TO: KSI/Scientific & Technical Information Division
Attn: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U.S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code KSI, the attached NASA-owned U.S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No.: 3,752,556

Government or Corporate Employee: U.S. Government

Supplementary Corporate Source (if applicable):

NASA Patent Case No.: N74-17153

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:

YES ☐ NO ☑

Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of column No. 1 of the Specification, following the words "...with respect to an invention of ...

Bonnie L. Woerner
Enclosure
REAL TIME MOVING SCENE
HOLOGRAPHIC CAMERA SYSTEM

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Field of Search 350/3.5; 352/44, 86; 352/84, 86

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ABSTRACT

A holographic motion picture camera system producing resolution of front surface detail. The system utilizes a beam of coherent light and means for dividing the beam into a reference beam for direct transmission to a conventional movie camera and two reflection signal beams for transmission to the movie camera by reflection from the front side of a moving scene. The system is arranged so that critical parts of the system are positioned on the foci of a pair of interrelated, mathematically derived ellipses. The camera has the theoretical capability of producing motion-picture holograms of projectiles moving at speeds as high as $9 \times 10^4$ cm/sec (about 21,450 mph).

3 Claims, 7 Drawing Figures
REAL TIME MOVING SCENE HOLOGRAPHIC CAMERA SYSTEM

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to holography and more particularly to an improved apparatus and method for producing holographic motion pictures having resolution of front surface detail.

2. Description of the Prior Art

Presently, there are several techniques for producing holograms. The general requirements for hologram production are that one uses a coherent beam of radiation as a source and a beam splitter to obtain two coherent beams, one referred to as the signal beam and the other the reference beam. The reference beam is generally allowed to pass directly to a photographic recording plate without any form of disturbance. The signal beam is made incident on the object under test, either by reflection of the signal beam from the test object, or by direct transmission of the signal beam through or by the test object. The test object being placed in the path of the signal beam, imposes a specific modulation on the signal beam. This modulated signal beam is then incident on a photographic plate along with the reference beam. At a given moment, the field pattern produced in the plane of the photographic plate (by the interference between the reference beam and the modulated signal beam) is essentially frozen by the photographic emulsion. This arrested field pattern is not a photograph in the usual sense since there is no image, but is simply a recorded interference or diffraction pattern. The developed photographic plate constitutes a reconstructable hologram. That is, if the developed hologram is placed in the path of the reference beam alone, the image of the object under test is reconstructed. The image of the test object appears authentically, in three dimensions and with parallax identical to the original test object.

Two types or methods for producing holograms in the past are the reflection method and direct method. The reflection method as the name implies, reflects the signal beam from the test object in a forward direction where it is then directed incident to the photographic plate. When a hologram taken by this method is reconstructed, the test object has excellent front surface resolution since it is front illuminated; however, this method has the disadvantage of extremely stringent requirements on the mechanical stability of the test object and the component parts of the holographic camera. In the direct method the signal beam is transmitted through or by the test object after having first passed through a diffuser plate positioned between the light source and the test object. The direct method has the advantage of partially relaxing the stringent requirements on mechanical stability of the test object but has the disadvantage of no resolution of detail of the front surface of the test object since the test object is only illuminated from the back.

Holography of moving scenes has motivated considerable interest and effort on the part of inventors, scientists and researchers working in this field. However, it has been found that any motion of the scene during the exposure of a hologram results in a spatial modulation of the recorded fringe contrast. On reconstruction, this produces a spatial amplitude modulation of the reconstructed wavefront, which results in a blurring of the image, not unlike that of a conventional photograph. For motion of the scene sufficient to change the path length of the signal arm, by approximately \( \lambda /2 \), this blurring is generally prohibitive (where \( \lambda \) is the wavelength of the radiation being used).

Moving scenes holography covered by previous interest and experimentation has included: microscopic particles, aerosol sprays, seeded gas flow and bullet type projectiles. The bullet or macroscopic projectiles have received considerable attention recently. A recent search of the literature by the inventors showed that the highest target velocity for which a hologram was successfully recorded, to date, was 375 meters/sec. No report of front light resolution of targets moving at high speeds was found however. This is certainly due in part to the severe \( \lambda /2 \) restriction on the change in path length of the signal arm of the holographic arrangement.

