Numerical tools for radiative transfer and the calculation of velocity fields on the Sun' surface

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Two families of numerical codes for the interpretation of past (SoHO), present (Hinode, SDO, IRIS, Solar Orbiter) or future solar and stellar space data are presented here :

- **Non-LTE radiative transfer codes in 1D and 2D dedicated to various solar (prominences, filaments, chromospheres, etc) and stellar structures.**
- **Coherent Structure Tracking (CST) codes computing horizontal velocity field on the Sun's surface by using solar granules as tracers.**

Radiative transfer codes

- For more than 30 years, numerical codes for Non-LTE radiative transfer have been developed at IAS. They are dedicated to various solar and stellar structures. Different geometries are considered: 1D, 2D cylindrical. Radiatve transfer (Feautrier method) is computed both for continua and for lines belonging to various atomic systems (H, He, Mg, Ca, Fe, Ni) and velocity fields are also included. These codes have already been extensively used for **SOHO**, and more recently for **AIA/SDO** images and **IRIS** spectra.
- A set of codes from IRAP in 1D and 2D cartesian geometries including modern numercial methods: MALI (Multilevel Accelerated Lambda Iteration), Gauss-Seidel, Multi-grid method combined with the method of short characteristics (Leger, PhD 2008) are also available at MEDOC, in preparation of the analysis of **Solar Orbiter** and future missions.

Where are these codes?

On MEDOC website:
https://idoc.ias.universite-paris-saclay.fr/MEDOC/Radiative%20transfer%20codes

Summary of available codes at MEDOC

- PROM5: 1D prominence model with profiles of varying physical properties across the prominence (H)
- PROM7: 1D prominence/filament, isobaric-isothermal atmosphere model (H, Ca)
- HYDR_NV/ATSTHS: 1D **semi-infinite atmosphere** (H, Mg, Ni, Na, Fe)
- PRODOP: 1D prominence model with velocity field (H, Ca, Mg, He)
- CYLA2DV: 2D cylinder model with velocity field (H)
- C2D2E: 2D cylinder model (H, He)
- Tools for Non-LTE radiative transfer (1D) can be used to construct new models using modern numerical methods
- H3CRD: 1D **semi-infinite atmosphere** (H). MALI combined with the method of short characteristics is used to solve multilevel non-LTE radiative transfer
- MALI and Gauss-Seidel: 2D prominence (H, He). Multilevel non-LTE radiative transfer solved either by MALI or by a Gauss-Seidel iterative scheme on a 2D Cartesian grid
- NLTE2D: 2D prominence (H). Multilevel non-LTE radiative transfer solved by MALI, Gauss-Seidel, and Successive Over-Relaxation (SOR) iterative schemes in 2D, together with a multi-grid algorithm, combined with the method of short chatacteristics in Cartesian geometry.

All theses codes are written in Fortran. The last three codes allow easy implementation of additional lines, e.g. lines observed by Solar Orbiter instruments.

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Work in progress

A benchmark based on NLTE2D code dedicated to ionization balance and a relevant documentation are in preparation.

Principle of the CST

The CST method allows to determine spherical velocity fields (V_r, V_φ, V_θ) from high to low spatial and temporal resolutions over the full Sun surface. The applications are various: diffusion of the magnetic field (quiet and active regions), detection of the filament eruptions solar rotation, meridian circulation, links with solar wind production,... CST codes are a set of codes written in Fortran and IDL. The IDL part is being converted into Python (work in progress).

