Understanding the radio beam of PSR J1136+1551 through its single pulses

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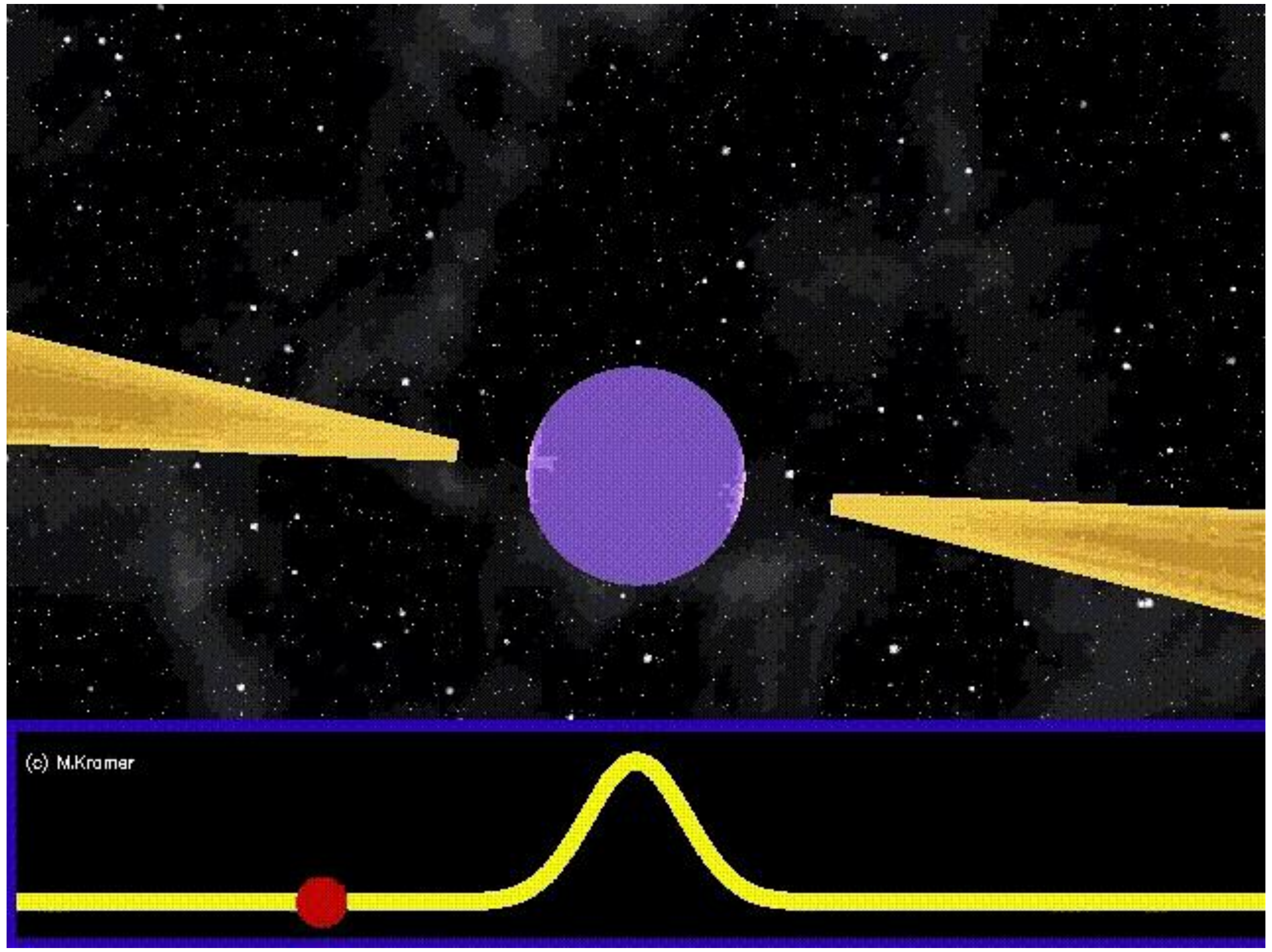
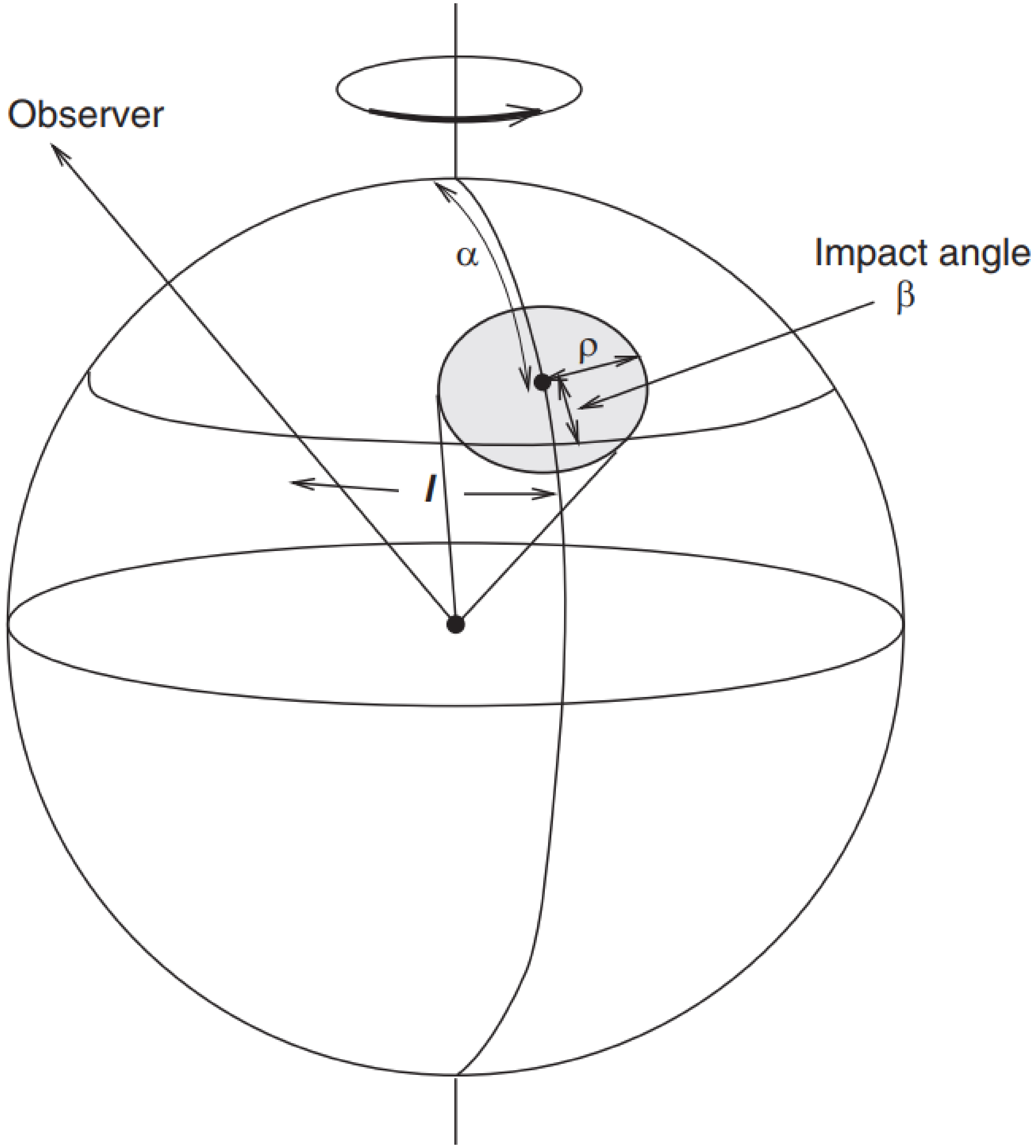
I. Introduction

Radio pulsar: basic geometry



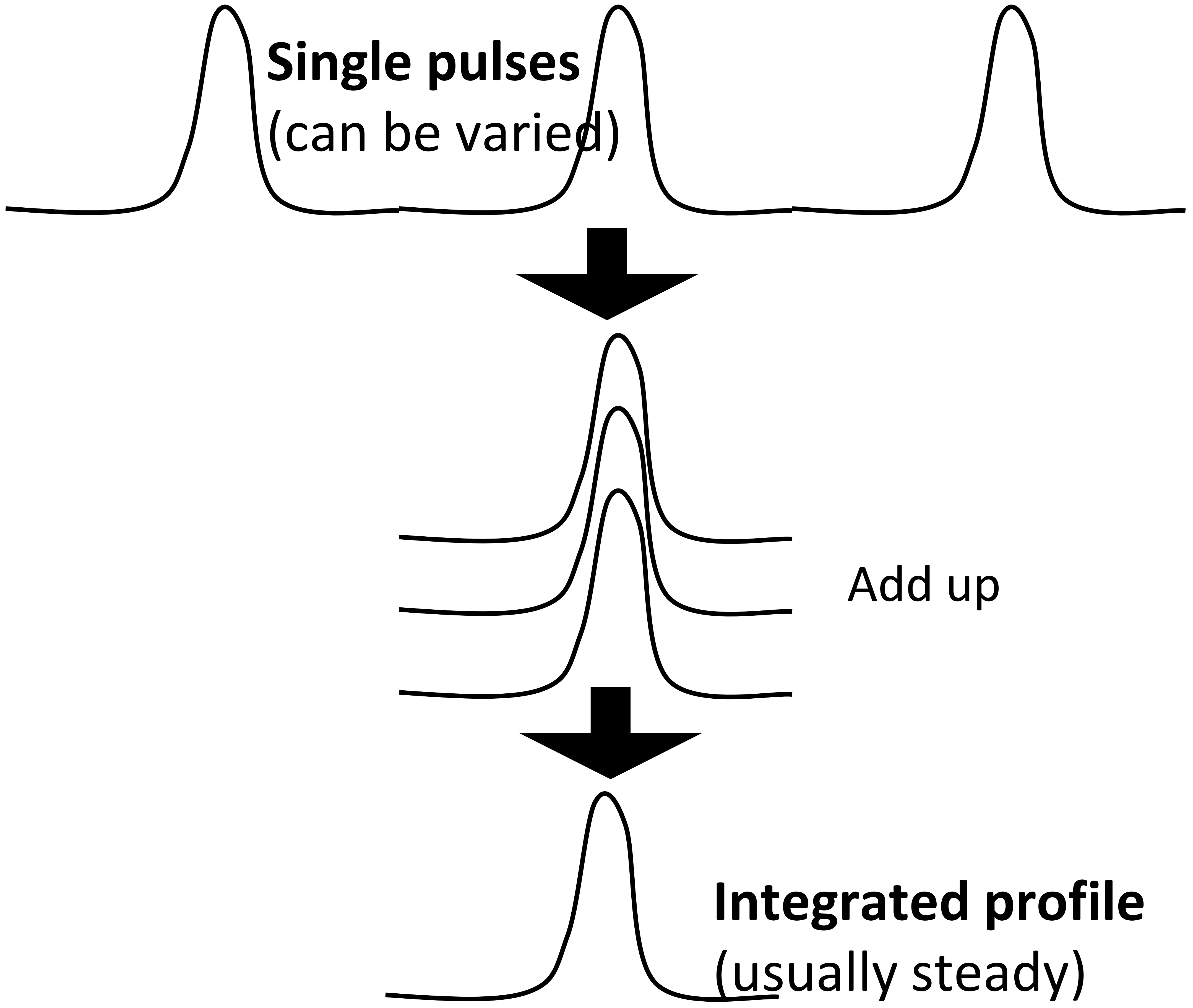
Credit: M. Kramer

“1D cut through a 3D magnetosphere”



