# Probing the solar corona with Doppler and range measurements of the spacecraft BepiColombo

Irene Doria, Paolo Cappuccio, and Luciano Iess
*Sapienza University of Rome, Radio Science Laboratory, Rome, Italy* (irene.doria@uniroma1.it)

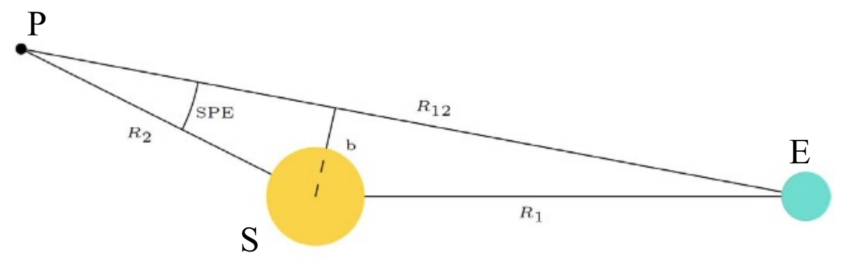


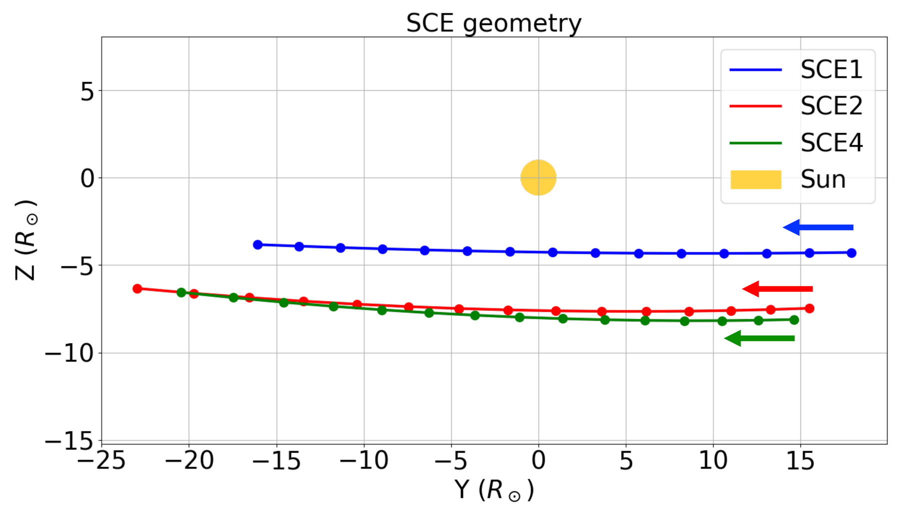
## BepiColombo and MORE

- BepiColombo is a joint mission ESA/JAXA, launched on 20th October 2018. It is currently in cruise towards Mercury and it has 16 experiments on-board to characterize it.
- MORE (Mercury Orbiter Radioscience Experiment):
  - Static gravity field and gravitational tidal response of Mercury
  - Mercury's rotational state
  - Fundamental physics tests→ determination of several post-newtonian parameters

### Superior solar conjunction geometry

- During a superior solar conjunction, the probe and the Earth are almost aligned with the Sun in-between
- The line of sight of the signal passes really close to the Sun, in the inner solar corona → the multifrequency link allows us to isolate the plasma contribution on the uplink and downlink leg
- Three solar conjunctions campaigns are considered: SCE1 (2021), SCE2 (2022) and SCE4 (2023)




