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BIF-048/001-2361-68
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BYE-68398/68

A SUMMARY OF

THE PAUL-BETA SENSOR OPERATION

AUGUST 23, 1968

BYE 68398-68

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SENSING TECHNIQUE

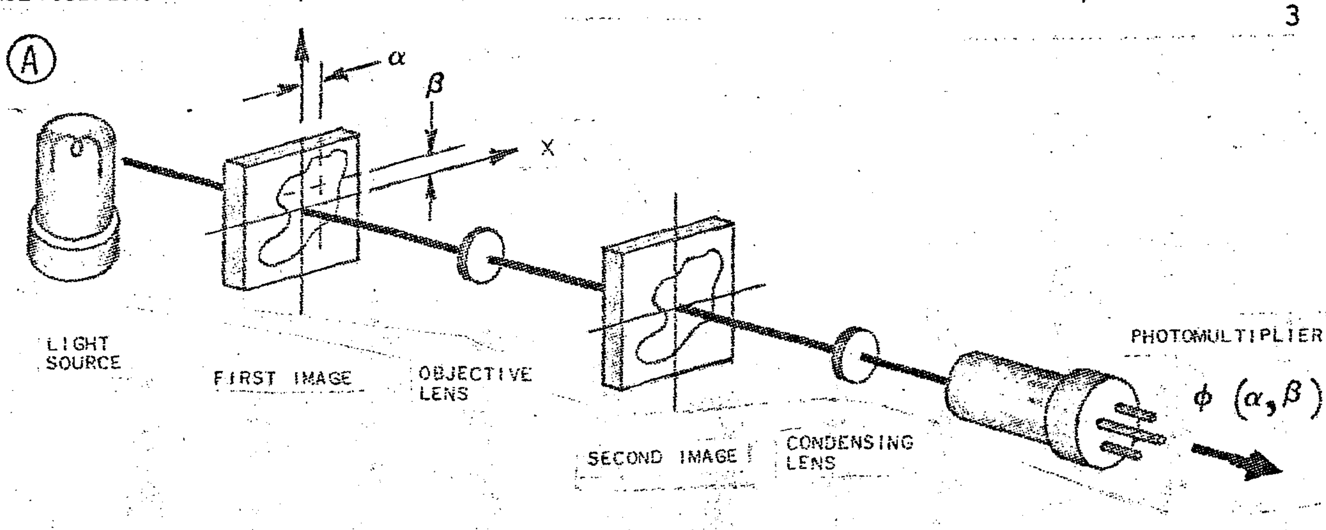
The PAUL BETA Subsystem measures the velocity of an optical image of a sector of terrain that is passing beneath a spaceborne vehicle. The velocity of the terrain image results from a combination of vehicle motions, Earth motions, and Tracking Mirror motions. The PAUL Sensor performs this measurement by continuously implementing the correlation function of the input optical image. This function is uniquely suited to this task, since it simultaneously and continuously utilizes all the information contained in the entire input image format, and is thereby relatively tolerant of noise which may be injected by the intervening medium or by the sensor itself.

A laboratory image correlation device is shown in A. The first and second images consist of photographic positive transparencies of a terrain sector. The first image is projected and focused on the second image by means of the lamp and the lens. The phototube collects the light that is transmitted through the two images, and provides a conversion to an equivalent electrical output signal. If the first image is displaced with respect to the second, then a position can be found where each of the individual target features of the first is exactly superimposed on the corresponding feature of the second. This is called the "match point", and results in a maximum transmission of light. Any displacement of the first image from the "match point" results in a reduction of the light received by the phototube.

The correlation phenomenon, whereby the transmitted light level is controlled by the relative displacement of two images, may be visualized by means of samples B and C. Image C may be removed from the envelope and positioned over B. By moving C, it may be observed that maximum light from within the circular aperture is seen when perfect registration is achieved. (The peripheral index marks may facilitate this adjustment.) Any displacement of C from this position, results in a reduction of the observed light.

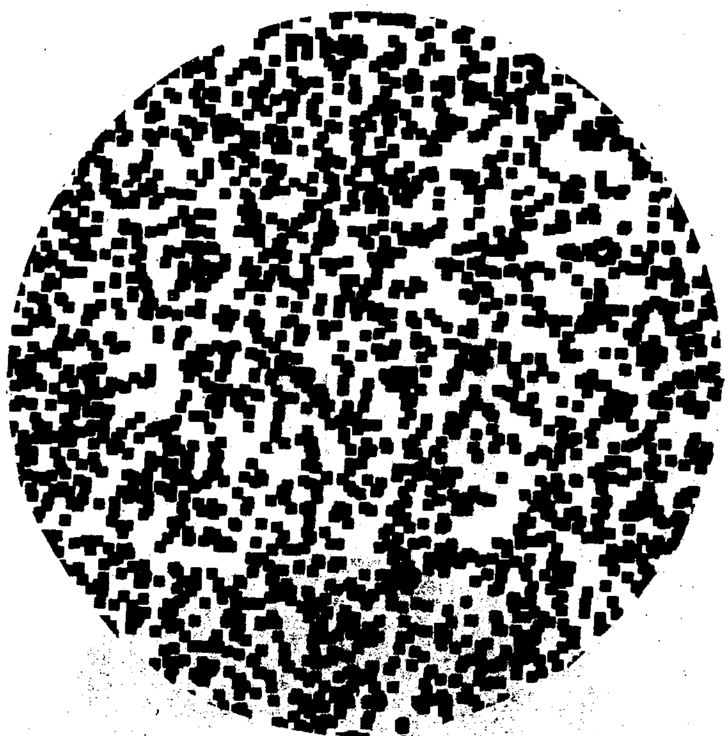
The A device is not representative of a spaceborne correlator, since the first photographic transparency is not required when viewing terrain directly through an optical system. Likewise, the lamp is not required, since the sun serves as the source of illumination after modification by the atmosphere and the terrain reflectance. This simplification does not result in an appropriate device, however, since it is desirable: a) that the positioning of the first image be accomplished electronically, rather than mechanically, and b) that the second image be temporarily stored electronically, rather than by means of photographic film.

