Introduction to Radio Wave Polarization

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1. Introduction

Polarization is a property of a radio wave that describes the shape of its electric field vector as a function of time. In general, the tip of the electric field vector (see sidebar) traces an elliptical path as it passes a point in space. Circular and linear polarizations are familiar but special cases of the more general elliptical polarization (figure 1). The plane of polarization is the wave front, which is at a right angle to the direction of propagation.

Electric and magnetic fields: All propagating radio waves consist of an electric and magnetic field at right angles to each other. In this article, everything said about the electric field vector also applies to the magnetic field vector, but the latter is left out for convenience.

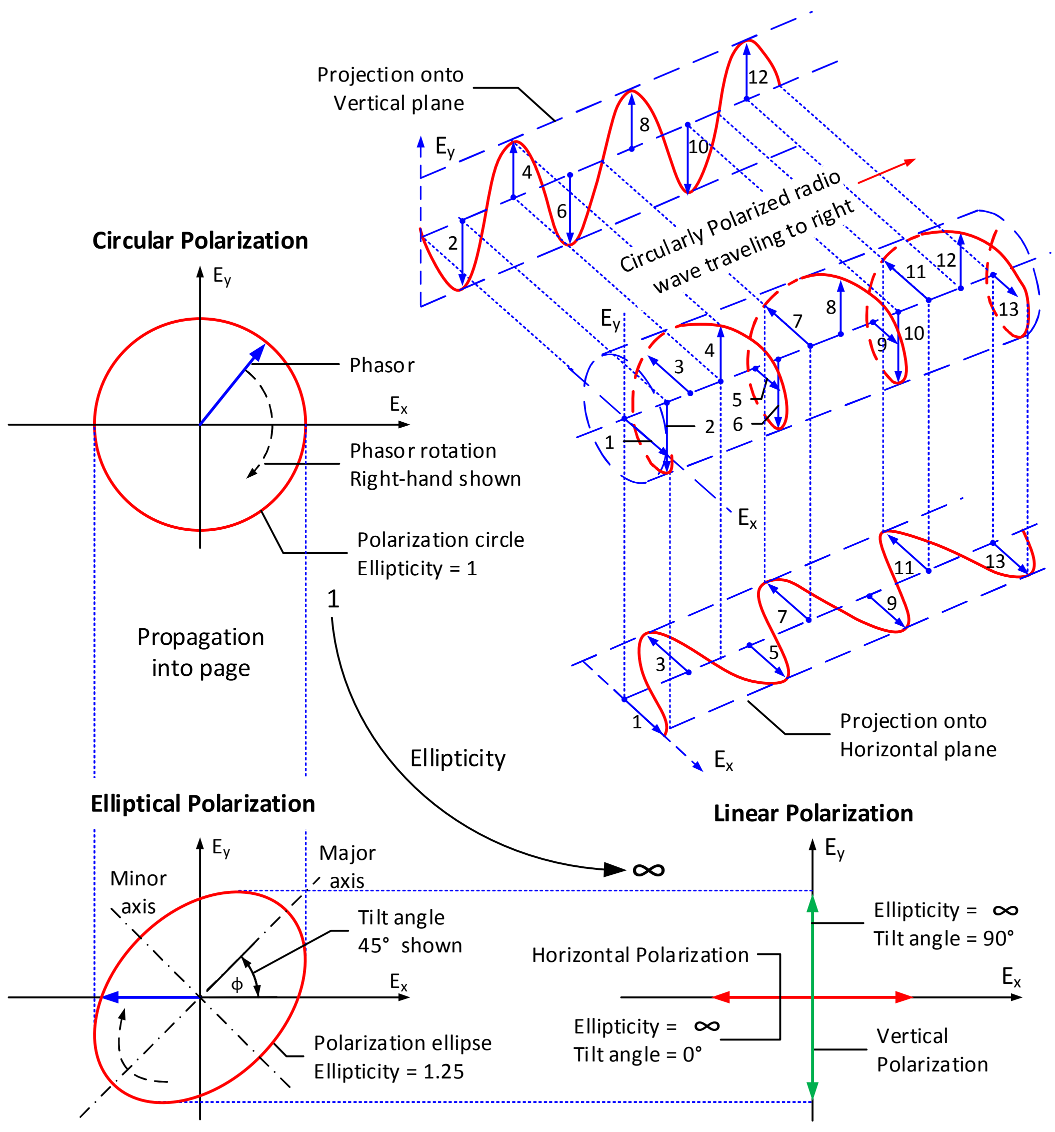


Figure 1 ~ Examples of polarization. Top-right: The radio wave is moving from left-to-right slightly into the page, and the electric field is rotating clockwise as it moves. Arrow 1 is the electric field vector (or phasor) at the start. As the wave propagates the vector rotates from position 1 to 2 to 3, and so on, where the numbers are multiples of π/2. The projection of the electric field amplitude on a horizontal plane with vectors 1, 3, 5 . . . is shown immediately below as the horizontal component of the elliptically polarized wave. The projection on a vertical plane with vectors 2, 4, 5 . . . is shown to the left. Note the 90° (π/2) phase difference between the horizontal and vertical projections. Top-left: If the ellipse has equal major and minor axes, it would be a circle, and the wave would be circularly polarized. Bottom-left: The ellipse indicates the line traced by the tip of the electric field vector as it rotates and moves into the page. Bottom-right: If the ellipse minor axis is zero and major axis has some value, the path traced by the electric vector would be a straight line, and the wave would have linear polarization. Both horizontal and vertical polarizations are shown. (Image © 2014 W. Reeve)