Results

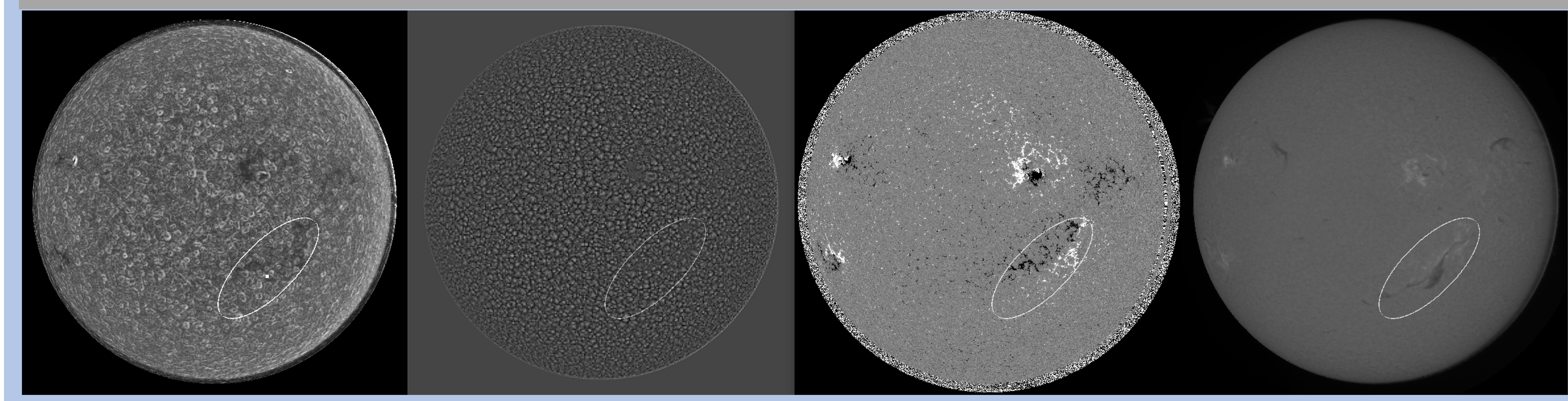
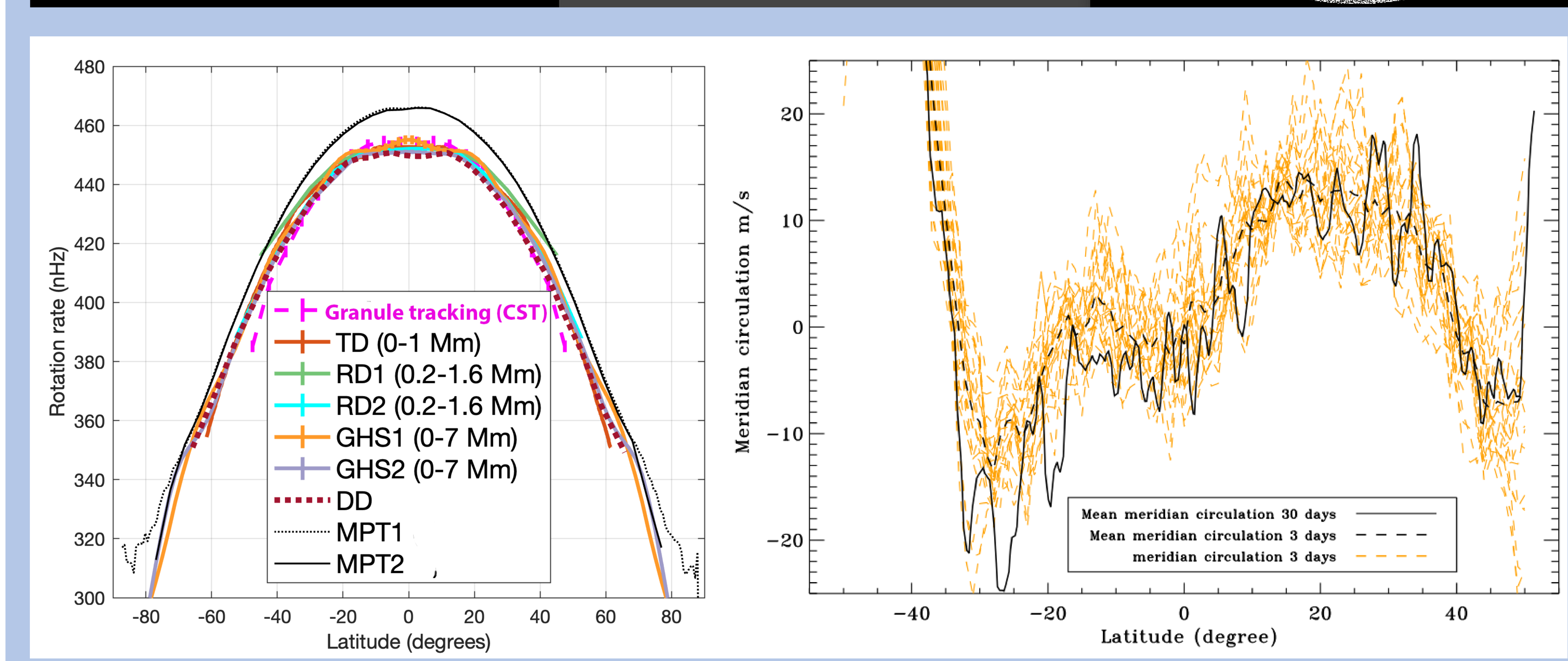


Fig 1: Full Sun observations on 26/01/2016, spatial resolution 2.5Mm.
From left to right (at small scales): horizontal velocity module and divergence fields produced by CST codes, longitudinal magnetic field (HMI/SDO), H_α image from GONG. *Roudier et al. A&A 618, A43 (2018)*



Where are these codes? On MEDOC website:
https://idoc.ias.universite-paris-saclay.fr/MEDOC/CST%20codes

Fig 2:
Large scales motions with CST. **Left:** CST solar rotation measurement (pink) compared to plots obtained with different other techniques (Upton et al. 2023 under publication). **Right:** meridional circulation measured with CST during obtained between 16/08-14/09 2010 of the 30-day series. (Roudier et al A&A 611, A92, 2018) .

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