The PAUL Sensor implements these desired features by utilizing a special deflectable image storage tube. The configuration of this tube is described on the next page.


Ⓐ
Y
α
β
X
LIGHT SOURCE
FIRST IMAGE
OBJECTIVE LENS
SECOND IMAGE
CONDENSING LENS
PHOTOMULTIPLIER
$\phi(\alpha, \beta)$


Ⓑ
STORED

TOP



LIVE

TUBE CONFIGURATION

The PAUL Sensor image tube is shown in Ⓓ. This tube represents a unique combination of selected elements from such standard, space-qualified, electron devices as the image storage tube and the vidissector. The major components of the tube are shown in Ⓔ. From left to right, these consist of:

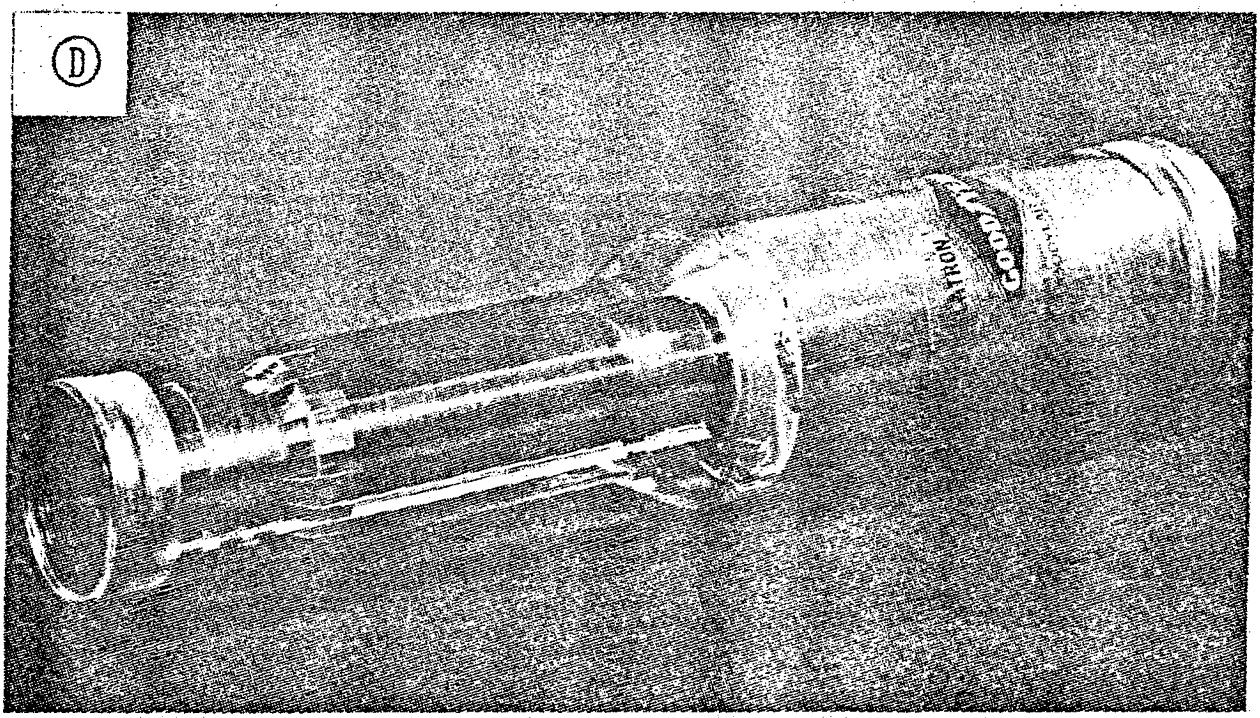
1) an S25 photocathode deposited on an optically-flat glass faceplate. This element converts the input optical image into a corresponding electron image. This element is specially fabricated to provide extended red response, low electrical impedance, very low fatigue, and excellent uniformity.

