



Leibniz-Institut für
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Evolution of coronal radio wave scattering during an M class solar flare

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Solar observations with LOFAR

The Sun is a strong radio source:

- Thermal: 10^6 K corona
- Non-thermal: Flares, CMEs

Intensities:

- Thermal: some 10^4 Jy
- Non-thermal: up to 10^8 Jy

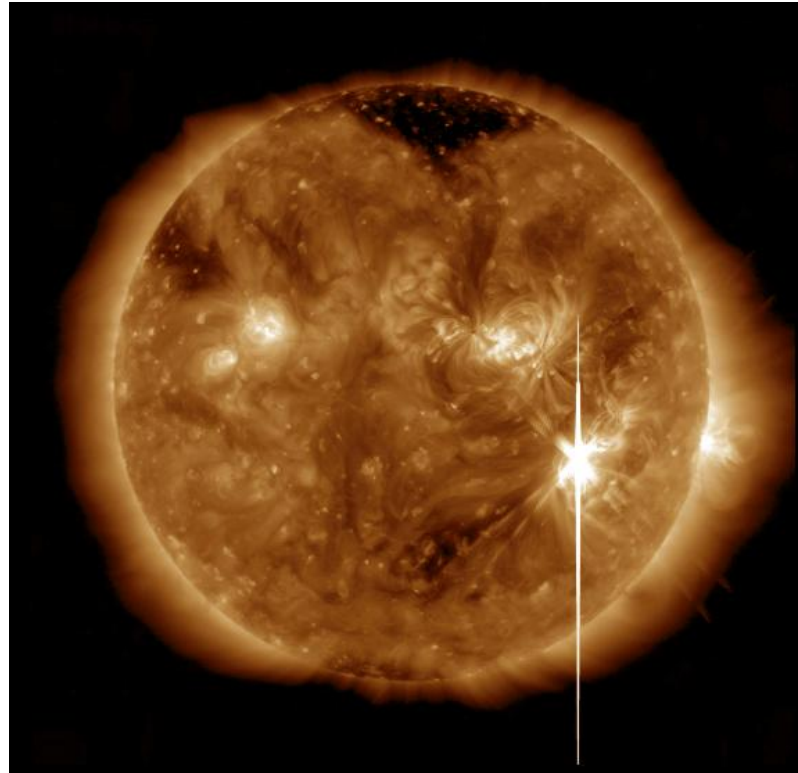
Non-thermal radio wave emission:

- Plasma emission
- Energetic electrons in the Plasma
 - Electrostatic instability, Langmuir waves
 - Wave-wave interaction creates radio waves
 - Wave emission at local plasma frequency:

$$f = \sqrt{Ne^2/(m_e\epsilon_0)}/(2\pi)$$

and its harmonics

The frequency f depends
only on the density N



LOFAR observation of an M class flare

Scheduled observations:

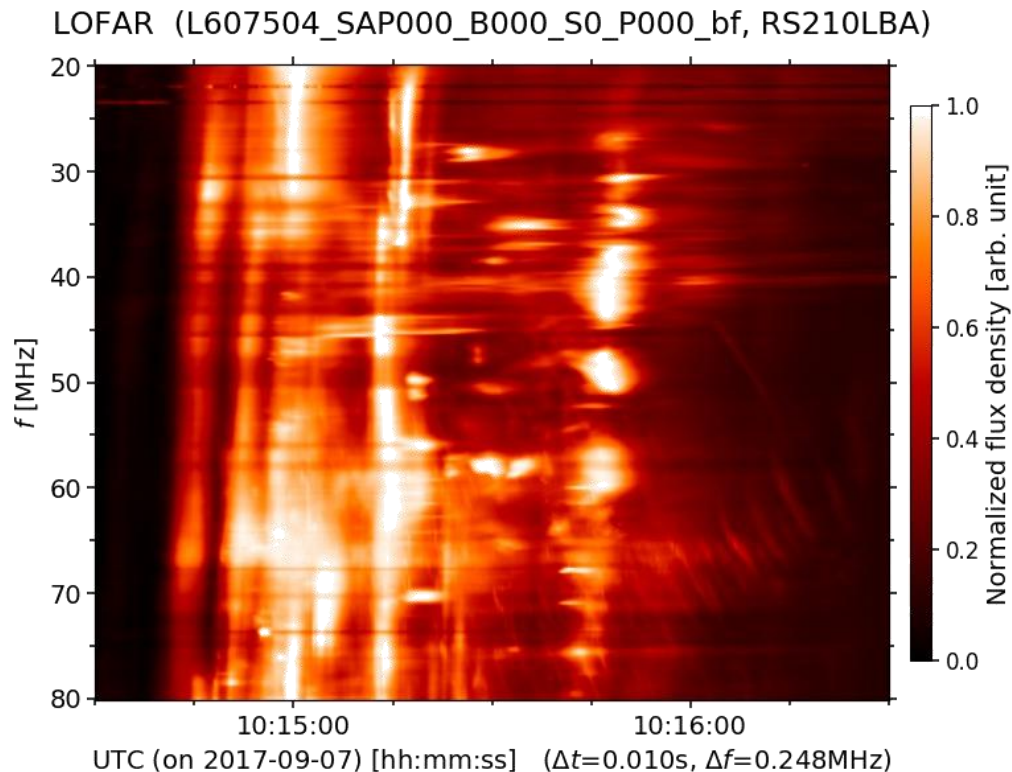
- Observations scheduled for enhanced solar activity
- 6 h observing time over noon
- 0.25 s imaging sequence
- Interferometric in LBA, dynamic spectra in LBA+HBA
- Old data, but among best flare observations