The electric and magnetic fields associated with an elliptically polarized radio wave rotate in the plane of polarization at a rate related to the radio wave's frequency. The electric vector completes one revolution in the period = 1/frequency while simultaneously varying in amplitude. As will be discussed in **section 2**, any radio wave can be decomposed into two perpendicular field components, for example, horizontal and vertical. Elliptical polarization results whenever the components have different phases or different amplitudes. In this case, the field is never zero because the two components do not pass through zero at the same time. In antenna engineering the shape of the ellipse is described by its *ellipticity*, which is the ratio of the ellipse major and minor axes. This ratio also is called *axial ratio*.

A wave with linear polarization has an ellipticity of infinity (minor axis is zero) and circular polarization has an ellipticity of one (major and minor axes are the same). The electric vector of a vertically polarized wave points in a vertical direction with respect to a reference such as Earth's surface, whereas a horizontally polarized wave is perpendicular to the vertical wave and points parallel to Earth's surface. Horizontal and vertical are arbitrary orientations in terms of celestial radio waves, which can take on any orientation. Polarizations of celestial radio waves are discussed in **section 4**. The electric field vector of a radio wave with elliptical or circular polarization rotates. Right-hand circular polarization (RHCP) or right-hand elliptical polarization (RHEP) means the vector rotates clockwise when viewed toward the direction of propagation. Left-hand circular polarization (LHCP) or left-hand elliptical polarization (LHEP) rotates in the opposite direction.

2. Decomposition of Polarized Radio Waves

Any radio wave can be decomposed (or resolved) into two component waves orthogonally (perpendicularly) polarized to each other. It is convenient to use vertically and horizontally polarized waves. There are two possible combinations of vertically and horizontally polarized waves that can produce a wave with a specific ellipticity. One combination will produce a wave with left-hand rotation and the other will produce a wave with right-hand rotation.