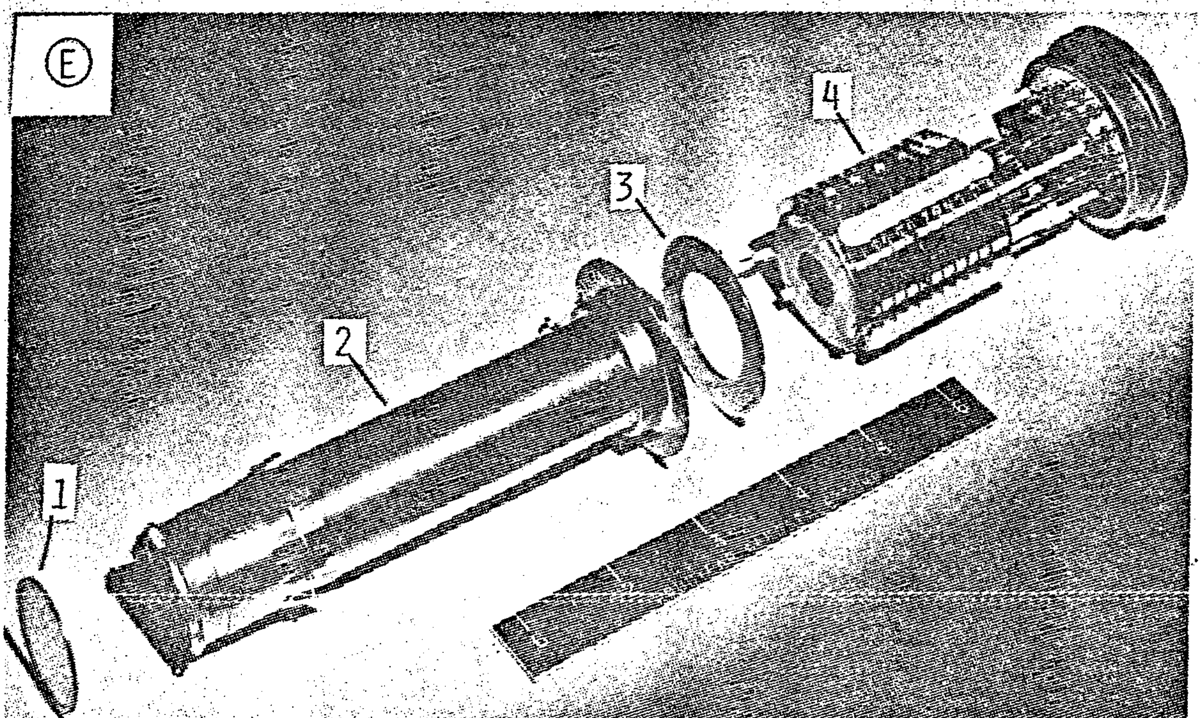
2) a drift section consisting of a field mesh at the input and a collector mesh at the output. This uniform potential section accelerates the electrons emitted by the cathode and then provides a constant velocity region. Orthogonal deflection yokes surround this section (external to the envelope) to provide magnetic displacement of the electron image.

3) a storage element consisting of a fine metal mesh upon which is deposited an insulator coating. This structure results in a two-dimensional array of capacitor elements, the front surfaces of which are electrically common. The charge level of each front surface element may be independently modified by means of the cathode electrons. All front surface voltage levels may be uniformly modified by a single adjustment of the rear surface, wire-mesh potential.

4) a mask element, an electron-multiplier section, and an anode element. The mask prohibits electrons which pass through the peripheral portion of the storage mesh from contributing to the tube output signal. The multiplier provides very low noise amplification by increasing the number of output electrons. The anode collects the output electrons and provides a corresponding output electrical current.

The PAUL Sensor Tube may be operated to provide electron image-area correlation. This is described on the following page.


D


E
1
2
3
4

ELECTRON IMAGE CORRELATION

The PAUL Sensor Tube provides electron image correlation as depicted in (F). At the start of a sequence, the tube is biased such that the electrons are accelerated and impinged on the storage surface with sufficient energy to dislodge secondary electrons. This net depletion of electrons results in a positive charge at the mesh positions which correspond to the highlight portions of the image. The initial storage of the input image is called the "write" mode, and normally requires about 50 msec to complete. The stored image is depicted in (F) as $I_1(x,y)$.

Next in the sequence of operation, the tube is biased such that little acceleration of the cathode electrons occurs. As a result, the electrons arrive at the storage mesh with insufficient energy to dislodge secondaries. The storage mesh is biased so that the previously charged front surface elements are below the cathode potential. Thus, the localized electrostatic fields provided by these elements are effective in modulating the number of electrons which pass through the mesh. The low energy electron image is depicted in (F) as $I_2(x,y)$. This image is magnetically deflected, as required to provide registration with the stored image. The deflected image is depicted as $I_2(x+\alpha,y+\beta)$. The image modulation is called the "match" mode, and persists until a new stored image is required, either because a different terrain sector is to be imaged, or because the appearance of a given sector has been significantly modified over a period of time by a large change in the optical sighting angle.

