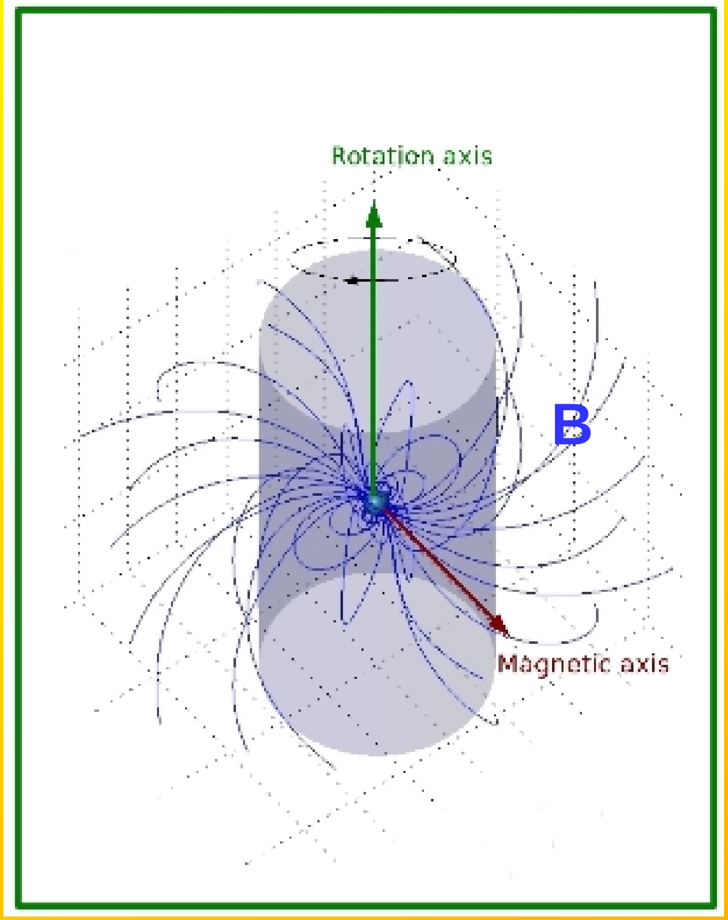
40 Years After: The Superluminal Pulsar Model (and its Surprising Applications) Revisited

Andrea Schmidt
John Middleditch
John Singleton

...and many, many others

Los Alamos
NATIONAL LABORATORY
EST. 1943

A (Very) Simple Picture of Pulsars



Pulsar: A rotating neutron star (Baade & Zwicky, 1934) with a very large corotating magnetic field **B** (Pacini, 1967, Gold, 1968).

→Observations show regular periods of rotation that range from 1.5 ms to 8.5 s.

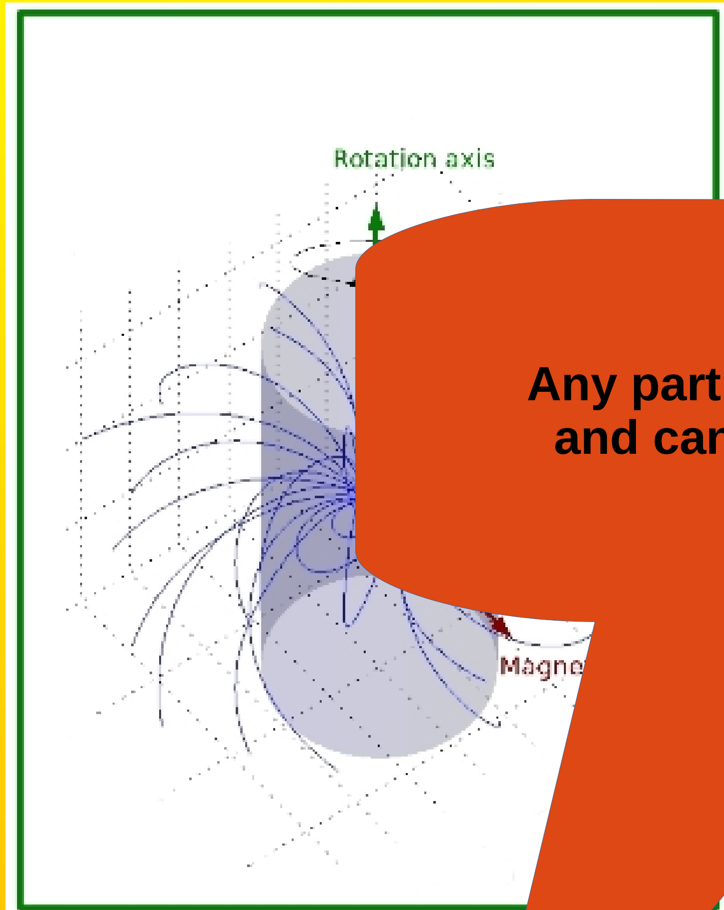
The magnetic field "swings" through the plasma- filled magnetosphere (Goldreich & Julian, 1969), forcing disturbances in the plasma to corotate rigidly with the magnetic field (and hence the neutron star).

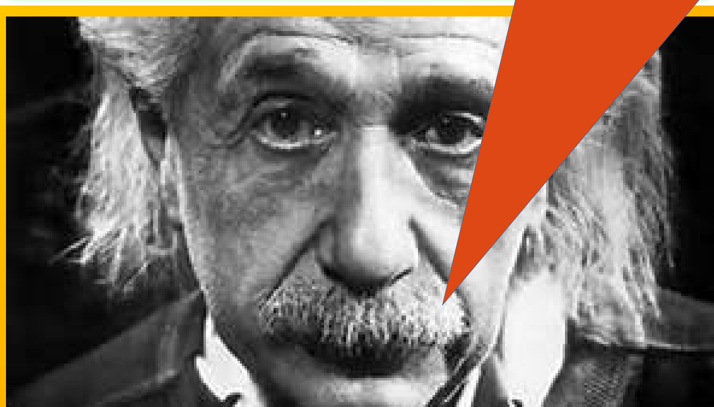
Velocity of **B** > c (i.e., faster than the speed of light) for

r > 75 km (1.5 ms pulsars)
r > 400,000 km (8.5 s pulsars)

B - which does not possess rest mass - rotates through the magnetosphere at velocities that exceed the speed of light. But how about the -ve and +ve ions that make up the plasma?

A (Very) Simple Picture of Pulsars





Pulsar: A rotating neutron star (Baade & Zwicky, 1934) with a very large corotating magnetic field **B** (Pacini, 1967, Gold, 1968).

Any particle that has charge also has rest mass and can, therefore, not move faster than light.

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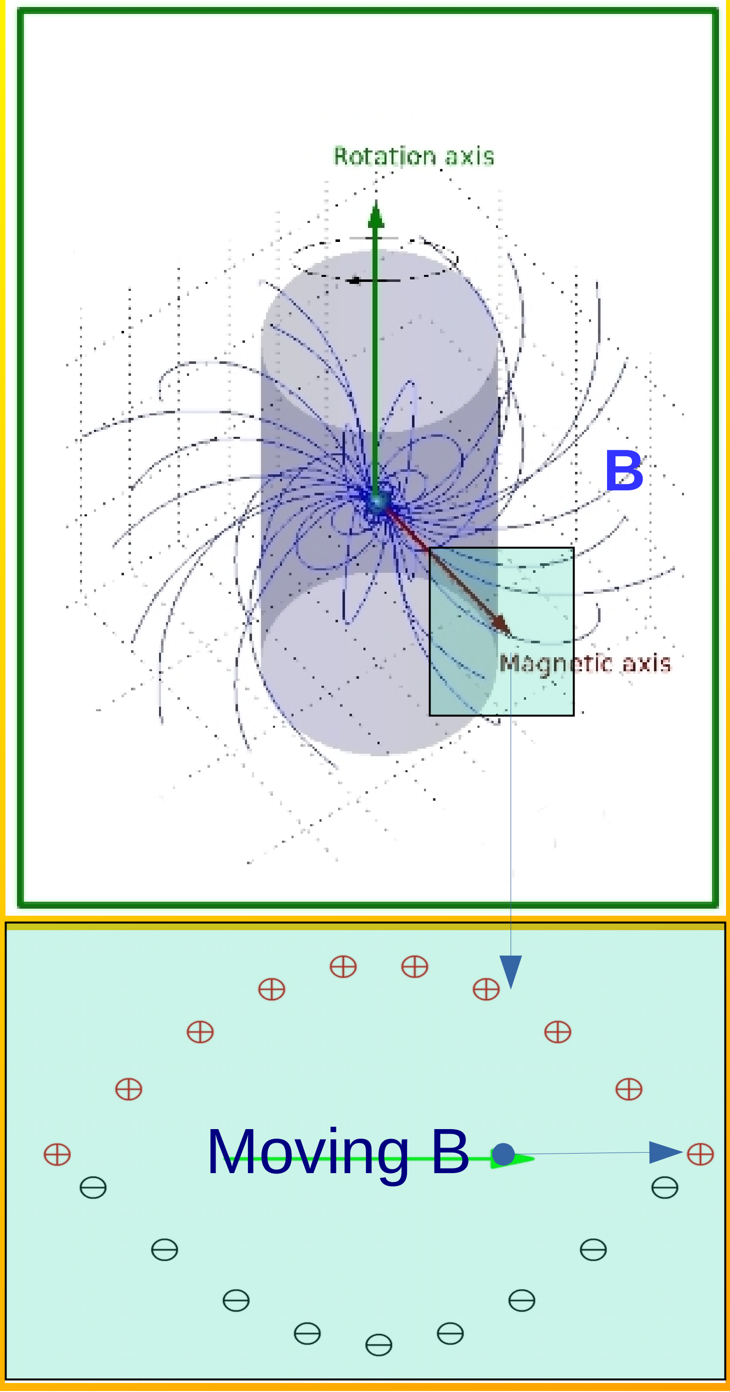
Speed Limit
299,792,458 m/s
IT'S THE LAW!

The Superluminal Pulsar Model (Houshang Ardavan, late 70's)



While special relativity precludes massive particles from moving faster than light, patterns or disturbances caused by the relative motion of individual charged particles are not restricted to subluminal speeds (Bolotovskii and Ginzburg, 1972).

Electromagnetism: A magnetic field that changes with time gives rise to an electric field:

$$\nabla \times \boldsymbol{E} = \frac{-\partial \boldsymbol{B}}{\partial t}$$

As **B** swings through the pulsar's magnetosphere, -ve and +ve ions are displaced in opposite directions

→a traveling region of electrical polarization **P** with speed *v* has been created.

Trivial solutions of Maxwell's equations show that the polarized region must keep up with the magnetic field's rotation → $v > c$ for $r > c/\omega$, where c/ω is the light cylinder.

Notice that the displacements of the massive particles are small and << *c*. Hence, the polarized region can move faster than light even though the individual particles do not.

