Operation and Interface Manual

Picasso C.R.T. Image Synthesizer

1. **General Information**

The *Picasso C.R.T. Image Synthesizer* generates a wide range of stimuli that are useful for neurophysiological and psychophysical vision research. These include oriented, drifting gratings and combinations of several gratings, each with its own orientation, spatial frequency, phase, temporal frequency, and contrast. In addition to such "spectral" stimuli, which are specified by their Fourier parameters, the *Picasso* also generates "localized" stimuli such as bars, edges, and circular center/surround fields, which are specified by 2-D position, shape, and size. These capabilities are further enhanced by Equipment Options for annular window generation; angular velocity control; dual independent dichoptic displays; 2-D Gaussian and 2-D Gabor functions. A further instrument generates moving random texture fields in windowed figure/ground channels with independent densities, disparities, speeds, and directions of motion.

The *Picasso* creates images through two independent spatio-temporal pattern generators, whose signals may be either added together or partitioned into separate image windows having specified rectangular, circular, annular, or split-screen apertures. The two pattern generators can produce spatially and/or temporally modulated patterns such as sinewave and squarewave gratings (stationary, drifting, and counterphasing), as well as windowed regions of specified luminance. These define bars, edges, and circular center/surround patterns of specified contrast and luminance, 2-D location, and dynamic properties such as flicker and movement.

Two frame rates may be selected, which are normally preset for 100 Hz and 200 Hz but may be internally modified. The raster frequency is 50 kHz, which produces an image consisting of 500 raster lines at 100 frames/second, or 250 raster lines at 200 frames/second. The orientation of each image frame may be specified with 10-bit resolution, yielding 1,024 distinct orientations in $360° \div 1,024 = 0.35°$ steps. A 3-digit LED display indicates the image orientation to the nearest degree between 0° and 359°. Each image frame contains up to two independent spatio-temporal Fourier components, generated by the two channels and either superimposed or partitioned by the windows. Frame interleaving permits many more Fourier components to be superimposed in different orientations, resulting, for example, in dynamic 2-D bandlimited textures with as many as two dozen Fourier components (in a dozen orientations) interleaved at 200 frames/second.

All significant spatio-temporal image parameters may be controlled both manually and by computer, with the mode of control separately selectable for each parameter. Computer control over any signal parameter or mode of operation is achieved through analog or digital ports.

2. **Laboratory Interface**

   (a) **Wideband cables for interface to Display Monitor.** The signals generated by the *Picasso* for two-dimensional patterns have a bandwidth greater than 5 Megahertz. Ordinary BNC coaxial cable (RG-58) cannot be used for these signals because its capacitance will degrade the image. Under Equipment Option 3, **Innisfree** supplies three wide-bandwidth coaxial cable assemblies for interfacing the X-, Y-, and Z-axis signals from the *Picasso* front panel to the Display Monitor input terminals. A maximum distance of 8 feet is allowed by these cables between the *Picasso* and the Display Monitor.

(b) Display Monitor requirements. The *Picasso* will drive any X,Y,Z Display Monitor that satisfies the following requirements:

- Z-axis bandwidth must be at least 5 Megahertz.
- X- and Y-axis bandwidth must be at least 2 Megahertz.
- X- and Y-axis phase separation must not exceed 1° at 250 kHz.
- X-, Y-, and Z-axis input impedances should exceed 10kΩ .
- Z-axis input amplifier polarity must be set so that the cathode ray is intensified (brightened) by a more-positive-going signal.
- X-, Y-, and Z-axis input amplifier gains and offsets must all be adjustable, and their ranges should be spanned by 1.5 V (peak-to-peak) signals.

The recommended Display Monitor is the **Tektronix** 608, with Options 23, 24, and 25, which is available through **Innisfree** under O.E.M. license. Among the many other C.R.T.'s satisfying these requirements are the **Tektronix** 604, 606, 624, and the **Hewlett-Packard** 1300, 1304, 1310, 1311, 1317, 1321, 1332, 1333, and 1335. The Display Monitor and the *Picasso* should be powered with common electrical ground to avoid possible ground-loop noise problems.

(c) Recommended computer I/O capabilities. Each of the *Picasso*'s spatio-temporal stimulus parameters and operating modes may be controlled by external computer, via an analog voltage, a digital word, or a single TTL bit. Each major stimulus parameter has an associated MANUAL/EXTERNAL control switch for specifying its mode of control.

A recommended basic configuration of computer I/O is as follows:

- Four bipolar 12-bit D-to-A Converters, operating in the ± 5 V range.
- 24 TTL output bits, either from three 8-bit bytes or from two 16-bit words.
- Two TTL input lines (if signal averaging or frame synchronous control is required).

Computer control can be further enhanced by adding: four more D-to-A Converters for other analog-controllable parameters; three A-to-D Converters for computer monitoring of manual settings of APERTURE WIDTH, LENGTH, and RADII; and seven open-collector TTL output lines for computer control over mode switches such as SINEWAVE/SQUAREWAVE, GRATING/FIELD, SUMMATION/PARTITION, CIRCULAR/RECTANGULAR APERTURE, and the FRAME RATE. These latter seven open-collector TTL lines interface to the *Picasso* via a standard 9-pin Type 'D' Subminiature socket located on the rear of the chassis, as discussed in greater detail in Section 9 on page 26.

Commercially available devices that can provide complete computer control over the *Picasso* from a PC/AT/Compatible or Apple include: card Model AOB6-P, $545 from **Industrial Computer Source**, San Diego, California, tel. (800) 523-2320 or (619) 279-0084; and the *1708 Picasso Controller* plus *VS* software package for running neurophysiological experiments from a PC/AT/Compatible, available from **Cambridge Electronic Design**, England, tel. +44 1223-420186.

(d) Equipment configuration. The wideband cable assemblies require that the *Picasso* be positioned within 8 feet of the Display Monitor, but the controlling computer can be remote. The *Picasso* dissipates 44 Watts into the laboratory environment by free air convection. It should be rack-mounted with room for free air circulation above and below.

3. | **Display Monitor Adjustments** |

The following adjustments and settings in the Display Monitor should be made if the Monitor was not acquired through **Innisfree**.

(a) **Display Monitor input impedances.** Some Monitors have a switch for selecting high input-impedance (typically 1 MΩ) or low input-impedance (typically 50Ω). All three inputs, X,Y, and Z, should be set for **high** input-impedance.

(b) **Display Monitor input polarities.** The X-, Y-, and Z-axis input amplifiers of the Display Monitor should have positive polarity. For the X- and Y-axis signals this only affects the orientation and direction conventions, but it is crucial for the Z-axis. In addition to the 2-D modulation signals, the Z-axis carries two sets of retrace blanking pulses: a 50kHz pulse train which blanks out the curvilinear raster retrace trajectory, and a frame-deadtime pulse which occurs between image frames. These clocked pulses reduce the Z-axis voltage by about -1 V, which must fully blank the cathode ray.

Some Display Monitors have a "TTL Blanking" input. This is used by the *Picasso* for dichoptic display generation (discussed later in Section 10.(d) – Dual Independent Externalized Z-axis Signals), and by the **Innisfree** *Dual Channel Velocity Field and Stereogram Generator*, but it can be ignored during normal *Picasso* operation because of the blanking pulses already mixed into the Z-axis. However, on some Display Monitors it may be necessary to connect this blanking input either to +5 V or GND, depending on its polarity, in order to display any image.

(c) **Display Monitor X,Y,Z input gains, offsets, and trace rotation.** All three input amplifier gains of the Display Monitor must be calibrated for optimal image quality and isotropy. (In Display Monitors purchased from **Innisfree**, these calibrations have already been performed.) The X- and Y-axis input gains are screw adjustments, which control the vertical and horizontal dimensions of image size. They must be matched to each other and set such that the image just fills the screen (or the phosphor "quality area"), but with minimal overhang of the image beyond this area. Image resolution and brightness are wasted if the X- and Y-axis gains are set too high, so that an unnecessarily large portion of the image overhangs the screen.

It is recommended that a circular window be constructed from opaque material for mounting permanently on the Display Monitor, with the diameter of the circular window equal to the smaller dimension of the Display screen. Otherwise, for a grating of a given spatial frequency, the number of cycles displayed on a rectangular screen would depend on the orientation of the grating. A circular window also serves to occlude the boundaries of the raster regardless of orientation; otherwise, keeping the raster boundaries always outside of the full rectangular screen would require making the image larger, thus diluting image brightness and resolution.

The simplest way to set the X- and Y-axis gains and to match them to each other is to use the *Picasso* to generate a circularly partitioned image: set MODE controls for SIGNAL PARTITION and CIRCULAR APERTURE, and set all other switches on the *Picasso* front panel also in their "up" position. The RADIUS and WIDTH controls in the APERTURE module should be adjusted to produce a large annular partition, which can be centered in the raster by the X and Y POSITION knobs in the APERTURE module. The raster itself should be centered in the screen by the Display Monitor's positioning knobs. Then the Monitor's X- and Y-axis gain

control screw adjustments should be set so that the raster just barely fills the exposed screen area of the Monitor, with the *Picasso's* electronic annular aperture having the same width as height. If the X- and Y-axis gains are not matched, then the electronic window will be elliptical rather than circular.

