LONDON, METEOROLOGICAL OFFICE.

Met.O.15 Internal Report No.61.

An introduction and guide to the Met O 15 hologram reconstruction and analysis system.
By BROWN, P.R.A.

London, Met.Off., Met.O.15 Intern.Rep.No.61, 1985, 31cm. Pp.34, 14 pls.2 Refs.

An unofficial document - not to be quoted in print.

METEOROLOGICAL OFFICE
London Road, Bracknell, Berks.

MET.O.15 INTERNAL REPORT

No. 61

An Introduction and Guide to the
Met O 15 Hologram Reconstruction
and Analysis System

by

Philip R. A. Brown

September 1985

Cloud Physics Branch (Met.O.15)

1. Introduction

Experience with the old manual hologram reconstruction system (Ref. 1) showed that the extraction of significant amounts of data from a hologram was a laborious and time-consuming task which severely limited the usefulness of the aircraft holography system as a means of obtaining cloud particle data. This was due to the large number of tasks which had to be performed by the operator. These included the movement of the hologram on an optical bench to bring images into focus, the adjustment of two micrometers to move an image to the centre of the monitor screen, recording the x, y, z position of the hologram together with the image size as determined by a caliper or graticule, and the transcription of this data into a form suitable for processing on COSMOS. The system was prone to the introduction of errors at almost every stage and it was impossible to obtain any statistical information such as size spectra or spatial distributions in real time. Attempts to develop a fully-automatic analysis system using the Quantimet image-analysing computer at CDE Porton Down proved unsuccessful, largely due to the difficulty of developing an algorithm which could recognise images reliably in all variations of brightness, contrast, and background noise. The present system was therefore conceived to automate as many functions of the manual analysis procedure as possible whilst retaining an operator to recognise the characteristic converging fringe pattern of images as they approach focus, a feature which could not be utilised by the Quantimet.

The new system uses the same optical layout as before, with the hologram mounted on an optical bench between a CW laser and a TV camera and being moved so as to form real images directly on the face of the camera tube. However, the hologram is now carried on a twin-axis motorized micropositioning system which is controlled via a desktop microcomputer. Focussed images are sized using a computer-generated cursor superimposed on the TV monitor. The computer can then calculate and display the true size and position of the image and record this data on a floppy disc.

Most of the hologram movement functions are performed fully-automatically by the computer and the hologram can thus be moved in a systematic manner to ensure the thorough analysis of a particular sub-volume contained within the total sample volume that can be reconstructed from the hologram. The limits of this sub-volume may be predefined at the start of analysis of the hologram. This method ensures that particle images lying in certain regions of the hologram do not escape analysis. The rapid access to image data recorded on floppy disc means that images can be checked against those already analysed to prevent double-counting.

The microcomputer has sufficient power to be able to process the recorded data at the end of an analysis session. Size spectra and spatial distributions may be produced in graphical form on the monitor or on a printer. This information may be useful to the operator in deciding the course of further analysis of the hologram.

The main benefits of the new system are a significant decrease in operator workload and a useful increase in the overall speed with which data can be obtained from a particular hologram. This makes the analysis of large numbers of holograms a realistic proposition.

The remainder of this report describes in detail the main features and mode of operation of the new hologram reconstruction and analysis system, and gives detailed instructions for its use. In addition, it gives some information about its performance in different cloud particle distributions which may be of use to potential users of the system. Ref. 1 describes the equipment and techniques used for recording holograms on board the Hercules aircraft.

2. Principles of hologram reconstruction

The aim of this section is not to give an exhaustive account of the processes of hologram formation and reconstruction, which may be found for example in Ref. 2. It is rather to provide some details which are necessary to explain features of the new analysis system.

2.1 Hologram formation

Hologram formation on the aircraft is by the so-called 'in-line' method (see Fig 1). The film records the interference pattern formed by light scattered by small objects and the remaining unscattered part of the incident beam. It may be shown that for a point scatterer lying on the optical axis this pattern consists of a set of concentric circular fringes with a sinusoidal modulation. This fringe pattern has optical properties analogous to those of a thin lens which simultaneously both converges and diverges incident light. The equivalent focal length of the system is given by

$$\frac{1}{f_o} = \frac{1}{v_o} - \frac{1}{u_o} \qquad (2.1)$$

where u_o and v_o are the source-film and object-film distances respectively (see Fig. 1).