M class solar flare:

- Starting at 10:14:40 UT
- Accompanied by several type III bursts

Type III radio burst observations:

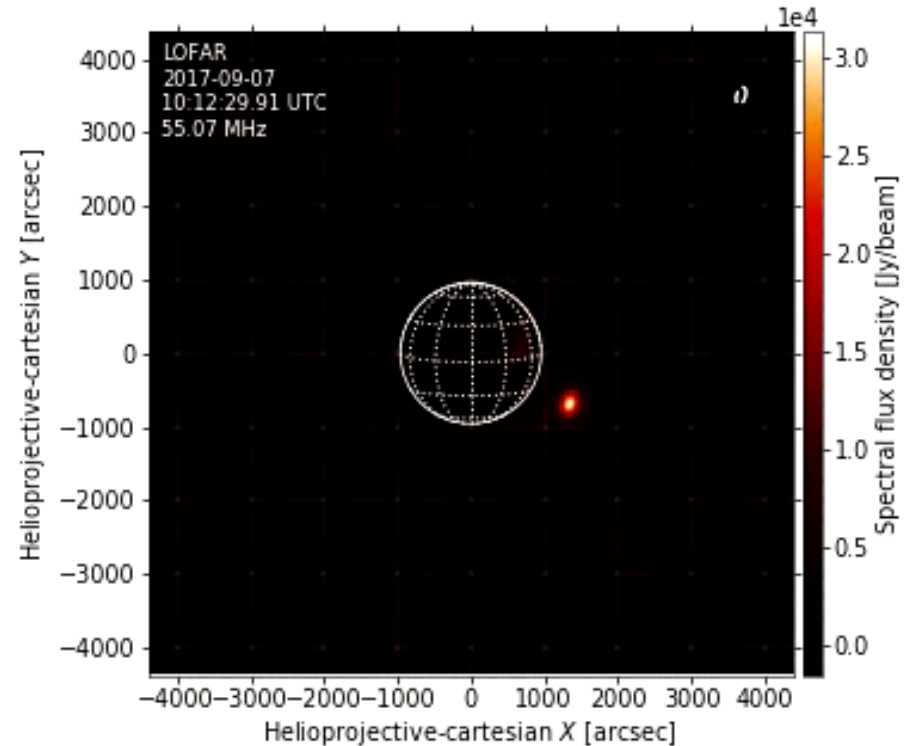
- Spectra show dense forest
- Fundamental and harmonic emission cannot be distinguished



LOFAR observation of an M class flare

Interferometric imaging with LOFAR:

- Burst appears as compact source
- Constant height: Plasma freq. = observing freq.
- Intermittent dual-source structure
- Interpreted as fundamental and harmonic emission
- Provides an opportunity to study F and H sources separately