The Display Monitor's Z-axis gain and offset (Intensity) controls must be carefully set to optimize the range of linear contrast. (Display Monitors purchased from **Innisfree** will already have appropriate Z-axis gain settings.) Actual stimulus contrast is proportional to the ratio of the Z-axis signal amplitude to the DC brightness level. Thus, for any given *Picasso* stimulus, the actual contrast will depend not only upon the *Picasso's* CONTRAST settings, but also upon the Display Monitor's Z-axis gain and Intensity settings.

All Display Monitors have a limited range of linear Z-axis modulation response. The consequence is that for stimulus contrasts which are too high, the actual luminance profile produced on the phosphor for a sinusoidal input signal will be distorted, usually flattened at the crests or troughs. (The spectral purity of the *Picasso's* digital generators exceeds 99.8%; the sinusoidal templates are generated from trigonometric tables stored in permanent memory.) The general rule for calibrating the Display Monitor's Z-axis gain and offset is that when the *Picasso* is generating sinusoidal gratings in partition windows, with the CONTRAST dials set for 10.0 and with the Monitor's intensity setting in the middle of its linear regime, the gratings should have the maximum contrast required while retaining their sinusoidal profile. The purity of the sinusoidal profile may be gauged visually (with a trained eye) or more precisely with a slit or spot photometer monitoring a small spot, past which a sinewave grating of low spatial frequency continuously drifts. It should be recalled that both the Monitor's Z-axis gain setting and its intensity setting will affect its linearity; and that the lower the intensity setting, the higher will be the contrast. One way to increase the intensity without affecting either the contrast or the Monitor's linearity is to reduce the image size, if possible, by reducing the Monitor's X- and Y-axis gains. Finally, if the intensity setting is either too high or too low, the Monitor may produce "modulation break-through" of either Channel's signal across or into the wrong electronic window, because the bandwidth of the Monitor's Z-axis amplifier depends upon this setting. Such modulation break-through does not arise within the *Picasso*, and the solution is to adjust the Monitor's intensity and/or Z-axis gain settings.

Once the Monitor's Z-axis gain and intensity settings are established, a photometer may be used to calibrate grating contrast (by making only two measurements) using the formula:

$$\text{contrast in percent} = 100\,\frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L_{max} and L_{min} are the luminance levels at the crest and at the trough of a grating, respectively. In order to find the true crest and trough of a grating, it may be easier to use a SQUAREWAVE than a SINEWAVE grating. The *Picasso* generates identical peak luminance values for both waveforms, for any given CONTRAST setting.

Most Display Monitors also have a small-angle "trace rotation" adjustment which rotates the raster orientation within small angles to compensate for variations in the earth's magnetic field. This setting will depend upon the Monitor's physical orientation and position; the total range of adjustment is only a few degrees. This adjustment is recommended in order for the *Picasso's* LED angle indicator in the ORIENTATION module to be correct. Using the ROTATE CW / ROTATE CCW switch (in MANUAL mode), bring the LED display to indicate 0 degrees.

Then adjust the Display Monitor's "trace rotation" screw until the image is vertically aligned. It should be noted that the *Picasso's* resolution for orientation is 0.35°, but the LED angle indicator display truncates the orientation to a whole degree between 0° and 359°.

(d) Phosphor protection. The *Picasso's* Z-axis signal contains a positive DC bias of approximately +0.6 V. This has the consequence that the Display Monitor's Intensity knob will be set much lower than it otherwise would, in order to achieve the same brightness in the absence of this DC bias. With this Intensity setting, the cathode ray is entirely blanked off unless the *Picasso* is turned on and its Z-axis signal connected. This serves as a kind of phosphor protection for the Display Monitor in case the *Picasso* is turned off, which would otherwise collapse the image into a single intense point, burning a hole in the phosphor.

4. Modes of Operation

The major modes of operation are determined by four switches: SIGNAL PARTITION / SIGNAL SUM, CIRCULAR APERTURE / RECTANGULAR APERTURE (both located in the MODE module, upper right); and two GRATING / FIELD switches (located in the two CONTRAST modules).

The two switches in the MODE module determine whether the two spatio-temporal signals are to be superimposed throughout the image or partitioned into distinct regions, and if they are to be partitioned, what the shape of the partitioning boundary will be. The shape, size, and location of the partition or window are then controlled by the APERTURE module. If an annular partition or window is employed, the inner radius is specified by the RADIUS controls (manual or external), while the outer radius is specified by the WIDTH controls.

The two GRATING / FIELD switches in each CONTRAST module determine whether or not each generator produces spatial modulation in its region of the image (or in its contribution to the SUMMED pattern). In GRATING mode, each generator produces a sine or squarewave grating whose parameters are specified by the corresponding SPATIAL FREQUENCY, DRIFT FREQUENCY, PHASE, and CONTRAST modules. The location of the grating in the image is determined by the MODE and APERTURE controls.

In FIELD mode, each generator produces (within its assigned image region) a spatially uniform, but possibly dynamic, luminance field. This luminance field should be regarded as a stationary or drifting grating having *zero spatial frequency*, in order to understand how its luminance is determined by the PHASE and CONTRAST controls. A "drifting" grating with 0 spatial frequency is a luminance field flickering at a rate equal to the drift frequency. Thus, the luminance field may be caused to flicker with a temporal sine or square waveform, by setting the associated DRIFT DIRECTION 3-position switch to either SCYLLA or CHARYBDIS; then the flicker rate is controlled by the DRIFT FREQUENCY module. The flicker waveform is set by the SINEWAVE/SQUAREWAVE switch (in the CONTRAST module), and the flicker waveform amplitude is determined by the CONTRAST setting.

In order to generate a given luminance field that is not flickering, the SINEWAVE/SQUAREWAVE switch should be set for SQUAREWAVE, and the DRIFT DIRECTION switch should be set at STOP. (The moment at which the squarewave flicker is stopped, will determine the bright/dark polarity of the luminance field. Under external computer control, this polarity may be determined via the PHASE inputs.) Then the luminance of the region is controlled by the CONTRAST setting, and

its polarity may be switched either by the DRIFT DIRECTION switch or by the PHASE controls. In the bank of four mini-switches marked PHASE SHIFT, the leftmost one (marked "π" radians) will always reverse the luminance polarity.

If both of the pattern generators are operated in the FIELD mode, and if the upper-right MODE switch is set for SIGNAL PARTITION, then all of the traditional localized stimuli (edges, bars, and center/surround structures) can be generated by the APERTURE module with dynamic contrast, luminance, and location. In SIGNAL SUM mode, the two fields become uniformly superimposed rather than partitioned, and they will have two independent flicker frequencies and amplitudes if the DRIFT controls are engaged. The flicker frequency of each component is matched by the TTL output signal provided in the associated PHASE module, which will be synchronous with the zero-crossings of the temporal waveform component.

Different combinations of these control modes generate such possibilities as a flickering or moving luminance region that partitions a grating, e.g., a bright or dark bar moving against a grating background. In SIGNAL SUM mode these two signals would be added without a window, causing change or flicker in just the DC component of a grating (mean luminance) without changing its modulation amplitude. In order to partition a grating stimulus with a blank field of *equal mean luminance*, such as an isolated patch or annulus of a grating with the same average grey level in the missing regions, the CONTRAST control of the appropriate generator should be set to zero (or switched to EXTERNAL with no voltage applied). The generator with zero contrast will produce the same luminance as the mean luminance of the modulated region.

Further modes of operation, including the synthesis of coherent and incoherent 2-D textures, in motion or with other dynamic properties, are described in Sections **7** and **8**.

5. | **Manual and External Controls** |

The *Picasso* consists of more than a dozen modules which can interactively generate a broad repertoire of spatio-temporal visual patterns, with both manual and external control over all significant parameters. Each module has a MANUAL/EXTERNAL switch for determining its mode of control. Eleven spatio-temporal image parameters may be externally controlled by an analog voltage: SPATIAL FREQUENCY$_{1,2}$, DRIFT FREQUENCY$_{1,2}$, CONTRAST$_{1,2}$, and 2-D APERTURE controls for POSITION$_{X,Y}$, WIDTH, LENGTH, and RADIUS. Three image parameters require digital words for external control, to be provided at the front panel 16-pin DIP sockets for ORIENTATION and PHASE$_{1,2}$.

An additional 9-pin D-socket on the rear of the *Picasso* provides external control (via open-collector TTL logic) over the mode switches for SIGNAL PARTITION / SIGNAL SUM, CIRCULAR / RECTANGULAR APERTURE, SINEWAVE / SQUAREWAVE, GRATING / FIELD, and FRAME RATE (100 Hz or 200 Hz). Interface details are given in Section **9**.

In addition to these control modes, there are several signals provided *by* the *Picasso* for external monitoring and for synchronization of other laboratory instruments. There are 5 TTL output BNC terminals on the front panel:

- FRAME SYNC marks the start of each new image frame, normally occurring at either 100 Hz or 200 Hz, by transition from the TTL low to high state for about 50 μsec.