Why does this polarized region emit radiation? Maxwell's equations III and IV

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_{\text{free}} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t}$$

Green terms describe the wavelike motion of electromagnetic radiation.

Conventional radiators (synchrotrons, antennas) use the free current of electrons **J** as source. But electrons are massive particles and, hence, restricted to $v < c$ (Einstein!).

The polarization current ∂**P**/∂t **contributes to the fields in just the same way as the current J of free charges**; however, as it is not carried by massive particles, it is not limited to subluminal speeds.

The "Mexican Wave," or *La Ola* , as it surges through the rows of spectators in a stadium.

Emission Time vs Reception Time, Picard’s Manoeuvre and Multiple Images

There is a very important way in which superluminal sources differ from subluminal ones: The emitted waves can intersect or “rub up” against one another. This is to say that the relation between retarded (source) and reception times <u>need not be one-to-one</u>: Multiple retarded times – or even an extended period of source time – may contribute to a single instant of reception. This naturally leads to focusing, e.g., the concentration of energy in one place. The more waves intersect, the more noticeable this effect will be →NEED ACCELERATION!

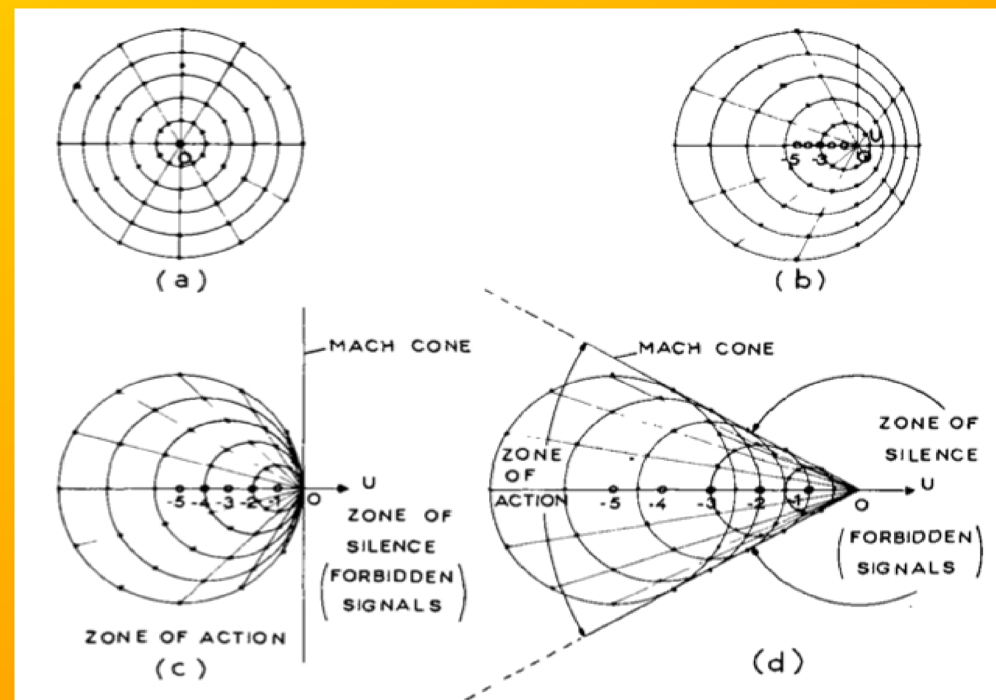
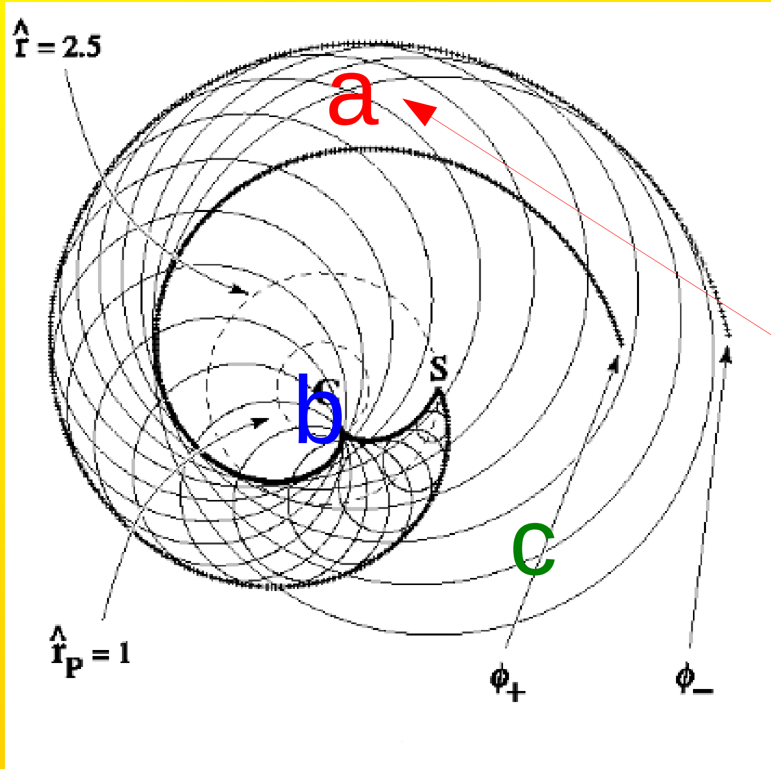


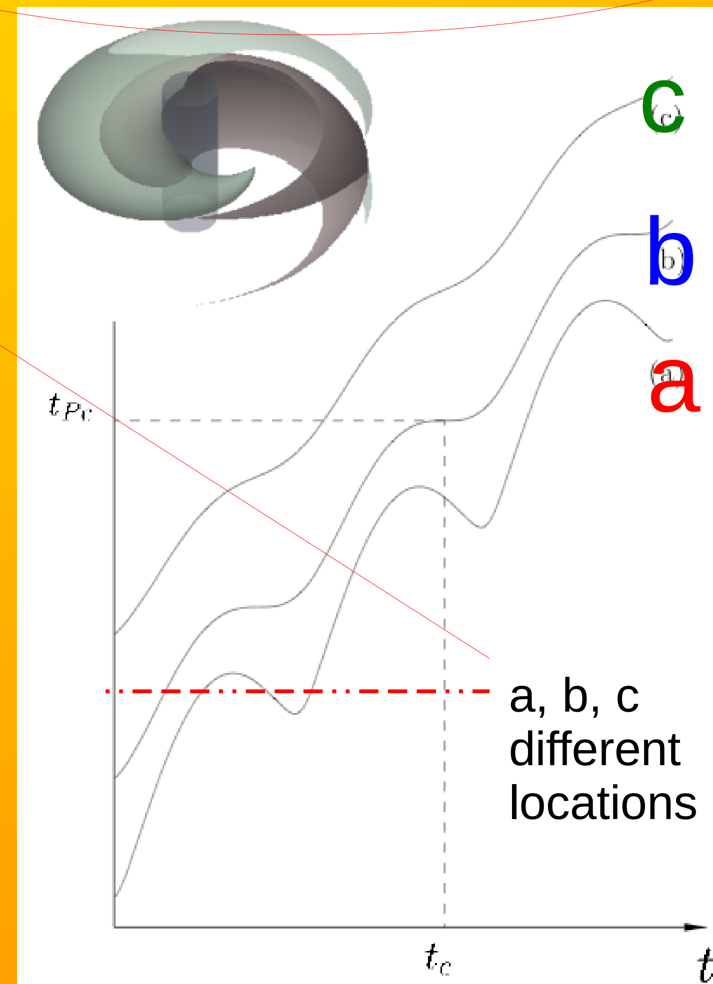
Fig. 42. Point source moving in compressible fluid. (*a*) Stationary source. (*b*) Source moving at half the speed of sound. (*c*) Source moving at the speed of sound. (*d*) Source moving at twice the speed of sound. (From Th. von Kármán, in *Journal of the Aeronautical Sciences*, *14* [1947], 374, by permission of the Institute of the Aeronautical Sciences.)

This effect is well known in aerodynamics:

Centripetal Acceleration



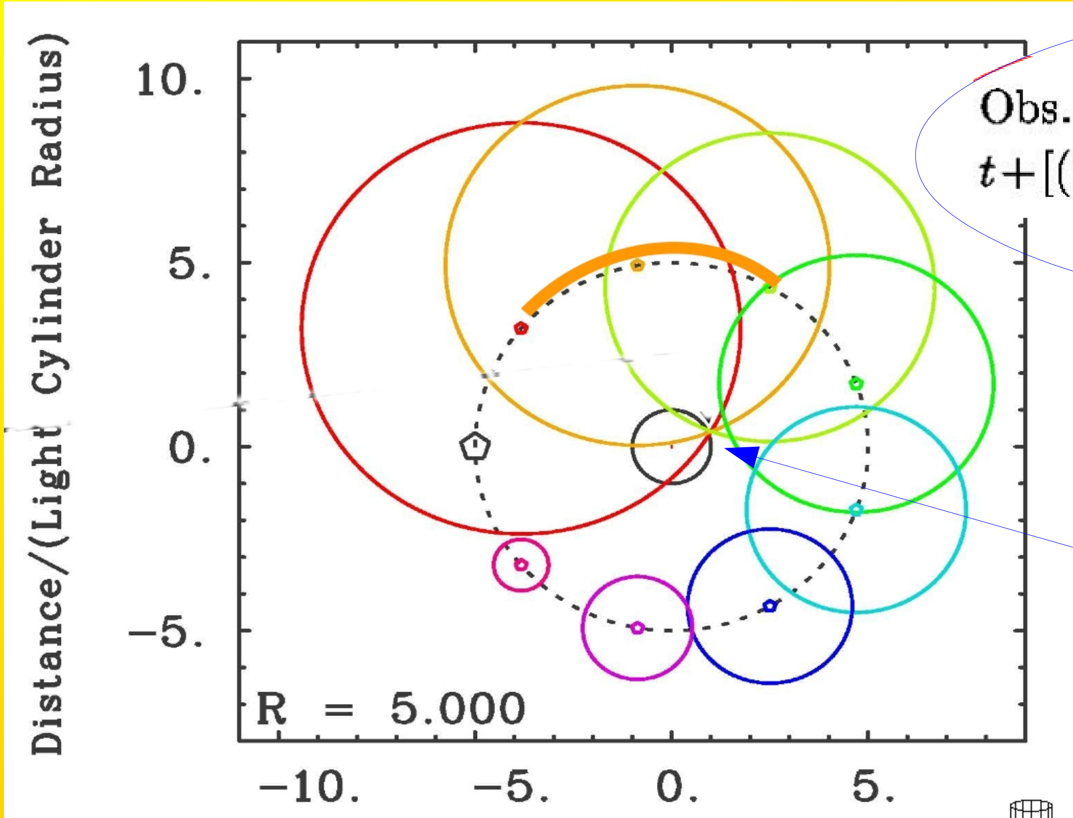
Obs. time t_P = source t + dist/c $= t + R_P/c =$
$$t + \left[(z_P - z)^2 + r_P{}^2 + r^2 - 2 r_P r \cos(\varphi_P - \hat{\varphi} - \omega t)\right]^{\frac{1}{2}}/c$$



Sources in superluminal acceleration possess a two-sheeted envelope and a cusp – a region of intense concentrated energy. The relationship between emission and observation time need not be monotone and one-to-one: Multiple retarded times – or even extended periods of source time – can contribute to a single instant of reception.