## Intensity spectrum analysis

- From the open-loop data of SCE1, intensity spectra are computed using the Welch method
- The following theoretical model for the intensity spectrum is assumed (Scott et al. 1983):

$$P(f) = \frac{2\pi(\lambda r_e)^2}{V}\int_{-\infty}^{+\infty}\Phi_n\left(k_x = \frac{2\pi}{V}f, k_y\right)F_{diff}(k)dk_y$$

$$F_{diff}(k) = 4\sin^2\left(k^2\frac{\lambda z}{4\pi}\right)$$

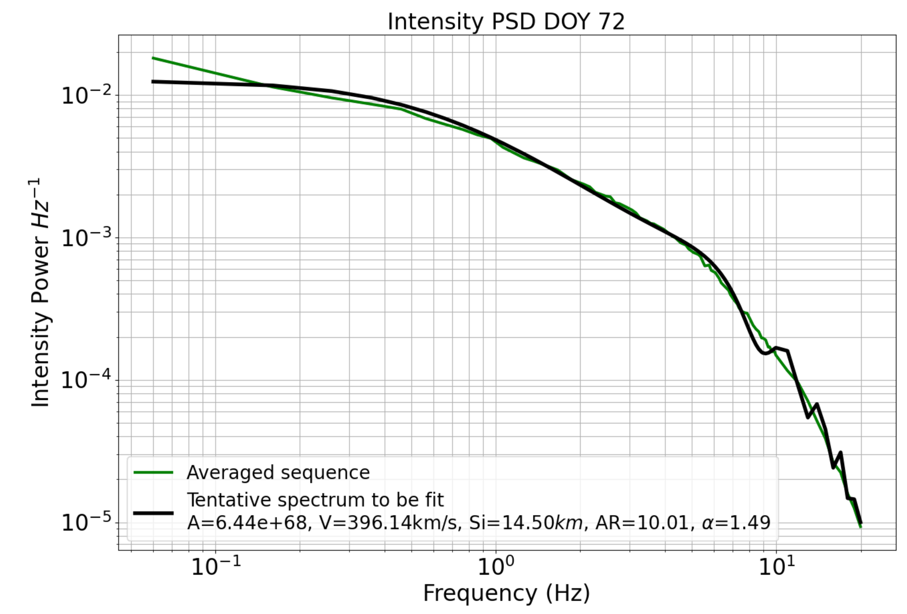
$$\Phi_n(k) = A\left(\sqrt{k_x^2 + \frac{k_y^2}{AR^2}}\right)^{-\alpha} exp\left(-\frac{k^2 S_i^2}{9}\right)R^{-4}$$

where $\lambda$ is the wavelength of the carrier signal, **$V$ the solar wind velocity**, **$AR$ the axial ratio, $A$ a constant, $S_i$ the inner scale, $\alpha$ constant of the power law**, $R$ the impact parameter, $z = \frac{L_1 L_2}{L_1+L_2}$ ($L_1$ and $L_2$ distances of Earth and spacecraft from closest approach), $k_x$ wavenumber in radial direction

- A least square fitting would be **very sensitive to the initial conditions.** We use a particle swarm optimization **(PSO) algorithm** to find a **global minimum** and then run a **least square fitting** starting from the output of the PSO.

- **Uncertainties**:

$\sigma_A = 1.97 \cdot 10^{69}$,
$\sigma_V = 30.05$ km/s,
$\sigma_{S_i} = 7.39$ km,
$\sigma_{AR} = 19.24$ and
$\sigma_\alpha = 0.995$



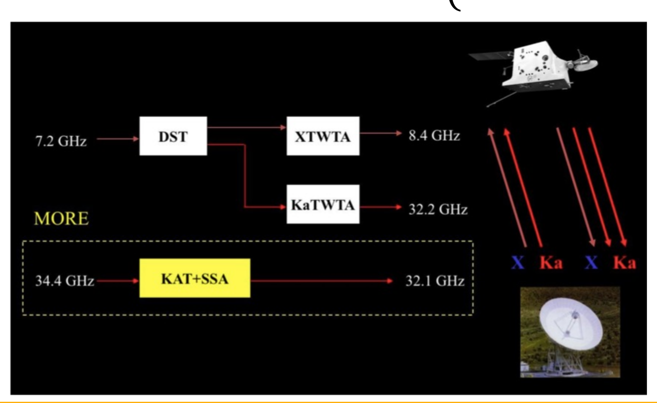

- The only parameter that we can constrain is the velocity. The uncertainties on the other parameters are too large