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- FRAME TOGGLE changes state on each frame, for distinguishing between "even-numbered" frames and "odd-numbered" frames in frame-interleaving applications.
- The TTL output of the AUXILIARY WAVEFORM GENERATOR marks the zero-crossings of its associated sinewave and trianglewave signals, which are used for temporal counterphasing of a grating or for sweeping a bar back-and-forth.
- The TTL output in each PHASE module marks the zero-crossings of the temporal waveform (drift frequency or flicker) of the associated pattern generation channel.

The latter TTL outputs are intended to trigger external signal acquisition devices such as neural spike averagers for constructing histograms that are phase-locked to a drifting grating, a sweeping bar, or a flickering stimulus.

Finally, three analog output voltages are provided on the rear of the *Picasso* for externally monitoring the manual settings for the 2-D APERTURE dimensions of WIDTH, LENGTH, and RADIUS. These may be useful, for example, in manually mapping a cell's "bar length" tuning curve, or assessing end-stopping inhibition under manual stimulus control, accompanied by computer measurement of the manual parameter settings. Two additional rear TTL outputs will be discussed later.

The following sections describe all manual and external controls and calibrations.

(a) **Spatial Frequency.** Each of the two digital spatio-temporal pattern generators spans a range of spatial frequency of about 40:1. At a frame rate of 100 Hz, this range is approximately from 2.5 cycles to 100 cycles across the width of the display. At the 200 Hz frame rate, these bounds would be halved.

Under EXTERNAL control, the spatial frequency of each channel is related nearly linearly to an applied control voltage in the range of 0 to +5 V that is provided at the associated BNC terminal, with the switch on EXTERNAL. As may be seen in Figure 1, which provides sample calibration data, the nearly linear relationship has a negative slope; thus the higher the applied voltage, the lower the spatial frequency. A useful method of calibration is linear or quadratic interpolation between about 20 such points in an empirical calibration curve. If high precision is required it may be necessary to construct separate calibration curves for each of the two channels, to allow for possible differences between them. Calibration measurements should be made with the equipment fully warmed up.

If less precision is required, then instead of the method of interpolating between measured calibration points, an approximate analytic function of the following form may be used to determine the applied control voltage required to produce a given spatial frequency:

$$\mathbf{V} = 5 - 5 \left(\frac{f - f_L}{f_H - f_L} \right)^{\lambda}$$

$\mathbf{V}$ is the applied control voltage, between 0 and +5 V

f is the desired spatial frequency

f_L is the lowest possible spatial frequency, determined by applying +5 V to the control terminal

f_H is the highest possible spatial frequency, determined by applying ground (0 V) to the control terminal

λ is a parameter to fit the calibration curve, approximately equal to 1.1
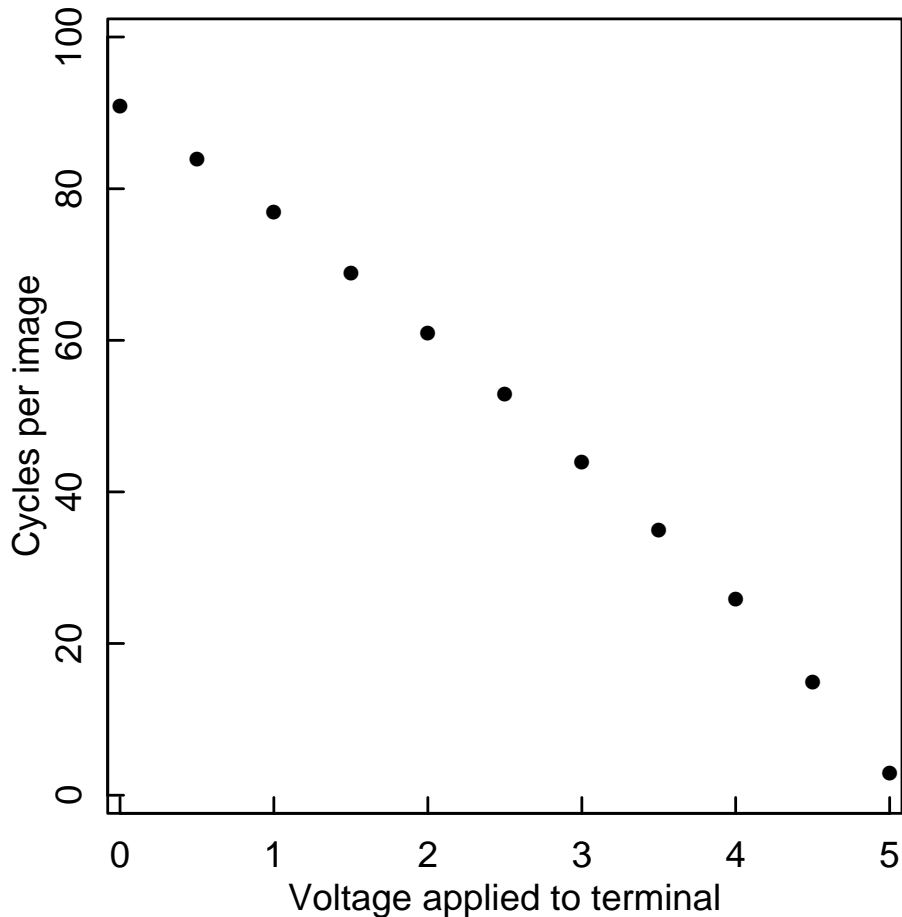
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Figure 1: Illustration of a spatial frequency calibration curve.

The spatial frequency calibration curve may be extended to still higher spatial frequencies by applying a negative external control voltage, although the approximate calibration curve given above is less accurate for negative voltages. At a frame rate of 100 Hz, spatial frequencies as high as 130 cycles across the image can be generated by a control voltage of -5 V. The externally applied control voltage should be as free as possible from noise and ripple, because the obtained spatial frequency will faithfully follow the control signal, including its fluctuations. If there is more than about a millivolt of noise in the control voltage, variation in spatial frequency will appear as phase jitter. The input impedance at the spatial frequency EXTERNAL control terminals is $2\text{k}\Omega$, so the source of the external control voltage should have an impedance of less than about 50Ω.

Under MANUAL control, spatial frequency is related to the settings of the associated 10-turn dial by a hyperbola:

$$\text{DS} = \alpha - \frac{k}{f}$$

where DS is the dial setting (from 0.00 to 10.00), f is the desired spatial frequency, α is a fitted parameter approximately equal to 10.25, and k is a dimensional constant. Again, this expression is only approximate and for greater precision it is preferable to interpolate from a measured calibration curve. As always, the obtained spatial frequencies in cycles/degree depend

upon the C.R.T. distance from the observer, the chosen frame rate, and the C.R.T.'s settings for X- and Y-axis gain.

(b) **Drift Frequency.** Each of the two digital spatio-temporal pattern generators spans a range of temporal frequencies between 0.1 Hz and 25 Hz, in two overlapping control bands (0.1 - 2.5 Hz, and 1.0 - 25 Hz), selected by a toggle switch. These temporal frequencies become the flicker frequency of a uniform luminance region in the FIELD mode, or the grating drift frequency in the GRATING mode (i.e. the rate, in Hz, at which cycles of the grating move past any given point in the image). A convenient way to measure temporal frequency is to monitor the output marked TTL_{OUT} in the corresponding PHASE module. This TTL state changes synchronously with every π radians of advancing or retarding phase at the starting edge of the image frame, and thus it tracks the phase cycle and therefore matches the temporal frequency of drift.

Under EXTERNAL control, the temporal frequency of each channel (drift frequency or flicker) is linearly related to an applied control voltage in the range of 0 to +5 V that is provided at the associated BNC terminal, with the switch on EXTERNAL. As may be seen in Figure 2, which provides sample calibration data, the linear relationship has a negative slope; thus the higher the applied voltage, the lower the temporal frequency. Calibration may be achieved by linear interpolation between measured data points, or by the following linear formula for determining the applied control voltage required to produce a given temporal frequency:

$$\mathbf{V} = 5 - 5\frac{f - f_L}{f_H - f_L}$$

$\mathbf{V}$ is the applied control voltage, between 0 and +5 V

f is the desired temporal frequency

f_L is the lowest possible temporal frequency, determined by applying +5 V to the control terminal

f_H is the highest possible temporal frequency, determined by applying ground (0 V) to the control terminal

The temporal frequency calibration curve may be extended to still higher frequencies by applying a negative external control voltage, down to about -5 V, although it is important to consider the temporal sampling frequency implicit in the image frame rate (100 Hz or 200 Hz). For example, with a frame rate of 100 Hz, a grating drifting "to the right" at 50 Hz must advance by one half-cycle of phase per image frame, and thus it is also equivalent to a 50 Hz leftward drift and to a 50 Hz counterphase, and so it really cannot be said to have any drift direction. Similarly, a rightward drift of 25 Hz is equivalent to a leftward drift of 75 Hz, since gaining a quarter-cycle of phase on each frame is the same as losing three-quarters of a cycle of phase on each frame. These Nyquist considerations restrict the range of meaningful temporal frequencies.

The input impedance at the temporal frequency EXTERNAL control terminals is 4kΩ, so the source of the external control voltage should have an impedance less than about 50Ω.