The concept of resolving any radio wave into two polarized components is worth examining in more detail. Consider two linearly polarized waves, one vertical and one horizontal, with the same frequency and a phase difference ϕ . The amplitudes of two waves A and B can be written

$$A = a \cdot \sin(\omega \cdot t)$$
$$B = b \cdot \sin(\omega \cdot t + \phi)$$

where ϕ is the phase difference in radians, ω is the radian frequency $2 \cdot \pi \cdot f$ in radians/second, *f* is frequency in Hz and t is time in seconds. The quantity $\omega \cdot t$ is the time-phase of the radio wave in radians. We will assume the wave amplitudes *a* and *b* are equal. First, we will examine the case when $\phi = 0°$, or

$$A = a \cdot \sin(\omega \cdot t)$$
$$B = b \cdot \sin(\omega \cdot t + 0°) = a \cdot \sin(\omega \cdot t)$$

The two waves A and B are in-phase – their peaks and zero crossings occur at the same time. This situation results in an ellipse with an ellipticity of infinity – a linearly polarized wave. The resultant is tilted 45° (see figure 2 for this and the other phase relationships in the following discussion). The peak amplitude when $\phi = 0°$ is

$$|C| = \sqrt{A^2 + B^2} = \sqrt{[a \cdot \sin(\omega \cdot t)]^2 + [a \cdot \sin(\omega \cdot t)]^2} = a \cdot \sqrt{2 \cdot \sin^2(\omega \cdot t)} = \sqrt{2} \cdot a \cdot \sin(\omega \cdot t)$$