From *Pulsar Astronomy*

Integrated profile, single pulses and sub-pulses



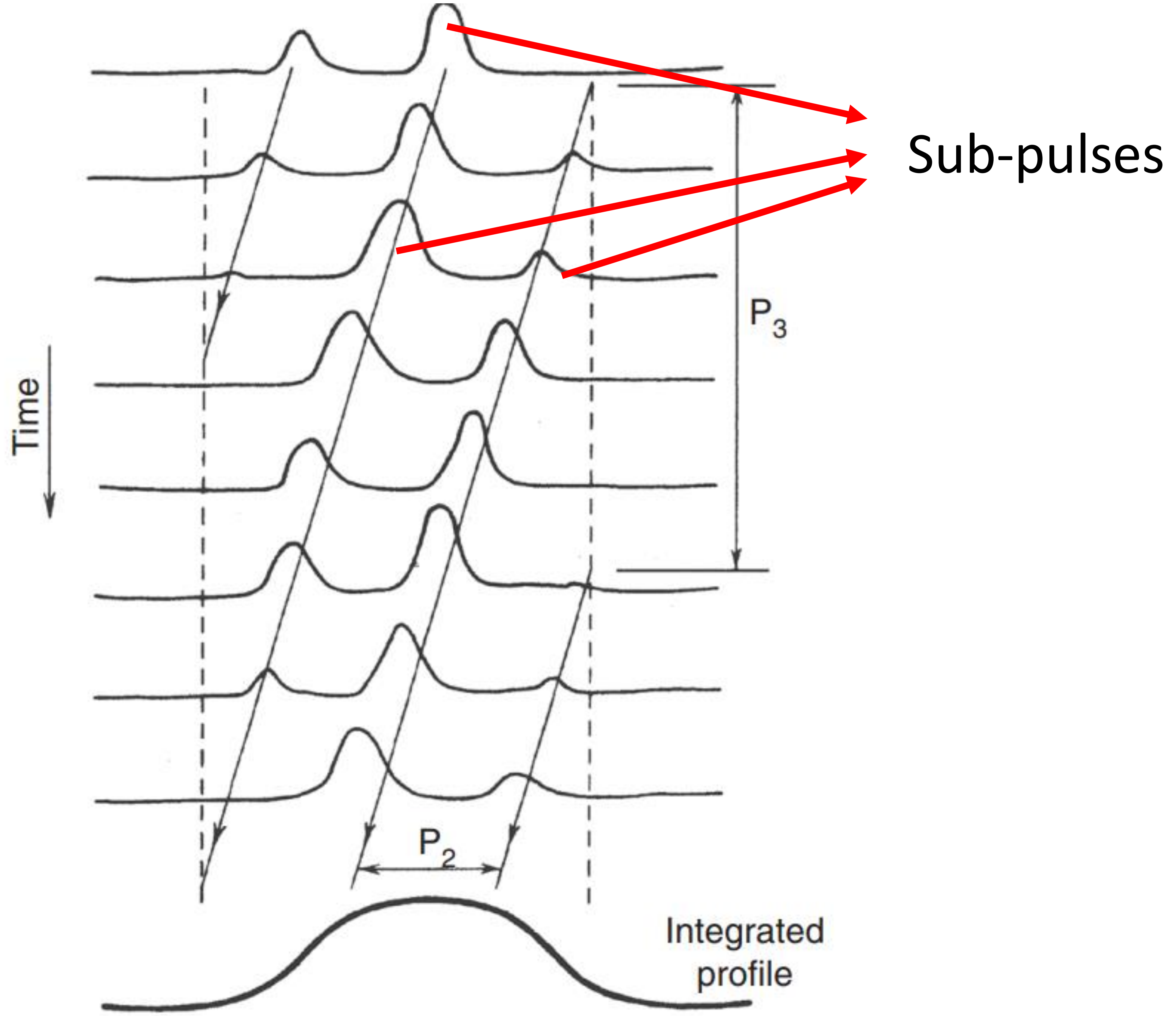
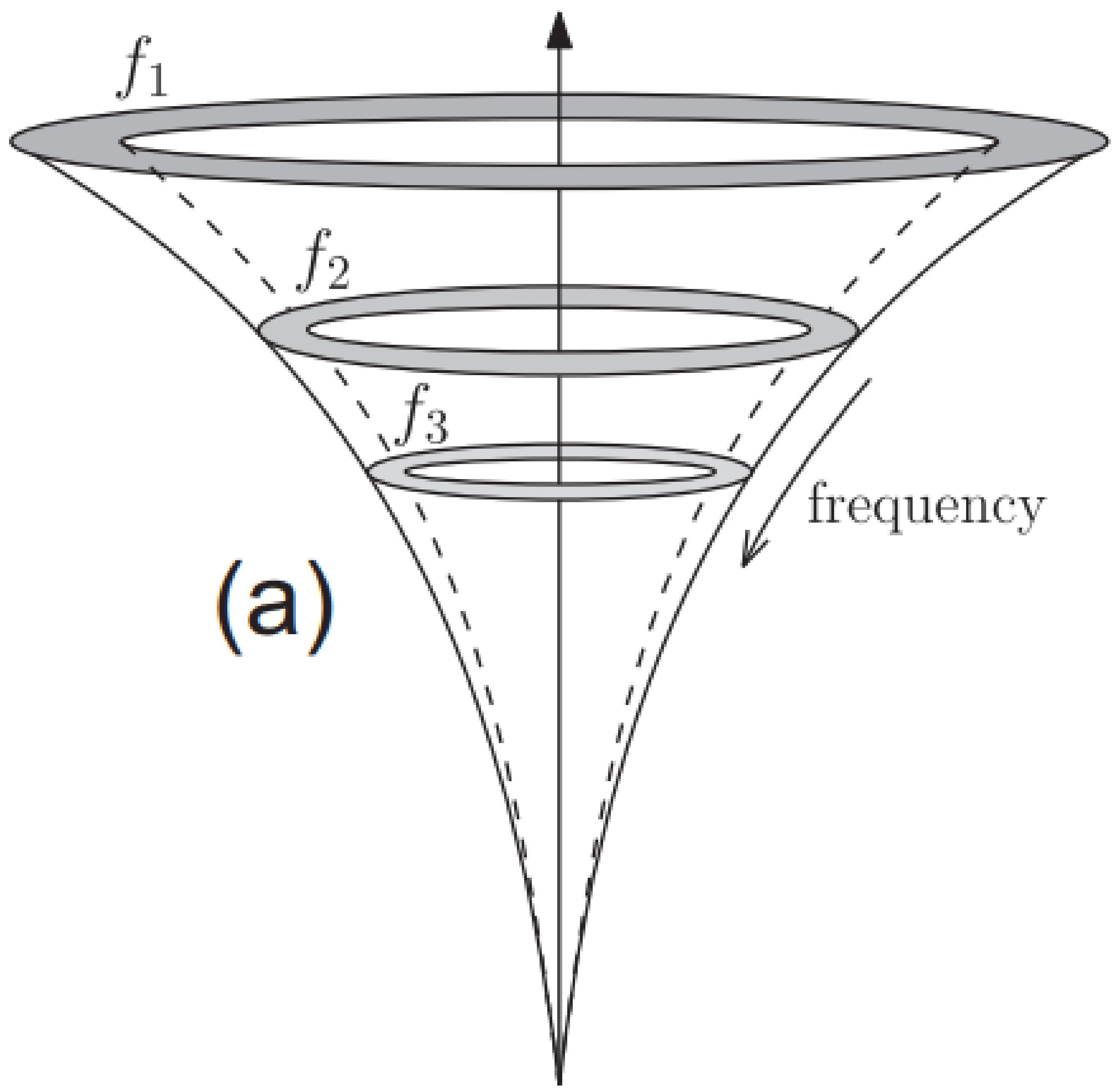


Fig. 16.6. An idealised pattern of drifting sub-pulses.

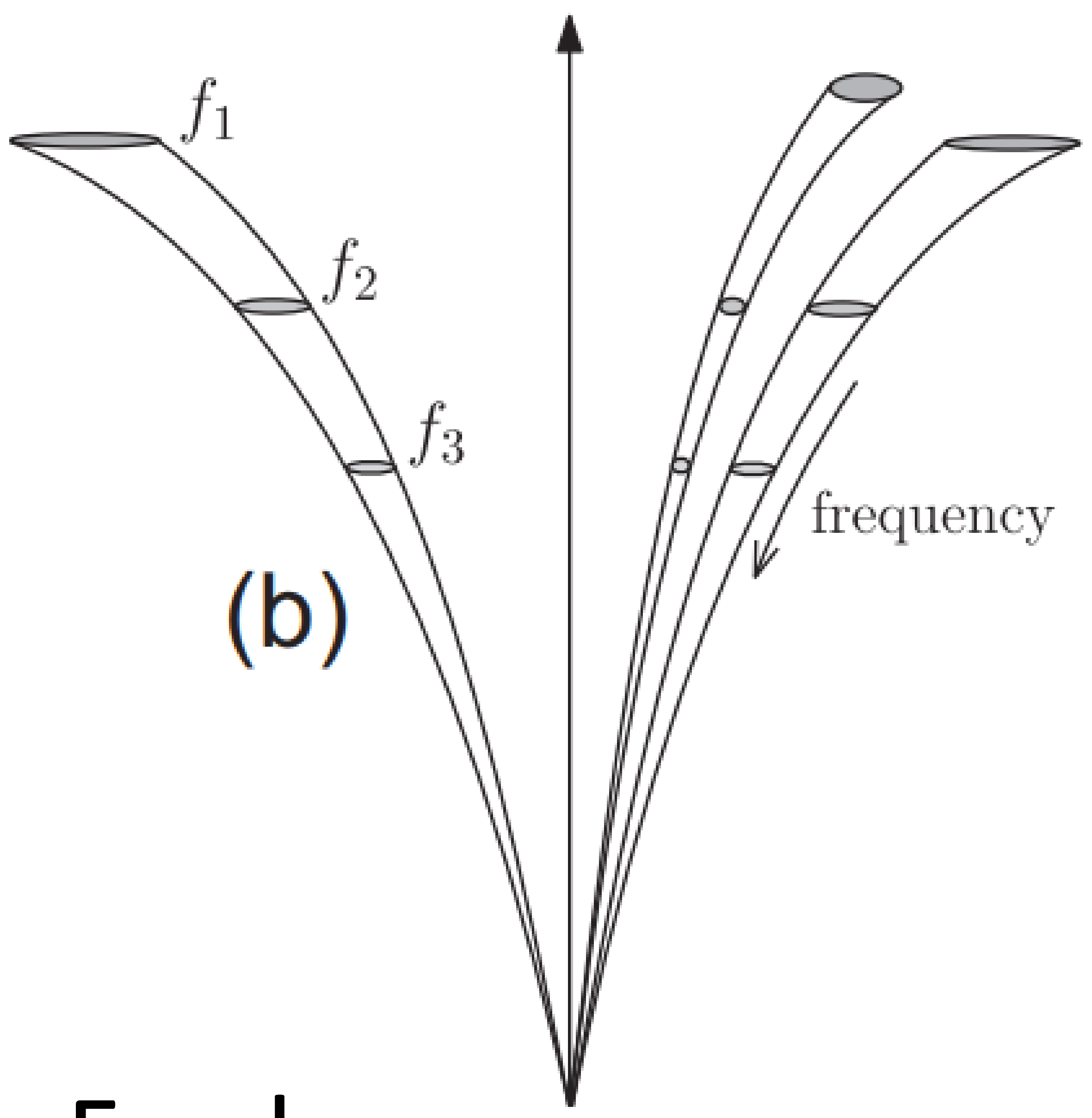
From *Pulsar Astronomy*

Separation of sub-pulses could change with frequency changing.

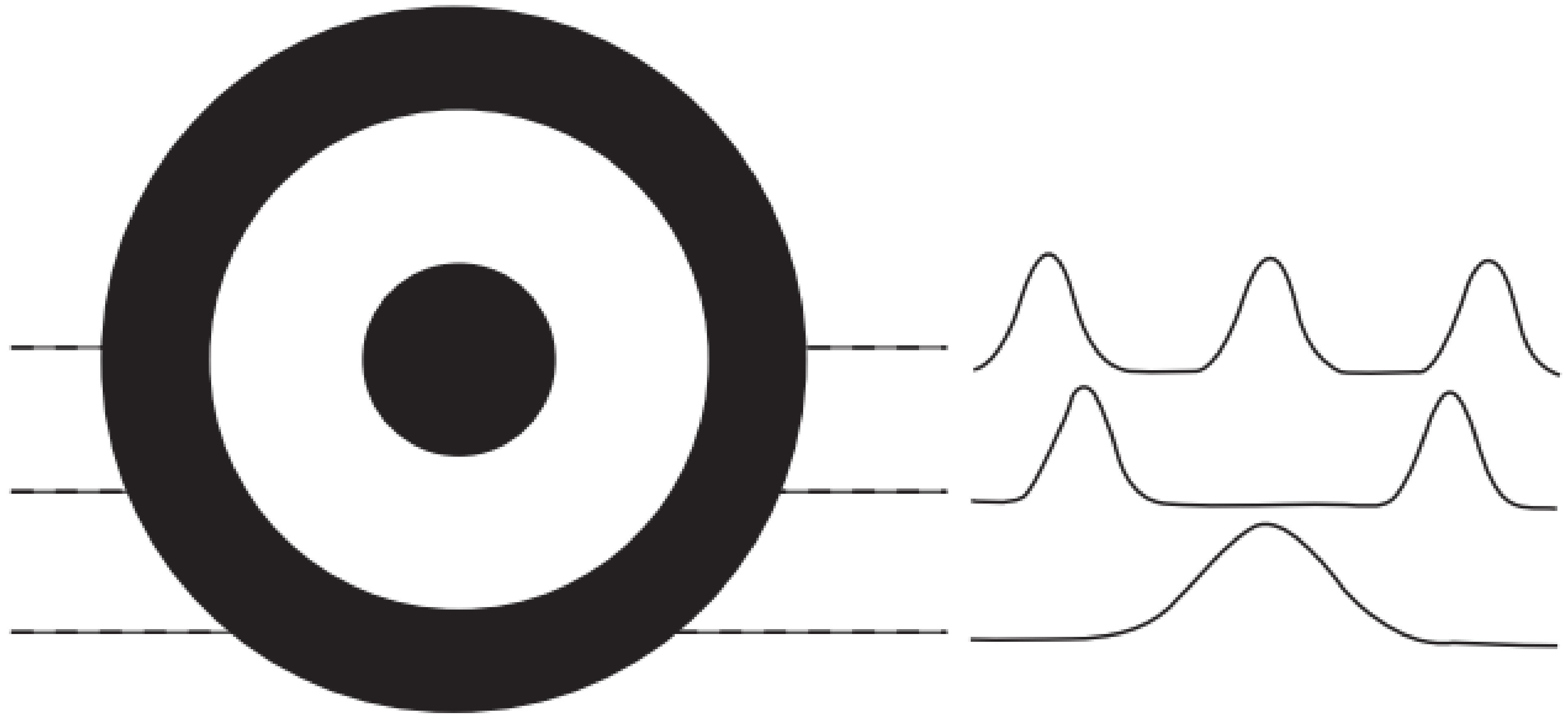
Radiation beam:



Hollow cone
(Rankin 1983)……



Fan beam
(Michel 1987)
(Dyks, Rudak & Demorest 2010)
(Wang et al. 2014)……

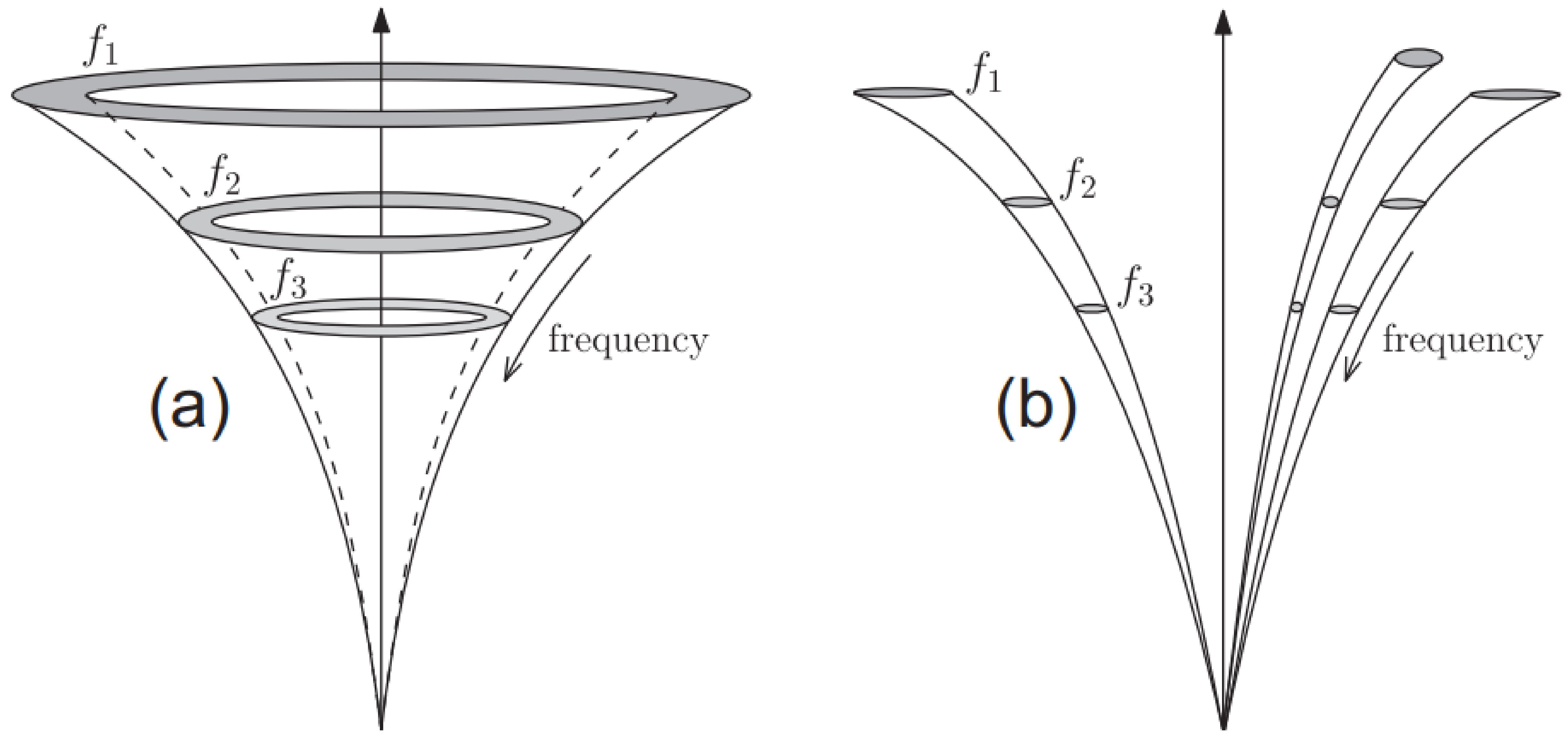


From *Pulsar Astronomy*

Radius to frequency mapping(RFM)

Separation of sub-pulses could change with frequency changing.

Radiation beam:



Pattern A?

Pattern B?

How does **separation** between sub-pulses concretely change with frequency?

The authors use PSR J1136+1551’s single pulses to see which beam model could yield a true pattern.

II. Observations and Data Processing

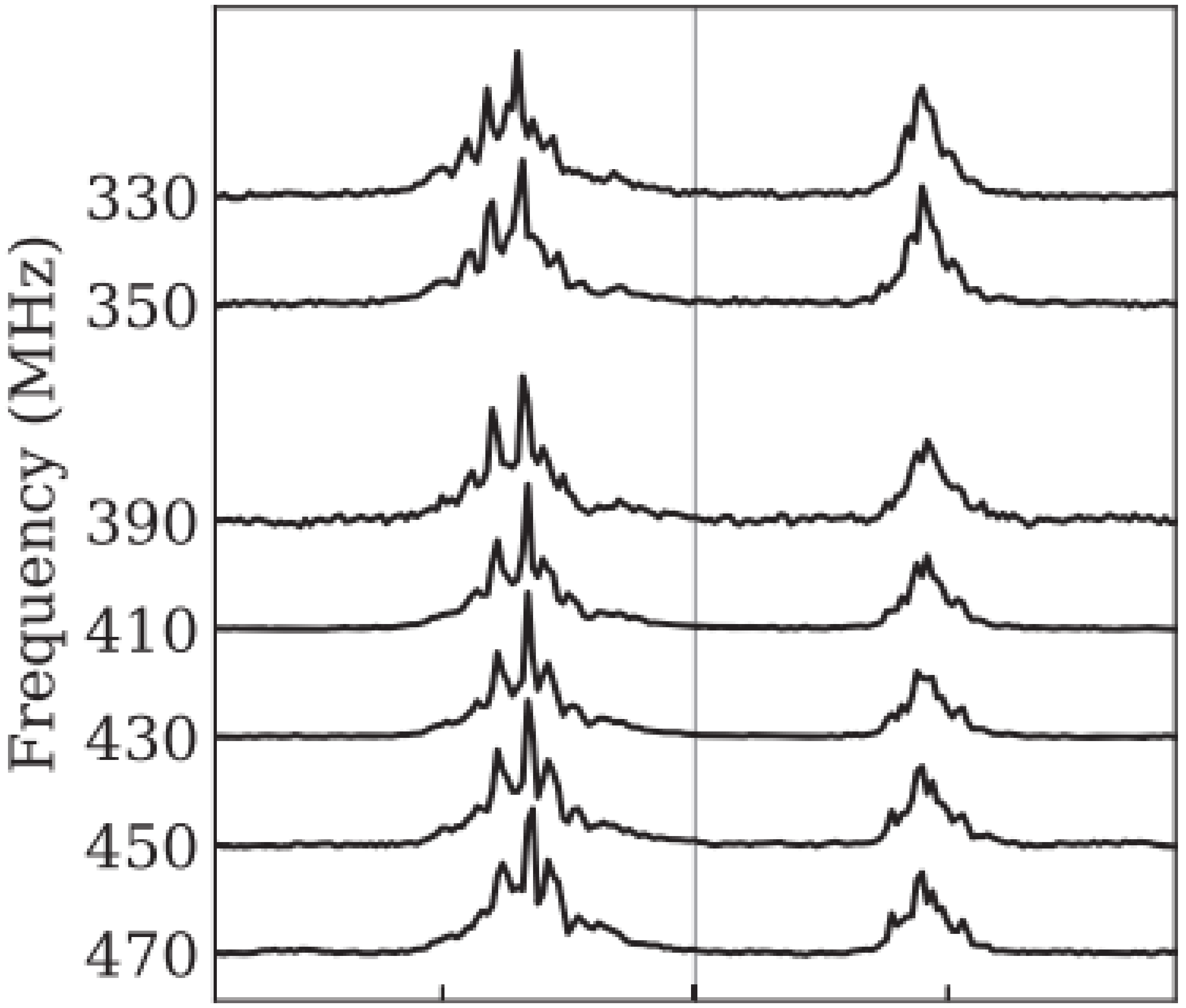
GMRT, wideband backend——300MHz~500MHz, 2048 channels
time solution 327.68μs

J1136+1551: P=1.188s, DM=4.892 cm^-3pc, totally 4759 pulses.

3600bins each period, ~3ms a bin.

Processing using DSPSR and PSRCHIVE.

The band is divided into **10 channels**, and
7 are left after zapping out RFIs——Example:



How to describe sub-pulses' separation quantitatively?

Firstly, identify the edges of the on-pulse region.

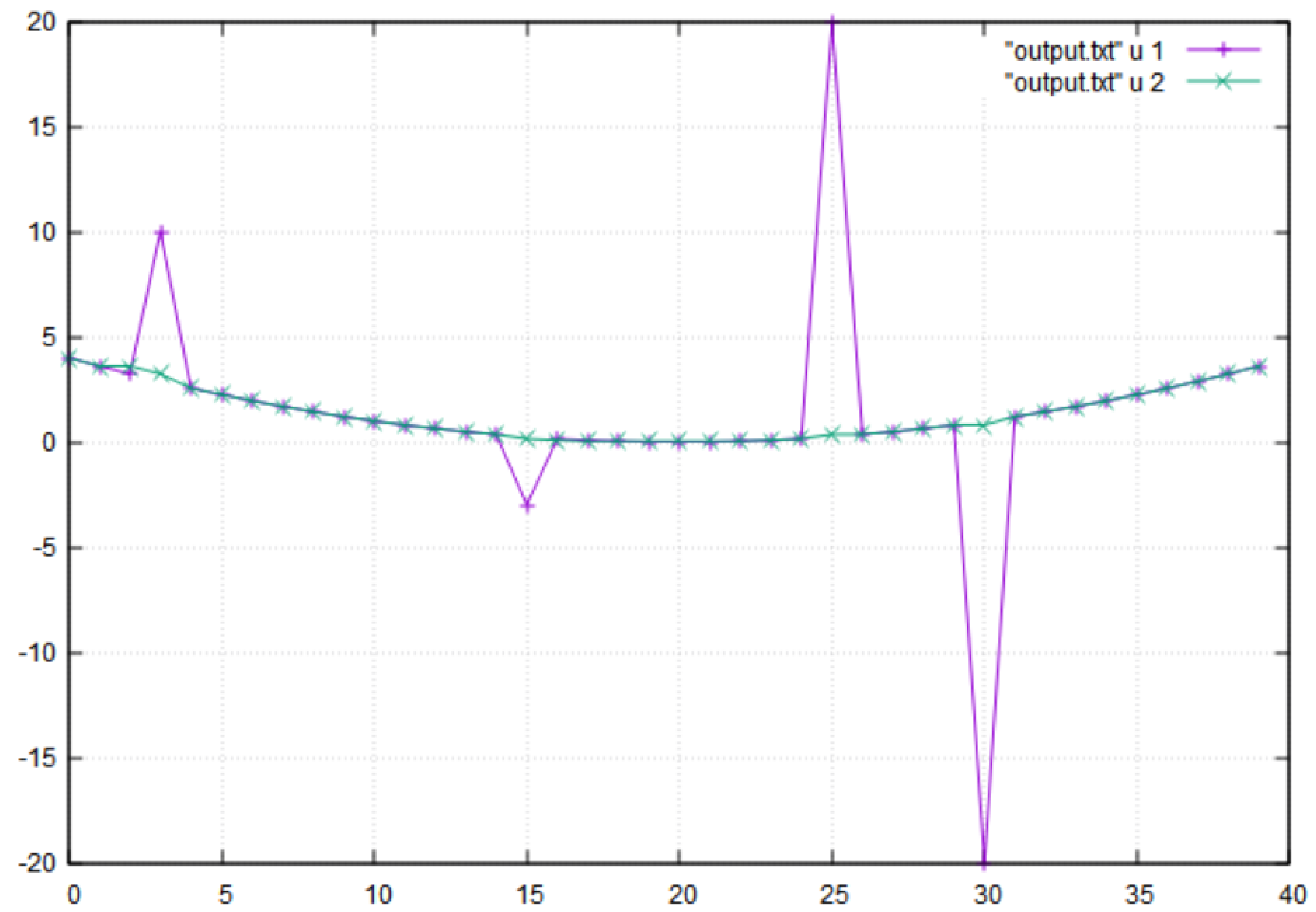
Normalized integrated profile → Median filter (smoothing)