Under MANUAL control, temporal frequency is related to the settings of the associated 10-turn dial by a hyperbola:

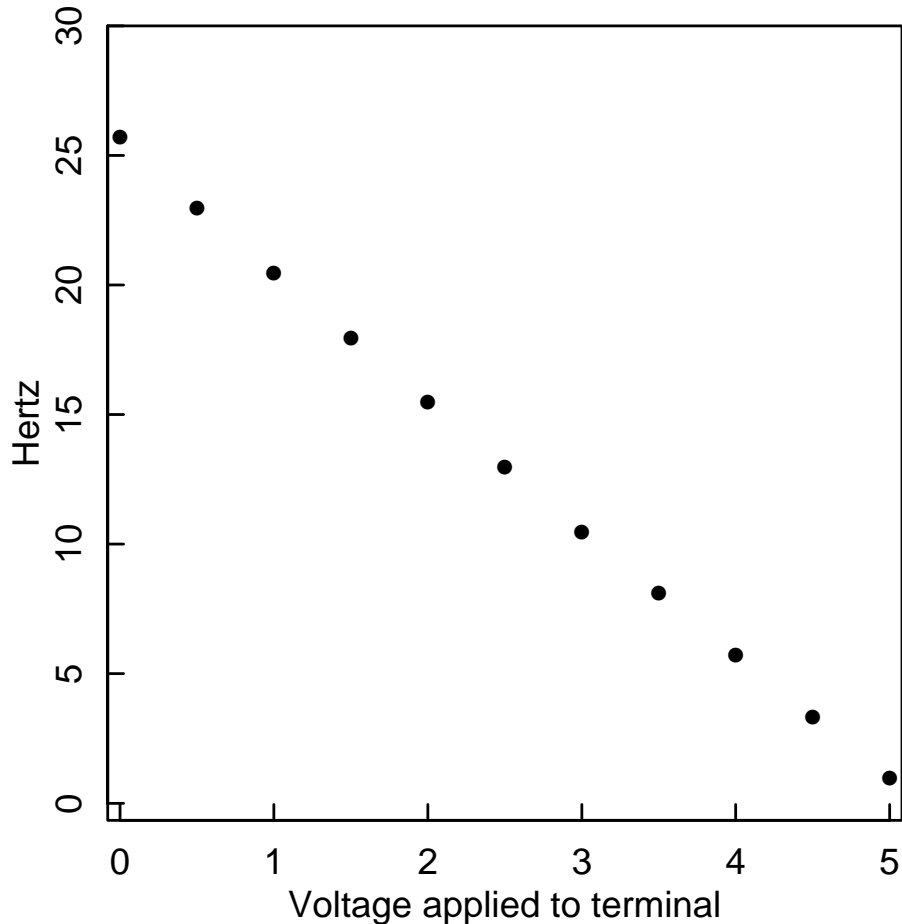$$\mathrm{DS} = \alpha - \frac{k}{f}$$

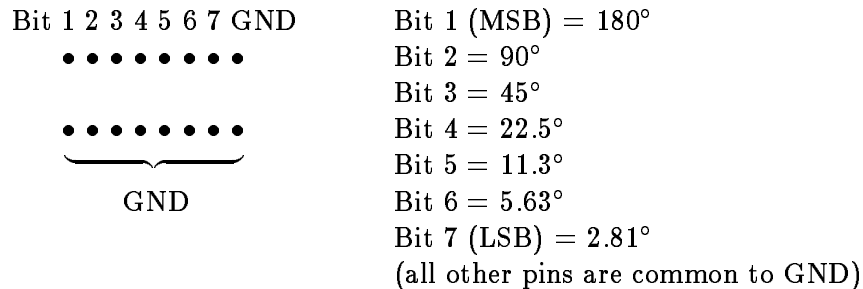Figure 2: Illustration of a temporal frequency calibration curve.

where DS is the dial setting (from 0.00 to 10.00), f is the desired temporal frequency, α is a fitted parameter approximately equal to 10.40, and k is a constant depending on the drift frequency band selected (0.1 to 2.5 Hz, or 1.0 to 25 Hz). The temporal frequencies obtained are independent of any C.R.T. parameters, and independent of the chosen frame rate (unlike the case for spatial frequencies).

The 3-position toggle switch for DRIFT DIRECTION permits manual reversal of the direction of drift, and cessation of drift. This offers a convenient way to set the absolute phase of a stationary or counterphasing grating. With a slow drift rate, alternating in direction via the toggle switch, a neurophysiological "null" phase angle may be found and locked-in. Subsequent discrete manual phase shifts in steps of 180°, 90°, 45°, or 22.5° phase angles are then possible (relative to the chosen absolute phase), through the use of the bank of four binary PHASE SHIFT switches.

Non-uniform drift waveforms (such as oscillatory, or go-stop-go-stop motion) can be obtained by direct specification of the PHASE under external computer control, as described below. Such control is also the best means of achieving drift if computer control over drift direction is also desired; alternatively, drift direction can be reversed under computer control by changing orientation through 180° (a single bit in the ORIENTATION socket).

(c) Phase. Each of the two digital spatio-temporal pattern generators provides 7-bit resolution of phase, allowing gratings to be displayed in any of 128 phase angles. When the PHASE control is switched to EXTERNAL, the grating's starting phase at the beginning of each image frame is determined by the 7-bit word present at the 16-pin PHASE socket at the end of the 50 μsec deadtime between frames. The end of this deadtime is signified by the FRAME SYNC pulse returning to its low state, and the PHASE word is then latched until the next deadtime interval (at the end of this frame). Thus in effect, external PHASE control is sampled at the frame rate. It is not necessary for external PHASE words to be supplied synchronously with the FRAME SYNC pulse; any change in the word provided externally will simply be read and latched after the next frame deadtime period.

The 7-bit PHASE control word in natural parallel binary is read from the 16-pin input socket as follows:

<div style="text-align:center">

Bit 1 2 3 4 5 6 7 GND
● ● ● ● ● ● ● ●

● ● ● ● ● ● ● ●
⎵‿⎵
GND

</div>

Bit 1 (MSB) = 180°
Bit 2 = 90°
Bit 3 = 45°
Bit 4 = 22.5°
Bit 5 = 11.3°
Bit 6 = 5.63°
Bit 7 (LSB) = 2.81°
(all other pins are common to GND)

If the PHASE control is switched to EXTERNAL, a grating will drift (or a uniform field will flicker) only if the externally supplied phase word is advancing or retreating accordingly. A 7-bit control word that is uniformly counting up or down would produce uniform drift in either direction, with a temporal frequency in Hz equal to the repetition frequency of the 7-bit control cycle (i.e. the clocking frequency ÷ 128). Non-uniform temporal waveforms (e.g. back-and-forth, or stop-go-stop motion) can be achieved by supplying the desired phase control words as a function of time.

Under MANUAL control, phases may be specified either in discrete binary steps or continuously. Using the 3-position DRIFT DIRECTION toggle switch and a slow drift frequency setting, a grating may be moved back-and-forth until the desired phase angle is obtained and the motion stopped. For example, a physiological "null" phase can be found by this searching method while the drifting grating is simultaneously counterphasing, by supplying the counterphase signal to the corresponding CONTRAST module under EXTERNAL control.

Manually controlled discrete phase shifts in steps of 180°, 90°, 45°, and 22.5°, or any combination of these to produce 16 distinct states, can be achieved by the bank of four DIP switches in each PHASE module. The phase steps, as fractions of 2π radians, are indicated to the left of the DIP bank. Thus, for example, the leftmost switch shifts the phase by π radians, or 180°, i.e. simply inverts the polarity of a spatio-temporal signal. By counting up or down in 4-bit binary code, it is possible to span manually a phase selectivity curve with 16 sampled phases. These four DIP switches are always active, regardless of whether the global PHASE switch is

on MANUAL or EXTERNAL. Their effect is simply to add or subtract a binary phase angle, referenced to the phase which is specified by all other factors (i.e. DRIFT controls and EXTERNAL PHASE controls).

The manually controlled discrete phase shifts can be extended to 128-sample resolution by inserting a 16-pin DIP switch (8 independent single-pole double-throw switches) into the 16-pin phase socket and proceeding as above in 7-bit binary code, with the PHASE control switched to EXTERNAL.

The TTL output BNC terminal in each PHASE module delivers a logic signal whose phase is locked to that of the associated spatio-temporal pattern. Thus a temporal waveform of drift or flicker will be matched in frequency and phase by this TTL bit stream, marking temporal zero-crossings by logical state changes. The output impedance at these BNC terminals is 100Ω. This TTL signal may be used for triggering electrophysiological signal averagers, so that a spike histogram or evoked potential averager will add responses phase-locked to the temporal phase of a drifting grating or a flickering field.