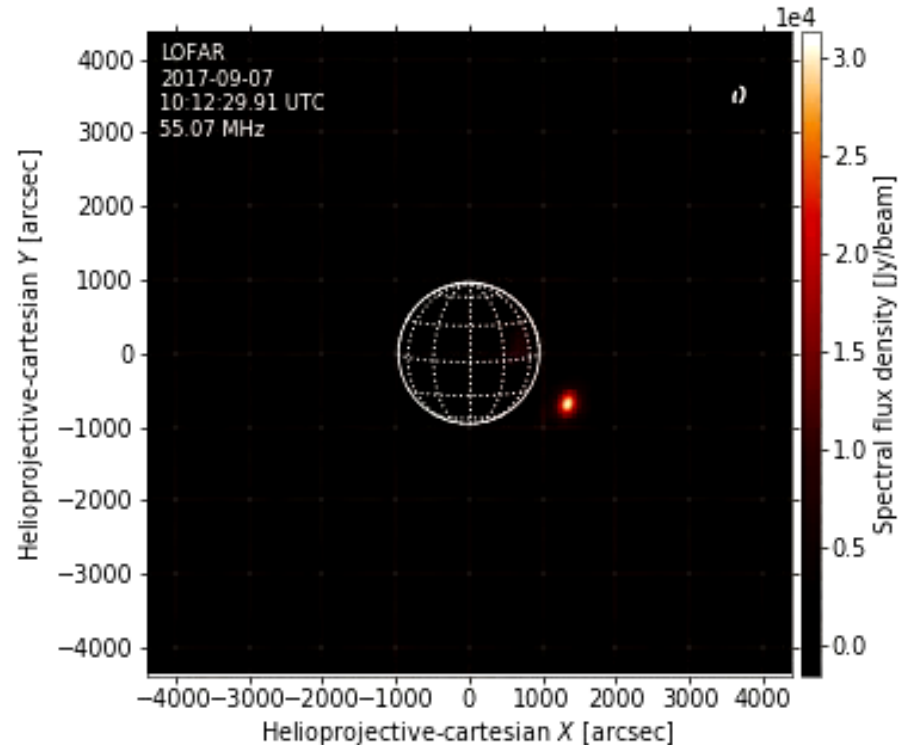
LOFAR observation of an M class flare

Interferometric imaging with LOFAR:

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Fundamental – harmonic pairs:

- Fundamental emission on one frequency, f
- Harmonic emission from twice that frequency, $2f$
- Should originate from the same coronal source region
- Relative shift due to scattering and refraction
- Changes in relative position: Changing coronal conditions



Fundamental and harmonic plasma emission

Given observation frequency: f_{obs}

Plasma frequency:

$$f_p = (N e^2 / (m_e \epsilon_0))^{1/2} / (2 \pi)$$

Refractive index:

$$n = (1 - f_p / f)^{1/2}$$

Fundamental emission:

$$f_p = f_{\text{obs}}, n \rightarrow 0$$

Harmonic emission:

$$f_p = f_{\text{obs}} / 2, n = 0.886$$

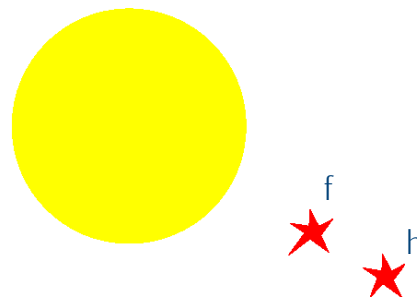
Fundamental and harmonic sources:

- f source: local plasma frequency is f_{obs}
- h source: local plasma frequency is $f_{\text{obs}} / 2$
- located higher in the corona

Separation of f and h sources

Fundamental – harmonic pairs:

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Radio wave propagation in the corona

Competing effects: Refraction and scattering

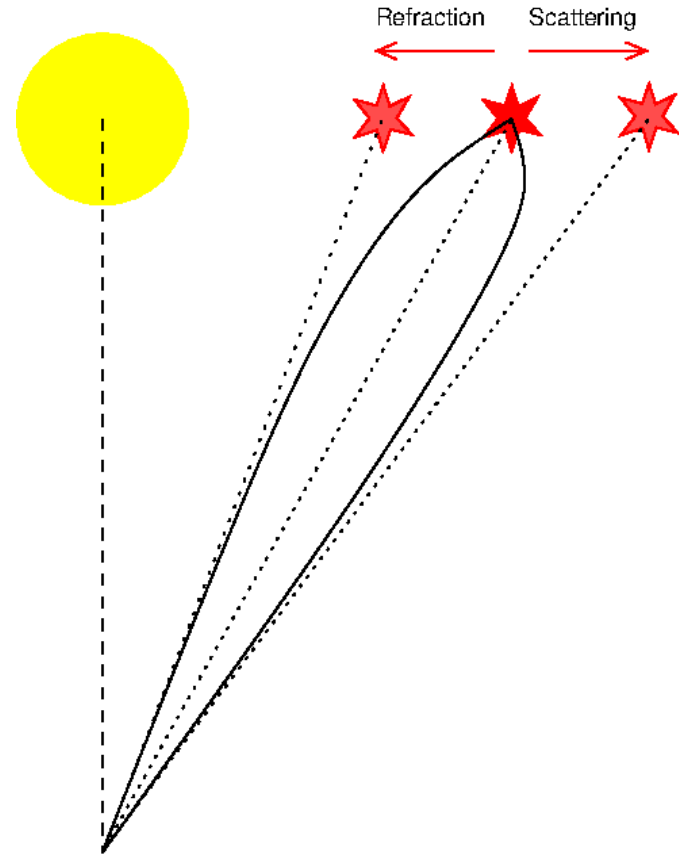
Refraction:

- Large-scale density decrease with height
- Refractive index increases
- Snell's law
- Ray path curved away from the Sun
- Shift of apparent source position toward the solar disk center

Scattering:

- Turbulent density fluctuations
- Variation of refractive index
- Distortion of wave fronts
- Not isotropic
- Net result is an apparent source position away from the Sun

These effects are stronger for f than for h emission.