2.2 Hologram reconstruction

When the fringe pattern recorded on film is re-illuminated it produces two images. One of these is a virtual image formed on the source side of the hologram. The other is a real image, which in this application is formed directly on a TV camera tube (see Fig 2). The position of this image may be determined from the lens formula

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \qquad (2.2)$$

where u is the source-hologram distance and u the hologram-image plane distance. The equivalent focal length f, of the fringe pattern during reconstruction differs from that at the formation stage, due to the use of lasers of different wavelengths. The focal lengths are however related by

$$\lambda f = \lambda_o f_o \qquad (2.3)$$

where λ_o is the formation wavelength (532.0 nm) and λ the reconstruction wavelength (632.8 nm).

Equations 2.1 to 2.3 can be used to determine the object-film distance v_o when a reconstructed image is in focus at distance u from the source.

$$v_o = \left[\frac{1}{u_o} + \frac{\lambda_o}{\lambda} \cdot \frac{d}{(d-u)} \right]^{-1} \qquad (2.4)$$

where d is the total distance from source to image plane. Alternatively, expressing u in terms of u_o,

$$u = \left(\frac{d \pm (d^2 - 4 \frac{\lambda_o}{\lambda} . du_o v_o)/(u_o - v_o)}{2} \right)^{1/2} \qquad (2.5)$$

There are thus two positions on the optical bench where the hologram can be placed to form an image of a particular object in the plane of the TV camera. These positions are symmetrical about the mid-point of the reconstruction optical system (see Fig 3). Fig. 3 also shows that v_o has a maximum value at u = d/2, this value being referred to as the 'reconstruction limit'. It represents the greatest object-film distance which still allows focussed images to be reconstructed. With the current values of u_o (142.0 cm) and d (160.7 cm) the reconstruction limit is 35.8 cm.

The lower limits on v_o are determined in practice by the available range of movement on the z-axis of the reconstruction system. The motor system currently gives a useable range of travel of 130 cm, but this is not arranged centrally on the optical bench. The lower limits on v_o are therefore 12.5 cm with the hologram at the low limit of u and 16.8 cm at the high-u limit. It is worth noting that the outer surface of the minipod is at v_o = 12.3 cm, and it is therefore impossible to move the hologram to a position where it is imaging a region inside the minipod.

It may also be shown that as a result of using diverging beams during the hologram formation and reconstruction processes the image produced at the TV camera is magnified. The total magnification may be expressed in the form

$$m_t = m_o m_r \tag{2.6}$$

where m_o and m_r are the separate magnifications due to the formation and reconstruction processes respectively, and are given by

$$m_o = \frac{u_o}{u_o - v_o} \tag{2.7}$$

$$m_r = \frac{d}{u} \tag{2.8}$$

The variation of m_t with u is shown in Fig. 3. It may be seen that the two different positions in which the image of a particular object may be brought to focus have different total magnifications. The region of the optical bench with $u < d/2$ is therefore referred to as 'high magnification' and that with $u > d/2$ as 'low magnification'. It may be seen that m_t varies rapidly with u in the high magnification region, and it is thus important to determine the image focus position accurately in order to obtain an accurate measure of the particle size.

2.3 Calculation of sample volumes

Fig. 4 shows an element of thickness δv_o at position v_o during the formation stage. The volume of this element is

$$\Delta V = \frac{\Delta x}{m_o} \times \frac{\Delta y}{m_o} \times \delta v_o \tag{2.9}$$

where Δx and Δy are the x and y dimensions of the area of hologram subsequently analysed. The total sample volume that can be reconstructed between given limits on v_o is therefore given by

$$V = \int_{vo_{min}}^{vo_{max}} \Delta x \Delta y . \left(\frac{u_o - v_o}{u_o}\right)^2 . dv_o \tag{2.10}$$

Evaluation of this expression with $\Delta x = \Delta y \sim 5$ cm, $vo_{min} = 12.3$ cm and $vo_{max} = 35.8$ cm gives a total sample volume for a single hologram of about 400 cm^3.