(d) **Contrast.** The contrast of each of the spatio-temporal patterns may be independently controlled either by its associated 10-turn manual CONTRAST dial, or by an external control voltage applied at the associated BNC terminal with the control switch on EXTERNAL. Contrast is proportional to the dial setting or to the applied external voltage, with 0 V yielding zero contrast and with opposite voltages reversing contrast polarity. Applied control voltages should be in the range of ± 5 V, from a low impedance source; the input impedance at these terminals is 50kΩ. A dial setting of 10.00 corresponds to a +5 V control voltage. If an oscillatory control voltage (DC - 50Hz) is applied to a CONTRAST terminal in GRATING mode, it will produce a counterphasing grating according to this temporal waveform; in FIELD mode, it will specify the flicker waveform. If the control voltage waveform is structured in the audio frequency band (100Hz - 20kHz) and repeats itself at the frame rate, as triggered by the FRAME SYNC pulse, then in GRATING mode it would specify a spatial contrast-modulation envelope for the grating across the extent of each image frame; in FIELD mode it would generate the corresponding luminance profile. For slow time-domain modulation of grating contrast or flickering luminance fields, the AUXILIARY WAVEFORM GENERATOR provides sinusoidal, triangular, and squarewave (TTL) outputs that may be used to drive the CONTRAST or PHASE inputs.

The GRATING/FIELD switch in each CONTRAST module specifies whether the associated spatio-temporal pattern generator produces a grating or a spatially uniform luminance field. The FIELD may be considered a grating of zero spatial frequency; therefore its "phase" and "contrast" determine its luminance, and its "drift frequency" becomes its flicker frequency, sinusoidal or squarewave. Other temporal modulation waveforms may be assigned to the field by supplying them externally via the CONTRAST input terminal, with the SINE/SQUARE switch on SQUARE.

With the main MODE switch set for SIGNAL PARTITION and with both spatio-temporal pattern generators operating in their FIELD mode, the image consists of two separate, spatially uniform, luminance regions partitioned according to the APERTURE controls. In this configuration one can generate the classical space-domain stimuli such as luminance edges, bars, lines, and circular center/surround structures such as annuli. Each region may be assigned its own

temporal flicker properties specified by the associated DRIFT or CONTRAST or PHASE controls. If the patterns are to be static, the SINE/SQUARE switches should be set to SQUARE so that the luminance field has a known "phase."

Combinations of the two spatio-temporal pattern generators in either SUMMATION or PARTITION modes, and GRATING or FIELD modes, permit a wide variety of stimuli based on partitioned dynamic fields and gratings, luminance-specified or flickering fields added to gratings, artificial scotoma, localized grating patches, etc.

The generation of 2-D Gabor wavelet stimuli (2-D Gaussian-modulated sinewave gratings), and 2-D Gaussian luminance fields, is discussed in Section 10(e) regarding Option 5.

(e) Other 1-D spatio-temporal waveforms. Any arbitrary 1-D spatio-temporal waveform, deterministic or stochastic, may be supplied externally in place of the internally generated sine and square waveforms. For the substituted spatio-temporal pattern generator, the control switches of the CONTRAST module should be set for EXTERNAL, SQUARE, and FIELD, and the desired waveform should be applied to the CONTRAST terminal. For arbitrary spatial modulation the supplied waveform should be triggered by the FRAME SYNC pulse so that the same pattern is produced from frame to frame. For example, a 1-D Gabor wavelet (a sinewave grating modulated along its wavefront by a 1-D Gaussian) can be produced in the SINEWAVE GRATING mode by supplying an external CONTRAST controlling waveform that is a Gaussian of the desired amplitude (peak contrast) and width, repeating at the frame rate, and synchronous with the FRAME SYNC pulse. (The APERTURE controls should be set to fill the screen without partition.) Since the grating is multiplied by the voltage applied to the CONTRAST terminal, its contrast waveform follows the Gaussian-weighted function. The delay between the FRAME SYNC pulse and the presentation of the Gaussian waveform controls the location of the wavelet in the image, and its phase velocity may be specified by the DRIFT FREQUENCY controls. 2-D Gabor wavelets may be generated using Option 5.

(f) 2-D Aperture control and aperture measurement. With the main MODE switch set for SIGNAL PARTITION, the manual and external controls of the two-dimensional APERTURE module are activated for rectangular and circular display partition assignments of the two spatio-temporal pattern generators.

The (X,Y) center coordinates of an aperture are specified by the sum of the manual settings and any control voltages applied at the POSITION input terminals, in the range of ± 5 V. These position coordinates are in the rotated coordinate frame, so that for an oriented bar or grating a change in the window position specified along one axis alone will be either parallel to or perpendicular to the axis of orientation. This facilitates a manual "centering" of the 2-D aperture coordinates over a cell's receptive field, following by a "sweeping" of the aperture back and forth across the field, using an external position control signal applied to just one of the two position inputs (normally the X-position input, for motion perpendicular to the bar's long orientation). More complicated 2-D trajectories of aperture motion require the appropriate positioning signals to be applied to both the X and Y APERTURE inputs, with the 2-D trajectory always being defined in the the rotated coordinate frame if there is rotation.

Simple back-and-forth sweeping motion of a stimulus aperture can be achieved by connecting

the trianglewave output of the AUXILIARY WAVEFORM GENERATOR (set for the appropriate frequency and amplitude of motion) to the X-position input of the APERTURE module. The TTL output of the AUXILIARY WAVEFORM GENERATOR may then be used to trigger external data acquisition equipment, so that signal averaging or spike histograms can be computed synchronously with the start (or reversal) of each sweep of the aperture. The sweep velocity, amplitude, and repetition rate are controlled by the FREQUENCY and AMPLITUDE settings. Non-uniform motions require position waveforms more complicated than a trianglewave. In general, some arbitrary 2-D trajectory of the aperture can be specified by supplying to the (X,Y) POSITION inputs the appropriate time-evolving coordinates $X(t)$ and $Y(t)$. It should be noted that the input impedance of these terminals is 10kΩ.

In a moving aperture containing a grating patch, the motion of the grating and the motion of the window are independent. The motion of the grating (phase velocity) is only controlled by the DRIFT and PHASE inputs, while the motion of the window is only controlled by the manual and external POSITION controls. These motion components can be studied independently or in specified combinations. Another **Innisfree** instrument, the *Dual Channel Velocity Field and Stereogram Generator*, which is used in synchrony with the *Picasso* and with windows automatically in registration, permits texture fields to be freely moving (or stationary) either in reference to the overall CRT display, or in reference to the horizontal coordinate of an aperture which might itself be in motion. By locking a foreground texture field to the coordinates of a moving window, it is possible to create moving "occluding" texture patches, as opposed to textures viewed apparently through a "transparent" window. These different types of windows for partitioning foreground and background texture fields are meant to simulate ecologically significant real-world object configurations.

The WIDTH and LENGTH of rectangular windows, and the RADII of circular or annular windows (as selected by the CIRCULAR/RECTANGULAR MODE switch) can be controlled either manually by the front panel knobs, or externally via the BNC terminals located on the rear of the chassis. These terminals can also be used to monitor the manual settings for aperture dimensions, for example when manually mapping out a "bar length" tuning curve and externally recording the manually-determined bar lengths automatically. The impedance at these three BNC terminals is about 10kΩ and thus they may serve as either control or monitoring terminals, depending on the impedance of the device to which they are connected. If connected to a low impedance device such as a D-to-A converter (typically 50Ω), then the associated window parameter will be strictly controlled by the applied voltage and will be independent of manual settings. If instead a terminal is connected to a high impedance input device such as an A-to-D converter (typically 1MΩ), then control resides strictly with the front panel manual knobs, and the external high impedance device can monitor manual settings without affecting the associated window parameter.

Whether externally controlling or externally monitoring, there is a relationship of direct proportionality between aperture WIDTH or LENGTH and the voltage present at the associated BNC terminal. The full range is spanned between 0 V and +3 V. There is a relationship of proportionality between the area (radius squared) of a circular window and the applied or measured voltage at the RADIUS terminal, with the full range being spanned between 0 V and +0.5 V. On instruments equipped internally with the ANNULAR WINDOW GENERATOR (Option 1), the inner radius of the annulus is specified by the normal RADIUS controls, while the outer radius is specified by the manual and external WIDTH controls. In specifying the

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outer radius of an annular aperture, the WIDTH controls have the same scale factor for area (radius squared) as the RADIUS controls have for the inner radius.

In supplying external control signals for any of the 2-D APERTURE dimensions, it is important that the control voltages be reasonably free of ripple or noise in order to obtain clear aperture boundaries.

(g) **Fixation spot.** A small, dynamic fixation spot with specified luminance and 2-D location (or trajectory) may be generated with the MODE switches set for SIGNAL PARTITION and RECTANGULAR APERTURE. The #1 Generator should be set for FIELD, and if either sinewave or squarewave flicker of the fixation spot is desired, the DRIFT DIRECTION switch will generate it, with a temporal waveform determined by the corresponding switch settings and temporal frequency controls. The APERTURE controls should be set for a small WIDTH and LENGTH to give the desired dimensions of the fixation spot. Thus the #1 Generator produces the fixation spot, while the rest of the stimulus field is created by the #2 Generator. The fixation spot may be caused to move around according to some programmed 2-D trajectory supplied as X- and Y-coordinates to the POSITION inputs, and it can be flashed on and off via the CONTRAST or PHASE (DRIFT) controls.

