients in wavelet domain

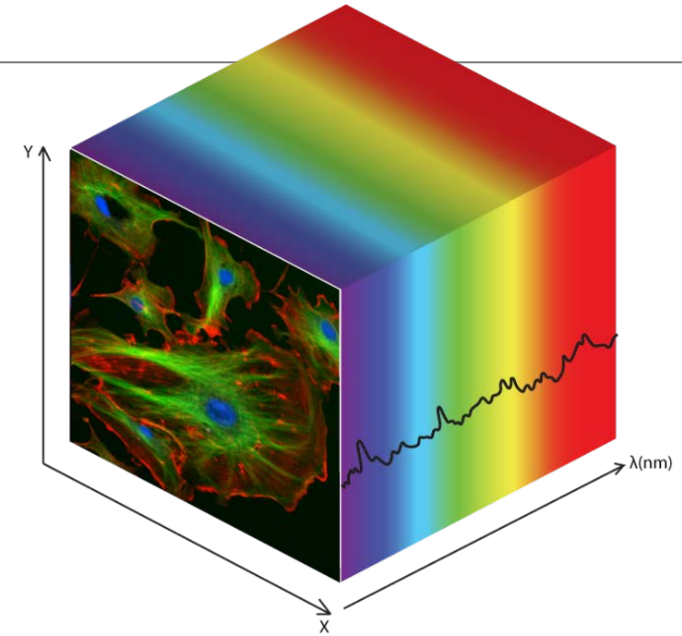
Original



95% compression

CS for multispectral instruments

- FCI/MIPAS = multispectral imagers
- High dimensional data cube
- However, highly redundant due to:
  - Intra-channel correlations (in one spectral band)
  - Inter-channel correlations (among several spectral bands)

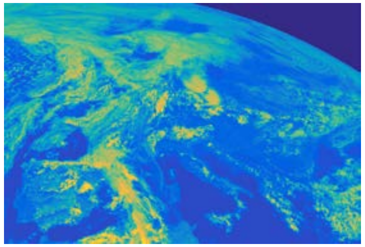


- → **efficient compression schemes must exploit both → goal for CS**

- Spectral data cube represented as $n1$ (spatial dimension) × $n2$ (spectral dimension) matrix