↓

Calculate SNR

$$\frac{|I - Median(profile)|}{1.4826 \times M(median)A(absolute)D(deviation)}$$

baseline



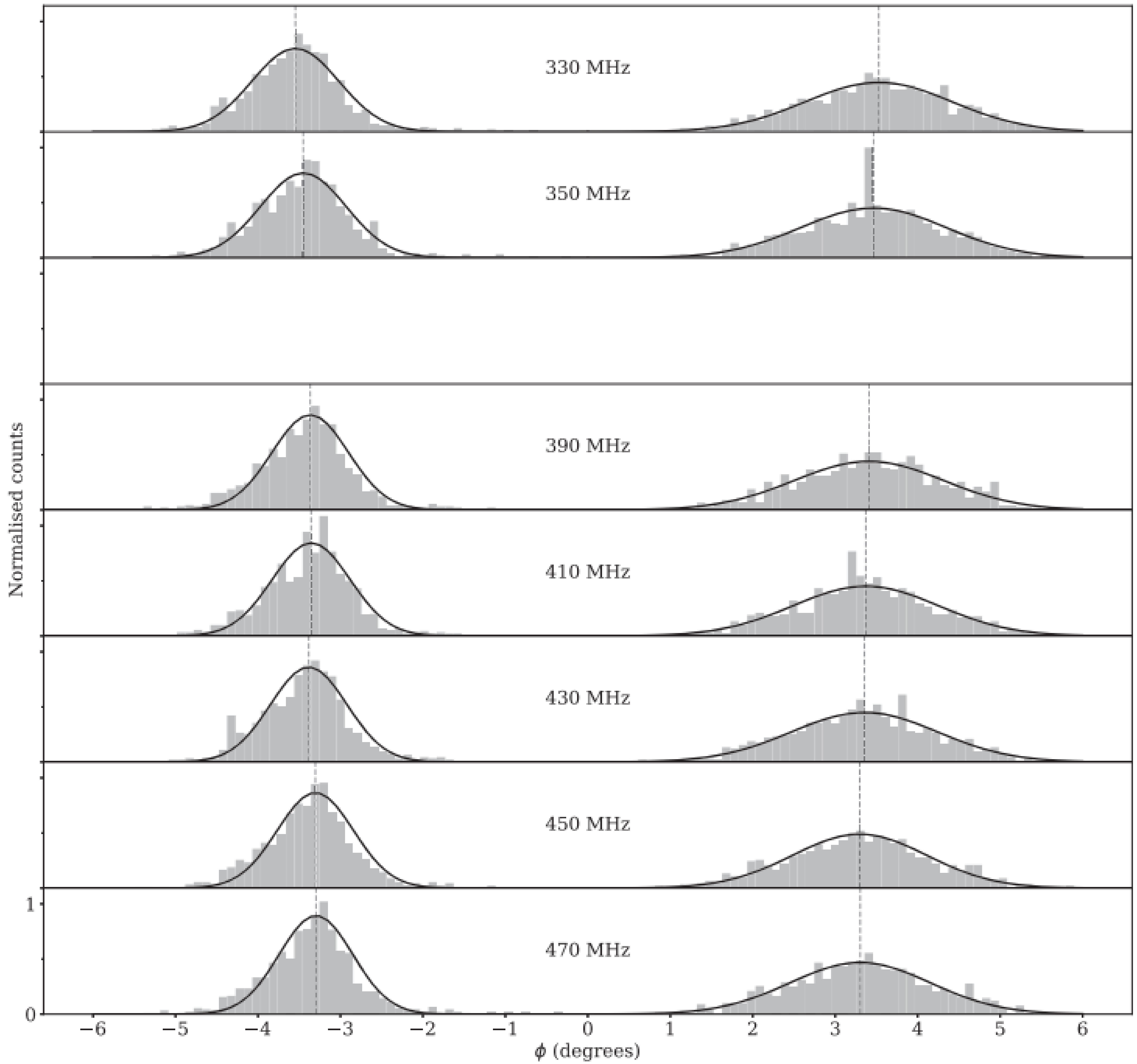
https://blog.csdn.net/liyuanbhu/article/details/48502005

Deem on-pulse region: SNR > 4

Then the authors use a Gaussian to correlate the on-pulse region, and identify the sub-pulses' positions.

885 double-peak pulses are finally used in the analysis.

Frequency (MHz)		470	450	430	410	390	350	330
Subpulse distribution 1 (left)								
Data	μ (°)	− 3.30	− 3.30	− 3.38	− 3.35	− 3.37	− 3.45	− 3.55
	σ (°)	0.45	0.46	0.46	0.47	0.46	0.52	0.53
Subpulse distribution 2 (right)								
Data	μ (°)	3.30	3.30	3.35	3.37	3.41	3.46	3.53
	σ (°)	0.85	0.82	0.89	0.88	0.91	0.88	0.89


330 MHz
350 MHz
390 MHz
410 MHz
430 MHz
450 MHz
470 MHz
Normalised counts
1
0
−6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
ϕ (degrees)

III. Simulations

Basic assumptions:

(1) Dipolar magnetic field; $r = K \sin^2 \theta$

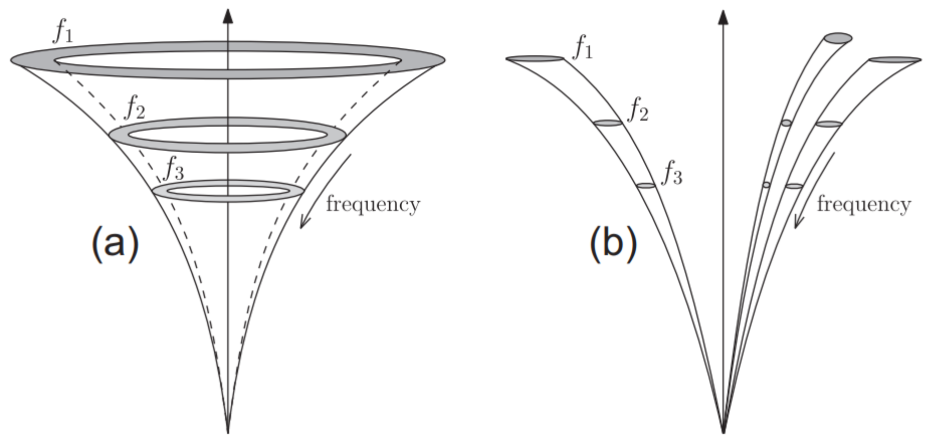
(2) Tangential emitting;

(3) Each frequency ←→ One single height;

(4) RFM(Lower frequency higher height)

(5) Emission from some specific region(Beam structure…)

(6) Same active field lines at different heights responsible for a sub-pulse observed across a broad-band.



$$r = K \sin^2 \theta$$

——From the last assumption:

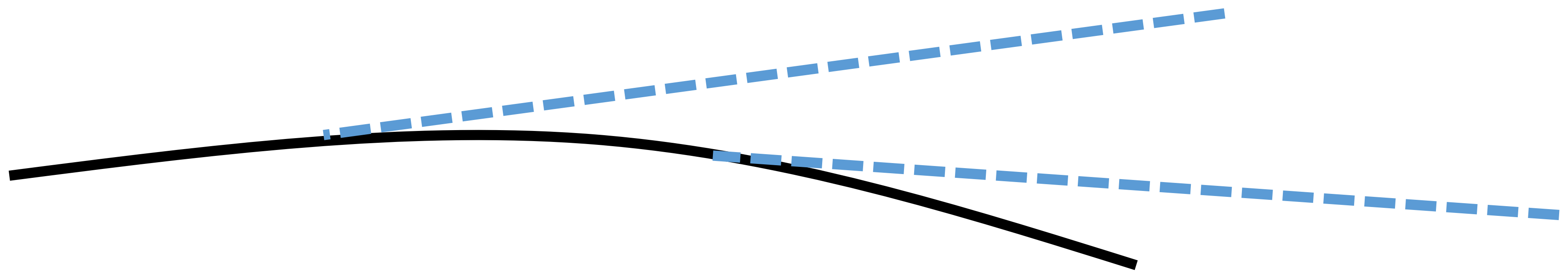
The authors suggest that the same sub-pulses **peaks** are from **only one** magnetic field line, of which the K constant could be yielded:

$$K^p = \frac{r_s}{\sin^2\left(s_L^p \arcsin\sqrt{r_s/R_{LC}}\right)}$$

Light Cylinder

=0.5 (σ=0.02&0.04 for Hollow cone, 0.03 & 0.05 for Fan beam)
Field line footprint
D_(magnetic axis to field line)/D_(magnetic axis to Last open field line)

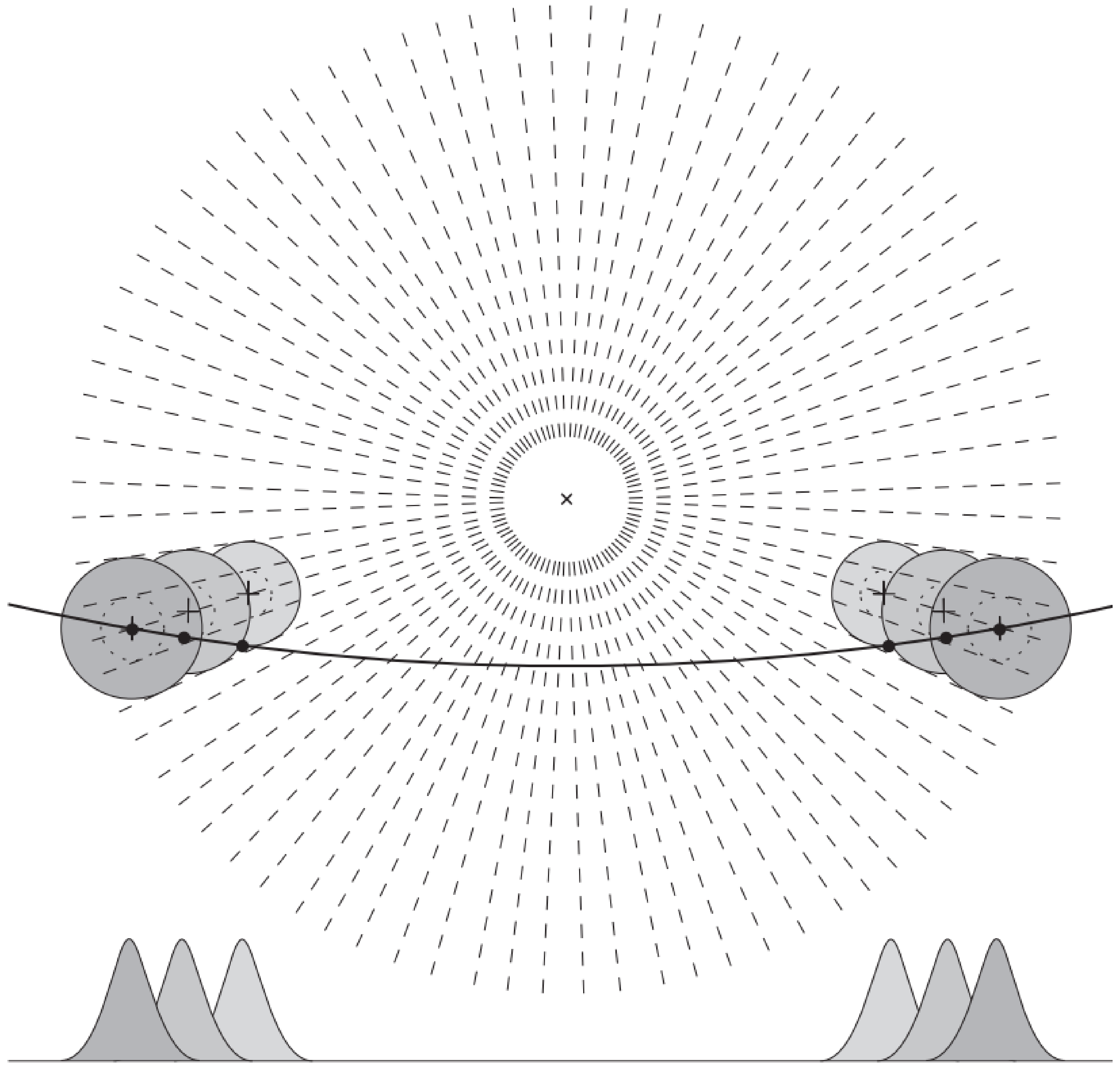
Pulsar radius (10km)