The electrons which pass through the storage mesh are amplified by secondary emission in the multi-stage electron multiplier and result in an output current, depicted in (F) as $\phi(\alpha,\beta)$. The change in the output signal versus the displacement of the input image is shown in (G). Displacements from the match point in either the α or β directions result in a reduction of the signal. Mathematically, the image correlation performed by the PAUL Sensor Tube may be expressed as:

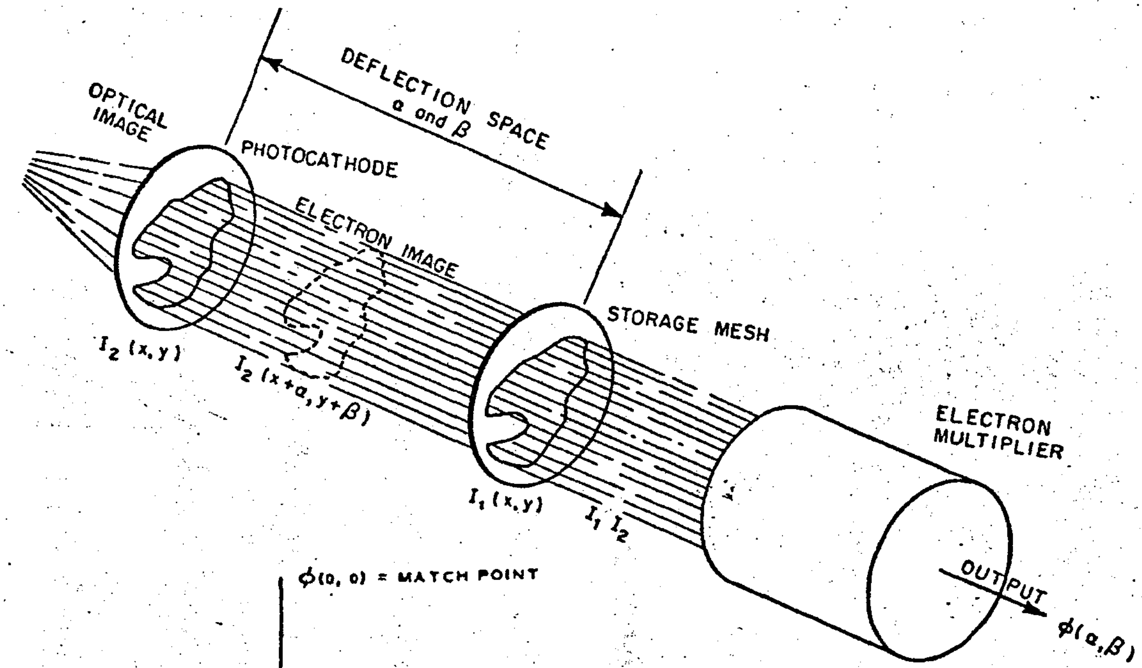
$$\phi(\alpha,\beta) = k \int_A I_1(x,y)\ I_2(x+\alpha,y+\beta)\ dA$$

Prior to the storage of a new image sector, the front surface elements of the storage mesh must all be returned to the cathode potential. This is performed by a ring of neon lamps external to the tube which provide a source of uniform flood illumination. Discharge of the mesh by low energy electrons from the entire cathode surface is called the "erase" mode, and requires about 50 msec to complete.

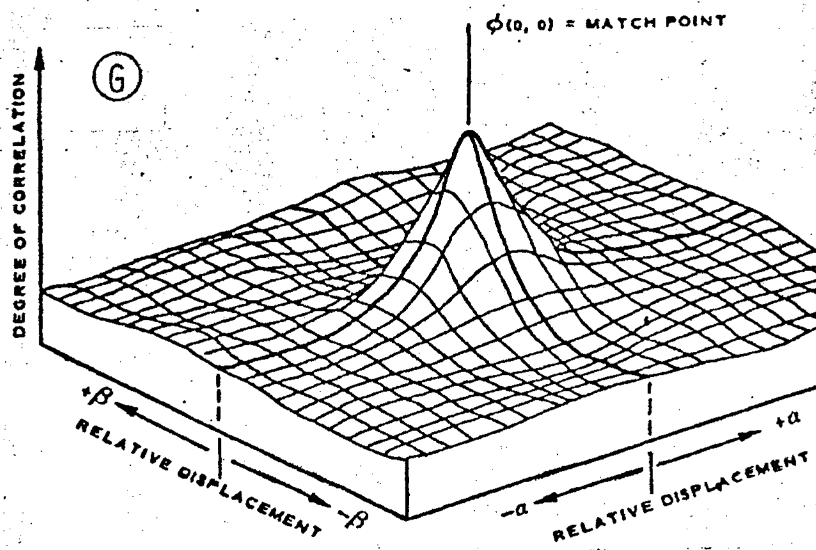
The match surface is shown in (H) in the X(or α) plane only. The small amplitude sinusoidal waveshape below the curve represents the 1000 hertz image dither, or nutation, which is purposely applied to generate an ac waveshape, which in combination with a synchronous demodulator can produce a $\pm$dc error signal, as required for a closed loop self-nulling system. Case I in (H) corresponds to perfect registration of the two images, and results in an output waveshape at the right which has a net value of zero volts during the one-half of the nutation cycle from 0 to π (shaded areas). Cases II and III in (H) correspond to small right and left offsets between the two images, and result in output signals which are predominately negative and positive, respectively.