Transform domain ? SEVIRI images = FCI reference images

VIS 0.6



VIS 0.8

IR 1.6

IR 3.9

IR 8.7

IR 9.7

IR 10.8

IR 12.0

IR 13.4

WV 6.2

WV 7.3

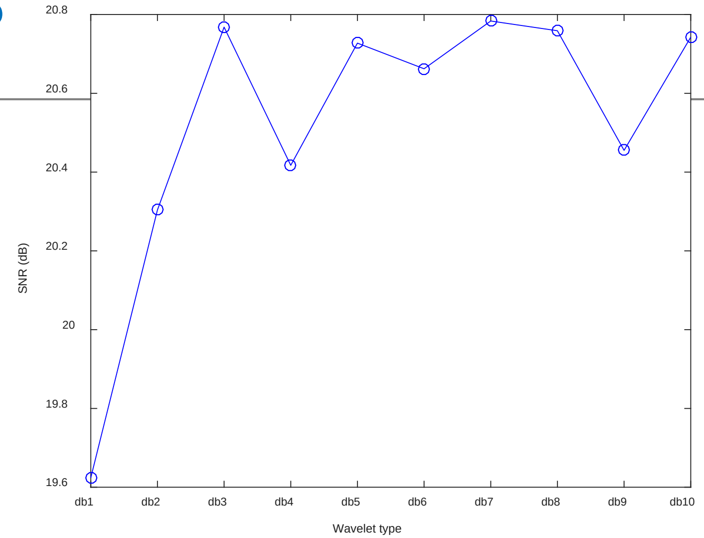
$$n_2 = 11$$

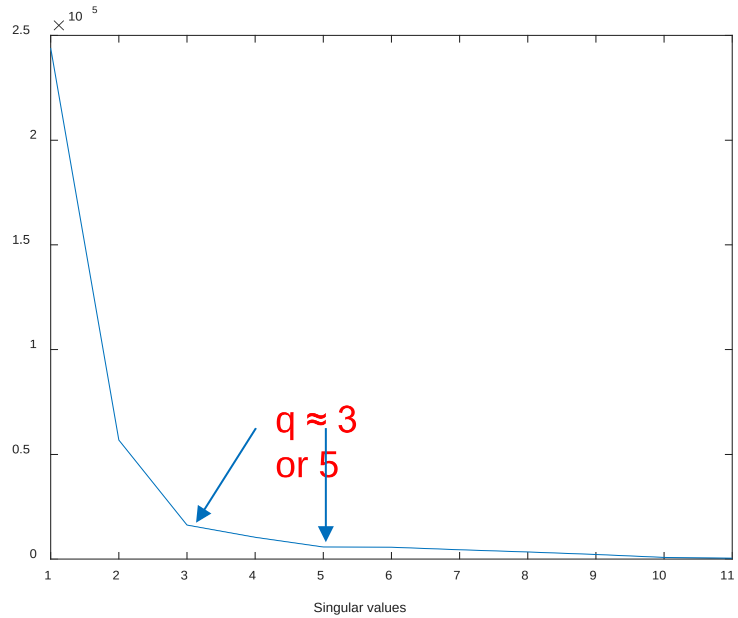
$$n_1 = 608 \times 1120$$

Sparsity in the transform domain ?

- **Choice of transform domain**:
  1. Curvelets → NOK
  2. Undecimated wavelet transform → NOK
  3. Daubechies wavelets → OK except db1
  4. SA: Sparsity Average model, concatenation of db5, db7 and db10 → the best

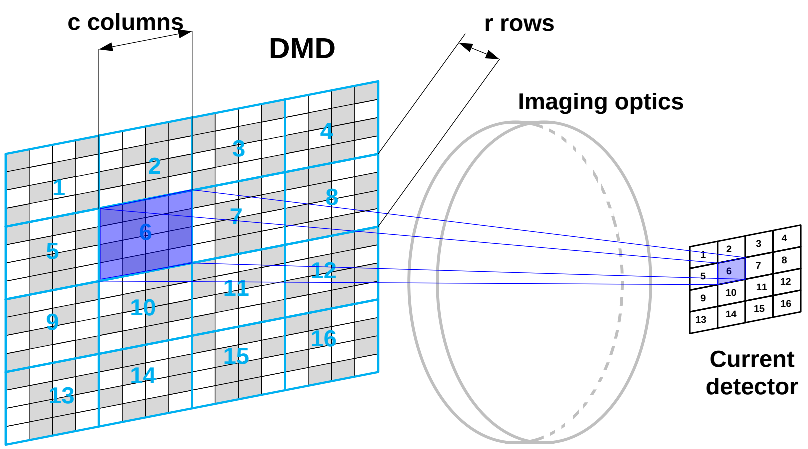
- **Singular Value Decomposition** to assess sparsity of reference image within the transform domain chosen



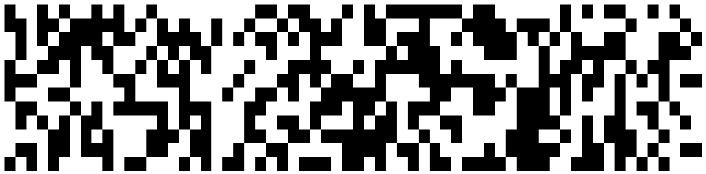


Measurement matrix

- Spatial sampling with DMD → Bernoulli distributed random variable
- With p= 0.5 → equal number of 0 and 1 maximises the light on the detector



- Bernoulli matrix for 12 meaurements:



- **Sense** channels **using different sensing matrix** for each channel

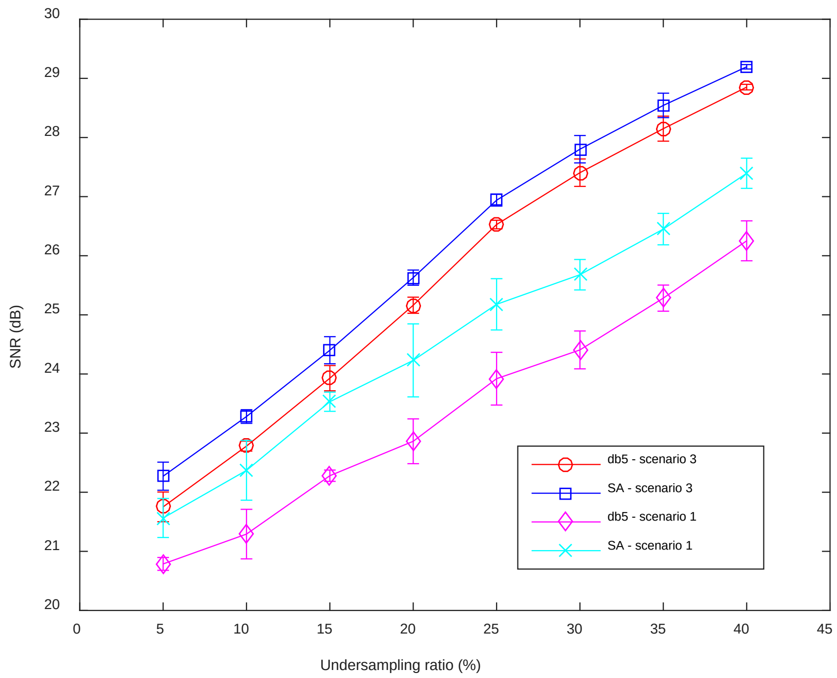
Reconstruction

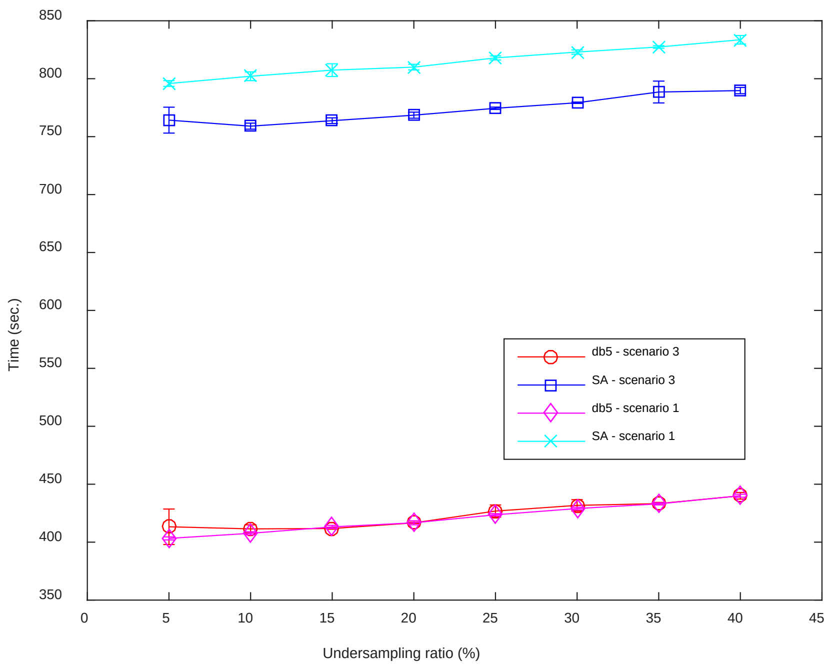
- Reconstruction = convex problem

$$\min_{X} \|X\|_* + \mu \|\Psi^T X\|_{2,1} \ \textit{subject to} \ \|Y - \mathcal{A}(X)\|_F \leq \epsilon$$