(h) **Frame interleaving module.** All stimulus parameters which can be placed under external analog control, with the exception of drift frequencies, can be interleaved between two alternative values via the FRAME INTERLEAVING module. Thus, for example, the center coordinates of a fixation spot or a stimulus patch can have one set of coordinates on the "even-numbered" frames, and a different set of coordinates on the "odd-numbered" frames. Similarly, different spatial frequencies can be interleaved by external control voltages distributed by the FRAME INTERLEAVING module to each of the two pattern generators. (The interleaving of different drift frequencies on alternate frames for each of the two generators must be implemented via their PHASE inputs.) Families of textured stimuli (such as two-component plaids, or patterns containing up to about ten 2-D Fourier components in each of the two channels) can be generated by interleaving different orientations together with other stimulus parameters such as spatial frequency. Further details and examples are given in Section 7 and in the Appendix. For example, by connecting the FRAME TOGGLE logic output to selected ORIENTATION bits (under EXTERNAL control), a certain set of stimulus parameters can be generated in one orientation on the "even-numbered" frames, while a different set of stimulus parameters is associated with a different orientation on the "odd-numbered" frames. In order to avoid perceptible flicker in such complex patterns, the higher frame rate of 200 Hz should be employed.

The FRAME INTERLEAVING module is best understood simply as a pair of single-pole double-throw analog switches, that are thrown by the FRAME TOGGLE logic signal that changes state on every frame. Thus, for example, on the "even-numbered" frames the output of PARAMETER A is internally connected to its IN_1 input, and the output of PARAMETER B is internally connected to its IN_1 input. On the "odd-numbered" frames, the two outputs are internally connected instead to their two IN_2 inputs. Because all six BNC terminals in the FRAME INTERLEAVING module have very low impedance, the notations IN and OUT are arbitrary and can be reversed, depending on whether it is desired to have one control voltage alternating between two different terminals, or two control voltages interleaved to the same output.

An example may be helpful: suppose the desired stimulus was a vertical, drifting grating inside the circular window, with a different drifting grating inclined at 45° outside of the circular window boundary. The desired spatio-temporal frequencies would be selected separately from the two digital pattern generators, operating in the SIGNAL PARTITION and CIRCULAR APERTURE mode. The FRAME TOGGLE output logical signal would be connected to Bit 3 (i.e., pin 3) of the ORIENTATION input socket under EXTERNAL control, so that the "even-numbered" frames would be vertical and the "odd-numbered" frames would be inclined at 45°, and with the frame rate set for 200 Hz. The (X,Y) POSITION coordinates of the circular aperture must be carefully centered so that the center of the circle matches the origin of coordinate rotation, in the center of the image; otherwise two superimposed circular boundaries would be visible instead of one. Since each image frame must display only the one grating associated with that frame's orientation, the CONTRAST of each generator must be turned alternatively on and off on alternate image frames. This is accomplished by connecting the two CONTRAST BNC terminals (switched to EXTERNAL) to the OUT terminals of PARAMETER A and PARAMETER B, respectively, of the FRAME INTERLEAVING module. Meanwhile the IN_1 terminal for A and the IN_2 terminal for B are grounded to yield zero contrast on the appropriate interleaved frames, while the IN_2 for A and IN_1 terminal for B are provided with the desired CONTRAST control voltage; for example, these might simply come from the +5 V output provided on the front panel. It should be noted that in a two-frame interleave, the effective contrast of a Fourier component that is displayed on just half the frames is divided by two.

(i) **Auxiliary waveform generator.** Auxiliary sinewave and trianglewave signals at low temporal frequencies (up to 25 Hz) are provided in this module, with manually controlled amplitude and frequency, and with a TTL logic signal of matching frequency. These waveforms may be used for counterphasing a grating whose CONTRAST control is set for EXTERNAL, or for sweeping a bar or other stimulus patch back-and-forth across some region of the image by providing the appropriate sweep signal to the X or Y POSITION terminal(s) in the 2-D APERTURE module. Discrete periodic changes in orientation or phase can be achieved by connecting the TTL_{OUT} logic output signal of the Auxiliary Waveform Generator to the desired bits of the corresponding modules for these variables under EXTERNAL control. For example, a grating can be given a squarewave counterphase in time (i.e., phase shifts of 180°) simply by connecting its most-significant PHASE bit (Bit 1 = MSB) under EXTERNAL control to this TTL_{OUT} logic signal. If two squarewave gratings are controlled in this fashion, matched exactly in spatial frequency but 180° out of phase (via the PHASE SHIFT manual switch), and partitioned by a RECTANGULAR APERTURE that has full width and whose length occupies only the central one-third band of the image, and with both of the #1 PHASE bits externally controlled by the TTL signal as described above, then a squarewave-counterphasing checkerboard results.

A grating can be flashed on and off at a specified temporal frequency by connecting its EXTERNAL CONTRAST control to the TTL_{OUT} logic signal of the Auxiliary Waveform Generator. If connected instead to its analog output, which is centered around zero DC bias, then a temporally sine or triangle counterphase waveform is produced. Because of the zero mean level for the analog waveforms, an aperture that is being swept back-and-forth via the POSITION inputs will have an average position determined by the manual POSITION knobs. For all such dynamic stimuli, the temporal frequency and phase (e.g. the start of each new sweep or of each new counterphase cycle) can be monitored by the TTL_{OUT} logic signal. This might be useful for triggering electrophysiological response averagers or spike histograms, in constructing receptive

field maps or averaging phasic responses.

(j) **Orientation.** Image orientation is controlled by a 10-bit digital image rotator with resolution of about one-third of a degree (0.3516°) in orientation. Thus any pattern can be displayed in any of $2^{10} = 1,024$ distinct orientations. A three-digit L.E.D. read-out display indicates the current image orientation truncated to the nearest degree, between 0° and 359°. Under MANUAL control, a three-position toggle switch permits orientation selection by rotating the image either clockwise or counterclockwise (denoted cw and ccw), and then stopping at the desired orientation. Under EXTERNAL control, a 10-bit word must be supplied (or just some upper fraction thereof in reduced resolution) via the 16-pin input socket with the following bit pattern:

$$
\begin{array}{llll}
(\text{MSB} = 180°)\ \text{Bit 1} & \bullet & \bullet & \text{Bit 9} \\
\text{Bit 2} & \bullet & \bullet & \text{Bit 10 (LSB} = 0.3516°) \\
\text{Bit 3} & \bullet & \bullet & \text{GND} \\
\text{Bit 4} & \bullet & \bullet & \text{GND} \\
\text{Bit 5} & \bullet & \bullet & \text{GND} \\
\text{Bit 6} & \bullet & \bullet & \text{GND} \\
\text{Bit 7} & \bullet & \bullet & \text{GND} \\
\text{Bit 8} & \bullet & \bullet & \text{GND}
\end{array}
$$

It should be recalled that any bits not actively specified (set or cleared) will automatically float to their TTL high state by default. Under EXTERNAL control, any orientation word that is present at the input socket is read and latched at the end of every 50 μsec deadtime between frames (hence at the frame rate), as indicated by the FRAME SYNC pulse making a TTL high-to-low transition. Thus for frame-by-frame interleaving of different orientations in sequence, the control words should be strobed (supplied) at every low-to-high transition of the FRAME SYNC pulse, which signifies the end of one frame and then allows about 50 μsec for the new orientation control word to settle before it is latched and executed for the next frame. The latching of the control word prevents any image rotation from occurring during a frame.

A separate ANGULAR VELOCITY CONTROLLER is available as Option 2, for spinning images at specified angular velocities, continuously or with stops and reversals of direction. In addition to generating rotational optic flow fields (non-zero motion vector **curl**) as stimuli, it can be useful for more rapidly (or more slowly) changing orientations under manual control of a stimulus orientation sequence than is possible by using only the cw/ccw switch on the *Picasso*'s front panel. The range of angular velocities for rotation is selectable over a range of 225-to-1 across two frequency ranges: from 0.01 Hz to 0.2 Hz, and from 0.17 Hz to 2.7 Hz. Complete operation and calibration instructions are provided in Section 10(b) of this Manual.