## Plasma calibrations

- The MORE radiotracking system relies on a **multi-frequency radio link**: three downlinks (X, Ka1, Ka2) and two uplinks (X, Ka).
- The signal due to the solar corona plasma can be isolated through precise calibrations exploiting the dispersive nature of the plasma itself:

$$\begin{cases} y^{obs}_{X/X} = y_{nd} + y_{pl\_up} + \frac{1}{\alpha^2_{X/X}} y_{pl\_dn} \\ y^{obs}_{X/Ka} = y_{nd} + y_{pl\_up} + \frac{1}{\alpha^2_{X/Ka}} y_{pl\_dn} \\ y^{obs}_{Ka/Ka} = y_{nd} + \frac{1}{\beta^2} y_{pl\_up} + \frac{1}{\beta^2 \alpha^2_{Ka/Ka}} y_{pl\_dn} \end{cases}$$

$y^{obs}_{X/X}$, $y^{obs}_{X/Ka}$ and $y^{obs}_{Ka/Ka}$ are the Doppler or range observables and $y_{pl\_up}$ and $y_{pl\_dn}$ are the **plasma contributions.**

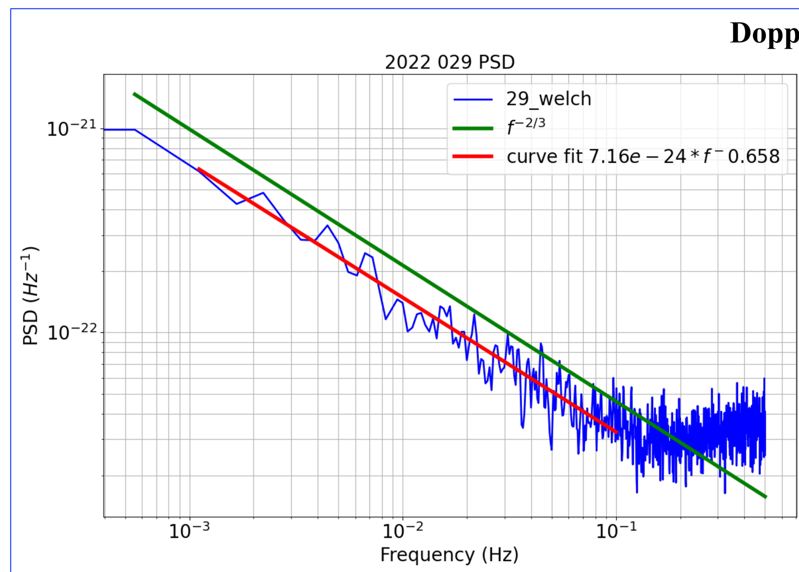



Configuration scheme of the BepiColombo radio system

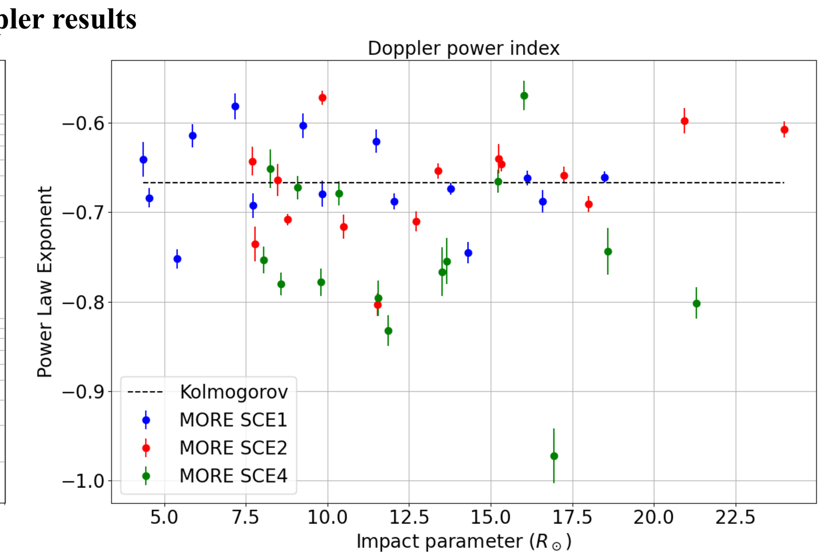
## PSD of plasma content on Doppler and range signals