3. System Description

3.1 System components and their operation

Fig. 5 shows the components of the optical bench, the layout of which is exactly the same as for the old manual hologram reconstruction system. A Helium-Neon CW laser is used to produce real images of particles. The hologram is moved on the optical bench to a position where these images are formed directly on the tube of a TV camera. The output from the TV camera is displayed on a monitor so that an operator is able to judge when an image is exactly in focus.

Movement of the hologram in the x and z-axes is now performed by motorized micropositioning equipment. This gives a total range of travel of 130 cm on the z-axis (parallel to the optical axis) and 6 cm on the x-axis, and is driven by means of stepper motors giving a resolution of 5 µm per step. The motors are controlled by a programmable interface unit which receives commands and data from a microcomputer, and which can also relay information on the position and status of each axis back to the computer. The interface unit can be operated in two different modes:

i) 'RUN'. An axis is driven at a constant speed until a stop command is received.

ii) 'INDEX'. An axis is moved by a fixed number of steps (the 'index length') after which it stops automatically.

The speed, index length and direction of axis movements may all be specified by appropriate command sequences.

The composite video signal generated by the computer is merged with that from the TV camera. The monitor can thus display axis positions, speeds, index lengths and other information superimposed on the camera output. In addition, it enables a computer-generated circular cursor to be superimposed on a particle image once it has been focussed. The size and position of this cursor on the screen are controlled by means of three potentiometers connected to the analogue input port of the computer. When the cursor has been correctly positioned, the true size and position of the object particle may be calculated, knowing the size and position of the image on the screen and the position of the hologram on the optical bench (which is used to calculate the magnification factors according to Eqs. 2.7 and 2.8). This data is then stored on a floppy disc.

Each motor axis is fitted with a pair of limit switches. These are Hall-effect proximity switches at the +x and +z limits, and infra-red optical switches at the -x and -z limits. Operation of any of these switches causes the computer to send a command to the interface which will stop any axis in motion, thereby preventing them reaching the physical limits to their travel and possibly causing damage to the leadscrews. In the event of a software error or computer failure there are also mechanically-operated microswithces which stop an axis in motion by disconnecting the 24V power supply to the stepper motors. In this case, the axis which has overrun must be wound back by hand.

The limit switches are also used to provide a position datum for each axis. They have a best resolution of about 25 μm between on and off positions. Movement of the hologram onto the datum positions is controlled automatically and is performed at the start of every hologram analysis session, and at any other time as requested by the operator.

Movement of the hologram in the y-axis is still performed by a manually-adjusted micropositioner, however it is no longer necessary to adjust this for every particle image. Instead the operator has merely to ensure that it is correctly set to a position which is calculated and displayed by the computer. This adjustment is only required infrequently and thus does not involve much operator effort.

3.2 Software control of hologram position

A major advantage of this system over the old manual reconstruction system is that the microcomputer is able to keep track of the position of the hologram, and thereby to control its movement to produce systematic scanning of a pre-defined subvolume contained within the total reconstructable sample volume. This considerably reduces the chances of the operator failing to observe particular images or counting others twice.

3.2.1 Scanning along the z-axis

At the start of analysis of a hologram the operator may specify upper and lower limits on the z-axis, between which the hologram will be examined. These limits are specified in terms of distance from the surface of the minipod during the hologram formation stage, but are stored by the computer as position limits on the z-axis of the optical bench. A single translation of the hologram between these limits with the x- and y-positions held constant is refered to as a 'scan'. As the hologram is moved away from its low-z limit then the reconstruction magnification will decrease (Eq. 2.8). The monitor will therefore display the image generated from an increasing area of the hologram (see Fig 6). To counter this the computer is used to draw a box on the monitor screen such that the box fills the whole screen area when the hologram is at the low-z limit. When the hologram is moved away from this limit the size of the box is decreased in proportion to the decreasing reconstruction magnification, and thus the screen area defined by the box always corresponds to a fixed area element of the hologram.