Prior art three dimensional motion holographic pictures have allowed animation of motion, that is, successive exposures with the scene being rotated or moved between exposures. The scene, however, was not allowed to be in motion during the exposure. Although simple back-lighted motion pictures have been obtained, resolution of front surface detail has never been obtained for high velocities. Some success has been found with very low velocities (a few centimeters per second) using a short pulse ruby laser. The present inventors know of no prior art applications of true real time holographic motion picture photography allowing resolution of front surface detail.

Accordingly it is an object of this invention to provide an improved holographic system.

Another object of this invention is to provide a real time holographic motion picture camera system allowing resolution of front surface detail.

Still another object of this invention is to provide a real time holographic motion picture camera system capable of photographing a projectile, vehicle or other object traveling at a very high rate of speed.

SUMMARY OF THE INVENTION

According to the present invention it has been found that a holographic motion picture camera system can be made to accomplish the aforementioned objectives by utilizing a coherent light source to produce a beam of radiation, splitting the said beam into a first direct signal beam and a reference beam, splitting a second direct signal beam from said reference beam, reflecting said reference beam into a motion picture camera back making said two direct signal beams incident upon a moving scene to be photographed so that both said direct signal beams produce front surface resolution of the moving scene and are then reflected into the said motion picture camera back. The invention is arranged so that certain functions take place at focal points located on the long axes of two interrelated ellipses arranged with their long axes normal to each other and with \( f_s \), the second focal point of both ellipse, coincid-
From the use of the backlighting arm (second signal beam 38), one is reasonably assured of a backlit hologram, i.e., a silhouette of the moving projectile 16, with this information one has more freedom to manipulate the ellipse 12, until one obtains front surface resolution of the silhouetted projectile 16.

The exact matching of the length of the three arms 28, 34 and 38 is of no real concern if one has a laser 26 with sufficient coherence length. The source 26 used by the present inventors has a coherence length greater than three meters, operates at 6943 Å and has a pulse length as short as 15 nanoseconds. The calculations which follow use a time of 35 nanoseconds, so the numerical values given in calculations below are conservative.

The following discussion relates to linear motion in terms of elliptic parameters. FIG. 2 shows a family of successive ellipses with constant separation of force. Consider FIG. 2a, the general equation of such an ellipse is given by:

\[ b^2 x^2 + a^2 y^2 = a^2 b^2 \]  

The line segment pp' is considered to be tangent to this ellipse at the point Q which lies on the perpendicular bisector of XX'. This line pp', in FIG. 2a, is identical to the tangent line pp' of FIG. 1. It is the "line of motion" of the high speed projectile; is parallel to the major axis XX', of the ellipse, and may be considered perfectly straight. The projectile travels along pp', of FIG. 2a, and reaches the point Q at some time \( t_0 \). The radiation incident at this point, at \( t_0 \), will be reflected to the film which is positioned at focus \( f_2 \). At this particular moment the ellipse passes through the point Q, with a beam splitter at \( f_1 \) and a film at \( f_2 \), and we have the situation depicted earlier, in FIG. 1.

As the projectile moves some incremental distance \( \Delta x \), along pp', past the point Q, it moves off this initial ellipse, but it can be considered to move immediately onto another ellipse, just slightly larger than the initial one. If the elliptic constant of the initial ellipse was \( 2a \), then the elliptic constant of this new ellipse will be \( 2(a+\Delta a) \). The radiation reflected or scattered from this moving projectile will then be incident on the film at \( f_2 \), and will interfere there, with the reference beam, as long as \( 2\Delta a \) is less than \( \frac{\lambda}{2} \).

In FIG. 2b, we construct a family of such ellipses, each successive ellipse being intercepted by the line segment PP', as one moves from Q toward the right along PP' parallel to the x axis of the coordinate system. We require that separation of the foci remain constant and equal to \( 2d \) for the entire family of curves. FIG. 2c is a convenient enlargement of the first quadrant of FIG. 2b. The points of interception of PP' with each successive member of the family of ellipses is given by \( P_1, P_2, P_3, \ldots \), respectively. We maintain that as PP' is traversed to the right, the original ellipse can be "grown" successively, to the next larger member of its family, while the foci separation distance \( 2d \), remains constant.