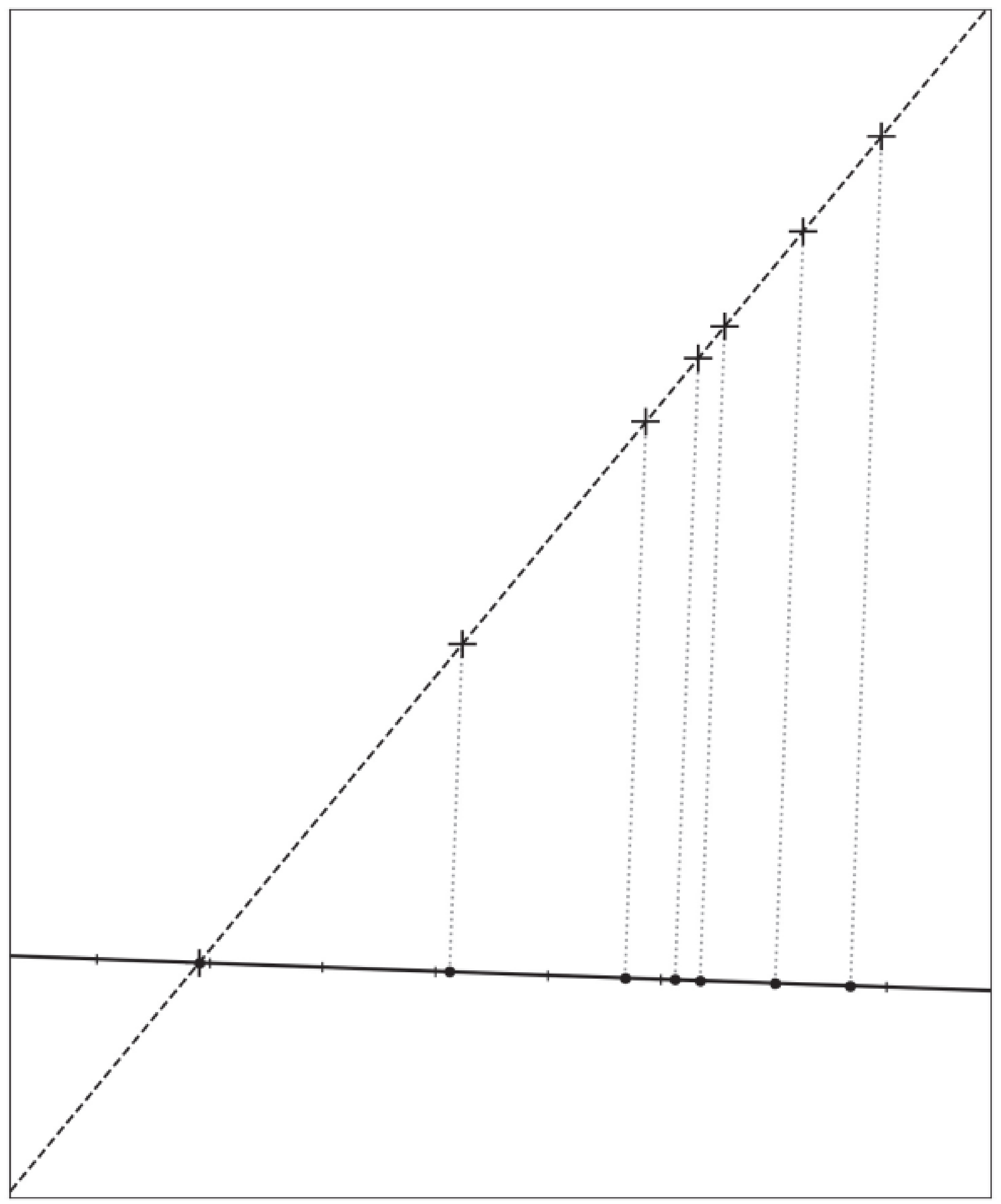


Make connection between sub-pulse data, field line and pulsar surface:

What we have known: Observation data sub-pulses' peak position ——$\mathbf{p}_{obs}$ at all frequency channels.

What we need: The position of the emission peak $\mathbf{p}_{peak}$ and how it relates with $\mathbf{p}_{obs}$ at all frequency channels.





The authors choose 330Hz(lowest frequency, highest height) as the reference frequency and define $\mathbf{p_{peak}} = \mathbf{E(p_{obs})} = \boldsymbol{\mu}$ at this frequency.

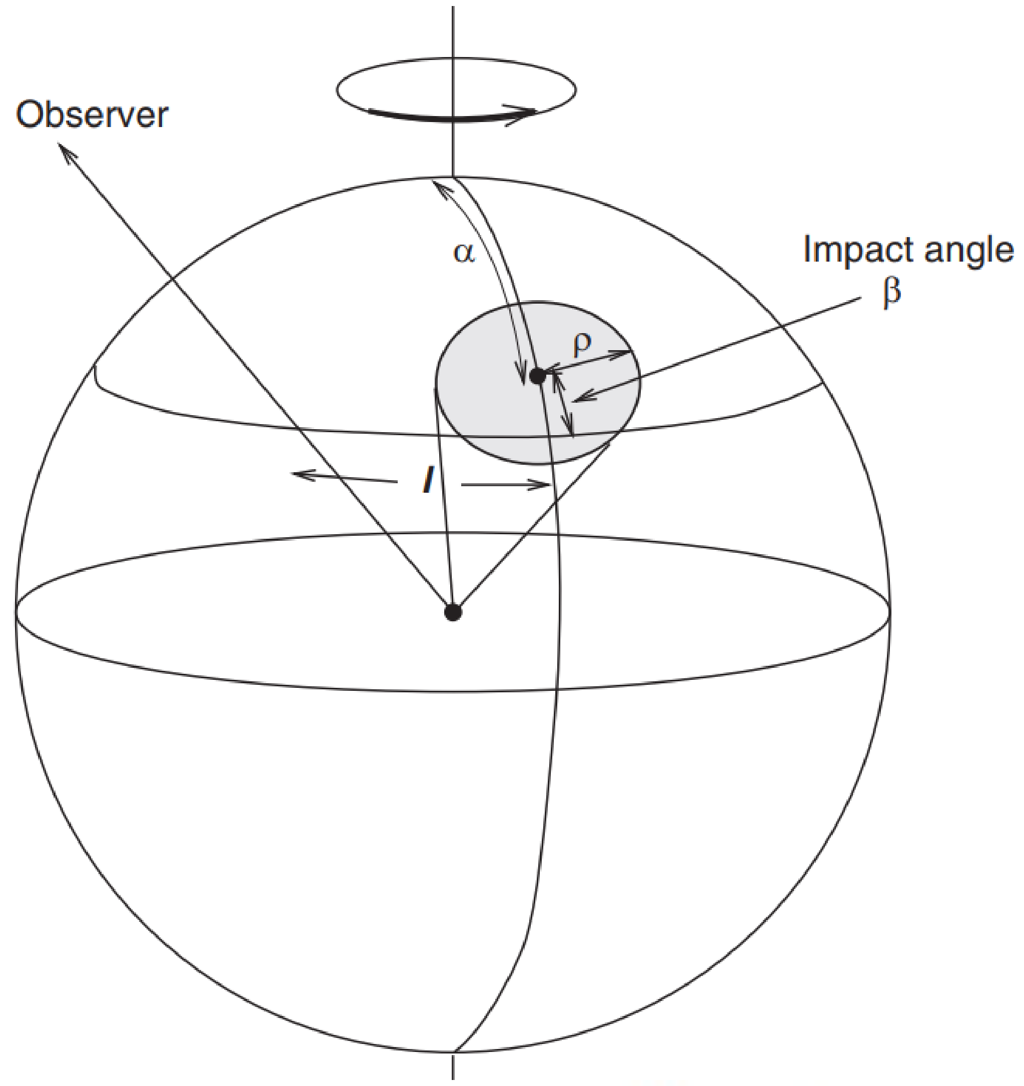
(On other frequencies, the relationship between $\mathbf{p_{peak}}$ and μ is determined by the beam model)

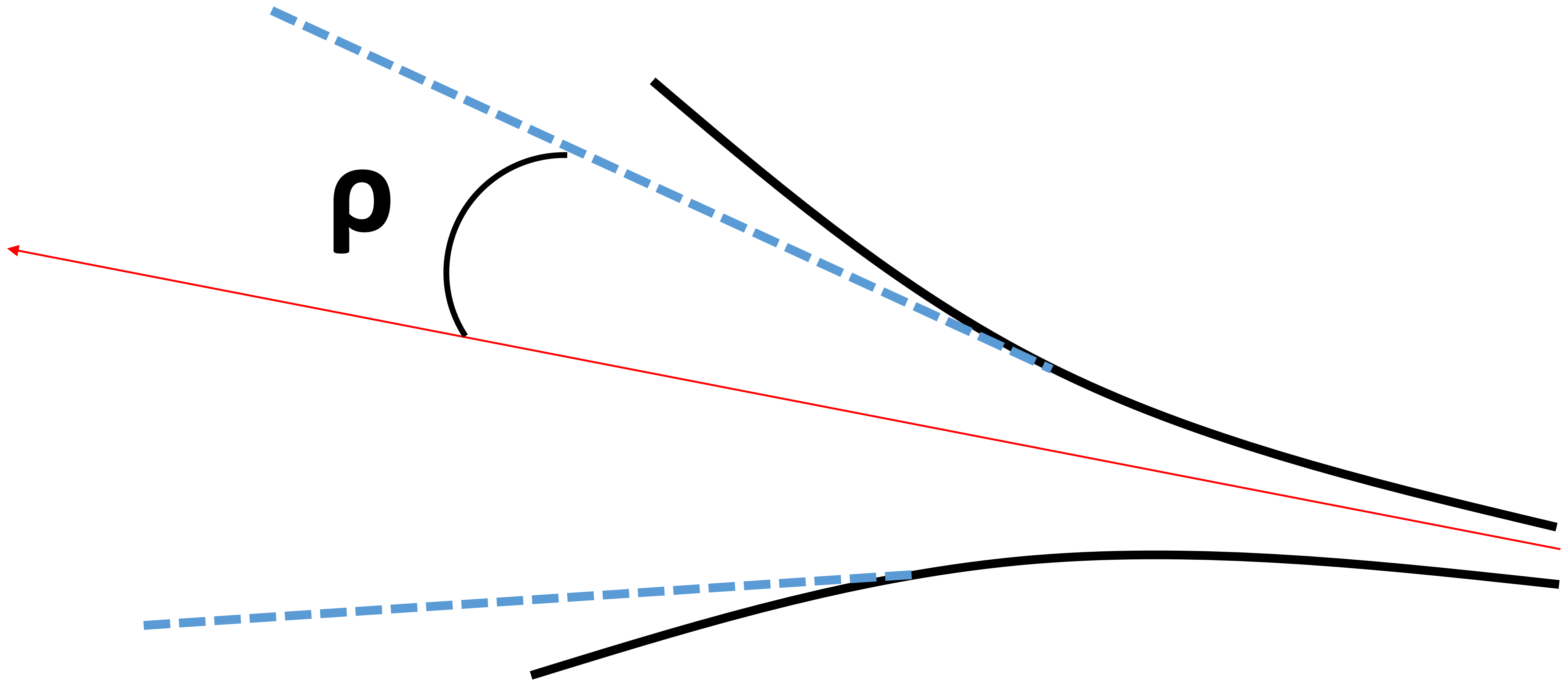
So what could the beam model give us?