Note that contributions from *three* retarded times received for case (a).

The Cusp: A “Natural” Focus of Energy

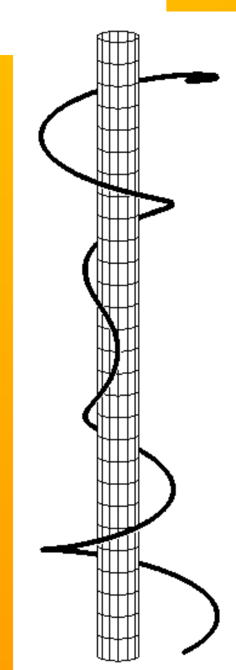


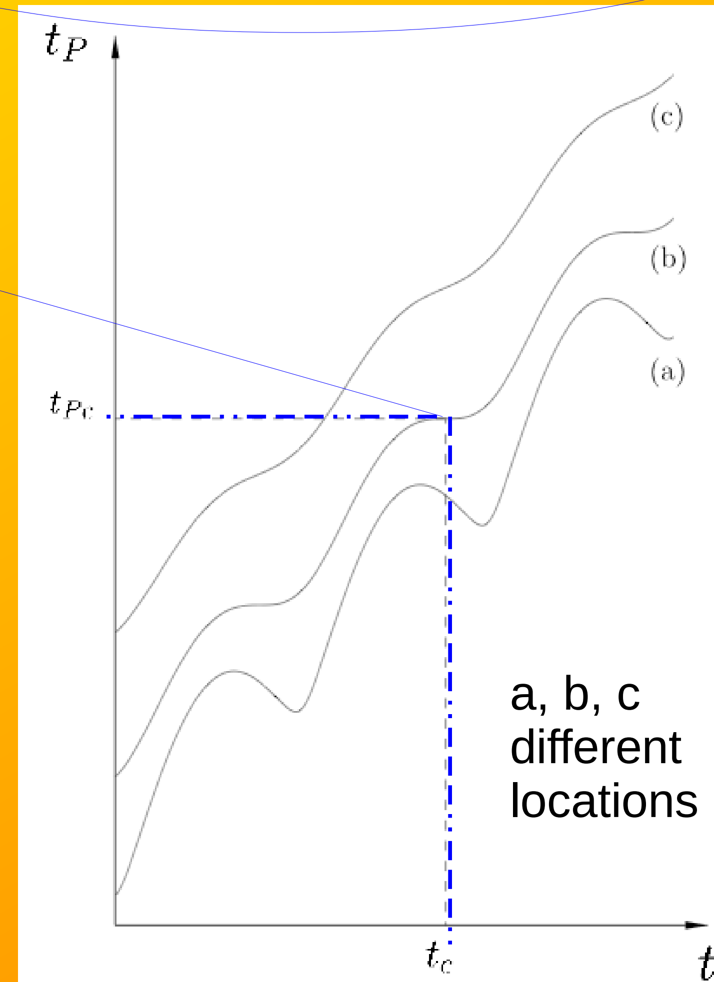
Obs. time t_P = source t + dist/c = $t + R_P/c$ =

$$t+[(z_P-z)^2+{r_P}^2+r^2-2r_P r\cos(\varphi_P-\hat{\varphi}-\omega t)]^{\frac{1}{2}}/c$$

Credit: J. Middleditch

For a source orbiting at a radius of 5 light cylinders (above), ALL the wavelets emitted between 10 hr 20 min to 1 o'clock (orange arc) are received in a single instant at a location tangent to the light cylinder at 2 o'clock.



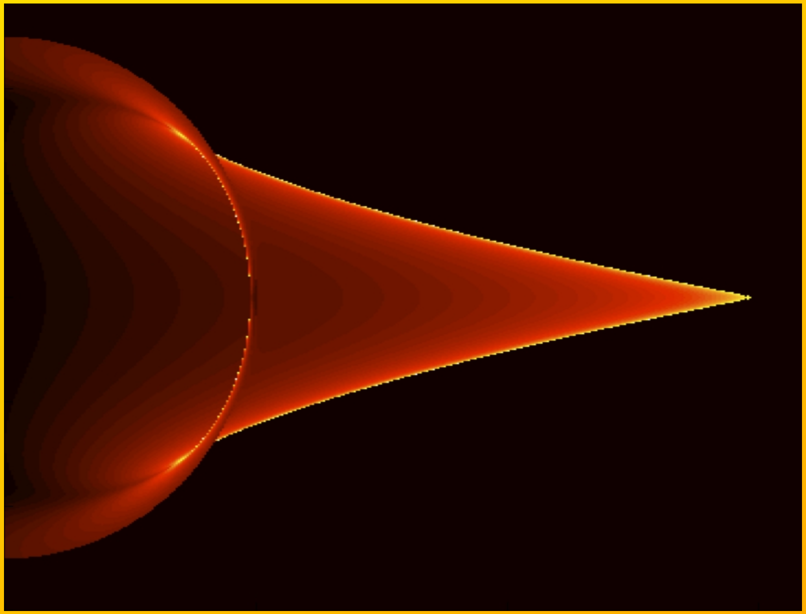


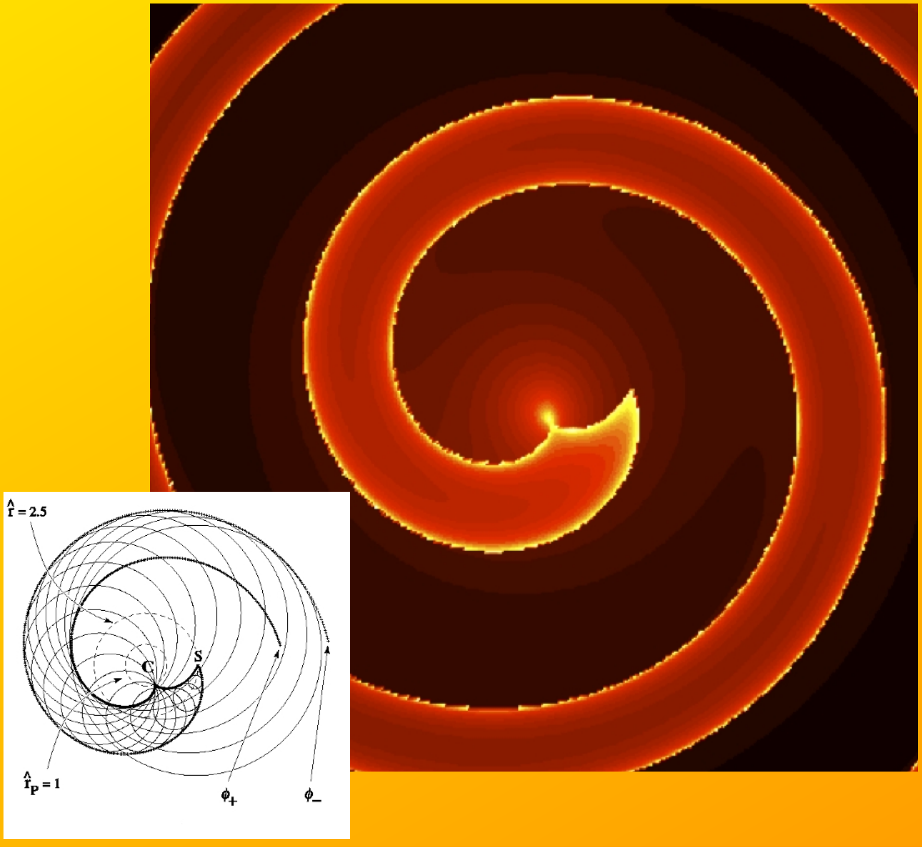
For case (b), an extended period of source time is received in a single instantof reception.

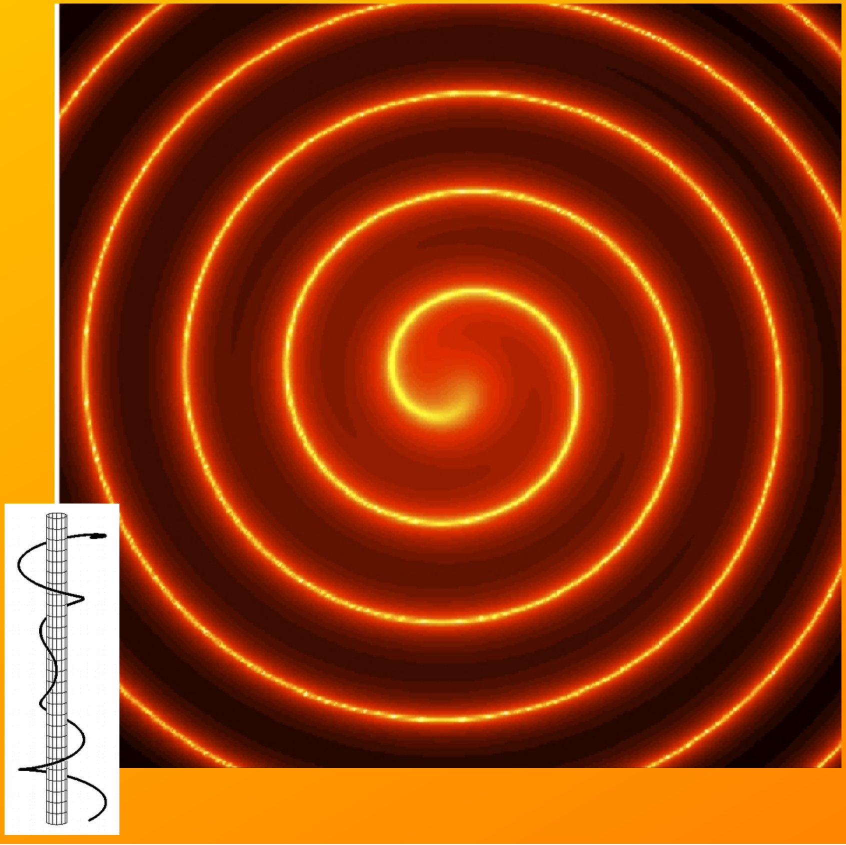
The radiation fields generated by a point charge in linear (top) and circular (bottom) superluminal acceleration.