If we consider that the ellipse is to "enlarge" during the time \( t \), then expanding to a larger ellipse, equation (1) becomes:

\[ b^2 x^2 + b^2 y^2 + a^2 y^2 + a^2 x^2 = a^2 b^2 b^2 \]

\[ \Delta x^2 + \Delta y^2 + \Delta a^2 = a^2 \Delta b + b^2 \Delta a \]  

\[ (2) \]
Since the direction of projectile motion is parallel to the x axis, $\Delta y = 0$ and we have,
\[ b^2 x \Delta x = a \Delta a (b^2 - y^2) + b \Delta b (a^2 - x^2). \]

However, from FIG. 2a,
\[ a^2 - b^2 = a^2; \]
where $d$ is a constant, therefore
\[ a \Delta a = b \Delta b \]
and equation (3), becomes,
\[ b^2 x \Delta x = a \Delta a [a^2 - b^2 - (x^2 + y^2)]. \]

From the basic equation for our ellipse, equation (1),
we may easily obtain
\[ x^2 + y^2 = b^2 x^2 (1 - b^2/a^2) \]
By substitution of (5) into (4), we obtain,
\[ x \Delta x = a \Delta a / ab^2 \left( a^4 - d x^2 \right). \]

For any ellipse $2a = L$, where $L$ is a constant and at present is the optical path length of the front illumination signal arm. When the ellipse "expands" due to projectiles travel along $PP'$, then $2a = L$ changes by $2 \Delta a = \Delta L$. Therefore since $\Delta a = \Delta L/2$ equation (6) becomes,
\[ x \Delta x = (\Delta L/2) 1/ab^2 \left( a^4 - d x^2 \right). \]

Now since we have taken the point Q as the reference point for $x$, i.e., $x$ is zero when the projectile is at the point Q, therefore, as measurement of the projectile motion starts from the Point Q and traverses to some point P, $x = \Delta x$, and equation (7) becomes,
\[ (\Delta x)^2 = (\Delta L/2) 1/ab^2 \left( a^4 - d (\Delta x)^2 \right) \]
or
\[ (\Delta x)^2 = \frac{\Delta L \Delta a}{2ab^2} \]
Making the assumptions that the magnitude of $d$ is not drastically different $b^2$ and $\Delta L/2 \ll a$, we have that
\[ \Delta L \Delta a / 2ab^2 \ll a \]
and equation (9) becomes,
\[ (\Delta x)^2 = (\Delta L/2) a^4 / b^2 \]
where $\Delta L = 2a$ is the variation in the original elliptic constant $2a$, due to the travel $\Delta x$, of the projectile along $PP'$. At a given velocity, $V$, for a time $t$,
\[ V = \frac{(\Delta L)^{1/2} \Delta a}{2t} \]
This $V_{\text{min}}$ is the minimum permissible value of the velocity for each specific value of $d$. Because each curve has a zero slope at this point, the region about this point is the most stable region with regard to possible
changes in the value of the elliptic parameters $a$ or $b$. 
(Changes in $a$, and therefore $b$, will occur as the ellipse
“enlarges” due to projectile travel $\Delta x$, further changes
in $b$, and therefore $a$, might occur due to the projectile
varying slightly off path as it travels along the “line of
motion”).

Now consider FIG. 4, where we display an ellipse 50
with velocity vector $S_2$ of the scene 54 oriented along
the direction parallel to the x axis 56. Then from the
previous description of the properties of this elliptical
orientation we know that front surface detail will be re-
solved from our scene 54 by this particular elliptical orien-
tation so long as the velocity of the scene 54 stays
essentially parallel to the x axis. 56. And, of course,
does not travel further than scene distance $\Delta x$ given by
FIG. 3. Scene 54 must stay in the field of view, where
the field of view is governed by the size of the ellipse
used. Therefore the particular orientation of FIG. 4 will
resolve front surface detail from the scene 54 so long
as the velocity vector $S_2$ travels essentially parallel to
the x axis. (i.e. its component along x).