- Parallel proximal algorithm (PPXA) discarded → no advantages
- **Primal-dual with forward backward iterations (PD-FB)** chosen
- Computational challenges:
  - sensing operator and its adjoint (transpose) at each iteration
  - sparsity operator and its adjoint (inverse transform) at each iteration for all channels
  - perform SVD decomposition of X at each iteration: $O(n$1^2 n2+n2^3)
- The total complexity per iteration is: $\boldsymbol{O\left(\frac{2n_2mn_1}{L} + 6n_2n_1 + n_1^2n_2 + n_2^3\right)}$
- → Reconstruction shall be made on powerful computer

Reconstruction with transform domain chosen





Reconstructions performed using a MATLAB on
a i7 quadcore processor at 3.6GHz with 64Gb of RAM

CS implementation consequences

- Transform domain/Orthonormal basis – sparse representation

  A priori knowledge of the signal/image of interest is needed

  → SSE instruments where signal/image content cannot be known a priori not appropriate

- Incoherence transform domain/sensing matrix → random measurement
  - Several measurements required

    → situations where capturing sample/image in allocated time is challenging → not appropriate
  - challenge: determine where to introduce randomness in the measurement system

    ⟶ component presents in standard architecture → low impact

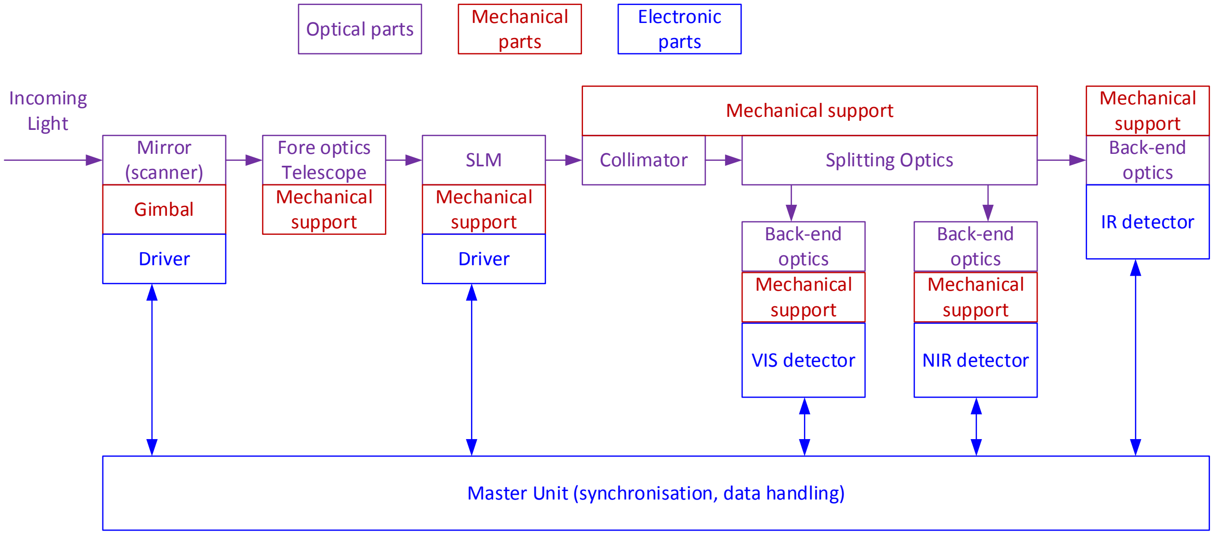
    ⟶ additional component → impact

- Reconstruction to take place where no limitation on processing resources exists