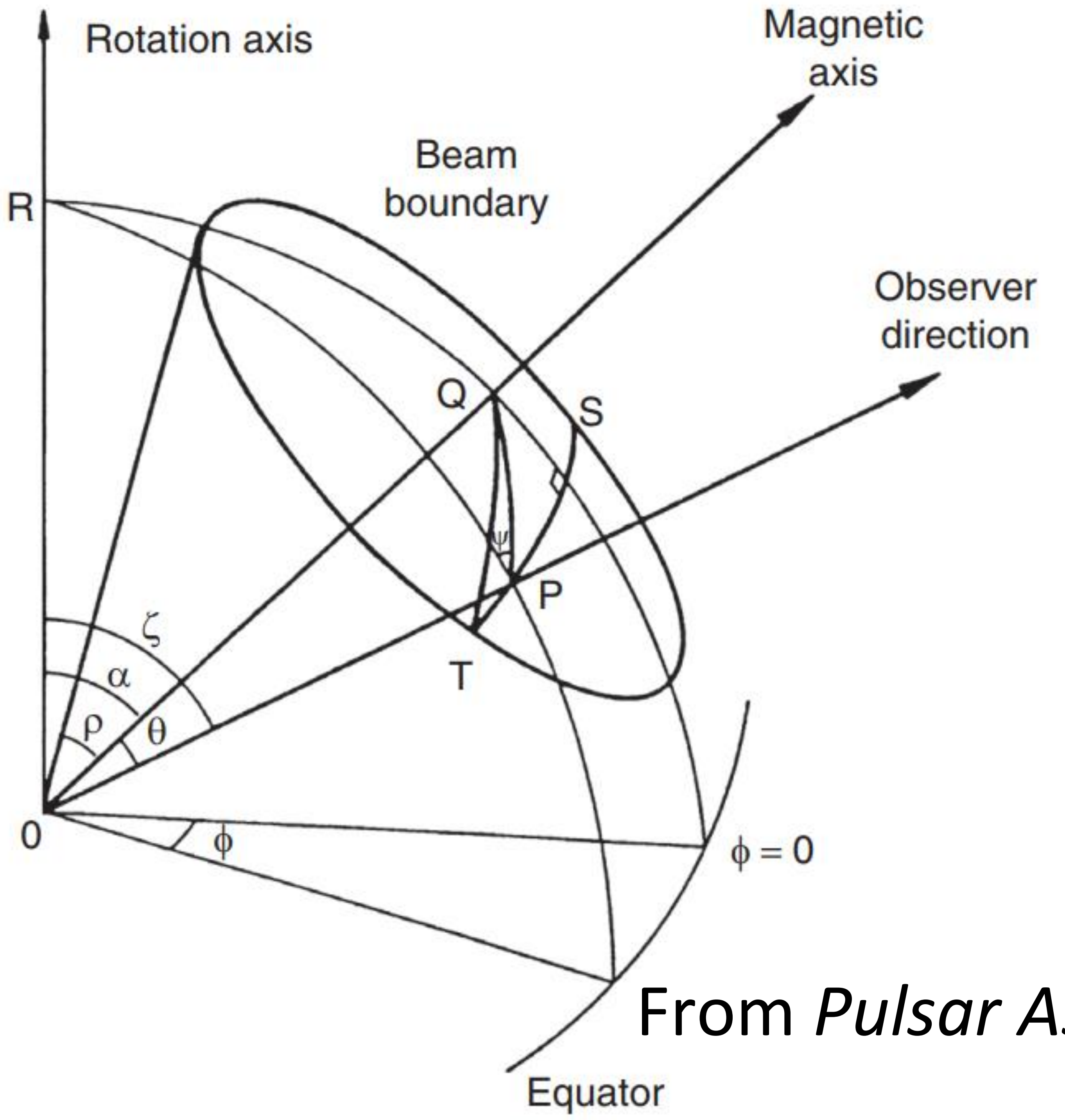
First let’s figure out what can we get from a sub-pulse’s peak position μ.

μ is related to the radiation beam half-opening angle ρ:

$$\cos\rho = \cos\alpha\cos(\alpha+\beta) + \sin\alpha\sin(\alpha+\beta)\cos(\mu)$$







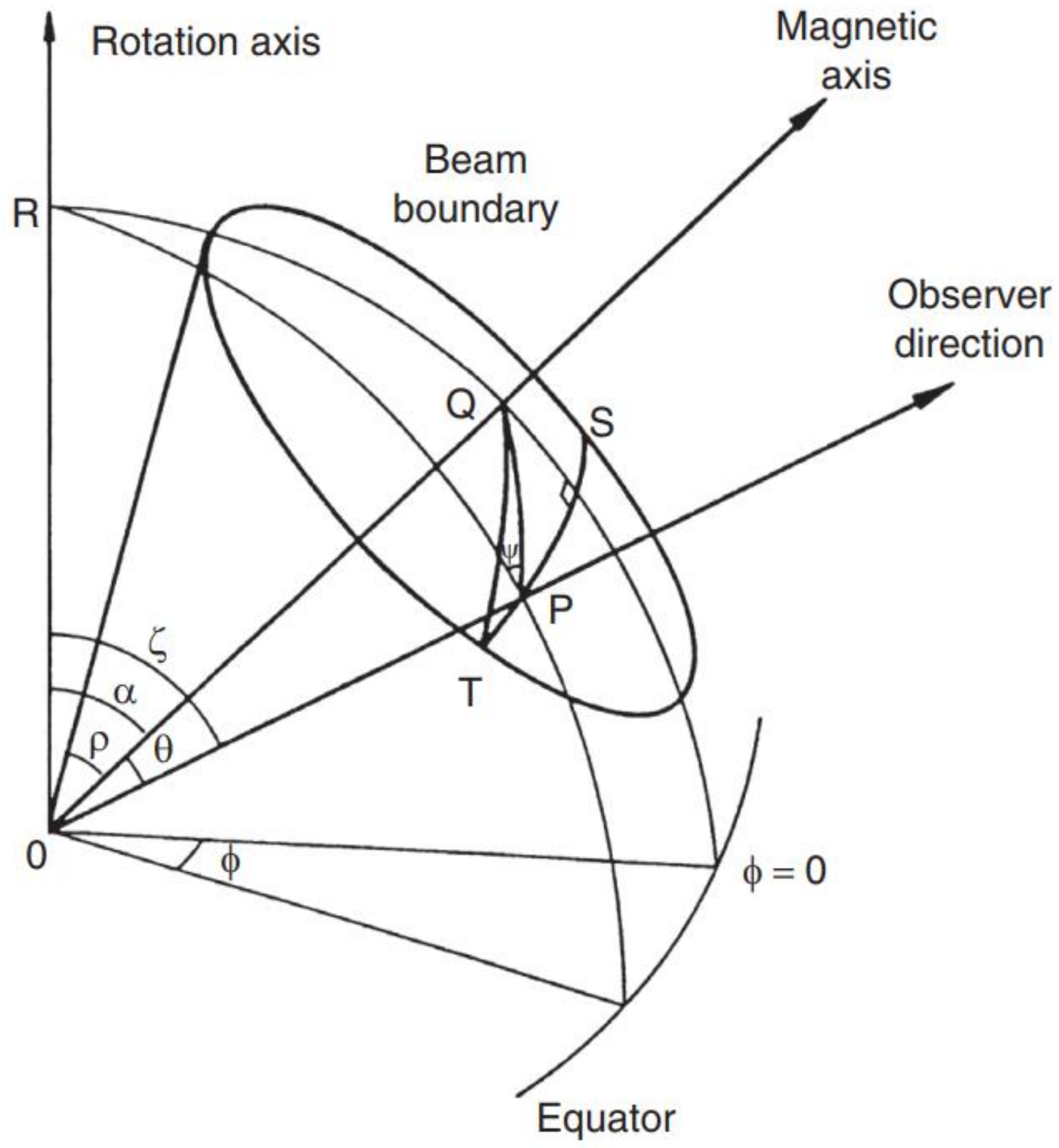
From *Pulsar Astronomy*

α and β can be yielded with fitting the RVM to the PA.

α=51.3°， β=3.7°

Then, ρ is related to spherical polar angle θ.

$$\cos(2\theta) = \frac{1}{3}(\cos\rho\sqrt{8+\cos^2\rho} - \sin^2\rho), -\pi \le \rho \le \pi$$

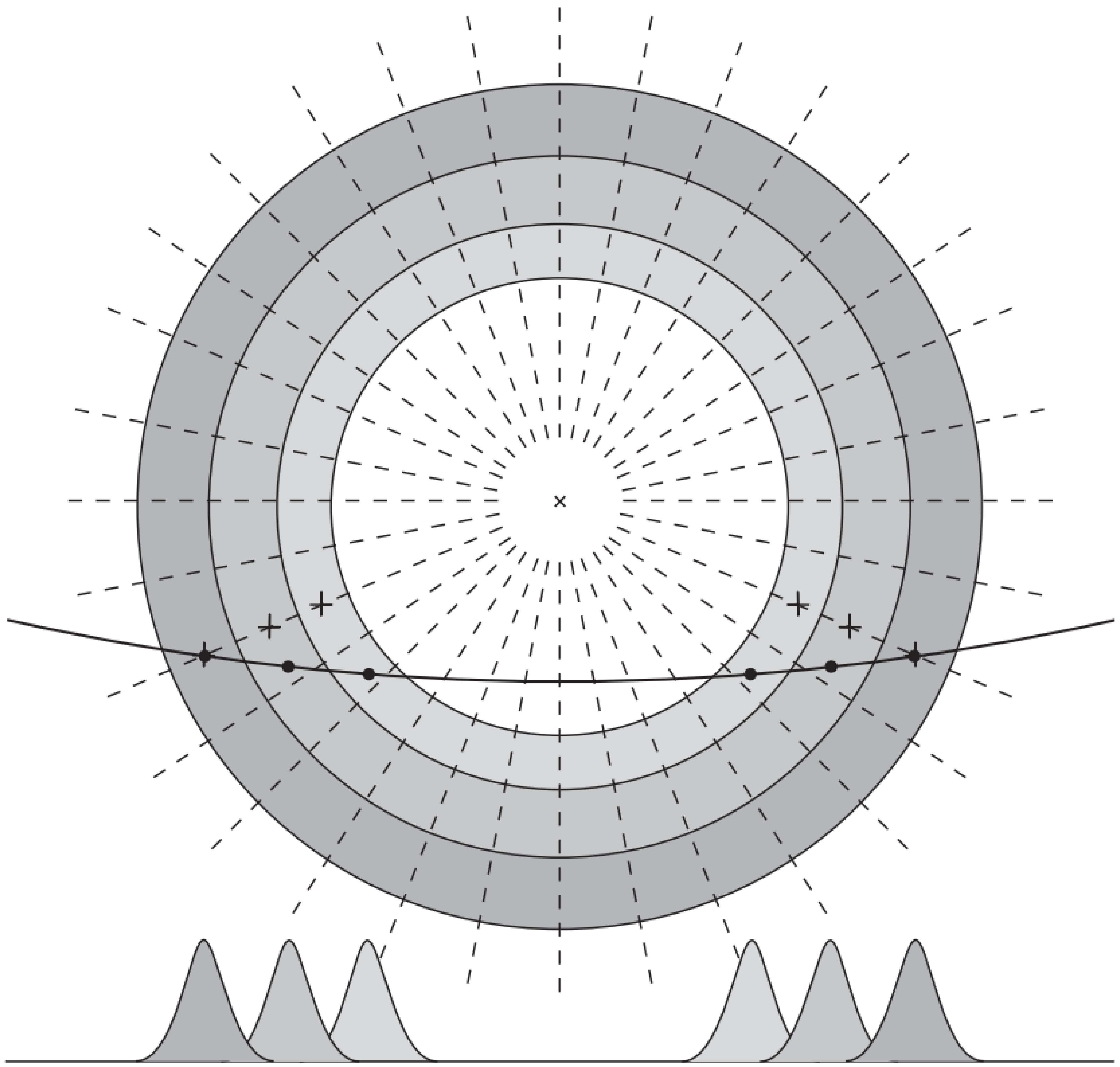


For each frequency, the radiation height could be calculated.
(RS model 1975, r=C*f^(-2/3))

After knowing the emission height and the dipole field constant K (p12),
The peak emitting polar angle θ_{peak} could be yielded.

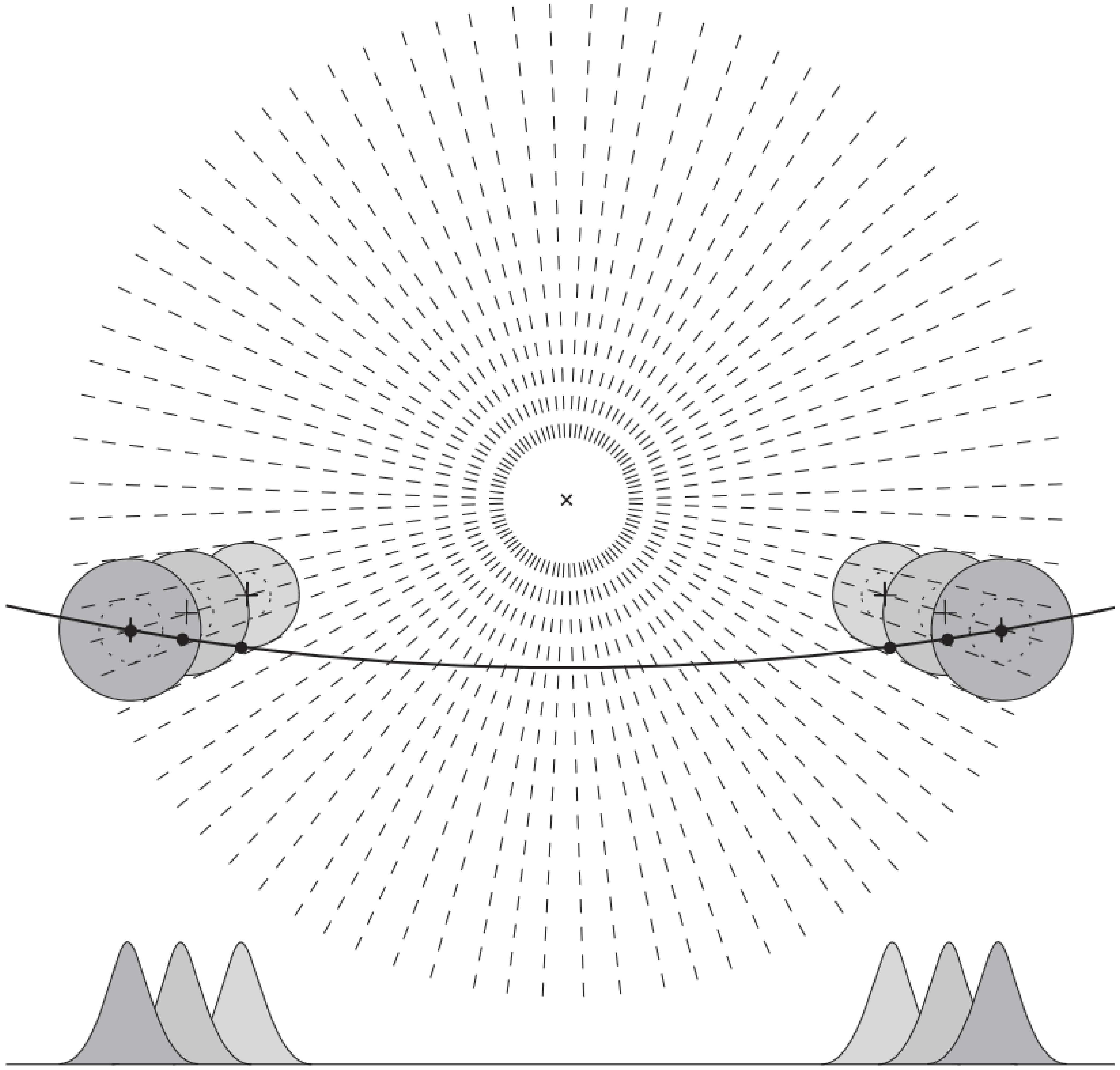
What models could affect——is how could θ_{peak} be converted to θ_{μ}
—— θ_{μ} can be used to calculate the theoretical μ, comparing with the observed μ.