Images may be superimposed at two or more different orientations by supplying the desired external control words in a cycle that is incremented by the FRAME SYNC pulse, with logic timing as noted above. If only two different orientations are desired without using active computer control on a frame-by-frame basis, a simple SELECT gate can be constructed so that the two orientation control words can be continuously present, rather than having to alternate on every frame. As described in Figure 3, each bit of the ultimate control word present at the 16-pin input socket is derived from a 3-input logic gate whose inputs are the two alternate bits plus the FRAME TOGGLE signal or its complement. In the Figure, the two 10-bit static
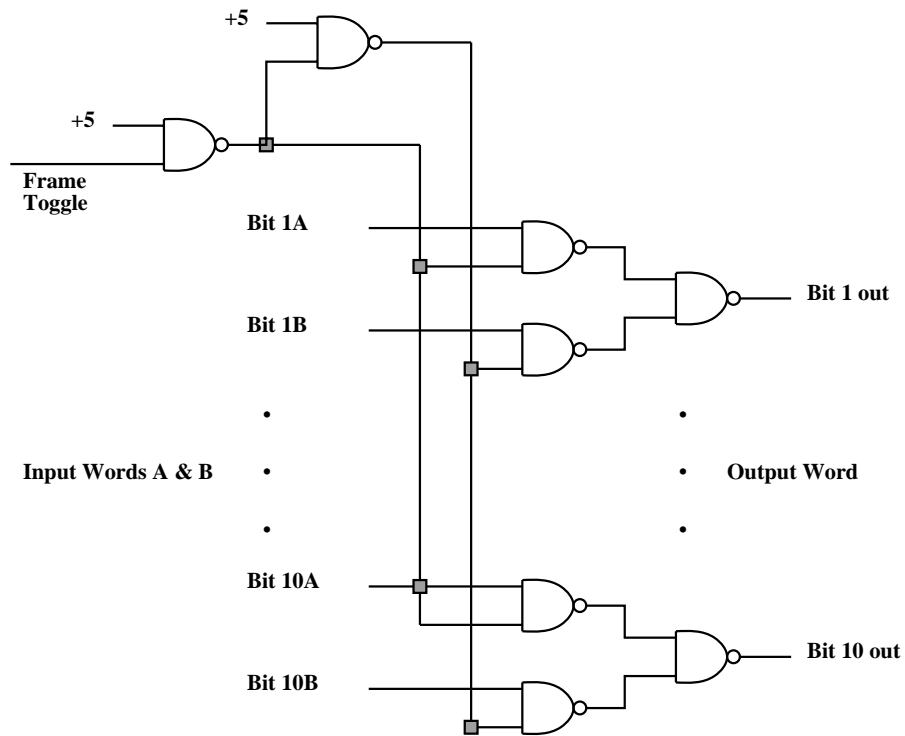
Figure 3: Logic circuit that will automatically interleave two externally specified orientation control words (denoted **A & B**) on alternate frames, for superimposing stimuli in two orientations.

orientation control words are denoted A and B. The FRAME TOGGLE control state comes from the *Picasso* front panel, as does the +5 V power supply which also serves as a reference TTL high state at two points in the circuit. The 10 output bits are connected to the 16-pin input socket for ORIENTATION under EXTERNAL control. This circuit eliminates the need for active computer monitoring of the FRAME SYNC logic signal in order to alternate between the two orientations. For full 10-bit control it requires 32 NAND gates, which are available in eight units of the generic quad NAND integrated circuit device 74LS00.

During use of the rotator under MANUAL control, image orientation can always be instantly reset to vertical (actually 359.7°) just by transiently flicking the MANUAL/EXTERNAL switch to EXTERNAL. This causes a default word of 1111111111 to be read in and latched, in the absence of any externally supplied word.

In experiments requiring less than the full 10-bit orientation resolution, or in case fewer than 10 control bits are available, the unused bits of the external control socket may simply be ignored. For example, if only Bits 1 - 8 were used, the effective orientation resolution would be $360° \div 256 = 1.41°$.

(k) Frame logic outputs. Two TTL output logic signals are provided in the upper-right corner of the front panel, and one on the chassis rear, which may be used for control and synchronization purposes. The FRAME SYNC output state is high during the 50 μsec deadtime between every image frame, while memory addressing counters and clocks are resynchronized; its TTL state

is low throughout each image frame. This pulse is useful for such purposes as: monitoring the frame rate; triggering externally supplied spatio-temporal waveforms on a frame-by-frame basis, as described in Section 5(e); and triggering each new vector of externally-supplied stimulus parameters in a frame interleaving sequence. In the case of interleaved ORIENTATION and PHASE control words, the FRAME SYNC pulse also indicates by its high-to-low transition the time by which a new control word must have settled in order to be latched and to be expressed in the upcoming image frame.

The FRAME TOGGLE logic output changes its state on alternate image frames. It is useful for two-fold interleaving sequences that need to distinguish between "even-numbered" frames and "odd-numbered" frames, for example in generating moving plaid patterns by superimposing gratings in two arbitrary orientations.

A third TTL output logic signal, marked TTL BLANKING and provided at the chassis rear, signifies the start of every new raster line. Its frequency is therefore the raster frequency, about 50 kHz. Its state is high during the write phase of every raster line, lasting about 16.5 μsec, and low during the raster flyback deadtime between lines, lasting about 3.5 μsec. During this flyback deadtime, the Z-axis signal to the CRT is blanked.

(1) **Window logic output.** This TTL logic signal is supplied on the rear of the chassis to signify which of the two digital spatio-temporal pattern generators is driving the Z-axis at any given moment, and thus it reflects the transitions of the raster between the display windows. If the raster is in a region of the display in which Channel #1 is active, its state is low, and if Channel #2 is active its state is high. This logic signal is used to interface the *Picasso* to a *Dual Channel Velocity Field and Stereogram Generator*, in order that the 2-D optic flow fields generated by the latter instrument are partitioned by windows that are in exact registration with the windows defining the greyscale and luminance stimuli generated by the *Picasso*.

6. **Simple Stimulus Examples**

The various control modules can be used interactively for the generation of a broad range of stimuli, through the image partitioning functions in conjunction with the dual independent spatio-temporal pattern generators. A few elementary stimulus configurations are described here for illustration.

Single grating. Either one of the two spatio-temporal pattern generators may be disabled to display only a single grating, either by setting its contrast to zero (via its 10-turn dial or just by switching its contrast control to EXTERNAL with no control voltage supplied), or by defining the boundaries of the partitioning 2-D APERTURE appropriately. For partitioned gratings, the inside of the 2-D APERTURE is driven by the #1 generator and the outside by the #2 generator, each with its own bank of control modules for spatial frequency, drift frequency, phase, contrast, and waveform. Temporal counterphase is achieved by supplying an external waveform oscillating around 0 V to the CONTRAST terminal under EXTERNAL control, or by supplying an alternating TTL signal to the most-significant-bit (MSB, pin 1) of the PHASE module under EXTERNAL control. Such analog or TTL waveforms may be obtained from the AUXILIARY WAVEFORM GENERATOR.

Amplitude-modulated and frequency-modulated gratings. In the case of one-dimensional AM or FM signals, the control signals for contrast and spatial frequency must be supplied externally and repetitively, triggered by the FRAME SYNC pulse, in order to produce AM or FM waveforms that are identical on every frame. In the case of two-dimensional AM or FM patterns, 2-D Fourier synthesis involving several orientations and spatial frequencies is required. Details and examples are provided in Section 7.

Luminance bars, edges, disks, and annuli. Spatially uniform luminance regions are generated in FIELD mode as gratings of zero spatial frequency; thus the controls for PHASE and CONTRAST determine luminance, and DRIFT FREQUENCY determines the flicker frequency, with a temporal waveform determined by SINEWAVE/SQUAREWAVE switches. The APERTURE module operating in the appropriate SIGNAL PARTITION mode (CIRCULAR or RECTANGULAR) determines the boundaries. Both of the CONTRAST modules must be switched to FIELD and SQUAREWAVE, and the corresponding DRIFT DIRECTION or PHASE controls must be used to achieve the desired luminance polarity for each of the two generators. Then, the corresponding CONTRAST controls determine the luminance of each region. Shifting the PHASE of either generator by 180° (π radians) reverses the polarity of the luminance region that it is controlling, and thus provides a means of producing a flashing bar or annulus; the same effect can be achieved by the use of DRIFT, with either SINEWAVE or SQUAREWAVE temporal waveforms. The 2-D location of the bar or annulus may be swept across the field by supplying the desired positioning waveform to the POSITION inputs of the APERTURE module; a uniform back-and-forth sweeping motion can be achieved by connecting the AUXILIARY WAVEFORM GENERATOR's triangle waveform to the X-POSITION input. Aperture WIDTH, LENGTH, and RADIUS (or radii in the case of annuli) can be controlled as described in Section 5(f).

Two gratings superimposed in different orientations. Only one of the two generators need be used if the same grating is desired at different orientations, since the orientation control word

simply needs to alternate on successive frames according to the FRAME TOGGLE TTL logic signal (see Figure 3). The FRAME TOGGLE signal can even be connected directly to those bits of the ORIENTATION socket which differ in the two orientations. If the two superimposed gratings are to have different spatio-temporal properties, then once again they could both be generated by the same generator with frame-interleaved spatial frequencies, but the simplest method is to employ both generators in SIGNAL SUM mode, with their CONTRASTS interleaved on-off in alternate frames so that each one is only producing a visible grating at the appropriate orientation. External CONTRAST control values can be interleaved through the FRAME INTERLEAVING MODULE, as described in Section 5(h).

Two gratings in different orientations, partitioned by a circular window. See discussion in Section 5(h).

Grating phase velocity versus group velocity. See discussion about the generation of moving 2-D Gabor stimuli under Option 5, described in Section 10(e).

Multiple image windows. Several grating patches or luminance bars may be displayed simultaneously against a uniform background field, by interleaving the desired APERTURE POSITION control voltages on successive frames. If more than two APERTURE control voltages are desired, then the center coordinates must be supplied directly on each frame, cued by the FRAME SYNC pulse. If only two separate windows are required, their respective position control voltages can be supplied statically to the FRAME INTERLEAVING MODULE, whose outputs to the X & Y POSITION inputs will automatically alternate on successive frames.