Bottom left: In the source's plane of rotation

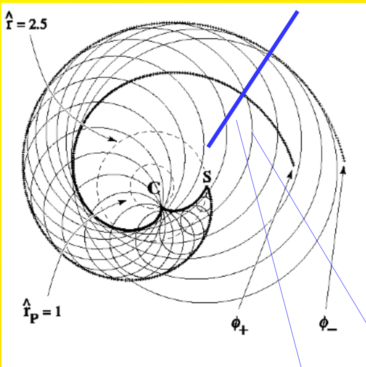
Bottom right: On the limiting cone of the cusp ($\sin(\theta) = c/v = c/r\omega$, where θ is the opening angle of the cone)







Comparisons to Astronomical Observations: Individual Pulses

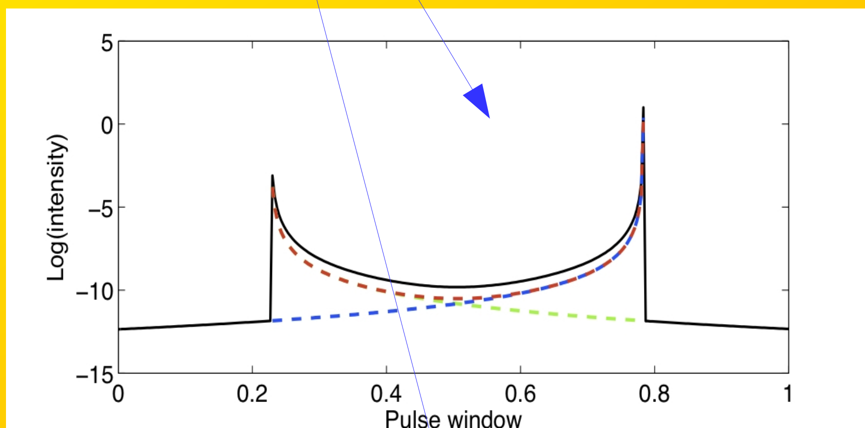


The Liénard-Wiechert field of a point source in uniform superluminal rotation at ($\mathbf{x}_p$,t_p) is given by:

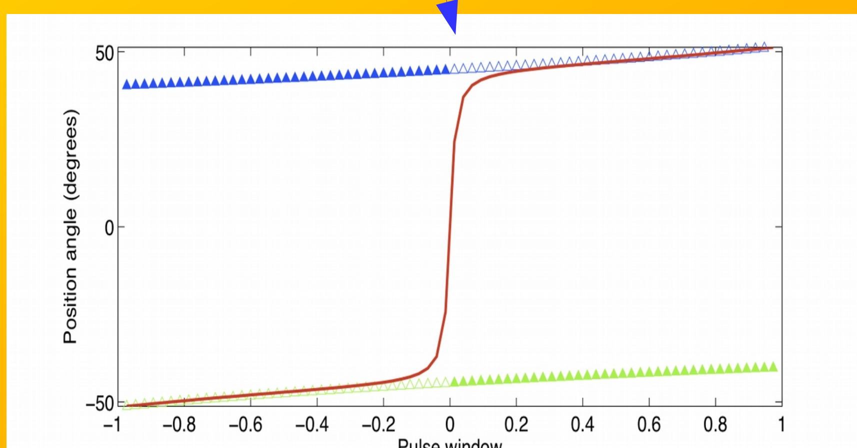
$$E(x_P, t_P) = q \sum_{t_{ret}} \left[\frac{(1-|\dot{x}|^2/c^2)\,u}{|1-\hat{n}\cdot\dot{x}/c|^3 R^2(t)} + \frac{\hat{n}\times(u\times\ddot{x})}{c^2|1-\hat{n}\cdot\dot{x}|^3 R(t)} \right],$$

$$B = \hat{n}\times E.$$

Here, $R(t) \equiv x_P - x,\ \dot{x} \equiv dx/dt,\ u \equiv \hat{n} - \dot{x}/c,$ and the unit vector $\hat{n} \equiv R/R$ designates the radiation direction.

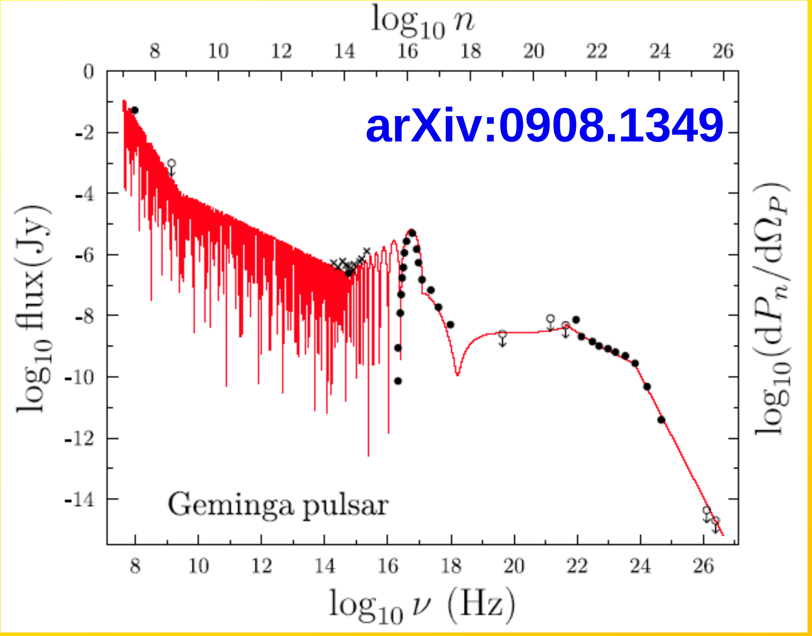


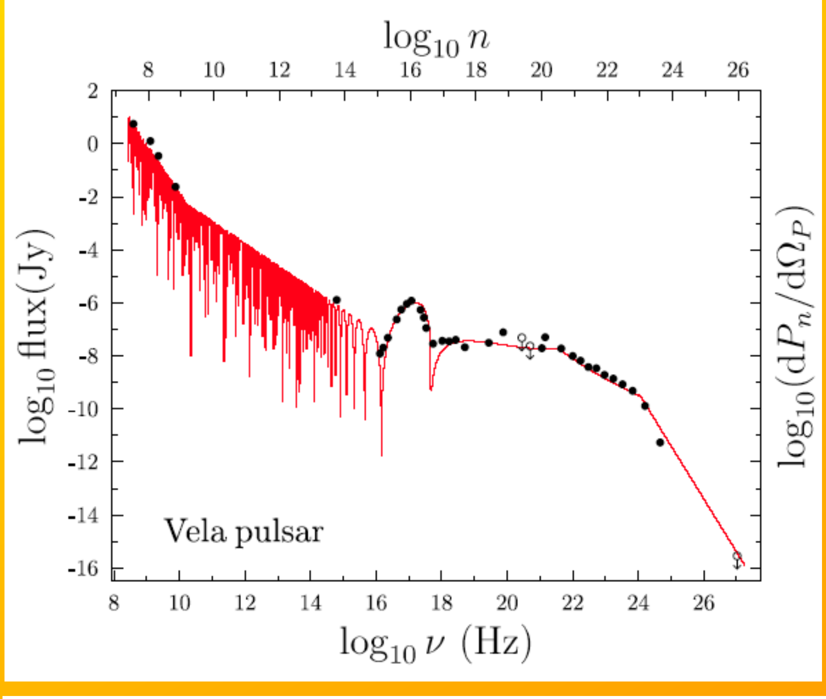
Intensity:
Calculated intensities of the contributions from the three retarded times (colour) and their resultant (black).



Polarization:
he three retarded times reproduce all of the features of the observational data, including the 90 degree swing.

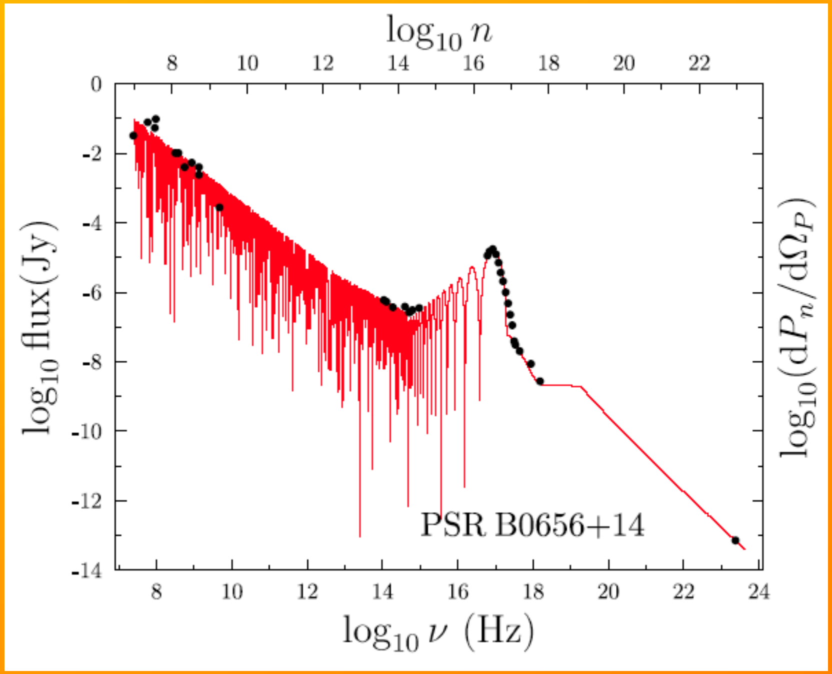
Comparisons to Astronomical Observations: Frequency Spectra