The hollow cone model:



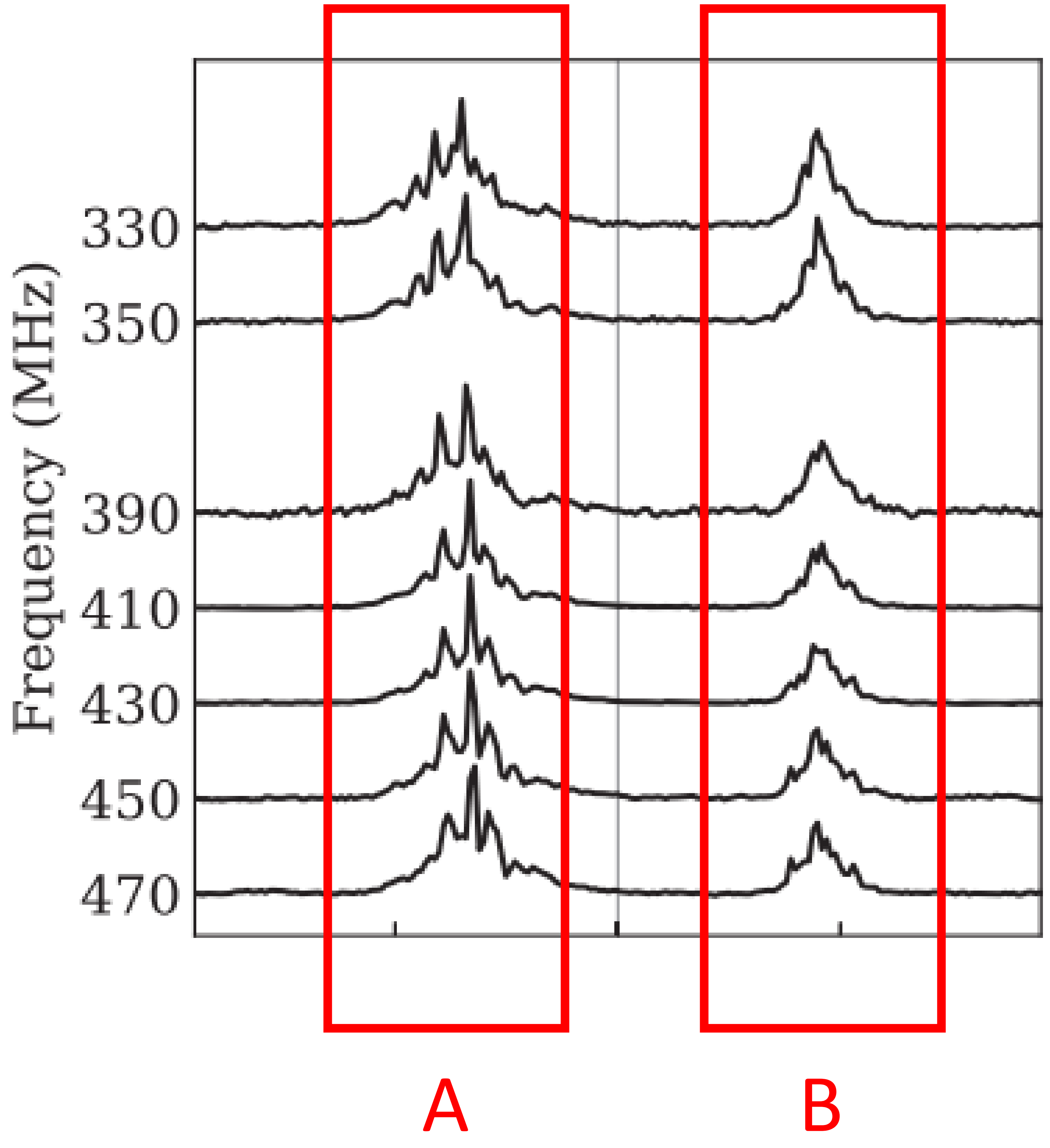
$$\theta^j_{\text{peak}} = \theta^j_{\mu}$$

The fan beam model:

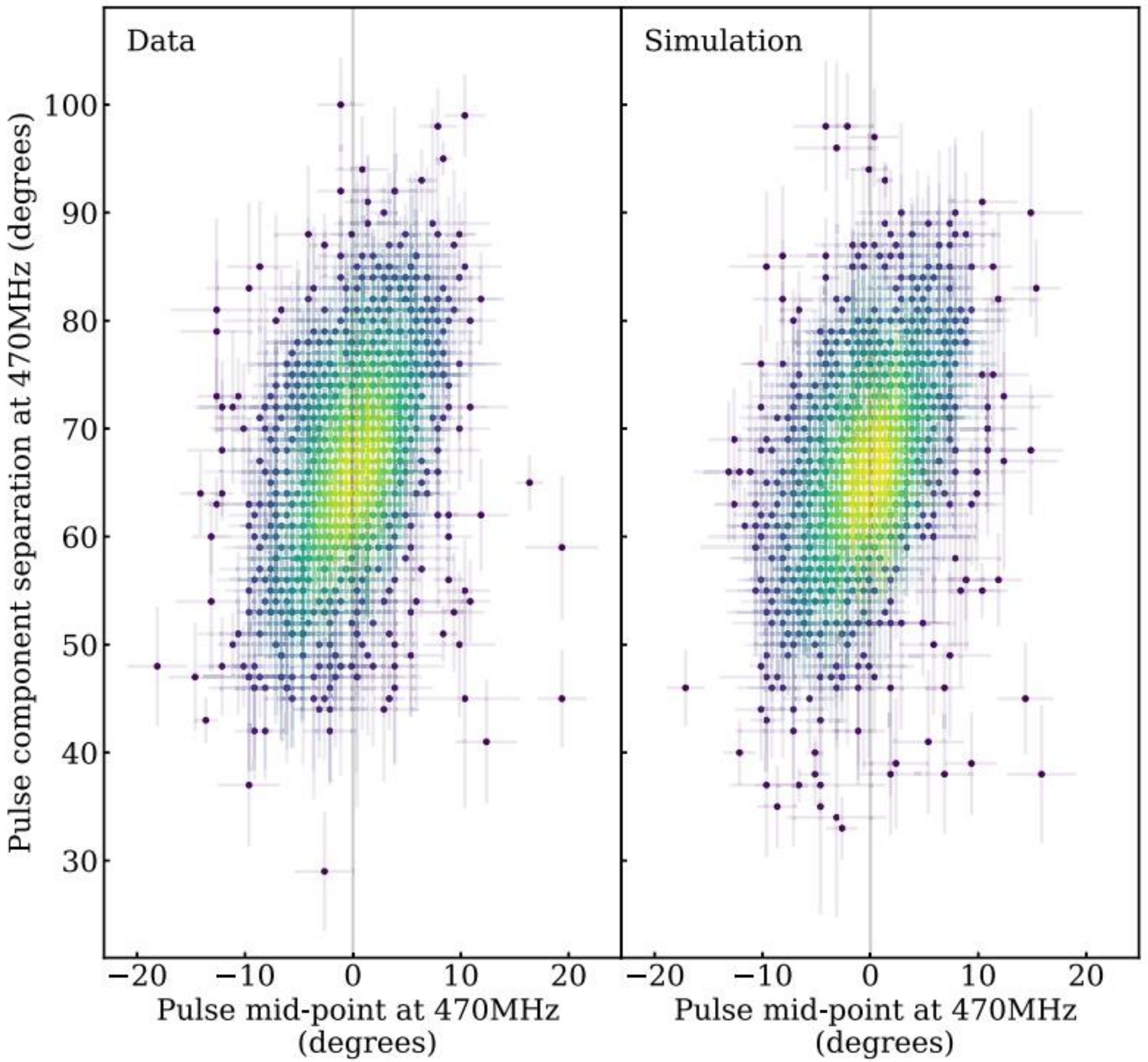


IV. Results

1. Independence of sub-pulses

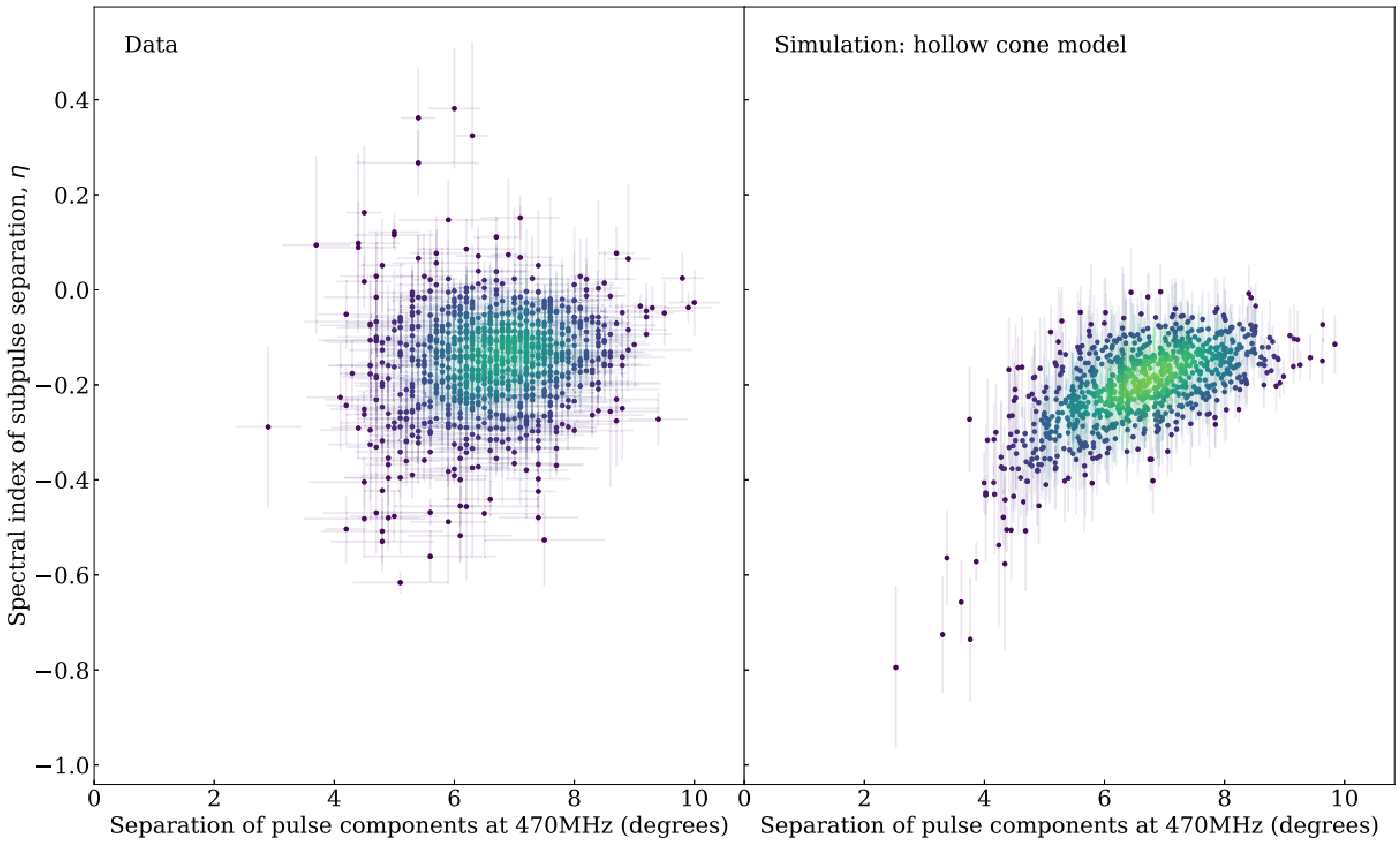


Randomly combine the two sets of sub-pulses



The positions of the two sub-pulses making up a single pulse are independent of each other.