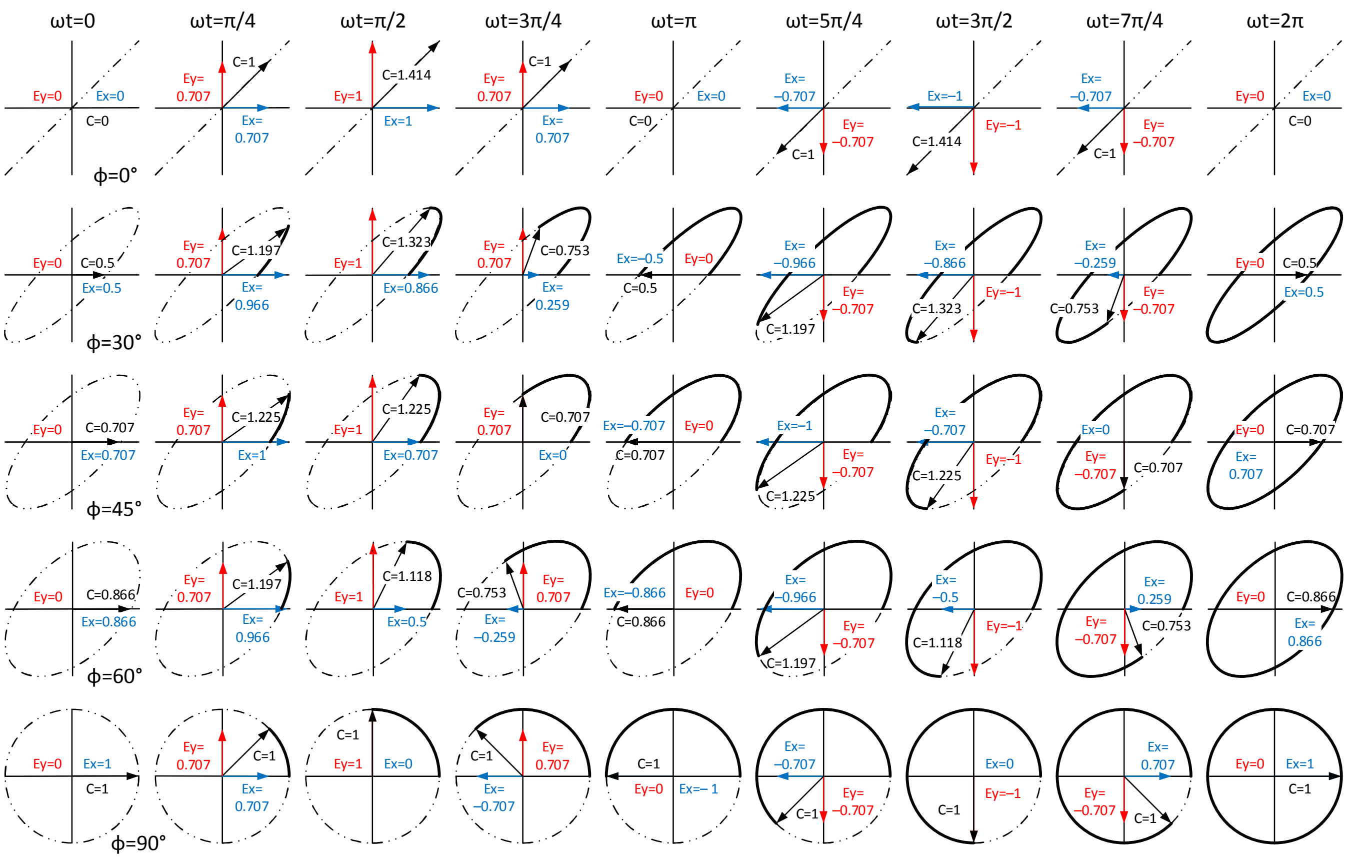


Figure 2 ~ Combination of two radio waves, one with vertical polarization (red arrow) and the other with horizontal polarization (blue arrow), with the phase difference shown on the left side of each series. The resultant is the black arrow drawn to scale and shown in increments of $\omega \cdot t = \pi/4 = 45°$ time-phase. The dotted-dashed line is the polarization ellipse and the thick solid black line traces the path of the resultant electric vector as it rotates. The two radio waves have equal amplitude (a=b=1). The upper drawing has 0° phase difference between the two polarizations and the phase difference in each succeeding drawing increases by 30° until there is 90° difference shown in the bottom drawing. When the phase difference is 0°, the resultant wave is linearly polarized with 45° tilt angle. As the phase difference increases, the resultant wave becomes elliptically polarized with decreasing ellipticity and counter-clockwise rotation. All ellipses for the situation shown have 45° tilt angle. When the phase difference is 90°, the ellipticity is 1 and the wave is circularly polarized with rotation in a counter-clockwise direction. We can change the direction of the elliptically and circularly polarized waves by shifting the phase one-half cycle, in which case the peak rotates in a clockwise direction. It should be noted that, although the electric vector makes one complete revolution per cycle, it does not rotate at a uniform rate except for circular polarization. For circular polarization, the rotation rate is a constant ω radians/second. (Image © 2014 W. Reeve)

For the case when $\phi = 30°$, $B = b \cdot \sin(\omega \cdot t + 30°) = a \cdot \sin(\omega \cdot t + 30°)$. The resultant electric field vector rotates in an elliptical pattern. The ellipse is tilted 45°. As the phase angle between the two waves is increased, the ellipse gets fatter (its ellipticity increases) until $\phi = 90°$. At this phase angle, $B = b \cdot \sin(\omega \cdot t + 90°) = b \cdot \cos(\omega \cdot t)$. Since the wave amplitudes are identical, $a = b$ and $B = a \cdot \cos(\omega \cdot t)$. The amplitude of the resultant electric field vector is

$$|C| = \sqrt{A^2 + B^2} = \sqrt{\left[a \cdot \sin(\omega \cdot t)\right]^2 + \left[a \cdot \cos(\omega \cdot t)\right]^2} = a \cdot \sqrt{\sin^2(\omega \cdot t) + \cos^2(\omega \cdot t)} = a$$

For this case, the amplitude always is the same and does not change as $\omega \cdot t$ increases from 0 to $2 \cdot \pi$ radians (0° to 360°) in a repeating cycle. The ellipticity is 1 and we have circular polarization.

If we continue increasing the phase angle between the two waves, the ellipticity will start to increase (ellipse gets thinner). Between 90° and 180°, the polarization ellipse will be tilted 135°. At 180° phase difference the ellipticity is infinite and we once again have linear polarization. If we continue increasing the phase beyond 180° to 270° and then 360°, the polarization ellipse will change in a similar way.