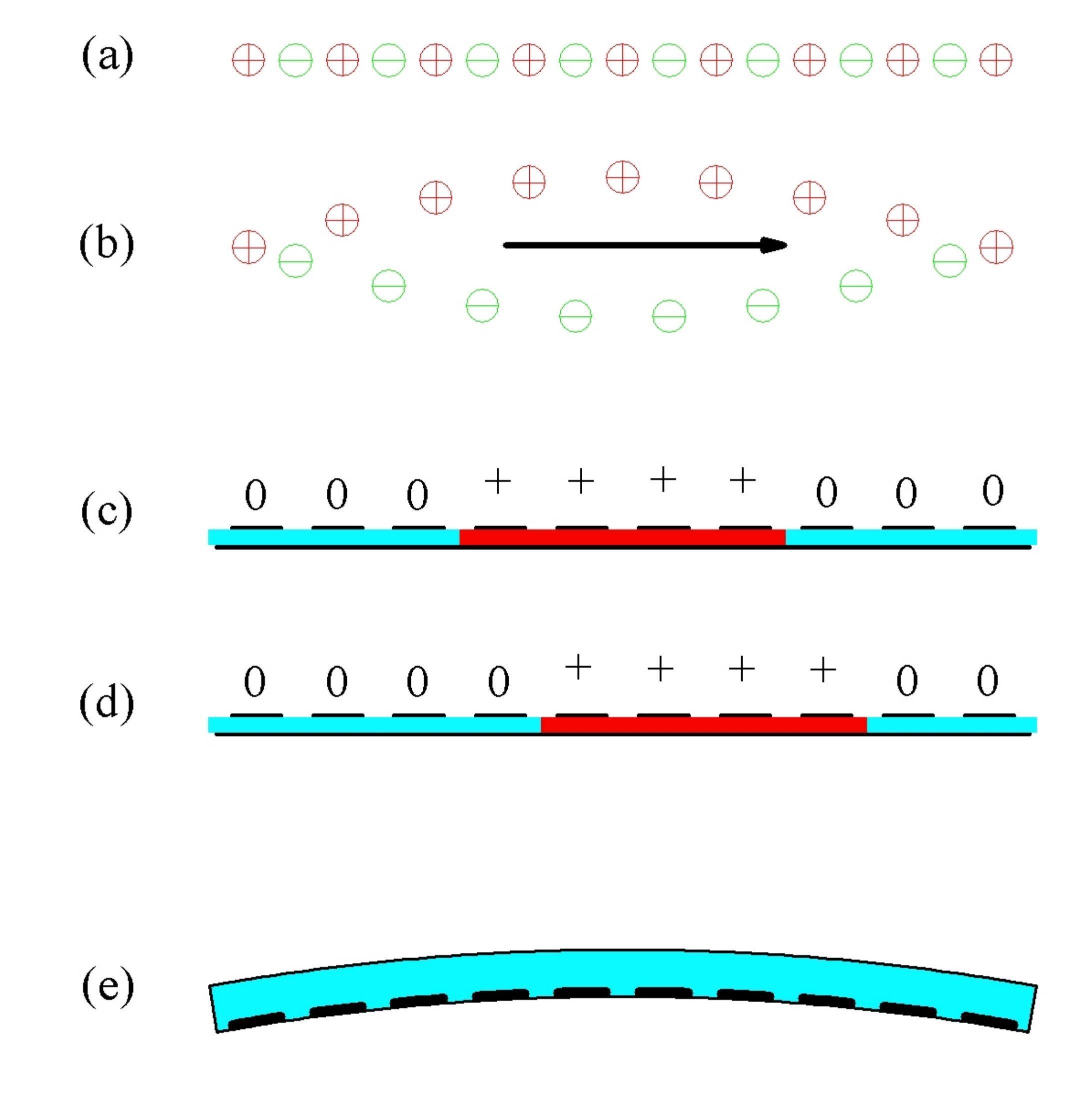


Same Model (---) fits *all* pulsars with broadband data (•, 9 in total):

Overall behavior given by superluminal nature of source:
Coarse features scale as (rotational period)^3 .
Detail differences due to resonances in pulsar atmosphere at emitting region (plasma freq., cyclotron resonance):
Typical fitted plasma densities ~ 10^4-10^5cm $^{-3}$
Magnetic fields ~ 10^8-10^9 Gauss



Electrostatic Excitation



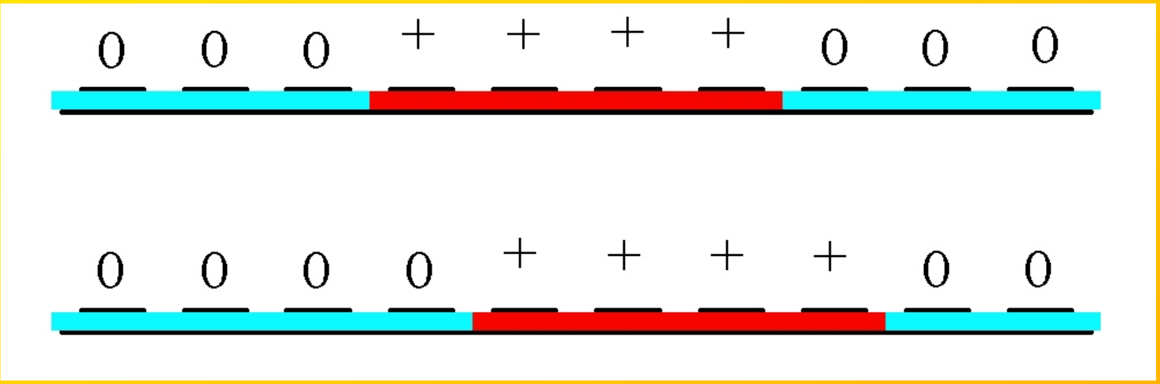
(a) Unpolarized solid containing ions.
(b) Turn on varying **E**-field → region of finite **P** that can be moved along arrow.
(c) Experimental realization; electrodes are placed above and below a strip of dielectric.
(d) Switch plates on and off in sequence → polarized region moves.

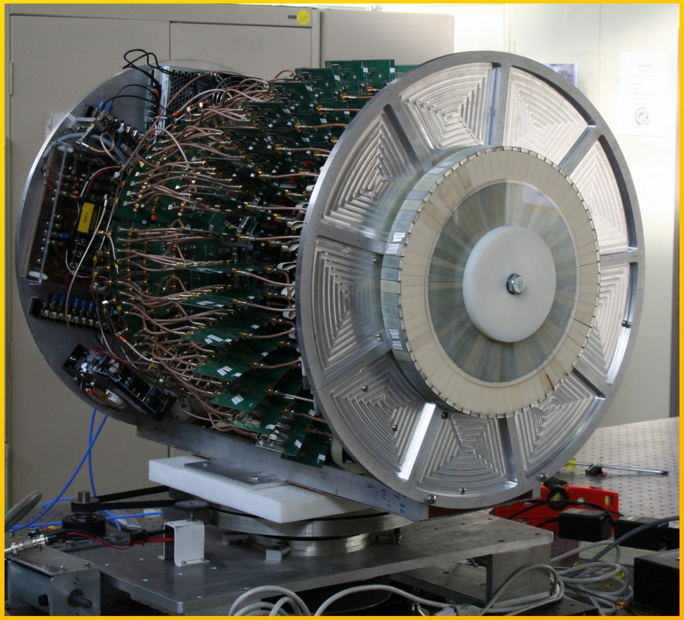
Moving a polarization current very fast is just a question of precise timing.

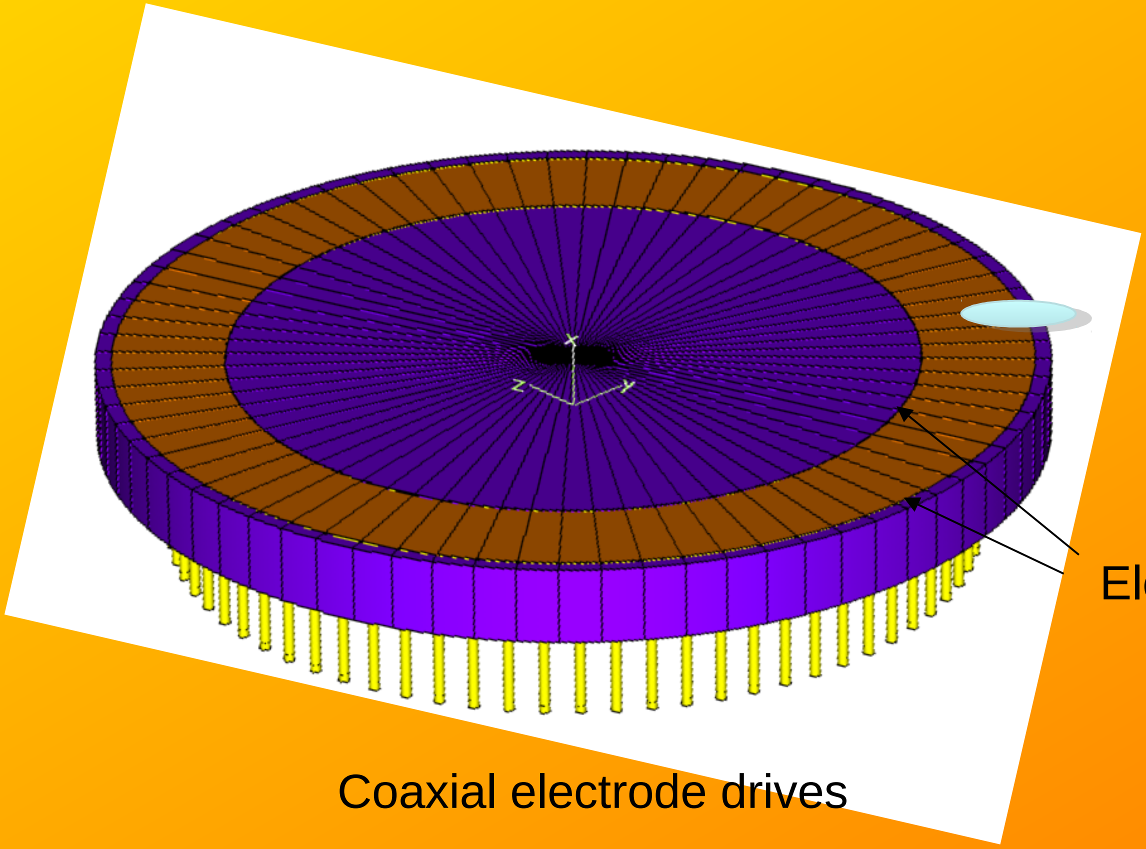
Moving the polarization current in a circle

Metal electrodes are placed on either side of a dielectric. Apply voltage (+) to create a polarized region. To move, switch electrodes on and off in sequence.

Our circular emitter has 72 electrode pairs placed on either side of a circular strip of alumina.