If such multiple windows are to incorporate different orientations (via the use of interleaved ORIENTATION control words), then the interleaved POSITION control voltages must take into account the fact that the position coordinates are defined in the rotated frame of reference. This pertains as well to the manual position settings that are added to any external control voltage for each position vector component separately. For simplicity, the manual controls should be set to center the relevant aperture on the origin of coordinate rotation, which is at the center of the image. In order to place a given aperture at coordinates (X, Y) on the display screen, with (0,0) being the center of the image, when an orientation θ is employed it is necessary to add "de-rotating" components $(\Delta X, \Delta Y)$ to the POSITION control voltages. These are derived from the 2-D Euler rotation matrix as follows, with the voltage gain factors for ΔX and ΔY being the same as for X and Y:

$$\Delta X = X \cos(\theta) + Y \sin(\theta)$$
$$\Delta Y = -X \sin(\theta) + Y \cos(\theta)$$

As in all interleaving applications, the higher frame rate (200 Hz) should be employed. Many different parameters can be interleaved simultaneously on successive frames, such as luminance polarity, spatial frequency, contrast, orientation, and 2-D aperture spatial location.

7. Synthesis of Dynamic Two-Dimensional Textures

A broad variety of dynamic spatial textures can be synthesized by the summation of 2-D Fourier components. By following certain spectral distribution rules (specified in Section 8), such punctate spectral images comprising from two to twenty dynamic 2-D Fourier components can simulate bandlimited noise, isotropic or anisotropic, as well as coherent or incoherent textures that may be static, dynamic, or rigidly moving with specified speed and direction.

A list of the desired 2-D Fourier components in the pattern must be specified in the host program which sends to the *Picasso* the desired control vector (orientation, spatial frequency, phase, contrast) for each component or pair of components on a frame-by-frame basis, synchronous with the FRAME SYNC pulse. Since each frame may contain only one or two co-directional Fourier components, partitioned or summed, a frame rate of 200 Hz or higher should be employed to avoid perceived flicker when several such frames are interleaved. On the occurrence of each FRAME SYNC pulse, signifying the beginning of each new frame, the host computer must output the desired new control words for whichever parameters are being controlled externally. If dynamic textures are to be synthesized in which each Fourier component has its own temporal frequency, then these must be specified via the associated external PHASE controls. Textures which are static or in which each Fourier component is to have the same temporal frequency do not require external PHASE control.

In general, the computer should loop through a table of desired parameters, sending out one "row" in the table every time a FRAME SYNC pulse occurs. All control words should settle before the end of the 50 μsec FRAME SYNC pulse. The digital words for ORIENTATION and PHASE are read and latched on the downward edge of this pulse, and the analog controls (SPATIAL FREQUENCY and CONTRAST) are continuously monitored and implemented.

The overall refresh rate of a complex texture is the ratio of the frame rate to the number of frames which must be interleaved in order to display all Fourier components. Thus, for example, a texture comprising ten Fourier components which fall on five radial trajectories in the Fourier plane (thus incorporating only five distinct orientations) would be synthesized by the two digital generators in the SIGNAL SUM mode in a five-fold interleave sequence, and the entire 10-component texture would be refreshed at 40 Hz if the frame rate were 200 Hz. Note that the DC (mean luminance) term is present on each of the 200 frames per second, so there is not a 40 Hz field flicker. However, large changes in the orientation of the raster sweep from frame to frame can introduce apparent flicker and therefore should be avoided, by appropriately staggering the different orientations in a sequence.

If the various 2-D Fourier components in a dynamic texture are to have different temporal frequencies, then the temporal frequency of each one must be generated by an appropriately advancing or retarding PHASE word in the interleave sequence. Suppose a particular 2-D Fourier component is being presented N times per second (N being equal to the frame rate divided by the number of interleaved frames). Then each time that component is presented, its PHASE word should increment (or decrement) by ω_t/N cycles in order for it to have a temporal frequency of ω_t Hz. The two 7-bit PHASE words can be conveniently combined into a single 16-bit standard word by multiplying one PHASE word by 256 (shifting it in base 2 by 8 bits), and adding it to the second. The new 16-bit word can then be separated into upper and lower bytes in the physical cable connections to the two PHASE sockets.

8. Spectral Distribution Rules for Various Classes of Dynamic Textures

Various classes of dynamic textures are generated by particular relationships among the spatial frequencies, orientations, and temporal frequencies of the 2-D Fourier components they comprise. These spectral distribution rules must be reflected in the list of control vectors that the host computer specifies on a frame-by-frame basis, following the protocol described in Section 7.

Spatially coherent textures. Various kinds of 2-D spatial coherence are associated with spectral conditions in which the 2-D Fourier components have some form of degeneracy, such as common orientation, common spatial frequency, or a common vector harmonic (common divisor). Strict 2-D periodicity of a pattern results if and only if all 2-D Fourier components lie on any set of parallel equidistant lines in the Fourier plane including the origin. The orientation and spacing of these lines scribing the Fourier plane specify the direction(s) and period(s) of strict 2-D periodicity of the pattern in the 2-D space domain.

Anisotropic, spatially incoherent textures. The 2-D spectral components are confined to some preferred band(s) of orientation (anisotropy), and do not satisfy any of the coherence conditions described above. An example is shown in the upper panels of Figure 4, comprising six 2-D Fourier components as follows:

Orientation	Spatial Frequency
-10°	4.9 cpd
-6°	6.3 cpd
-2°	5.8 cpd
+2°	4.5 cpd
+6°	5.4 cpd
+10°	4.7 cpd

Isotropic, spatially incoherent textures. The 2-D spectral components are distributed rather uniformly in orientation, without falling into the coherence conditions. An example is shown in the lower panels of Figure 4, comprising ten 2-D Fourier components as follows:

Orientation	Spatial Frequency
24°	3.5 cpd
95°	2.9 cpd
167°	2.8 cpd
220°	2.7 cpd
293°	3.2 cpd
58°	2.5 cpd
132°	3.5 cpd
186°	3.8 cpd
258°	3.7 cpd
330°	3.4 cpd

Temporally coherent textures. All Fourier components are assigned harmonically related temporal frequencies. Then any particular "frozen" state of the dynamic texture will repeat itself every $1/\omega_t$ seconds, where ω_t is the largest common denominator of all the temporal frequencies.

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A special example of such a condition arises when the PHASE module(s) are set for MANUAL control with some constant DRIFT FREQUENCY; then all Fourier components have exactly the same temporal frequency. In any temporally coherent texture, any local luminance value in the image is strictly periodic in time with period $1/\omega_t$. It should be noted that in general, there need be no actual spectral energy corresponding to this repetition period. The same is true for the orientation and spatial frequency of strict 2-D spatial periodicity, as was noted at the beginning of this Section.

Temporally incoherent textures. The various temporal frequencies associated with the various 2-D Fourier components are not harmonically related. The resulting texture is not periodic in time.

Dynamic textures with stationary 2-D beat patterns. All 2-D Fourier components are assigned the same temporal frequency, for example by keeping PHASE under MANUAL control and using some fixed DRIFT FREQUENCY. Spatio-temporal beat patterns are determined by the 3-D vector difference frequencies among the actual spectral components.

Rigidly drifting textures. The 3-D spatio-temporal spectral constraint that is equivalent to rigid motion in the image domain is that all spectral energy is confined to a plane which includes the origin. Thus all Fourier components must have temporal frequencies that obey some bilinear function of spatial frequency and orientation when resolved into their Cartesian coordinates in the Fourier plane. For each given Fourier component, having spatial frequency ω_s and orientation θ, define its two Cartesian spectral projections ω_x and ω_y:

$$\omega_x = \omega_s \cos(\theta)$$
$$\omega_y = \omega_s \sin(\theta)$$

Rigid motion of the pattern just requires that each associated temporal frequency ω_t satisfies the rule:

$$\omega_t = A\omega_x + B\omega_y$$

where A and B are the same for all the Fourier components. The parameters A and B determine the elevation and azimuth of the spectral plane in 3-D frequency space, which correspond respectively to the speed and direction of the rigid motion of the texture:

$$\text{speed} = \sqrt{A^2 + B^2}$$
$$\text{direction} = \arctan(B/A)$$

As a special case of this 3-D spatio-temporal spectral constraint corresponding to rigid image motion, it should be noted that two superimposed drifting gratings having different orientations always just translate rigidly together in some third direction. The phenomenal perception of rigid plaid motion is sometimes called "coherent motion," but it just reflects the fact that three points determine a plane: the two Fourier components, plus the origin of 3-D spatio-temporal frequency space. Clearly, the two spectral components corresponding to the two gratings are always coplanar with the origin of 3-D spatio-temporal frequency space, as required for rigid motion. Thus what is interesting about "coherent motion" for plaid patterns is not the fact that sometimes we see coherent motion, since after all the combined signal truly does undergo rigid translation in the perceived direction, but rather the fact that sometimes we do not perceive it in that way.

Figure 4: Examples of anisotropic (top) and isotropic (bottom) incoherent textures, created by superposition of the Fourier component ensembles shown on the left. Spectral components listed on page 23.