In the foregoing discussion, the amplitudes of the two wave components are equal and we only varied their phase difference. By varying both amplitude and phase, we can derive (or synthesize) any polarization ellipse with any ellipticity and any tilt angle. The special and general cases can be summarized as follows:

Linear polarization: A radio wave is linearly polarized if the electric field vector is always oriented along the same straight line at every instant in time. The field vector either has only one component or two perpendicular linear components that are either in-phase or multiples of 180° out-of-phase (multiples 1, 2, ..., n);

Circular polarization: A radio wave is circularly polarized if the electric field vector traces a circle as a function of time. The field vector must have two perpendicular linear components. These two components must have the same magnitude and must have a time-phase difference of odd multiples of 90°;

Elliptical polarization: A radio wave is elliptically polarized if the electric field vector traces an elliptical locus in space as a function of time. Also, a radio wave is elliptically polarized if it is not linearly or circularly polarized. The field vector must have two perpendicular linear components. The two components can have the same or different magnitudes. If they do not have the same magnitude, their time-phase difference must not be 0° or multiples of 180° (because the resultant will then be linearly polarized). If they are the same magnitude, their phase difference must not be odd multiples of 90° (because the resultant will then be circularly polarized). If the wave is elliptically polarized and the two components do not have the same magnitude but have odd multiples of 90° phase difference, the polarization ellipse will not be tilted but will be aligned with the principal axis of the field component. The major axis of the ellipse will align with the axis of the larger field component and the minor axis with the smaller component.

For a more mathematically complete discussion and derivation of linear, circular and elliptical wave polarization, see [Kraus-84], [Kraus-86] and [Johnson]. For visual aids see the online polarization animations {Polar1} and {Polar2}.

Note: Internet links in braces { } and references in brackets [ ] are provided in **section 6**.

The Stokes Parameters provide an alternative mathematical description of polarization and its components but their discussion is beyond the scope of this article; for additional information, see [Kraus-86].

It is possible for a radio wave to be unpolarized (also called randomly polarized), in which case the electric field vector traces out ellipses that change through all shapes and orientations as the wave passes a point in space (figure 3). When the radio wave contains both randomly and elliptically polarized components it is said to be *partially polarized*. The *degree of polarization* d for a partially polarized radio wave is the ratio of completely polarized power to the total power, or

$$d_{Polarization} = \frac{\text{Polarized Power}}{\text{Total Power}} \qquad (1)$$

A similar ratio can be used to express the degree of right-hand and left-hand rotation for radio phenomena that have components rotating in both directions. In this case,

$$d_{Rotation} = \frac{\Delta\text{p}}{\text{Total Power}} = \frac{\text{LHCP} - \text{RHCP}}{\text{LHCP} + \text{RHCP}} \qquad (2)$$

where Δp is difference in the powers associated with each rotation direction and LHCP and RHCP are the powers associated with the individual rotations. For the expression shown, a positive $d_{Rotation}$ indicates predominantly LHCP and a negative $d_{Rotation}$ indicates predominantly RHCP. An application of Eq. (2) is given in **section 4**.

Although Eq. (1) and (2) are based on power ratios, other suitable parameters proportional to power may be used, such as flux density and noise temperature.

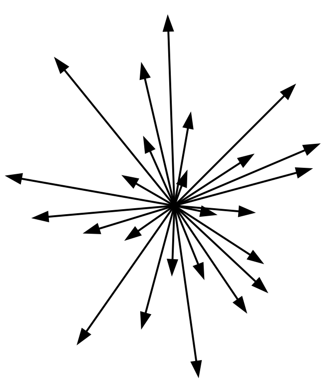


Figure 3 ~ Random polarization, in which the electric field vector takes on any magnitude and angle at any time as the radio wave passes a point in space. Each arrow represents the field vector at a different point in time.

3. Reception

The coupling efficiency (or polarization loss) of radio waves with different polarizations to different antennas is tabulated for common combinations (table 1). When the wave and antenna polarizations are matched, the coupling efficiency is highest. The coupling of unmatched polarizations varies from 0.5 to 0 depending on the combination.