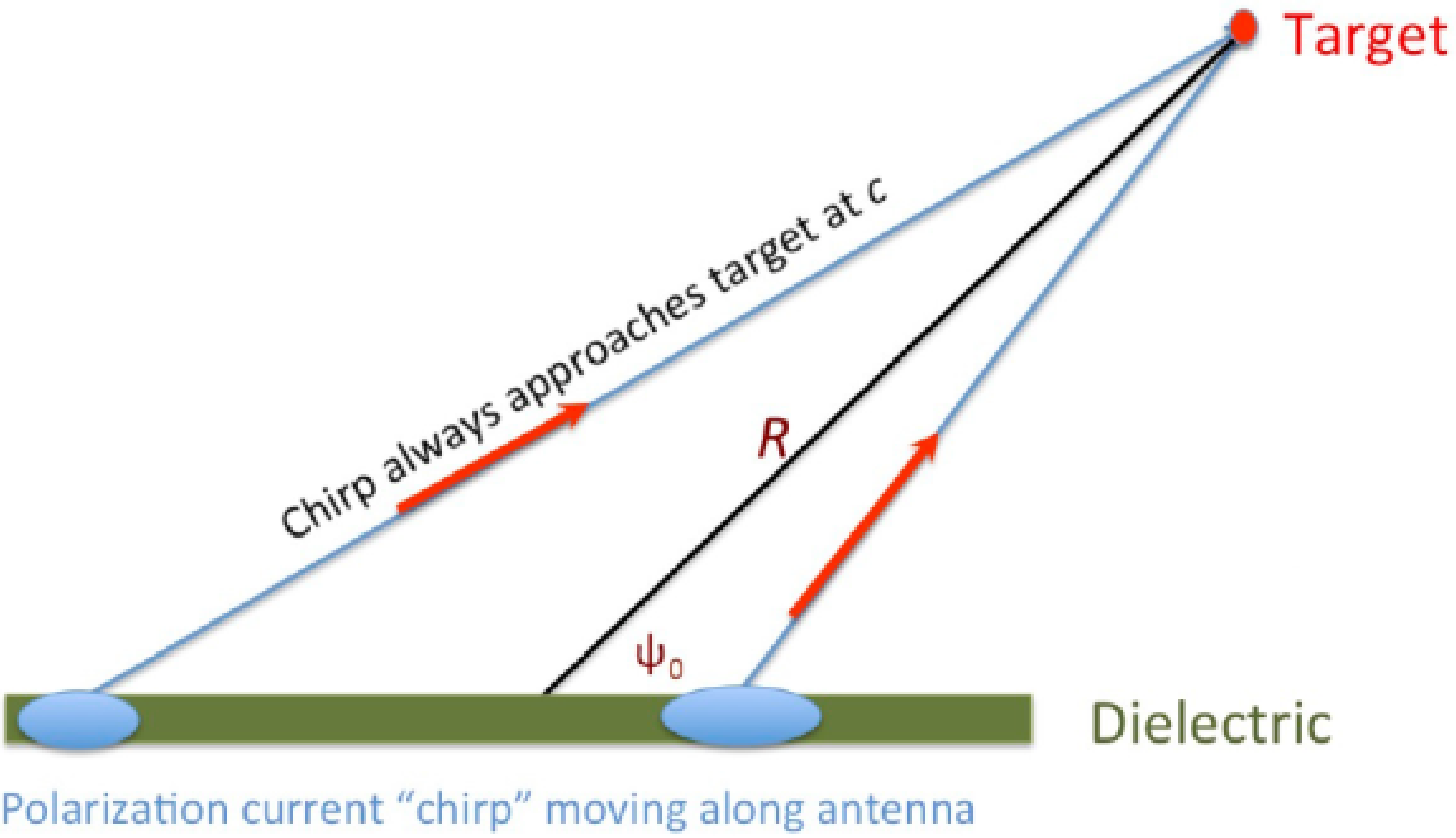




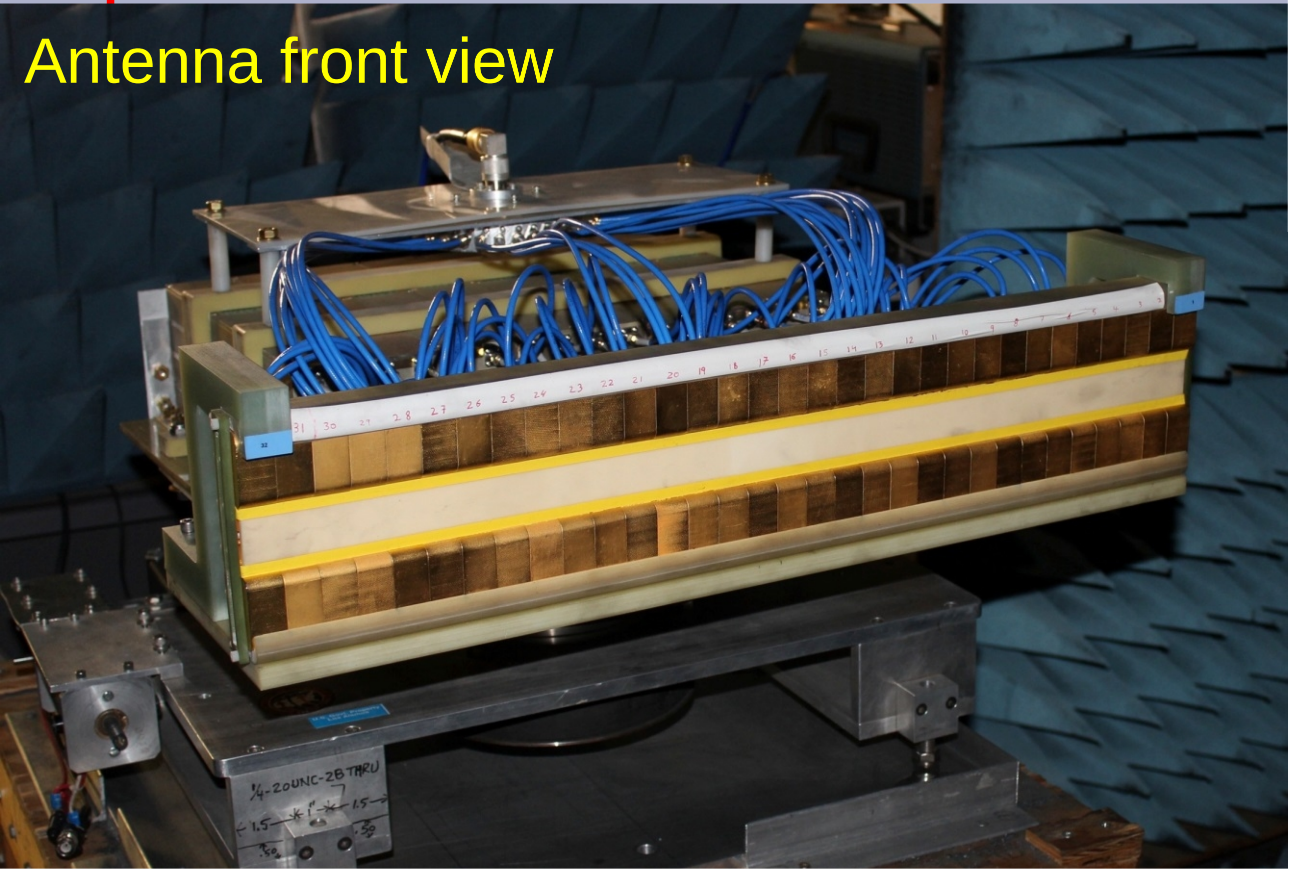



University of Oxford
Department of Physics

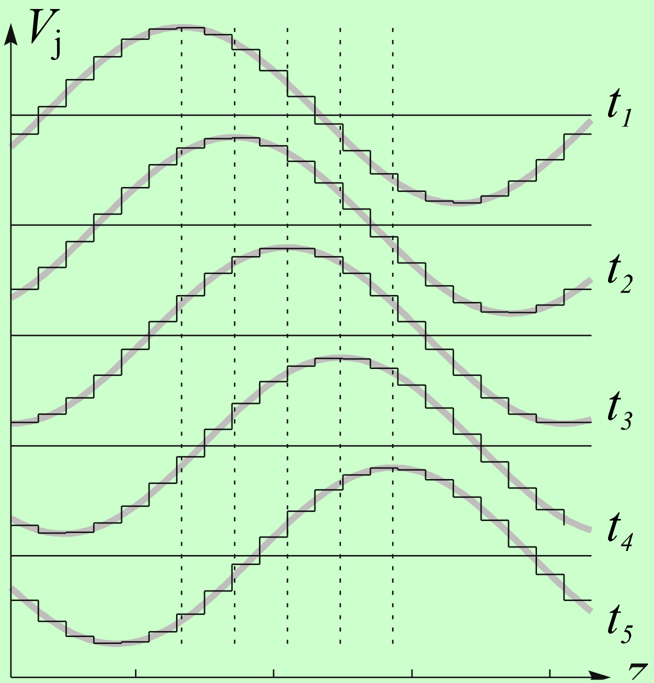
Experiment: Focusing a Signal



Experiment: Choice of Antenna

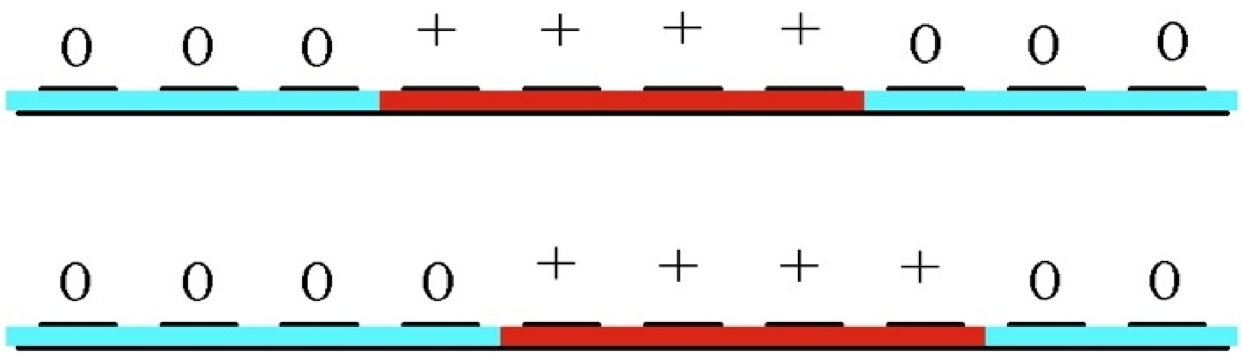


The linear antenna used for the experiment; 32 elements; mounted on turntable.