2. Hollow cone simulation:



2. Fan beam simulation:

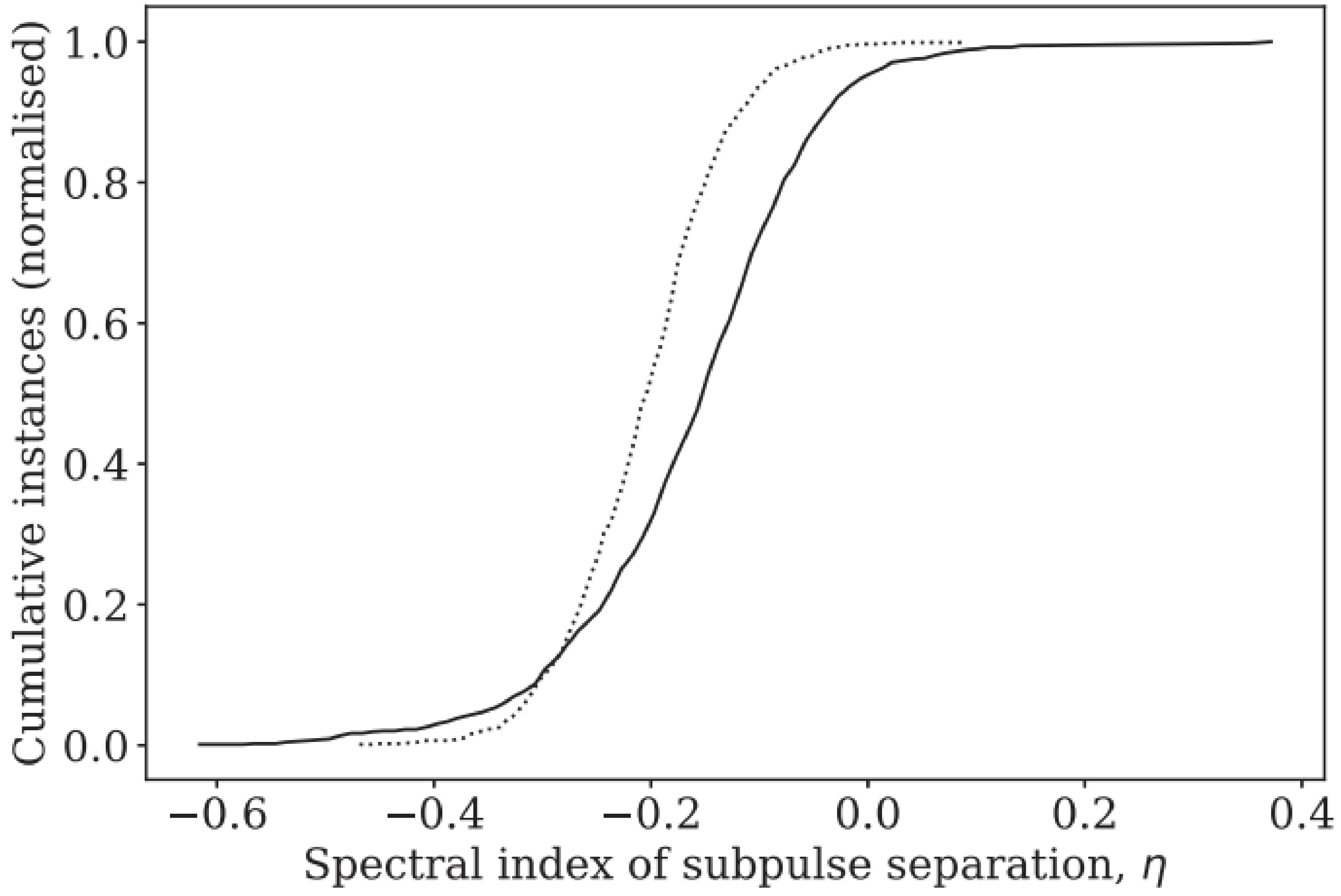


Figure 9. Cumulative distributions of spectral index of subpulse separation (η) for the data (solid) and the RFM model with the fan beam emission region (dotted).

2. Fan beam simulation: ——an justification——add OPM in

OPM(orthogonally polarized plasma modes):

(Backer et al. 1976, Melrose and Stoneham 1977……)
Sub-pulses may have orthogonal polarization modes.
(leading to PA jumping 90° and low linear polarization degree for integrated profile)

X mode: does not evolve with frequency
O mode: as before(simulate with the method discussed in section III)

sub-pulse number X : O = 7: 3 gives the best fit:

2. Fan beam simulation:

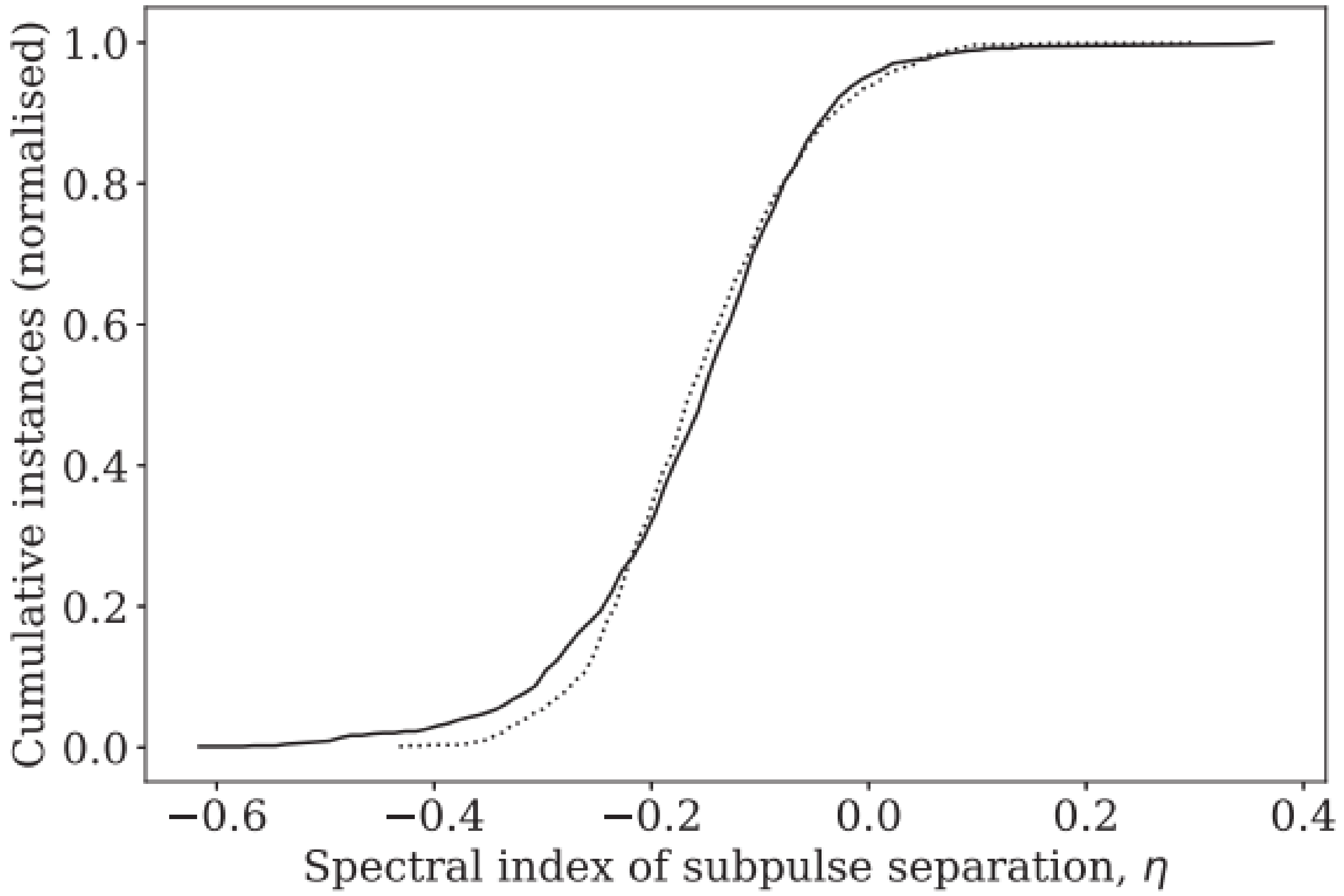
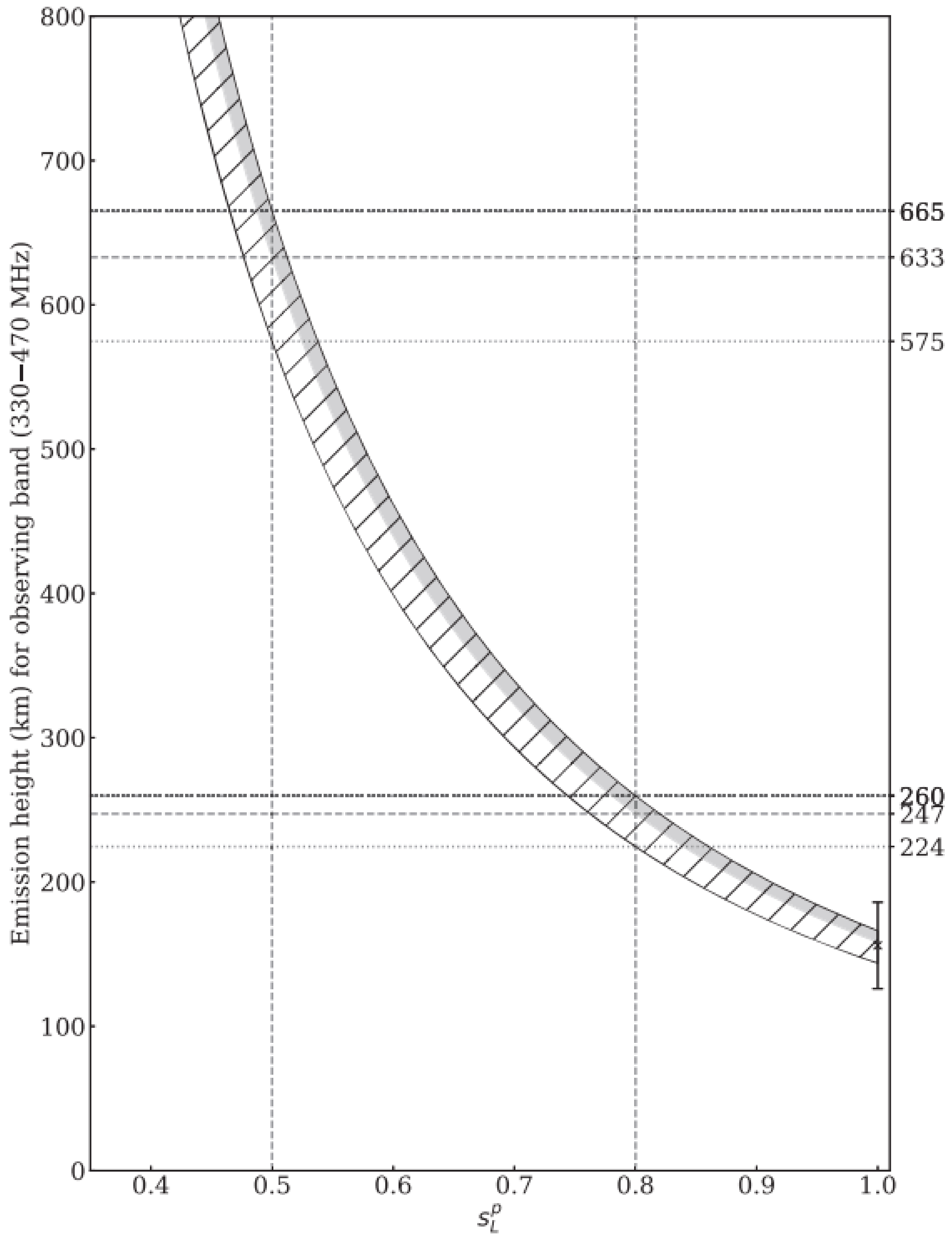


Figure 12. Cumulative distributions of the spectral index η for the data (solid) and the mode divergence model with fan beam emission region (dotted).

V. Discussions

1. Emission height:

The authors' results do not constrain footprints of field lines, which could affect emission heights.



2. Aberration and retardation:
Make a phase lag between the intensity and PA profiles at a given frequency.
——Could be used to fit and measure emission height——change footprint
——Polarization data can be used for a further study

3. Emission region shape:
Each frequency can be emitted by an extended region along the beam.

VI. Conclusion:

After a physical and geometry analysis to make a simulation, fan beam model with OPM performs best in explaining the single pulse sub-pulse data from J1136+1551.

Thank you
for your attention