If at the end of a scan the x-axis position is incremented by Δx, the width of this element, then the volumes mapped out by sucessive scans will adjoin each other. A series of contiguous scan volumes may be built up by moving the hologram between pre-defined x-axis limits thus forming a 'slice'. On completion of a slice the y-axis position is incremented by Δy, the height of the basic area element and the hologram returned to the lower limit positions on the x- and z-axes. Starting from a lower limit position on the y-axis, a series of adjoining slices can therefore be scanned until the operator decides that a sufficiently large sample volume has been accumulated. The subvolume thus analysed is referred to as a 'zone' (see Fig 7).

3.2.2 Automatic-scanning mode

When the system is in automatic-scanning mode the x,y,z position of the hologram is saved by the computer on completion of each movement of the hologram on the z-axis. Before initiation of a further z-axis move the system first checks to ensure that the hologram is still in this saved position. If it is then the new move will be initiated immediately, otherwise the hologram will first be restored to the saved position. Auto-scanning may be de-selected at any time during the analysis session. In this case, the hologram position is not saved after moves on the z-axis and the saved position remains with the values at the end of the last move made in auto-scanning mode. In addition the hologram may be moved beyond the limits set for the current analysis zone. By de-selecting auto-scanning the operator can thus examine images 'out-of-sequence'. When auto-scanning is re-selected the hologram will be returned to the correct position to resume systematic scanning of the hologram.

3.2.3 x- and y-axis movement of the hologram in auto-scanning mode

When the hologram has been moved to its limit position on the z-axis, in other words a single scan has been completed, the hologram x-axis position is automatically incremented by the correct amount to move it to the next adjoining scan position. Similarly, when the hologram reaches its upper limit position on the x-axis and a slice has been completed then the y-axis micrometer setting will be calculated and displayed. The operator must ensure that this value is correctly set before scanning can be resumed. In auto-scanning mode therefore, all movements of the hologram on the x- and y-axes are under the control of the computer. This ensures that the hologram is scanned in a systematic manner, thereby reducing the chances of the operator failing to observe images which lie within the pre-defined sample volume. There may however be occasions when the operator wishes to make small adjustments to the x- or y-position of the hologram, for example to move a large image so that it is completely in view on the screen. These adjustments may be made using the x-axis motion commands or by using a separate facility for entering a temporary value of the y-micrometer setting. In either case the resultant hologram positions are not saved by the automatic scanning facility. At the start of the next z-axis move, the hologram will first be restored to its saved position, if necessary by the operator resetting the y-axis micrometer.

3.2.4 Choice of high or low magnification

An analysis zone is defined by limits on the z-axis in the hologram formation coordinate system (ie. on the z-axis position of object particles relative to the minipod surface at hologram formation time), and by a defined area of the hologram. However Eq 2.5 shows that for a given object particle position there are two positions on the optical bench where in-focus images will be produced and these have different overall magnifications. The operator may choose to analyse particle images in either the high or low magnification regions. However the increments to be applied to the x and y axes by the auto-scanning facility depend on the reconstruction magnification and hence on which of the two regions is being used (see Fig 6). This choice is therefore made at the start of analysis of a particular hologram and all analysis zones will have their z-axis limits converted to lie within the selected region.

3.3 Sizing and Classification of focussed images

3.3.1 The classification scheme.

A facility is provided to enable the operator to develop a subjective classification of a focussed particle image which specifies a number of different attributes of the image. The facility operates via a series of selection panels which are displayed on the monitor screen. Fig 8 shows the operation of the facility in terms of a flowchart. The result of the classification is a 4-digit decimal integer (IP%) the meaning of which is summarised below.

1st digit (least significant) indicates ice crystal type.

1. Needle
2. Column
3. Plate
4. Stellar crystal
8. Graupel
9. Unidentified

2nd digit indicates the regularity of the image

- 0 A regular crystal of types 1-4.
- 1 An irregularly-shaped particle.
- 9 An unidentifiable image.