Specific parameters of the PAUL Sensor Tube which influence the characteristics of the correlation output signal are described on the following page.

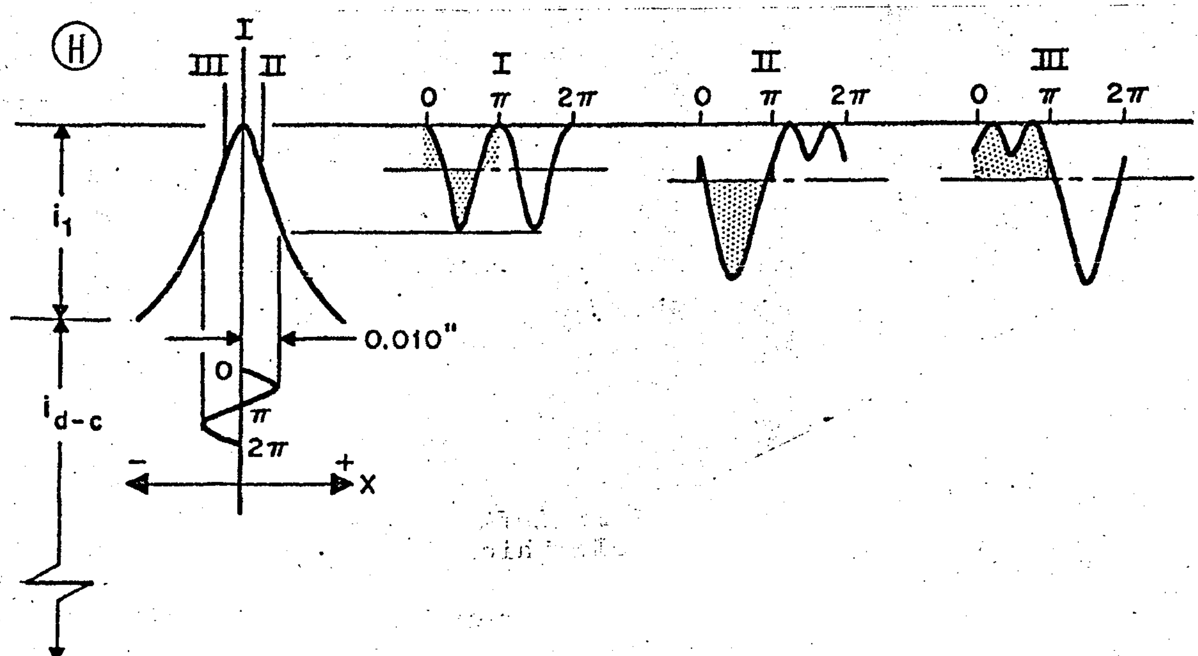
F


DEFLECTION SPACE
α and β
OPTICAL IMAGE
PHOTOCATHODE
ELECTRON IMAGE
STORAGE MESH
I_2 (x, y)
I_2 (x+α, y+β)
ELECTRON MULTIPLIER
I_1 (x, y)
I_1 I_2
OUTPUT
φ(α,β)

G


φ(0, 0) = MATCH POINT
DEGREE OF CORRELATION
+β
RELATIVE DISPLACEMENT
−β
+α
−α
RELATIVE DISPLACEMENT

H


I
III
II
0
π
2π
i_1
i_{d-c}
0.010"
−
+
X

TUBE CHARACTERISTICS

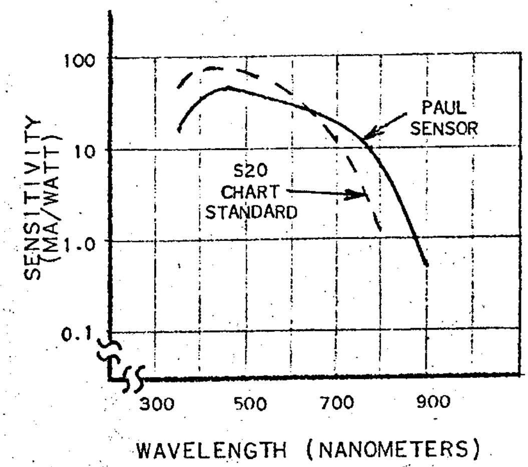
The PAUL Sensor Tube utilizes an S25 photocathode which has a spectral sensitivity as shown in (I). The comparison with the standard S20 shows that processing techniques are used whereby a small sacrifice in the blue sensitivity can be traded for a significant increase in the red response. The efficiency shown in (I) corresponds to a rating of 200 μa/lumen. Cathodes having a rating of greater than 250 μa/lumen are not uncommon. The increased red response is significant for spaceborne applications since the sun as a source has rich components in this part of the spectrum, and since reflectance from terrain vegetation provides strong contrasts in the near infra-red. Loss of some blue sensitivity is not serious, since haze due to scattering off the atmosphere is predominately at this end of the spectrum.