For elliptically polarized waves, the coupling varies over a range of 0 to 1 depending on how well the antenna is matched to the radio wave's ellipticity, tilt angle and rotation. For example, if the wave polarization has an ellipticity (axial ratio) of 6 with right-hand rotation and the antenna has an ellipticity of 1 (circularly polarized) and also is right-handed (RHCP), the coupling efficiency is 0.85 (0.73 dB polarization loss). If this wave is received by a circularly polarized antenna with LHCP, the efficiency drops to 0.16 (8 dB coupling loss). If a radio wave is received by an elliptically polarized antenna with matched ellipticity and rotation, the coupling efficiency varies from 0.48 to 1 (3.2 dB to 0 dB coupling loss) depending on the relative tilt angle. For other combinations, see [Ludwig] or {Ludwig}.

Table 1 ~ Ideal polarization coupling efficiency for various polarizations received by resonant antennas over narrow bandwidth.

Wave polarization	**Antenna polarization**	**Coupling efficiency**	**Nominal coupling loss (dB)**
Vertical	Vertical	1	0 dB
Horizontal	Horizontal	1	0 dB
Vertical	Horizontal	0	Typically 20 dB or higher
Horizontal	Vertical	0	Typically 20 dB or higher
Vertical or Horizontal	RHCP or LHCP	0.5	3 dB
RHCP	RHCP	1	0 dB
LHCP	LHCP	1	0 dB
RHCP	LHCP	0	Typically 20 dB or higher
LHCP	RHCP	0	Typically 20 dB or higher
RHCP or LHCP	Vertical or Horizontal	0.5	3 dB
Random	Vertical or Horizontal	0.5	3 dB, see text
Random	Vertical $\perp$ Horizontal	1.0	0 dB, combined, see text
Random	RHCP or LHCP	0.5	3 dB, see text
Random	RHCP and LHCP	1.0	0 dB, combined, see text
Elliptical – RHEP (LHEP)	RHCP (LHCP)	0.5 to 1	Depends on ellipticity
Elliptical – RHEP (LHEP)	LHCP (RHCP)	0 to 0.5	Depends on ellipticity
Elliptical	Elliptical	0 to 1	See text

When a randomly polarized wave is received by a linearly polarized antenna, such as a single horizontal or vertical dipole, the received power will be one-half of the total power in the wave (polarization coupling of 0.5). The dipole reacts only to the field component of the wave that is parallel to the antenna and it will align only 50% of the time for a randomly polarized wave. The perpendicular vector component of the wave's electric field does not interact with the dipole. Similarly, a circularly polarized antenna (either RHCP or LHCP) will receive only 50% of the power in the randomly polarized wave (polarization coupling of 0.5).

To capture all the power in a randomly polarized radio wave, it is necessary to have two perpendicular linearly polarized antennas (for example, two dipoles) with independent outputs. These two outputs cannot be combined at a simple junction or parallel connection to obtain the total power because only the wave components that are in-phase (the matched polarization) will add, and the wave components that are out-of-phase will cancel. It is necessary to connect the two antennas through a quadrature coupler (90° hybrid coupler), in which case each coupler output port will contain one-half the total power in the randomly polarized radio wave. Similarly, two circularly polarized antennas with opposite rotation directions (one RHCP and one LHCP) each will receive one-half of the total power.

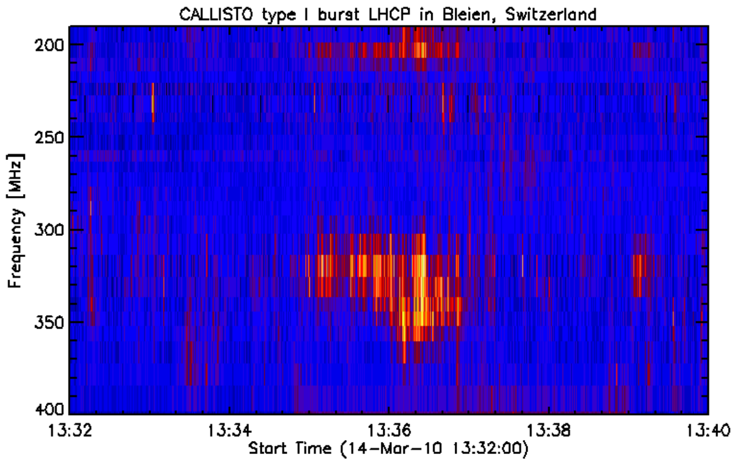
4. Polarization of Celestial Radio Waves