3rd digit has the value 1 to 9, indicating the estimated mass of the particle which exists as accreted rime, in tens of percent.

4th digit indicates the phase of the particle.

- 0 Water droplet
- 1 Single ice crystal
- 2 Aggregate or graupel.

Some examples of this will now be given.

IP% = 1004 indicates a single unrimed stellar crystal.

IP% = 1019 indicates a single ice particle of irregular shape, which may be a fragment.

IP% = 1099 indicates a single particle which cannot be clearly identified as water or ice.

IP% = 2019 indicates an aggregate in which the basic crystal type cannot be identified.

IP% = 2212 indicates an aggregate of columns which is 20% by mass of rime.

In this classification scheme, water droplets will always be coded with IP% = 0, and graupel particles with IP% = 2918.

3.3.2 Sizing of particle images

The particle sizing routine uses the computer graphics facilities to draw a circular cursor on the monitor screen. The radius and x,y position of the cursor may be adjusted using the three potentiometers on the control unit which are connected to the computer analogue interface. The cursor may thus be moved so that it overlays a focussed image, with the diameter of the cursor measuring a representative dimension. For water droplets the cursor will normally be adjusted to circumscribe the image and thus measure its radius, whilst for ice crystals it will be adjusted to span the maximum linear dimension of the image. There is at present no facility for recording more than one linear dimension of a particular image, although such a facility could be introduced with relative simplicity if required. When the cursor has been satisfactorily positioned, the true size and position of the object particle are calculated by the computer using the known position of the hologram on the optical bench and the size and position of the cursor. The true radius and z-coordinate together with the particle type indicator IP% are displayed on the monitor.

3.3.3 Recording particle image data

Particle image data may only be recorded when the system is operating in the automatic scanning mode. This eliminates the possibility of double-counting that might exist if images were being examined out of the sequence imposed by automatic scanning. As a further guard against double-counting, the data recording routine compares the position of the displayed image with the positions of all images recorded during the current and immediately preceding analysis slices. If no coincidences are detected, the true size and position of the displayed image, the particle type indicator IP%, and the x,y,z position of the hologram on the optical bench are all recorded on the floppy-disc unit. If however the particle position is found to coincide with that of an image already recorded then a warning message is displayed. The operator may then choose whether or not to record the new image. The main situation in which double-counting is likely to occur with the automatic-scanning facility in use is when an image lies on or close to the boundary of the scan box eg images P1 and P2 in Fig. 9. An image in either of these positions will appear in view on two successive scans or slices. Since the automatic-scanning facility always moves the hologram in the positive x- and y-directions, it is only necessary for the double-count prevention routine to examine the current and immediately preceding slices for possible coincidences (see Fig 9). The format of the disc file holding the recorded image data is described fully in Appendix A.

3.4 The analysis of recorded image data

The BBC Model B microcomputer has sufficient computing power to be able to process the recorded image data to calculate bulk quantities such as ice- or liquid-water contents and statistical information such as size spectra. The main limitation to its use for such processing is that its high-resolution graphics mode severely restricts the amount of memory available to hold programs and data. However the relatively rapid access time for both programs and data stored on floppy disc means that it is quite feasible to write the data processing programs in several parts, each of which may be loaded and run separately, and which use the disc as a temporary storage medium for passing data between programs. Although this restricts the overall speed of the program it avoids the necessity of transcribing hologram data, for example for processing on COSMOS.

4. The System in Operation

The aim of this section is to give some information on the capabilities of the new hologram reconstruction and analysis system, for example the speed at which data can be obtained and the accuracy of the data. This will be of assistance to users in planning a strategy for the analysis of holograms from a particular flight.

4.1 Achievable rates of analysis

The rate at which particle images can be analysed is dependent on three main factors:

i) the number density of particles within the sample volume,

ii) the speed used for translation of the hologram along the z-axis,

iii) the magnification region in which analysis is taking place.

When the number density of particles is high and the hologram has only to be moved a short distance between successive images, then the main limitation on the image analysis rate is the time spent on moving the sizing cursor over the focussed image. After a certain amount of practice, with the system in its current configuration it is possible to analyse about 30-40 images per hour in high magnification when the number density is greater than about 25 cm^{-3}. This is significantly better than could be achieved using the old manual reconstruction techniques.