- The PSD of the plasma contribution is computed using the **Welch method** in order to filter the thermal noise: Hanning window of length 1800 seconds for Doppler signals and 3600 for range signals.
- The resulting PSD is expected to follow the exponential law of the **Kolmogorov spectrum**: $f^{-2/3}$ **for the Doppler** observables and $f^{-5/3}$ **for the range** ones.
- In order to compute the power-law index, it's important to correctly choose the interval of frequencies, where the PSD follows the Kolmogorov spectrum.

### Doppler results

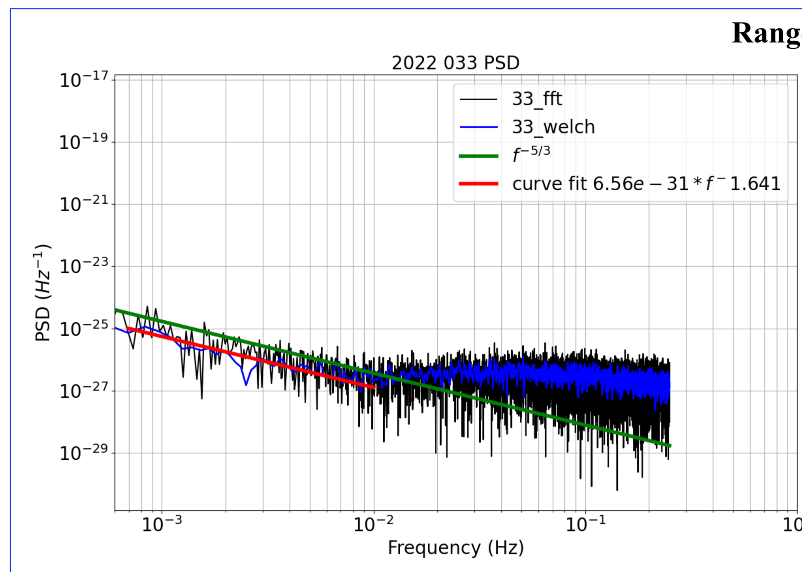



29th January 2022 PSD Doppler

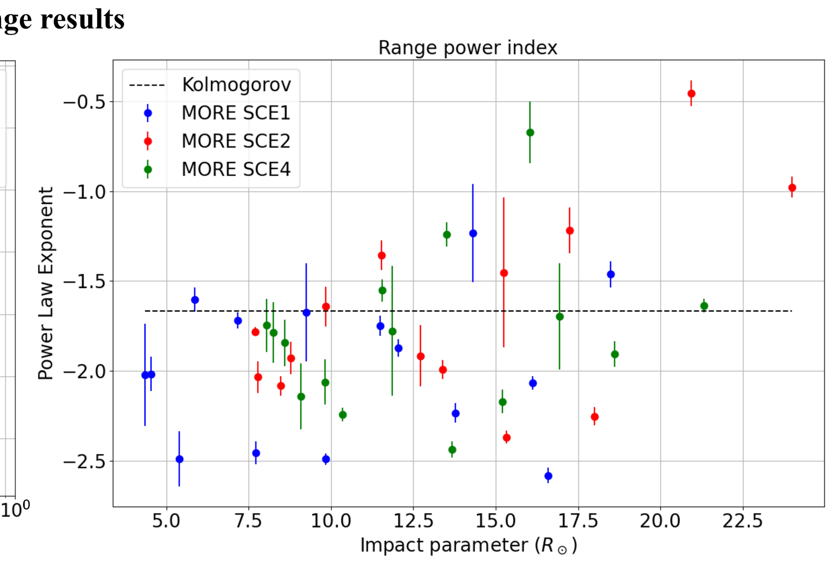



Doppler power-law indexes for SCE1, SCE2 and SCE4

### Range results




2nd February 2022 PSD Range




Range power-law indexes for SCE1, SCE2 and SCE4

## Electron density model

- The **Mercier-Hollweg electron density model** has been considered (David B. Wexler *et al.*, 2019):