Now consider the following change to the device
shown in FIG. 4. Simply rotate the system of FIG. 4 by
90° about the point S and retain the same xy coordinate
system. Now let the scene 54 travel explicitly parallel to the
y axis (i.e. 90° to its travel in FIG. 4). In this case
our particular orientation will resolve front surface
detail from the scene so long as the velocity vector re-
mains essentially parallel to the y axis 58 (its compo-
nent along y).

From vector analysis however we know that any arbi-
trary vector $A$ is completely described (in 2 dimen-
sions) by its two components respectively in the two di-
rections i.e.

$$A = A_x + A_y = iA_x + jA_y$$

our velocity vector can be described by

$$V = V_x + V_y = iV_x + jV_y$$

Therefore if we properly combine the orientation of
FIG. 4 with that of the 90° rotation described above we
then have the arrangement shown in FIG. 5, which is
an illustrative embodiment of the present invention.

Consider the particular orientation called ellipse No. 1,
designated by numeral 60. Then from the above this
system will record front surface detail from the scene
88 for all scene motion having a velocity component 72
parallel to $x$ (61) or $x'$ (62). Further, ellipse No. 2 des-
ignated by numeral 63 will record front surface detail
from the scene 88 for all scene motion having a velocity
component 74 parallel to $y$ (64) or $y'$ (66). Since both
systems make the modulated signal beams 68 and 70
incident at $f_2$ they both will combine and interfere with
the common reference beam 86 at $f_2$ to form a holo-
gram of the total information content of the scene.
Since we have all the information of both components
$V_x$ (72) and $V_y$ (74) of the resultant velocity vector $V$
(76) we have all the information from the total velocity
vector of the scene available to us. Further, since we
have recorded this in moving frames on film located at
the back (78) of the motion picture camera 90 (syn-
hronized with the laser source) we have obtained mo-
tion pictures. Since we have arrested interference pat-
tterns we have retained the phase information; conse-
quently we have three dimension motion pictures of the
activity of the scene.

One cycle of operation of the embodiment of the in-
vention shown in FIG. 5 follows: Laser 80 produces a
beam 82 of coherent coherent Beam 82 strikes beam
splitter 84 where it is split into reference beam 86 and
signal beam 68. Signal beam 68 is incident upon scene
88 and reflected to the film located at back 78 of con-
ventional motion picture camera 90. Reference beam
86 strikes beam splitter 92 where signal beam 70 is re-
lected off to mirror 94. Signal beam 70 is scattered
from moving scene 88 and then incident on film, lo-
cated at back 78 of motion picture camera 90. Refer-
ence beam 86, after passing through beam splitter 92
is reflected by mirror 96 against film located at back 78
of motion picture camera 90. If desired, diffusers 98
and 100 may be added in the path of signal beams 68
and 70 respectively in a manner already known in the
art of holography.

In accordance with theory given before, foci $f_2$
of both ellipses 60 and 63 coincide at a single point. The
plane of the film (focal plane of the camera) located at
back 78 of motion picture camera 90 is positioned at
f2 so that it (the plane) is perpendicular to line $f1f2$ of
ellipse 60 and contains line $f1f2$ of ellipse 63. There-
fore, camera 90 records motion of scene 88 in a direc-
tional parallel to $x$ (61) and $x'$ (62), represented by
$V_x$ (72), and in a direction parallel to $y$ (64) and $y'$
(66), represented by $V_y$ (74), consequently in the
direction of $V$ (76), the resultant vector of $V_x$ (72) are
$V_y$ (74).

From the foregoing, it may be seen that applicants
have invented a holographic motion picture camera
which can produce three dimensional motion pictures
having resolution of front surface detail of moving
scenes. Moreover, the technique is capable of record-
ing resolution of front surface detail from a projectile
moving at very high velocities, depending upon the
pulse duration of the laser source, its power output and
the tolerance of the optical path difference. This inven-
tion allows three dimensional images of any scene
where one would naturally use a conventional two di-
mensional motion picture camera. The invention may
incorporate folded optics to make the system package
smaller. The length of the $x$ and $y$ dimensions are deter-
mined by the magnitude of the velocity of the scene
through consultation of the curves shown in FIG. 3.