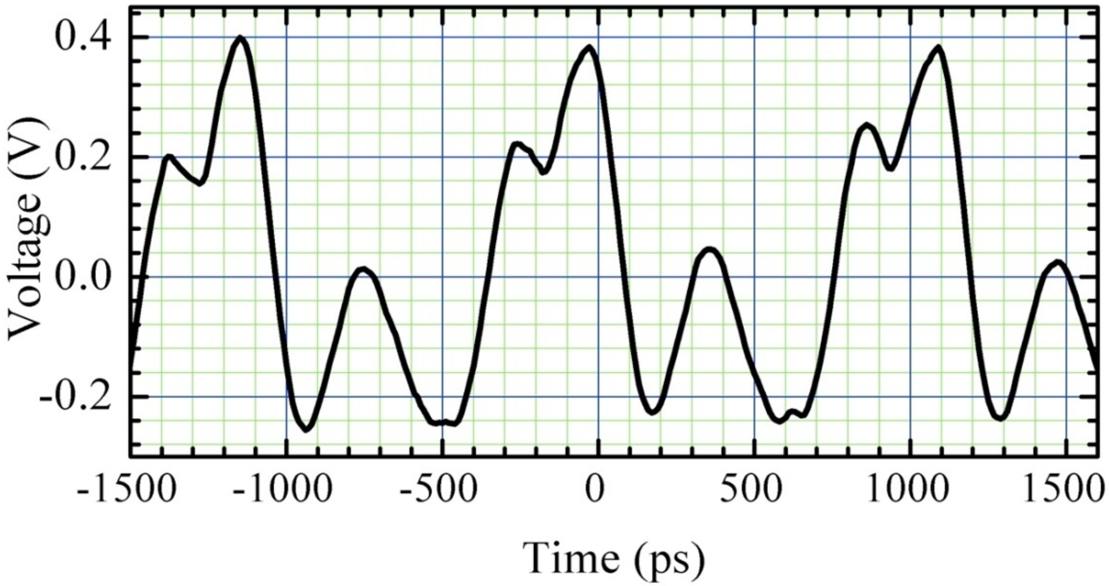


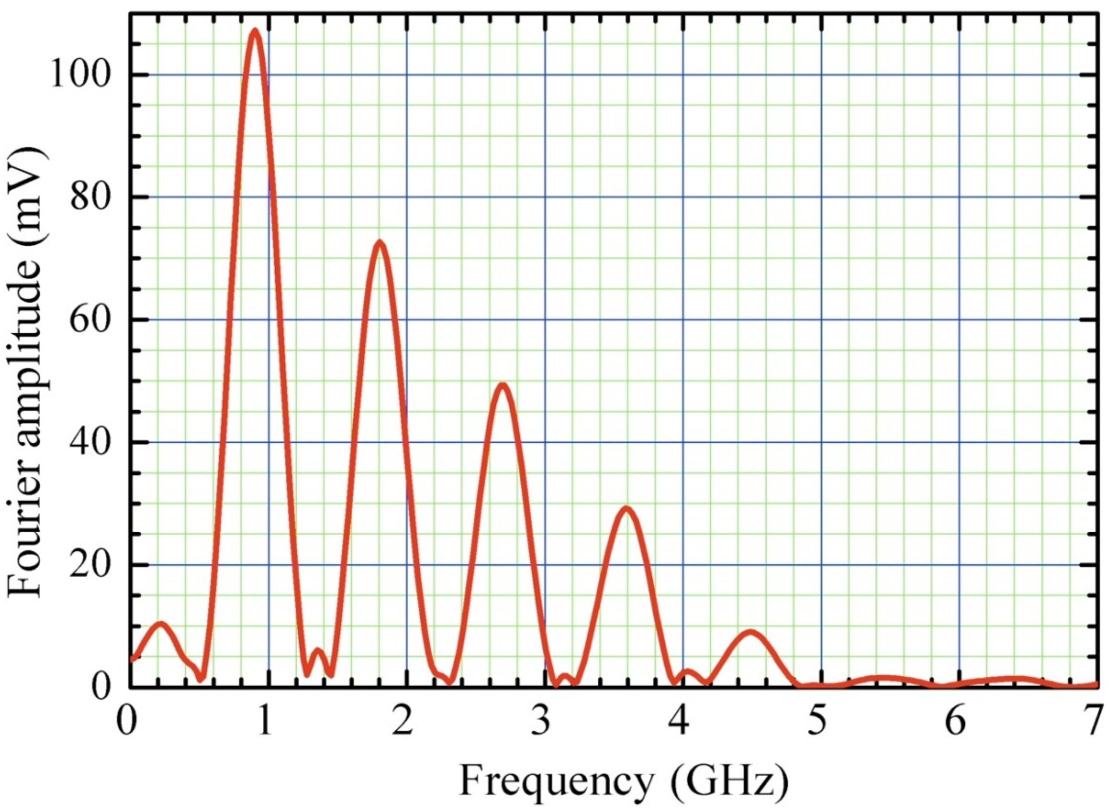
We feed signals with different delays to each electrode so that the waveform moves at the desired speed.

Schematic: electrodes above and below strip of dielectric. Apply voltages to electrodes; polarized region moves.



Experiment: The Broadcast Signal

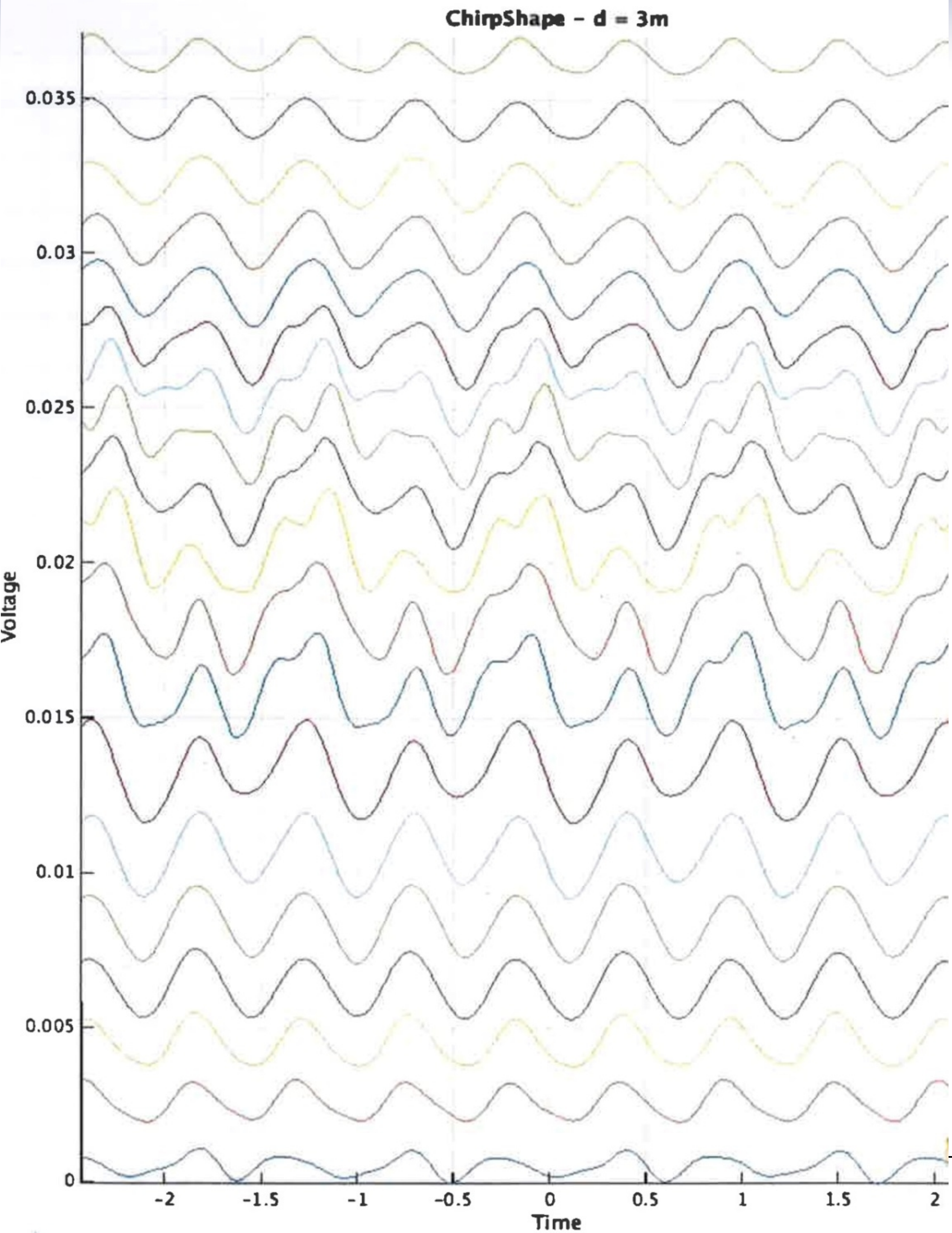




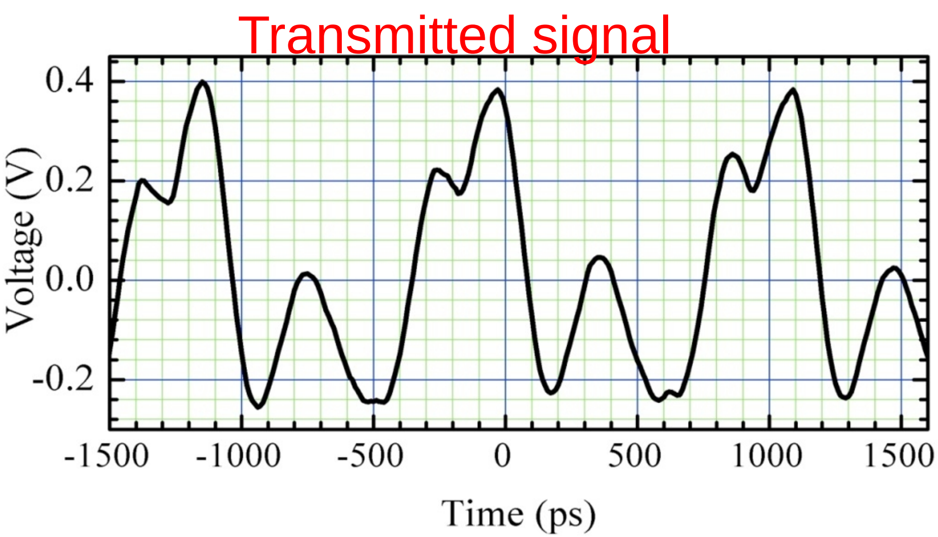
IED

- Little work done on modulation rates ~ carrier frequency. For 3.6 GHz, DDS capable of this costs ~k$100 or more.
- Impossible within current project resources to synthesize a chirp of the form used in the extant simulations.
- Single chirps also problematic for detection.
- Synthesize stream of bursts with a very distinctive (“triangular”) frequency spectrum.

Experiment: Evidence for Focus at Desired Angle



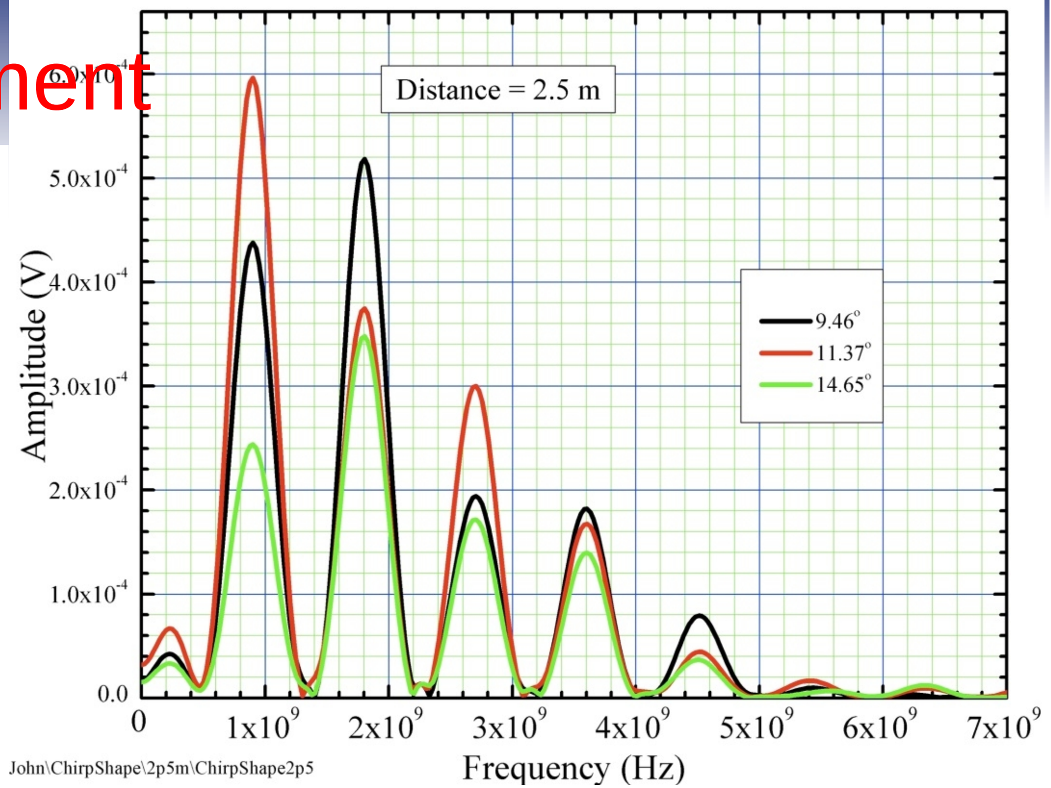
Set distance to 3.0 m; rotate antenna through focus angle (11.7°) in 1° steps; at each angle, look at time dependence of received signal and compare with transmitted signal. Only at 11.5° (central orange trace) is received signal exactly the same as the transmitted signal.