$$N_e = \left(\frac{65}{r^{5.94}} + \frac{0.768}{(r-1)^{2.25}}\right) \times 10^{12} \quad e^-/m^3$$

- Relation between electron density and Total Electron Content (TEC), which is the total number of free electrons contained in a column (1 m² cross section) joining satellite and receiver:

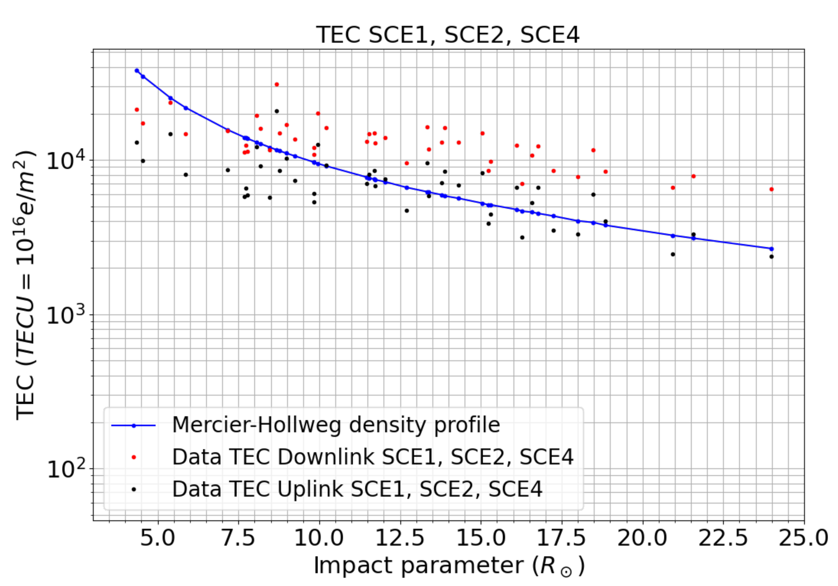
$$TEC = \int_{sat}^{rec} N_e(s)ds$$

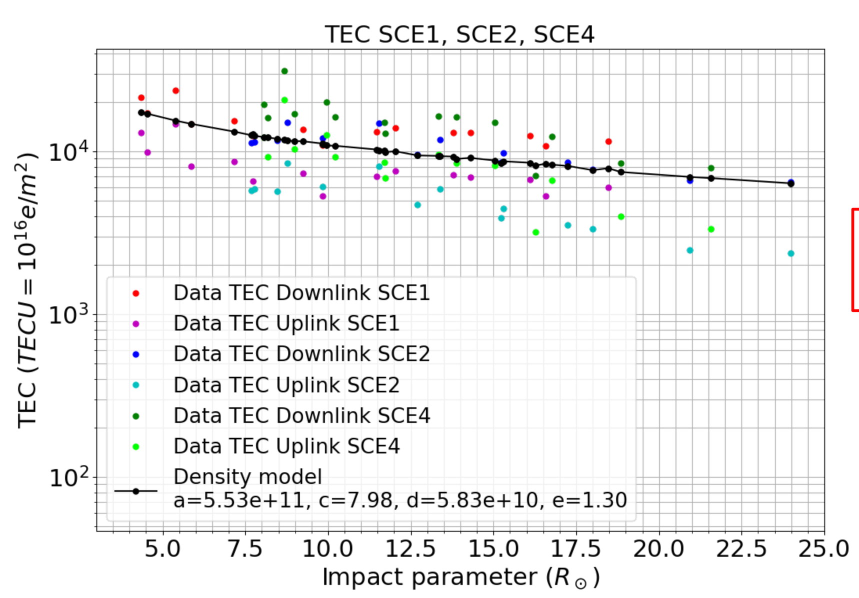
- Moreover, the **TEC** can be computed **from range observables** with the following expression:

$$TEC = \frac{\Delta s \cdot f^2}{k}, \qquad k = \frac{e^2}{8\pi\, m_e\, \epsilon_0}$$

where f is the carrier frequency and $\Delta s$ is the delay induced by the solar plasma (retrieved from the calibrations on range observables).