The effective resolution of the PAUL Sensor Tube is shown in (J). This shows that significant correlation signal amplitude is maintained at 100 line-pairs/inch. The (J) curve indicates that for a slant range of 80 n. mi., terrain features having an edge dimension as short as 14 feet will provide a significant contribution to the total correlation output signal. It should be noted that this is not a direct measure of the tube registration accuracy. The indication of misregistration generated by the tube is an average obtained by simultaneously measuring all the localized misregistrations of each of the individual target features throughout the entire image format. These characteristics allow a sensitivity that is 5 to 10 times better than the tube resolution. The use of "parallel processing" to achieve the desired sensitivity, rather than a fine resolution, is also effective in simplifying the sensor configuration since mechanical adjustment of the input lens system is not required to compensate for the small defocusing which results from changes in the slant range to the terrain.

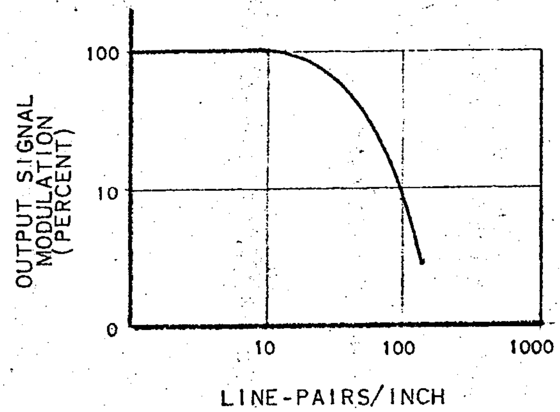
The electron modulation characteristics of the PAUL Sensor Tube storage mesh are shown in (K). During the "match" mode, front surface elements at -1.25 volts prohibit the passage of all incident image electrons. Elements at -0.25 volts allow passage of nearly all the incident image electrons. This relatively narrow range of approximately 1.0 volts can be used to enhance the apparent contrast of the stored image. This is shown by (L) which represents a portion of a two-level low contrast image, as indicated by the large dc component and the smaller ac component. During the "write" mode, the exposure is controlled so that the average illumination level causes a front surface charge of +2.5 volts. During the "match" mode, the mesh potential is adjusted so that this level is biased at -0.7 volts, and is centered on the transmission curve. This causes the limited ac components of the image to be distributed over nearly the entire transmission characteristic, and likewise places all the dc components of the image into cut-off. This feature, therefore, allows a low contrast image to be stored as a high contrast charge pattern having full control over the subsequent electron flow. Returning to the image samples on page 3, this is the reason why the mounted image (B) is labeled "stored" and has a higher contrast than the envelope image (C) which is labeled "live".

The sensor tube is the primary component of the PAUL Sensor. Peripheral components are required, however, to provide a complete subsystem. These are described on the following page.

(I)

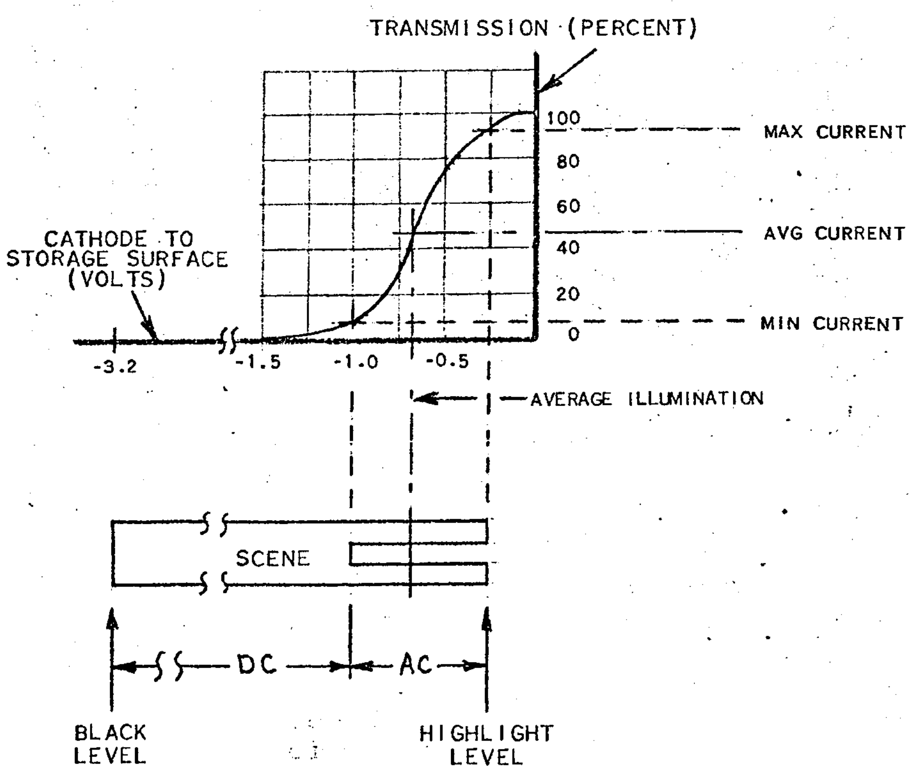

100
10
1.0
0.1
SENSITIVITY (MA/WATT)
PAUL SENSOR
S20 CHART STANDARD
300
500
700
900
WAVELENGTH (NANOMETERS)

(J)


100
10
0
OUTPUT SIGNAL MODULATION (PERCENT)
10
100
1000
LINE-PAIRS/INCH

(K)