  → On-board reconstruction not recommended

EBB demonstrator concept for practical assessment

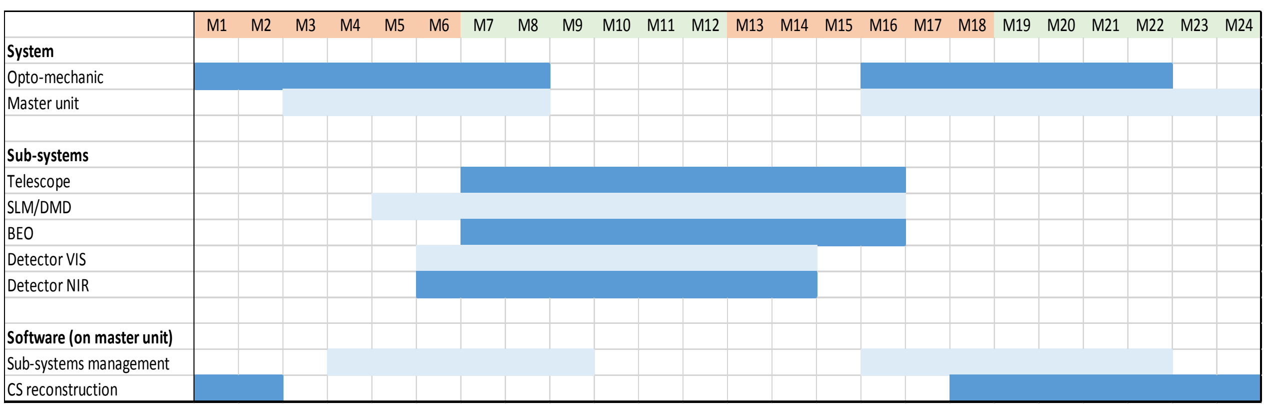
- Breadboard concept:



- Keep practical **comparison option with an existing standard instrument** leads to costly solution (spare parts, reproduction, etc.)
- → build a **breadboard configurable as standard and CS instrument**
- Focus on parts ONLY related to CS implementation challenges, not on other engineering fields (optics, detector, etc.)

Development roadmap

- EBB concept:
  - same hardware to compare standard and CS to address all factors discussed
  - Set EBB parameters as existing instrument (e..g. FCI VIS 448x4, 224x4, 112x4)
  - Not looking to increase TRL of building-blocks
  - Breadboard built with off-the-shelf components (DMD, DMD driver, foreoptics, etc.)
  - Limitation on engineering constraints → spectral channels limitation (no cryogeny) 3-5 spectral channels (e.g. min/max and central)
  - CS transform domain, measurement matrix and reconstruction already identified
  - Activity: ROM Cost 1.45 kEuro 24 months



Findings

- For large instrument such as FCI or MIPAS, introduction of SLM → negligable impact on mass and volume
- Large instrument + No need to on-board reconstruction → CS is competitive
- The project shows CS advantages in term of:
  1. compression ratio: 94% with 5% undersampling or 69% with 25% undersampling (target 5%)
  2. image capture time: 97% with 10% undersampling or 83% with 75% undersampling (target 5%)
  3. processing time: 100% (= 0)
  4. power consumption: 85% with 5% undersampling or 27% with 25% unders. (target 40%)
- **For SEVIRI like dataset** and **DMD as SLM** transform domain, measurement matrix and reconstruction algorithm are identified
- CS = lossy compression → degradation depends on transform domain, measurement matrix, undersampling and reconstruction algorithm → can be predicted and algorithms improved
- EBB designed
- EM development roadmap proposed based on developments for critical building-blocks

How to go for CS for other optical instruments ?

- PI or main user to be convinced that even with loss of information during measurements, predictable results can be exploited
- + practical consequences of CS precepts addressable within optical instrument architecture
- Receipt for CS:

Step	Description
1	Acceptance by the concerned scientific community to use «degraded» signal/image
2	Sparsity precept of the signal/image of interest ?
3	Availability of time to make several measurements ?
4	Low spatial resolution of detector in the spectral band of interest ?
5	Randomness introducible in the system architecture ?
6	Can reconstruction be where no limitation on resources is present ?

Thank you for your attention!

Follow us on

www.csem.ch