- The TEC data obtained with this last formula are then fitted with the theoretical model for electron density $N_e = \frac{a}{r^c} + \frac{d}{(r-1)^e} \quad e^-/m^3$ (the parameters to be estimated are $a$, $c$, $d$ and $e$). The initial conditions for the **least squares fitting** are retrieved from the PSO algorithm.




$$N_e = \frac{5.53 \cdot 10^{11}}{r^{7.98}} + \frac{5.83 \cdot 10^{10}}{(r-1)^{1.30}} \quad e^-/m^3$$

Comparison between data obtained from range observables and the electron density profile obtained from the fitting procedure

## Plasma features space-time localization

**Cross-correlation between uplink and downlink** Doppler time series allows to localize in space and time plasma structures, like Coronal Mass Ejections (CME); in particular, the method proposed by Richie-Halford has been considered (A. C. Richie-Halford *et al.*, 2009). The steps are the following:

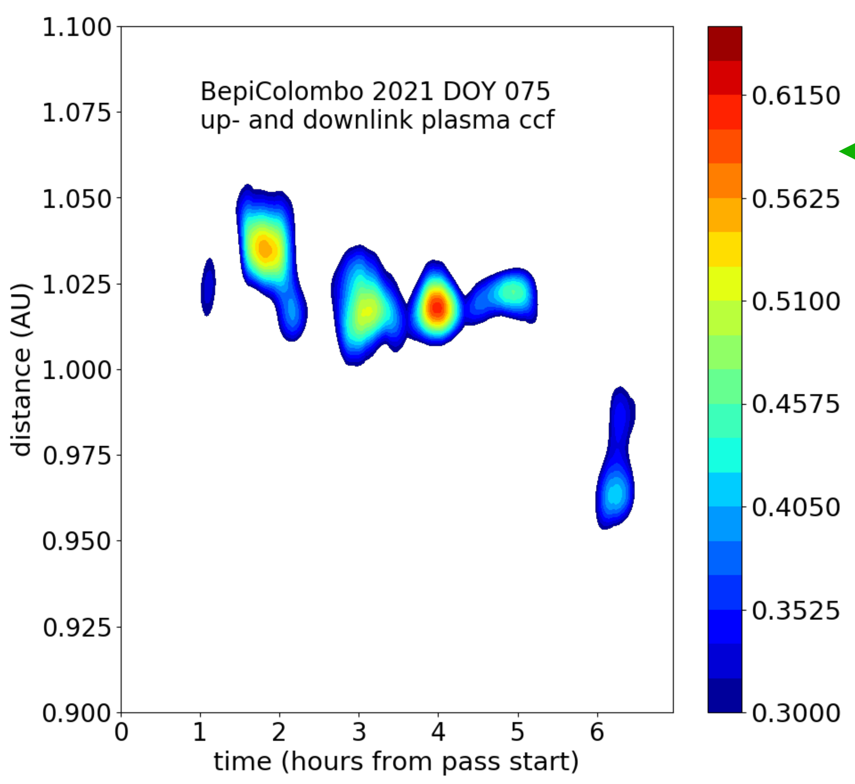
- Bandpass filter: order 5, lowcut=0.001 Hz, highcut=0.05 Hz
- **Triangular time window**:

$$\begin{cases} \Lambda(t) = 0 \;\; if\; |t| > 1 \\ \Lambda(t) = 1 - |t| \;\; if\; |t| < 1 \end{cases} \rightarrow \quad \Lambda_{down}(t) = \Lambda\left(\frac{t-t'}{1800\ s}\right), \quad \Lambda_{up}(t) = \Lambda\left(\frac{t-t'-T_2+1000\ s}{1800\ s}\right)$$

where $T_2$ is the round-trip light-time (1500 s) and the offset of 1000 s in the uplink is due to the apriori expectation that the main plasma contribution is at ~1AU