Radiation from many celestial radio sources extends over a wide frequency range. Within any bandwidth Δf the radiation consists of the superposition of a large number of statistically independent (random) waves of various polarizations. The resulting wave is randomly polarized. However, most celestial radio waves are partially polarized and may be considered to have two parts, one completely unpolarized and another completely polarized. The polarized components may be very small compared to the unpolarized components depending on the emission mechanism of the radio source. Astrophysical processes like synchrotron radiation can emit partially polarized emissions but they are never fully polarized. Some additional examples are (these were taken from online information provided by various national radio observatories)

- Free-free emissions from ionized hydrogen (HII) clouds are unpolarized (free-free emissions are produced by free electrons scattering off ions without being captured, resulting in being free before and after the interaction)
- Thermal radiations are unpolarized
- Synchrotron emissions can have 0-60% linear polarization but are typically 0-10%; circular polarization typically is small at 0-0.1%
- Pulsar emissions have high linear polarization but the direction of polarization changes throughout the pulse
- Maser source emissions are coherent and can have very high levels of polarization
- Manmade radio emissions (radio frequency interference) usually are 100% polarized

The polarization or lack of it can be changed to some extent by the media through which the radio wave passes – the interstellar medium (ISM), interplanetary medium (IPM) and Earth's ionosphere. If the medium reflects, refracts, or absorbs one component of the polarization while allowing the others to pass, the reflected and refracted wave components are then polarized. Thus, the degree of polarization may indicate the characteristics of the medium. Interstellar matter can polarize unpolarized emissions or de-polarize polarized emissions.

Some solar and Jupiter radio bursts have significant polarized components. For example, the polarization of a Type I solar radio noise storm in 2010 changed from strongly left-handed to strongly right-handed circular polarization and back again over a period of 30 days (figure 4). A Type I noise storm consists of short, intense, narrow-bandwidth bursts that usually occur in large numbers with an underlying low-intensity continuum.



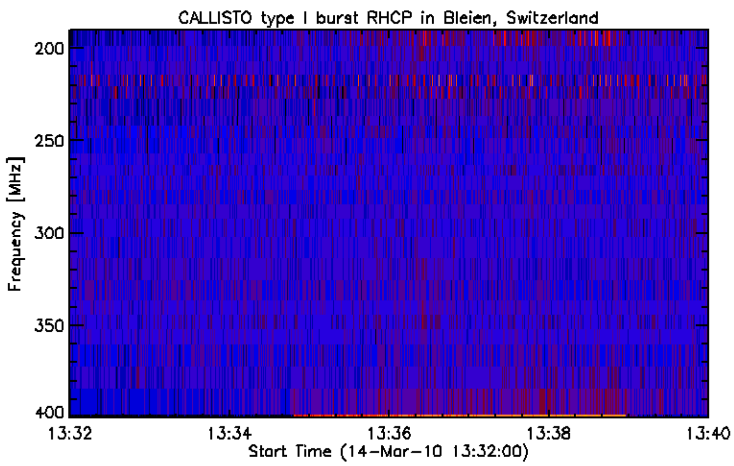
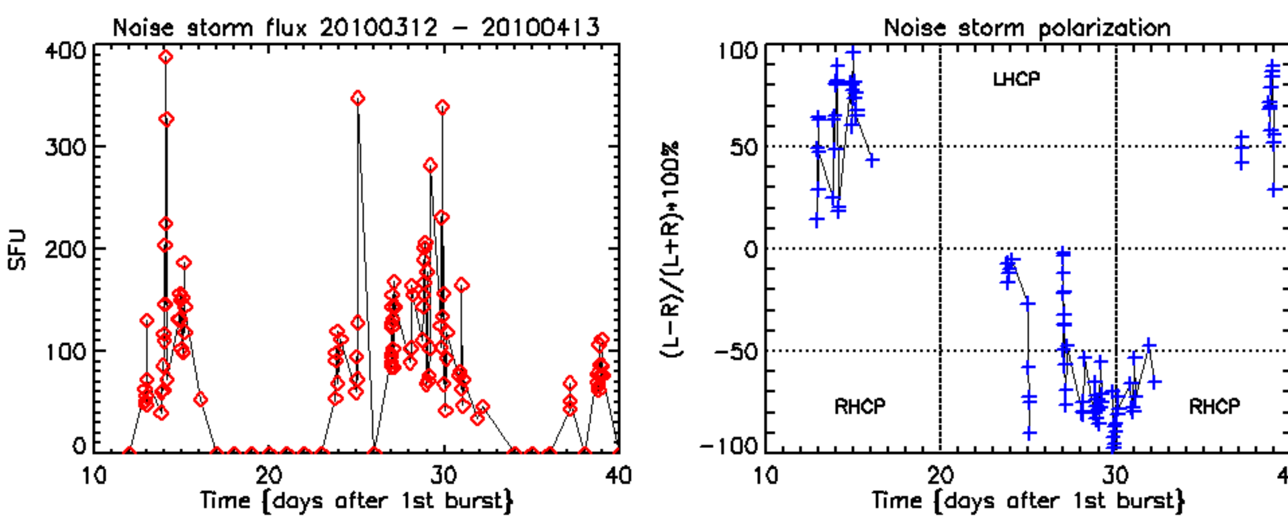