Evolution of f and h sources

Gaussian fits:

- Strongest source (blue)
- Subtract this source
- Second strongest source (red)

Source positions:

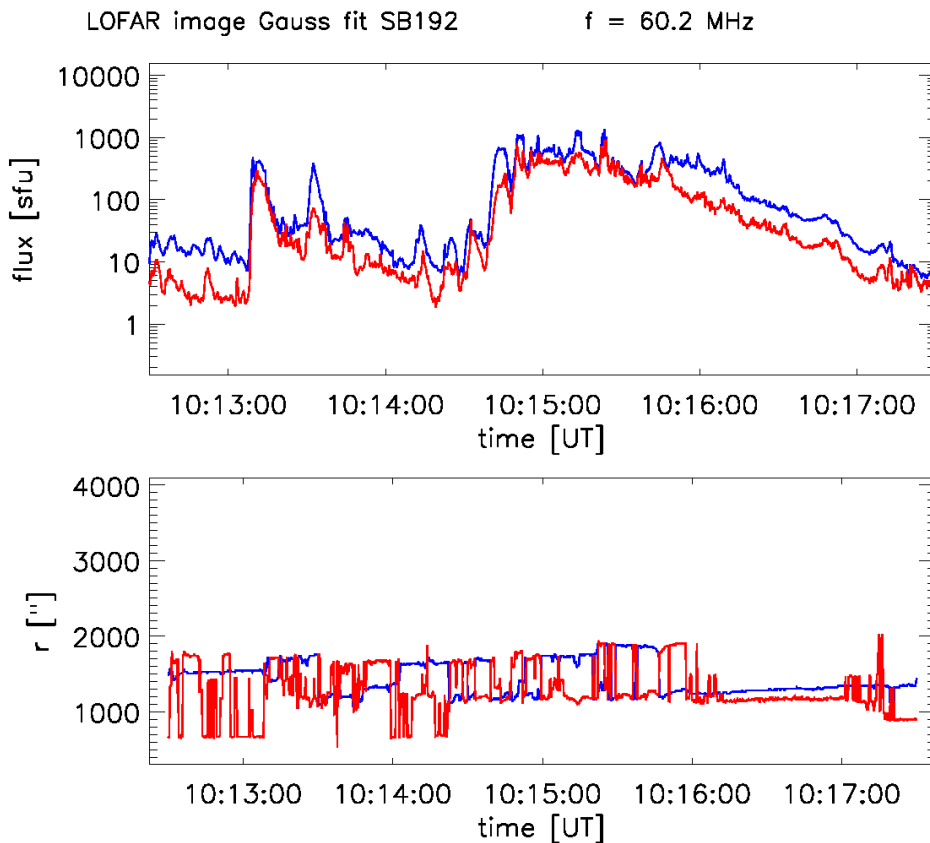
- (x, y) positions from Gaussian fits
- Compensate for drift over time

Fundamental and harmonic fluxes:

- Areas around (x, y)
- Integrate flux over these areas

Result:

Separate lightcurves for fundamental and harmonic sources



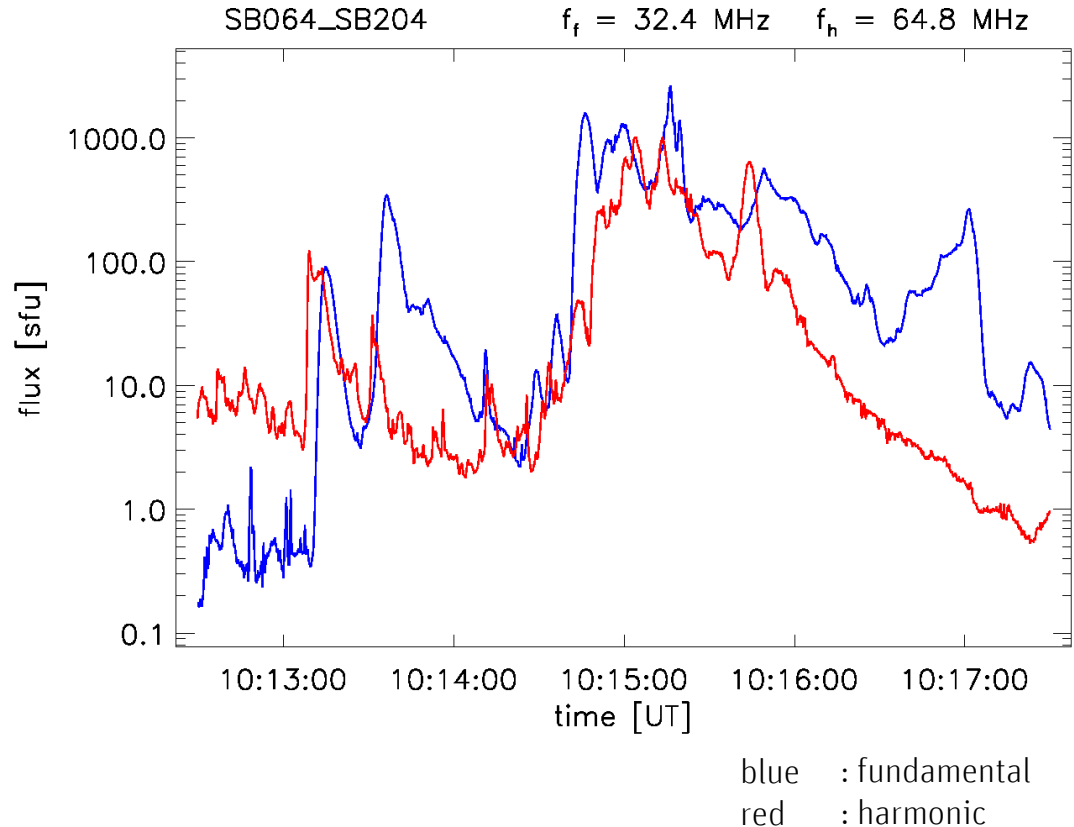
Fundamental – harmonic pairs

Example: 32.5 / 65 MHz:

- Fundamental emission at 32.5 MHz
- Harmonic emission at 65 MHz
- Originate from the same source region

Differences between lightcurves:

- Earlier onset for harmonic at 10:13:05 UT
- Not visible at 10:14:30 UT
- Caused by dispersion relation of plasma waves



Fundamental – harmonic pairs

Example: 32.5 / 65 MHz:

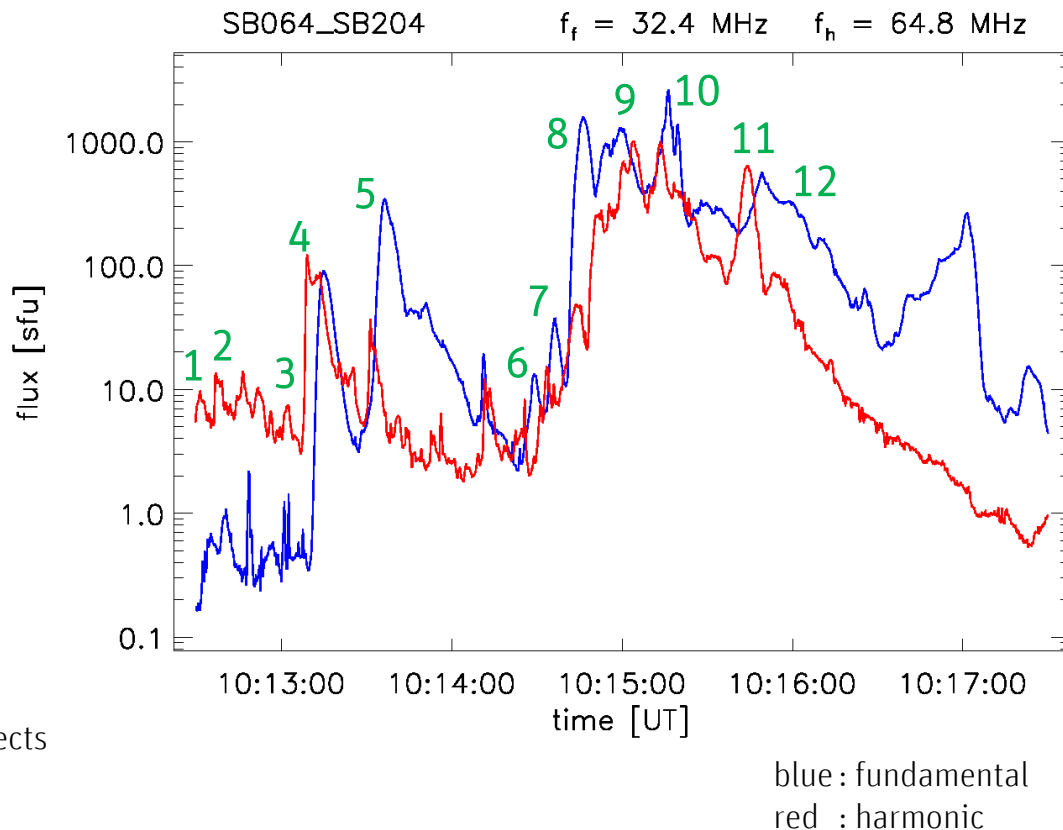
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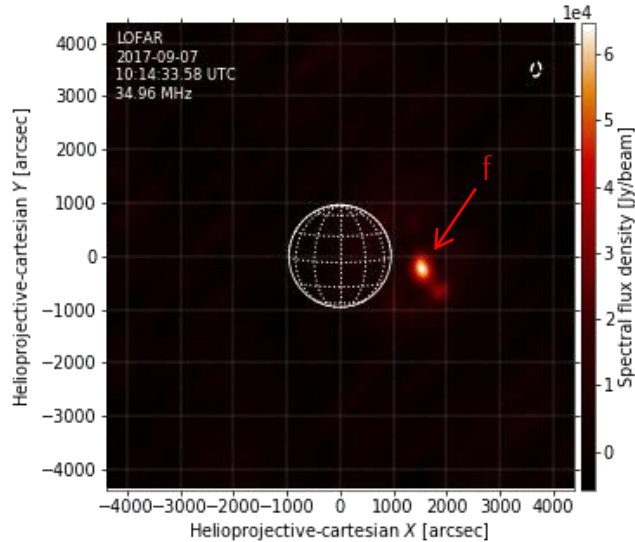
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Comparison of F and H source positions:

- 12 individual bursts during the flare
- From pre-flare over impulsive to gradual phase
- Time near burst onsets to minimize diffusion effects

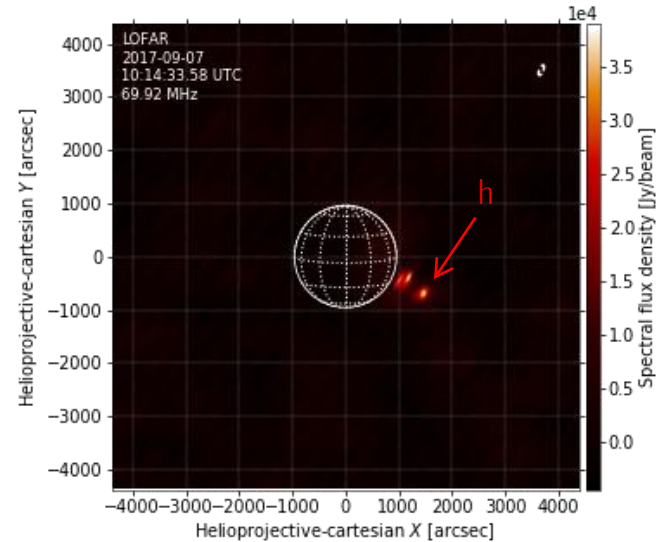


Relative positions of fundamental and harmonic sources



Position of fundamental source:

$x = 1528''$, $y = -226''$, $r = 1545''$



Position of harmonic source:

$x = 1430''$, $y = -667''$, $r = 1578''$

$$\Delta x = -98'', \Delta y = -441'', \Delta r = 33''$$

Same source region: Scattering and refraction is stronger for fundamental emission

→ Insights into radio wave propagation in the corona

Temporal evolution of relative source positions

Plotted position differences

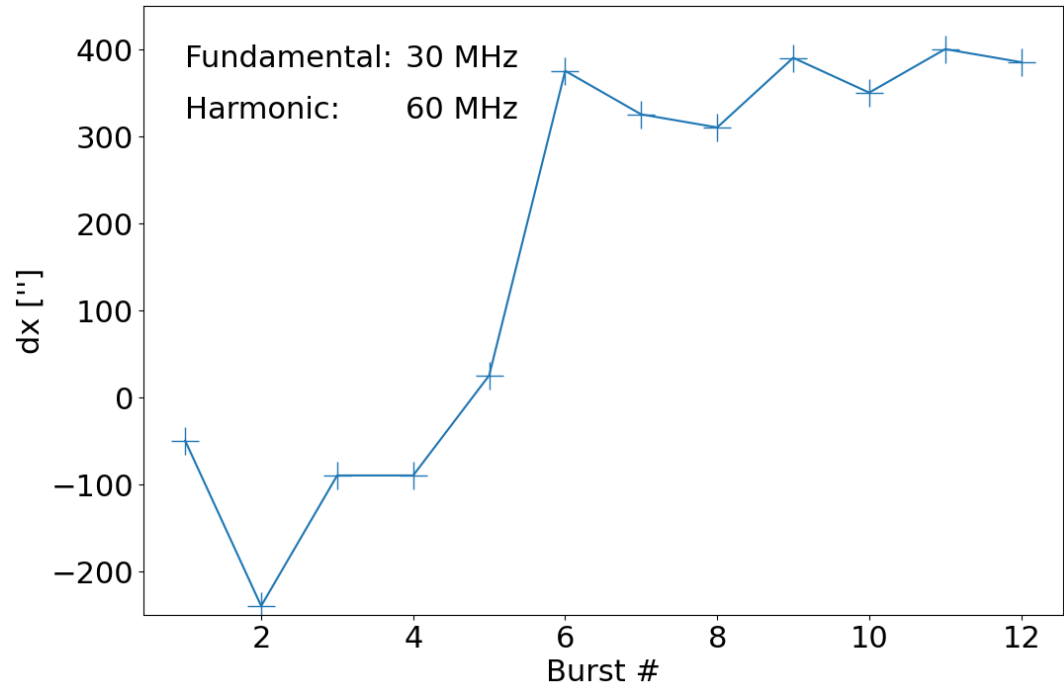
- Flare location is near the Western limb
- Only solar coordinate x (E – W) considered
- Scattering increases x , refraction decreases it
- Stronger effect on F emission than on H
- Shown: $dx = x(F) - x(H)$

Results:

- dx increases during the flare
- Relative outward motion of the F source

Conclusion:

- Scattering becomes stronger for the F source
- The flare increases the level of coronal turbulence



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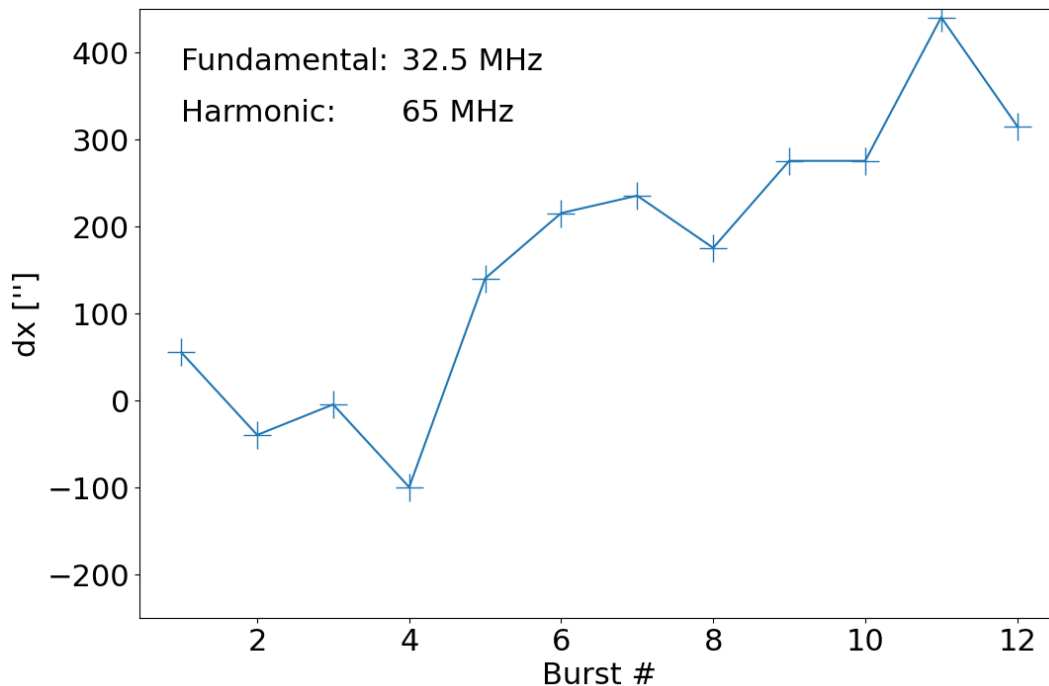
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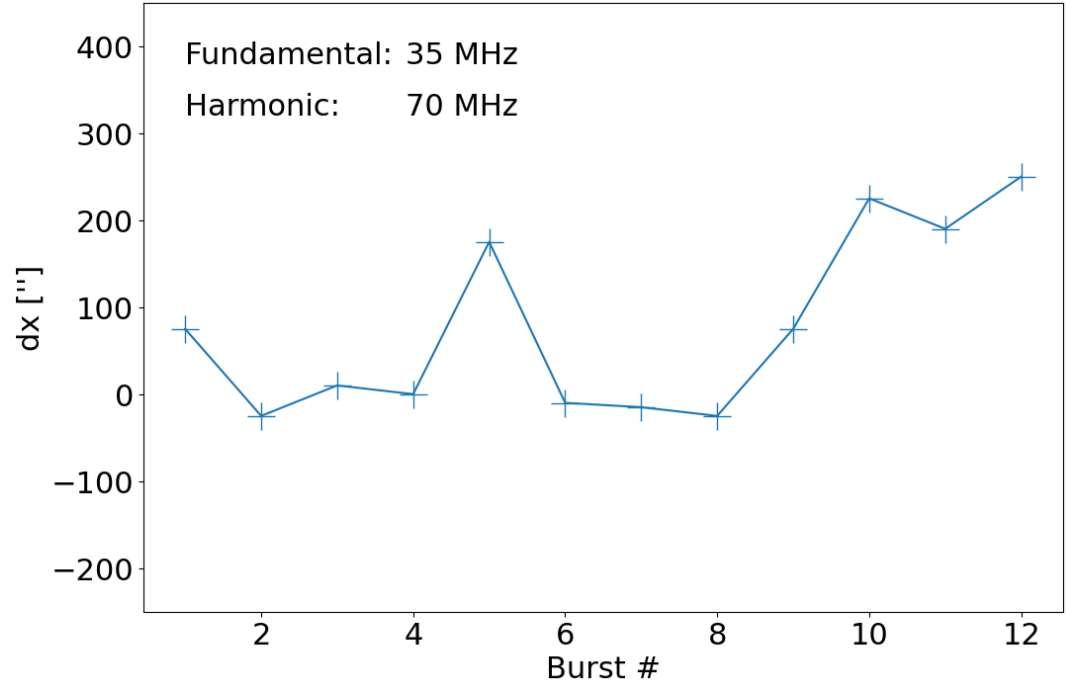
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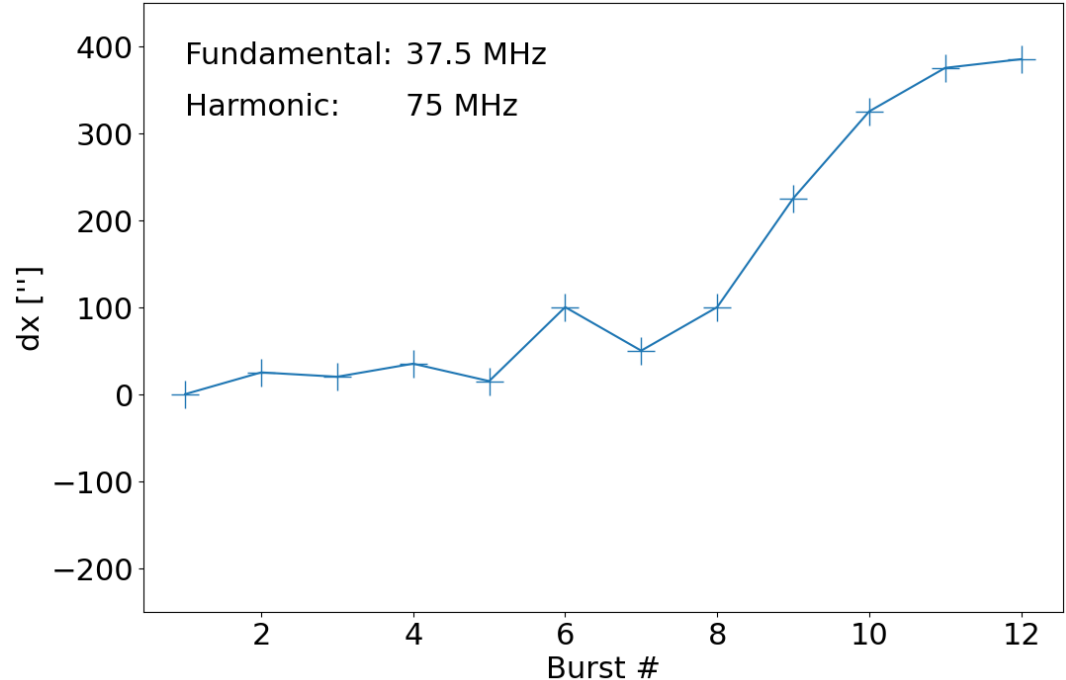
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Summary and conclusion