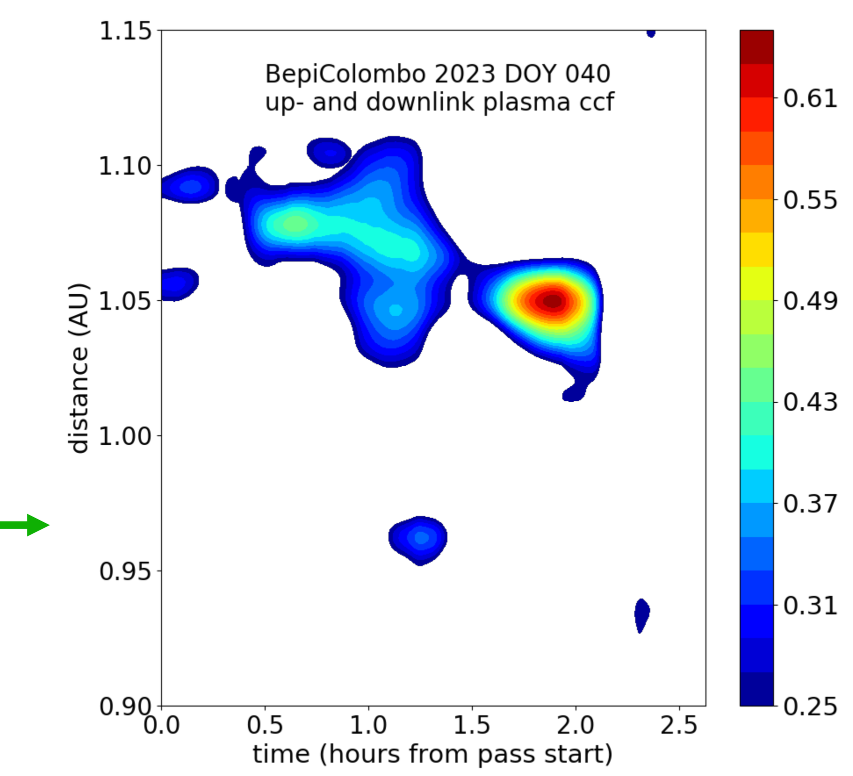
- Cross-correlation between the two time series

The **time window** is then advanced by **10 s** and the process is repeated until the end of the time series is reached.




- The highest peak is ~0.61, about 4h after the start of the pass and at ~1.018 AU from Earth
- The plasma blob due to the CME has a spatial dimension of ~0.01 AU considering ccf > 0.5 (or ~0.023 AU with ccf > 0.3)

- The highest peak is ~0.64, about at 1.89h from the start of the pass and at ~1.05 AU from Earth
- The plasma blob due to the CME has a spatial dimension of ~0.017 AU considering ccf > 0.5 (or ~0.033 AU with ccf > 0.3)




**References**

- David B. Wexler *et al.*, Spacecraft Radio Frequency Fluctuations in the Solar Corona: A MESSENGER-HELIOS Composite Study, *ApJ* **871** 202, 2019
- A. C. Richie-Halford *et al.*, Space-time localization of inner heliospheric plasma turbulence using multiple spacecraft radio links, *Space Weather*, **7**, S12003, 2009
- S. L. Scott, W. A. Coles and G. Bourgois, "Solar wind observations near the sun using interplanetary scintillation", *Astronomy and Astrophysics* **123**, 207-215, 1983

EGU 2023 Vienna, Austria & Online | 23–28 April 2023