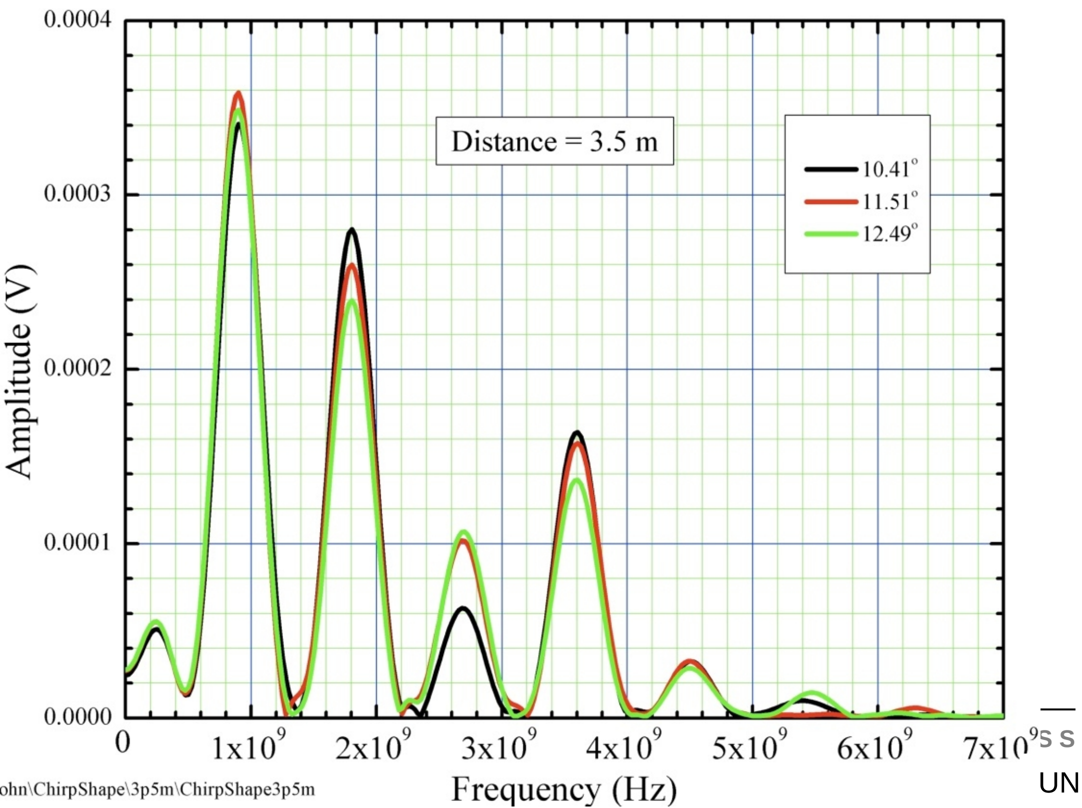


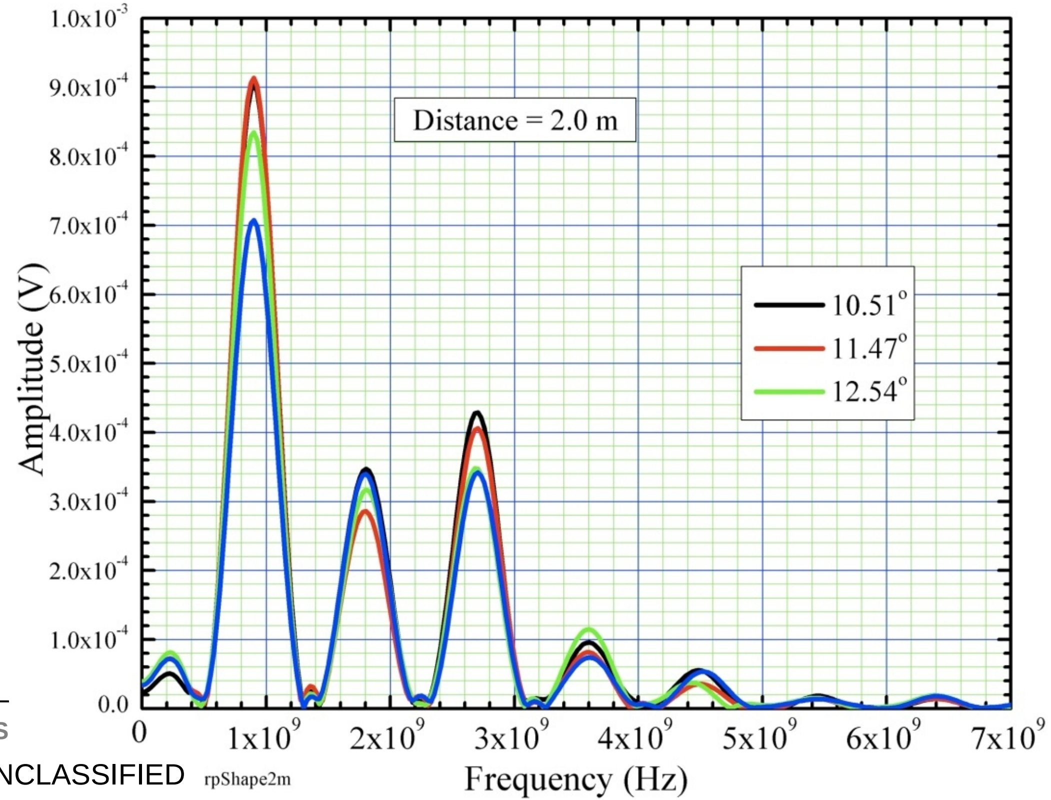
Experiment: Radial confinement

Look around focus angle of 11.7°. The “triangle” Fourier spectrum is slightly distorted at 2.5 m and greatly perturbed at 2.0 m and 3.5 m.

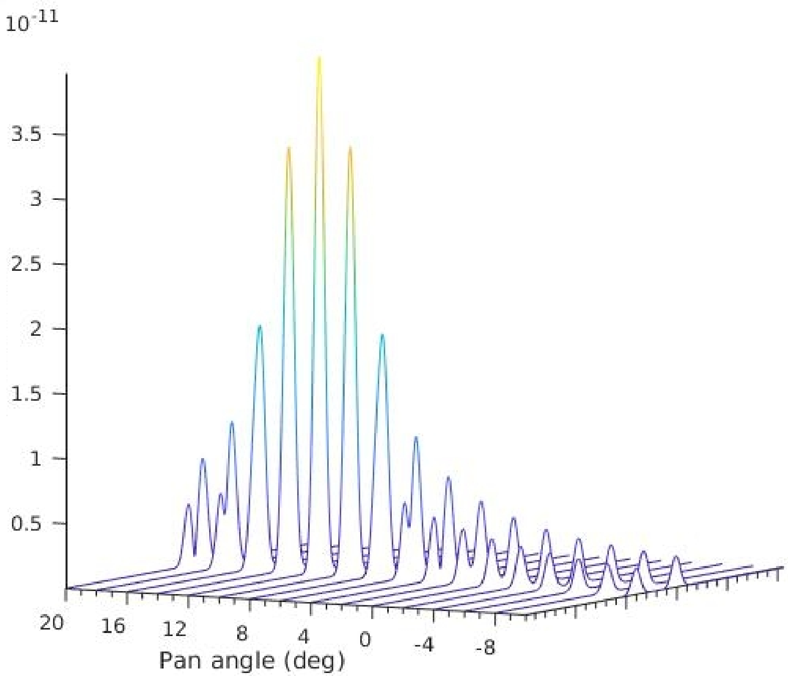
Signal is reproduced only close to the desired distance of 3 m.

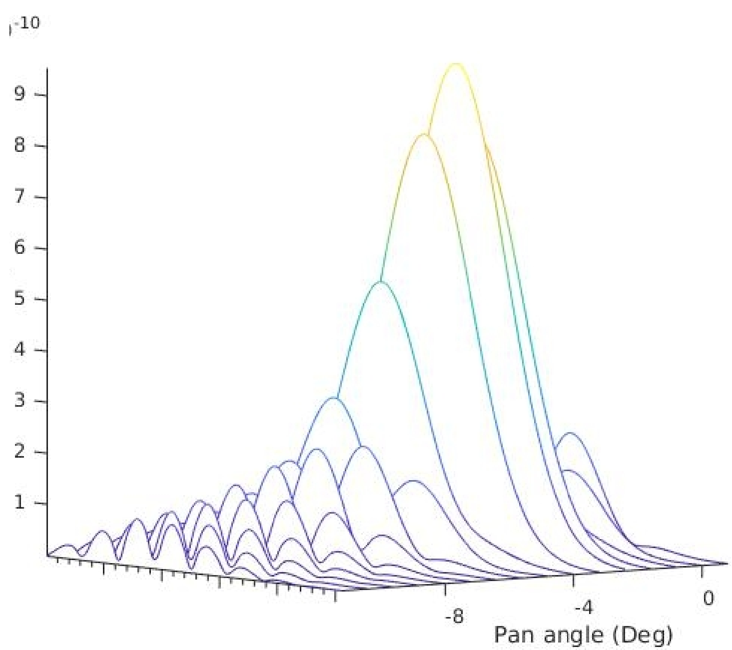






Predicted Observation: Amplitude and Frequency Patterns





- The signal is expected have maximum strength at a pan angle of about 12^{o}. Despite the simple acceleration scheme, it is evident that the signal will be "scrambled" and suffer rapid decay with increasing angular distance since the relation between emission and reception time is neither linear nor 1:1.
- Similarly, the signal loses its frequency content rapidly and becomes "illegible".
- The degree of "scrambling" is directly related to the complexity of the acceleration scheme and, hence, the multi-valuedness of the t vs t_P relation.