The laser source for this invention is preferably a
high intensity argon type having 2-3 watts of continu-
ous power. An even higher intensity source would be
better, if it were available. If the laser source used in a
particular application is not of high enough intensity to
properly practice this invention, one may use the con-
cept of pre-biasing the film. Then the intensity avail-
able in the argon lines will be sufficient for multiple
type exposures commensurate with moving scenes.

Using the technique disclosed herein and a pulse
length of 35 nanoseconds, a projectile velocity of
$9 \times 10^6$ cm/sec would not cause an optical path dif-
ference of more than 1/8. This is well within the tolerance
necessary for producing good holograms. It should be
noted, however, that the resolution of front surface de-
tail obtained by this invention is not due solely to the
"stop action" of the pulse length of the laser pulse. This
is obvious from the fact that for a pulse length of 50
nanoseconds, a velocity as low as 694.4 cm/sec would
cause a phase shift of 1/2 which borders on prohibiting
the recording of a hologram.
It is necessary in practicing this invention to use a specific orientation of the holographic system, as described in detail above. With this specific orientation, the path of the reflection arm is constrained to change by an amount equal to \( \lambda/8 \), an arbitrary figure well within the \( \lambda/2 \) limitation. Thus resolution of front surface detail can be obtained, although this was heretofore unobtainable for moving targets, by previously known methods.

I claim:

1. An apparatus for producing holographic motion pictures of a moving scene, said moving scene having a velocity of motion represented by \( X \) and \( Y \) velocity components, comprising:
   a light source for producing a coherent beam of radiation;
   first beam splitter means positioned to receive said coherent beam and to split said coherent beam into a first signal beam which passes straight through said first beam splitter means and becomes incident upon said moving scene and into a reference beam which is reflected;
   second beam splitter means positioned to receive said reflected reference beam and to split a second signal beam from said reference beam, whereby said reference beam passes straight through said second beam splitter means and said second signal beam is reflected;
   a first light reflector means positioned to reflect said reference beam, after said reference beam passes through said second beam splitter means;
   a second light reflector means positioned to reflect said second signal beam so that it becomes incident upon said moving scene, after said second signal beam is split from said reference beam by said second beam splitter means;
   a motion picture camera back, said camera back having a film mounted on it, said film being positioned to receive said reference beam after reflection from said first light reflector means and said first and second signal beams after they are reflected from said moving scene, whereby said reference beam and said first and second signal beams all interfere with one another in the plane of said film; said first beam splitter means being positioned at the first focus of a first ellipse, and said second light reflector means being positioned at the first focus of a second ellipse, the said two ellipses being interrelated by having their long axes perpendicular to each other and their second foci coinciding, said two ellipses being oriented so that said \( X \) velocity component of said moving scene is tangent to said first ellipse, said \( Y \) velocity component of said moving scene is tangent to said second ellipse and said long axes of said two ellipses are respectively parallel to said \( X \) and \( Y \) velocity components, the plane of said film being positioned so as to pass through the said coinciding second foci of the said two ellipses, said moving scene being positioned on the circumference of each of said ellipses in the vicinity of the intersection of the circumference of each said ellipse with its own semi minor axis, the size and shape of each of said two ellipses and the location of their said foci being determined by the formula \( Vt = (\Delta L/2) \), where \( V \) is the velocity component; \( t \) is the time of exposure \( L \) is the optical path length of said first signal beam and is equal to the ellipse constant, \( 2a \), \( \Delta L \) is the maximum change in length \( L \) caused by the component of scene travel which is tolerable without causing blurring; \( a \) is the semi major axis; \( b \) is the semi minor axis; \( d \) is the distance of separation between a focus and the origin of the ellipse; and \( a \) and \( b \) are related to the third ellipse parameter \( d \) by the formula \( a^2 = b^2 + d^2 \).

2. The apparatus for producing holographic motion pictures of claim 1 including a first diffuser in the path of said first direct signal beam between said first beam splitter means and said moving scene.

3. The apparatus for producing holographic motion pictures of claim 2 including a second diffuser in the path of said second direct signal beam between said second light reflector means and said moving scene.