(L)


TRANSMISSION (PERCENT)
100
80
60
40
20
0
MAX CURRENT
AVG CURRENT
MIN CURRENT
CATHODE TO STORAGE SURFACE (VOLTS)
-3.2
-1.5
-1.0
-0.5
AVERAGE ILLUMINATION
SCENE
DC
AC
BLACK LEVEL
HIGHLIGHT LEVEL

SENSOR IMPLEMENTATION

The PAUL BETA Sensor provides the functional flow shown in (M). The main path flows from the optical input at the upper left, flows through the sensor tube, and terminates in the electrical output signal at the lower right. The output rate signal is fed back to the tube deflection yoke to provide a closed loop configuration. This results in a self-nulling system, wherein the input and stored electron images are continuously maintained in best registration, regardless of the motion of the input optical image. In this regard, it should be noted that the feedback path includes an integrator which converts the output rate signal to a corresponding internal position signal. This maintains an internal position null which maximizes the correlation sensitivity, while allowing the external output signal to be in a proper form to control the rate of the Tracking Mirror. The feedback configuration is also very effective in stabilizing the sensor scale factor, and to a large extent is effective in stabilizing the frequency response of the sensor. This control is necessary, since wide variations in the quantity and the quality of the input optical image information content can be experienced, thus introducing large changes in the gain of the forward path.

The waveshapes along the lower portion of (M) show the typical operation. The input image normally has a high initial rate, $\dot{\theta}_i$. In a period of time, t, this is brought to zero as the BETA Sensor refines the Tracking Mirror rate. Over this period of time, the optical input can also be depicted in terms of a changing position, θ_i. The third waveshape, θ_o, shows that the internal feedback signal is equal and opposite to the input position change, thus maintaining registration of the electron images within the tube. The output signal, $\dot{\theta}_o$, has a 1:1 relationship to the input rate.

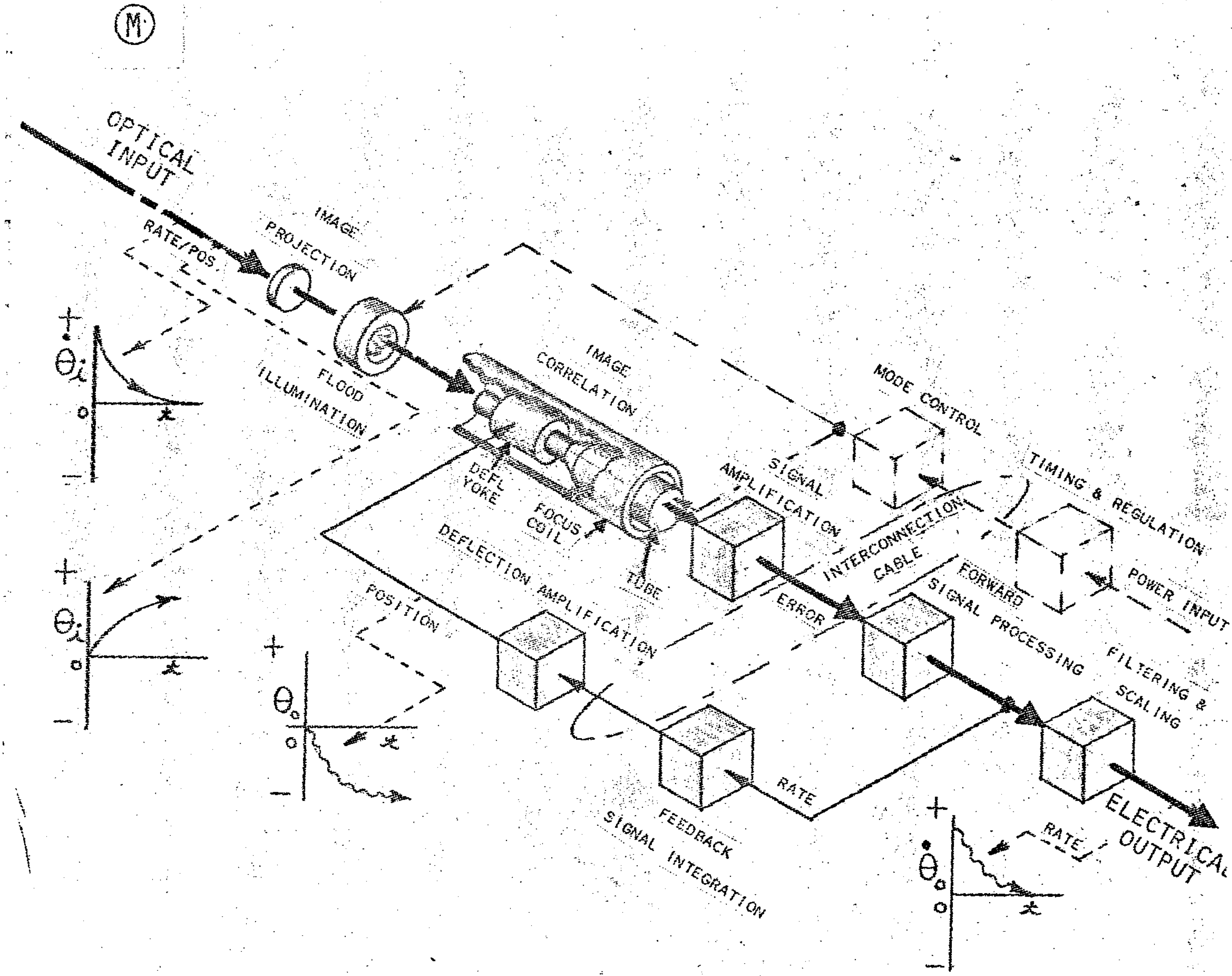
The PAUL Sensor parameters provide an overall transfer function which has the mathematic form:

$$\frac{E_o}{\dot{\theta}_i} = \frac{10}{\left[\frac{S}{2\pi(30)}+1\right]\left[\frac{S}{2\pi(52)}+1\right]\left[\frac{S}{2\pi(195)}+1\right]\left[\frac{S}{2\pi(3.5)}+1\right]} \quad \frac{\text{volts}}{\text{inch/sec}}$$

This results in a response that is 3 db down at approximately 3.5 hertz. The phase lag at this frequency is approximately 56 degrees. It should be noted that the PAUL implementation shown in (M) utilizes no moving parts. As a result, the time constants indicated above are all introduced by discrete electronic components. Complete freedom may be exercised, therefore, in selecting gains and responses to optimize the interface between the BETA Sensor and the Tracking Mirror Assembly.

The dashed functions along the top of (M) provide the required voltages and mode sequencing. In addition, they include self checking and parameter adaptation functions. These, along with the other major characteristics of the PAUL Sensor, are summarized on the next page.

NRO APPROVED FOR
RELEASE 1 JULY 2015



SENSOR CHARACTERISTICS

The PAUL Sensor consists of the two major subassemblies shown in Ⓝ. At the left is the sensor package, and at the right is the electronics package. To minimize the weight of the sensor package, this assembly incorporates only the components which must be placed in close proximity to the sensor tube.

Besides power supplies, mode sequencing, and diagnostic monitoring circuits, the electronics package also includes the self-checking and parameter adaptation functions necessary to insure that the sensor performance is optimized and that the output signals are fully valid. The self-checking circuit continuously compares the correlation signal energy with the noise energy and terminates the output rate signals when marginal conditions exist. Readout is also inhibited when the input illumination level is insufficient, when the input image rates are beyond the linear range of the sensor, and when the Tracking Mirror response is such that excessive electron image displacements are accumulating within the tube. The adaptation circuits automatically adjust the exposure parameters during the "write" mode as a function of input illumination level, adjust the forward gain as a function of the image information content, and adjust the nutation deflection amplitude as a function of image spatial frequency content.

The input and output characteristics shown in Ⓝ correspond to the measured performance of the present breadboard sensor, or are conservative projections based on the analysis and the preliminary testing of the Engineering Prototype Evaluation Model.

ELECTRICAL OUTPUT

DYNAMIC RANGE:
0 TO 0.5 INCH/SEC

ACCURACY:
BETTER THAN 0.01 INCH/SEC

THRESHOLD:
LESS THAN 0.001 INCH/SEC

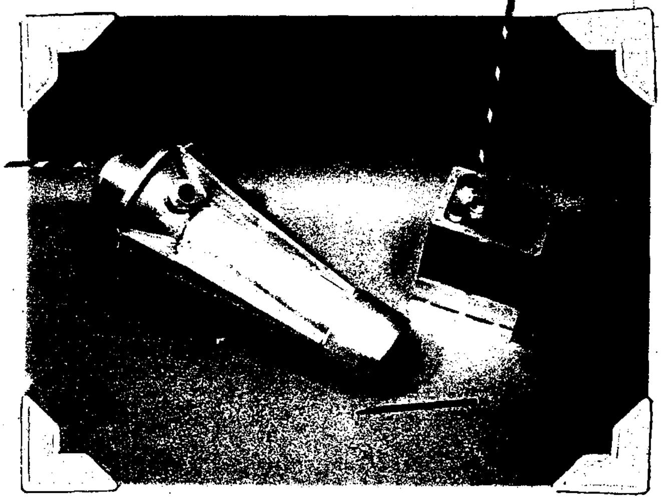
(N)

OPTICAL INPUT

MINIMUM ILLUMINATION:
0.005 FT-C

MINIMUM CONTRAST:
10%

SPATIAL FREQUENCY:
0.36 TO 36 LINE-PAIRS/INCH



SUMMARY OF FEATURES

- o CONTRAST..........enhanced via extended red cathode response and image slicing
- o SENSITIVITY.......optimized via S25 cathode efficiency and high electron transmission
- o SIGNAL/NOISE.....maximized via simultaneous use of full image format
- o LIFE..............extended via low fatigue cathode and all solid state circuitry
- o RELIABILITY.......insured via no hot filaments and no moving parts
- o LINEARITY, STABILITY.........improved via electronic feedback control
- o UTILIZATION.......extended via self adaptation of critical parameters
- o CONFIDENCE........enhanced via continuous self checking