Figure 4 ~ Circular polarization changes of a Type I noise storm over a 30 day period. Observations were made by Callisto instruments at Bleien Observatory, Switzerland, using a 7 m parabolic dish antenna. At the time of the observations, the instruments were calibrated in solar flux units (sfu). (Images courtesy of Christian Monstein)

The upper and middle images show 8 minute snapshots of LHCP and RHCP. At the time of these snapshots the bursts were predominantly LHCP (the image for RHCP shows no bursting).

The lower image shows plots of total flux and polarization percentage for a 30 day period starting 10 days after the first burst. A positive polarization indicates LHCP; see Eq. (2). During the first 6 days, measurements indicated between +10% and +100% LHCP, followed by a 7 day break with no bursts. The polarization then changed to between 0 and −100% RHCP during the subsequent 9 days followed by another break of about 5 days. The polarization then changed again with up to +90%. LHCP

It should be noted that a physical explanation for the polarization changes is not known. Open questions are: why does polarization change; what is the reason behind the change; and why does it take days to change polarization?



5. Summary

Polarization describes the shape of a radio wave's electric field vector over time. In general, the electric field vector rotates in an elliptical pattern described by its ellipticity (or axial ratio), which is the ratio of the ellipse major and minor axes. Linear and circular polarizations are extreme cases of elliptical polarization. Radio waves may be completely polarized or completely unpolarized (randomly polarized) or a combination (partially polarized). Polarization is an important parameter in radio astronomy because it provides information about a celestial radio source and the medium between the source and the receiver. The response of a radio telescope is maximized when the polarization of the antenna matches the polarization of the radio waves.

6. References and Internet Links

[Johnson] Johnson, R., Jasik, H., editors, Antenna Engineering Handbook, 2nd ed., McGraw-Hill Book Co., 1984

[Kraus-84] Kraus, J., Electromagnetics, 3rd ed., McGraw-Hill Book Co., 1984

[Kraus-86] Kraus, J., Radio Astronomy, 2nd ed., Cygnus-Quasar Books, 1986

[Ludwig] Ludwig, A., A Simple Graph for Determining Polarization Loss, Microwave Journal, September 1976

{Ludwig} http://antennadesigner.org/ludwig_chart.html

{Polar1} http://www.youtube.com/watch?feature=player_detailpage&v=Q0qrU4nprB0

{Polar2} http://www.youtube.com/watch?v=Fu-aYnRkUgg

Document information

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