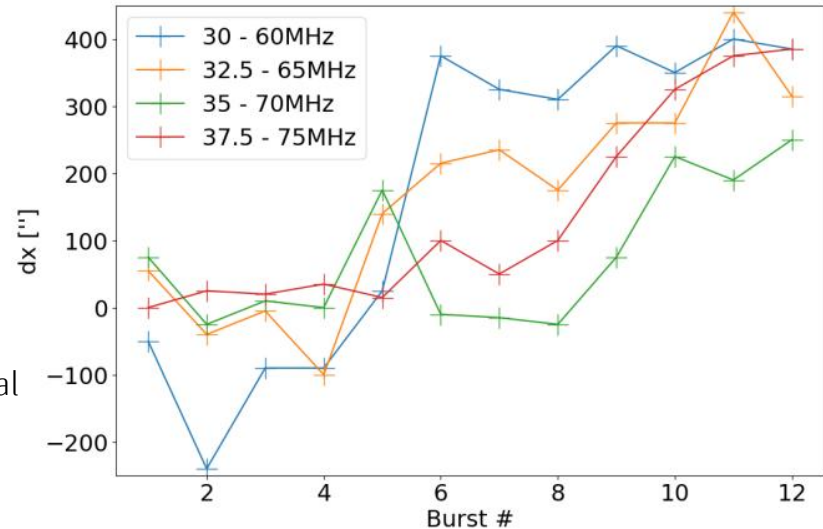
LOFAR M class flare observations:

- Dominated by strong type III emission
- Images show intermittent dual source structure

Interpretation: fundamental and harmonic emission

- At given frequency: Outer source is harmonic, inner is fundamental
- Separate lightcurves for both sources
- Fundamental-harmonic pairs: Same source region
- Relative source positions determined by competing effects of refraction and scattering
- Fundamental source moves away from the Sun over the course of the flare
- Signature of increased scattering by coronal turbulence

→ The flare leads to a significant increase in coronal turbulence level



Outlook

LOFAR2.0 perspective:

- Simultaneous observations in low- and high band
- Covers the upper and middle corona

Radio burst observations at low frequencies:

- Harmonic emission at 20 MHz corresponds to a plasma frequency of 10 MHz
- Fundamental emission is inaccessible to ground-based telescopes
- High corona, transition to interplanetary space

Useful aspect for joint observations with spacecraft
like Parker Solar Probe and Solar Orbiter