When the number density falls below about 5 cm^{-3}, the main limitation on the analysis rate becomes the speed with which the hologram can be translated between successive focus positions. If too high a speed is used there is a possibility that the operator may fail to observe certain images, particularly those of small cloud droplets which pop in and out of focus very rapidly. In practice a speed of 1500 steps/sec has been found most suitable for the region close to the minipod surface, particularly when the hologram is noisy or the images faint. This may be increased to

3000 or 4000 steps/sec as the hologram is moved to reconstruct regions further from the minipod. In the high magnification region it is generally possible to achieve a volume scanning rate of about 1 cm^3 per hour, thus giving an image analysis rate of about 5 to 10 per hour in a hologram from a cloud with low number density.

By scanning in the low-magnification region, the volume scanning rate can be increased to about 50-100 cm^3 per hour. This represents a large fraction of the total sample volume of about 400 cm^3. Low magnification scanning is therefore particularly suited to the analysis of holograms containing images of particles with radius ≧ 30 μm in concentrations ≧ 0.1 cm^{-3} (100 l^{-1}).

4.2 Particle size errors

4.2.1 Screen cursor resolution

Because of the relatively limited memory of the microcomputer and the large size of the controlling program, the graphics screen on which the cursor is drawn has a resolution of 320 x 256 pixels. The cursor radius is varied between 0 and 127 pixels with a resolution of 1 pixel. The true radius resolution will vary with the total magnification and hence with the position of the hologram on the z-axis. Fig 10 shows the true radius resolution as a function of particle distance from the minipod surface for both high and low magnification regions. Two points are worth noting:

i) for the high magnification region and particles 5-10 cm from the minipod, likely size errors due to the resolution of the screen cursor are about ± 1.5 μm or about the same as for the FSSP on Range 0. It is likely that most analysis of small droplets will be done in this region.

ii) for analysis in the low magnification region size errors due to this cause will be about 20% for r = 30 μm (about the smallest size for which analysis is practical) falling below 10% for r ≧ 80 μm.

It should be stressed that these errors represent a case in which the cursor can be fitted to the image with an accuracy of ± 1 pixel. Whilst this may be achieved for good quality images, poorer ones may remain fuzzy even in the optimum focus position and the achievable accuracy will be worse than this. In such cases the accuracy of particle sizing depends to a considerable extent on the judgement of the operator as to what constitutes the image boundary. Users should bear in mind that the image quality may vary noticeably over a single hologram, due mainly to the non-uniform intensity cross-section of the aircraft laser. It is generally worth spending some time on a brief examination of images from different parts of the hologram in order to determine the most suitable area for analysis.

4.2.2 Focussing resolution

The degree of precision with which particle images can be focussed depends on both the total magnification and overall quality of the image. The error in particle radius due to errors in determining the focus position of an image is shown in Fig. 11. Reasonably bright images in the high magnification region can generally be focussed with a precision of 20-50 steps (0.01 - 0.025 cm). Thus the error in the calculated radius of the particle is generally better than 0.1% except for particles lying close to the minipod surface. In the low magnification region the focussing precision is generally about 250 - 500 steps (0.125 - 0.25 cm) which gives a radius error of about 0.3% or better. In both cases the radius errors are much less than those due to the limited resolution of the screen cursor.

4.3 Particle counting errors

The system controlling software has been designed so as to reduce the possibility of double-counting of particle images. There remain however some circumstances in which the operator might fail to observe and record genuine images.

4.3.1 Small particles

Particles with a radius of around 10 µm or less become increasingly difficult to identify at both the high and low magnification extremes. In the low magnification limit, the size of the focussed image of such particles on the monitor screen falls below 1 mm and the operator may simply fail to see such small images. Towards the high magnification limit the chracteristic dimensions of the background noise in the holographic image is also increased. This makes it more difficult to observe the distinctive circular fringe pattern produced by an image as the hologram is moved close to its focus position. The problem is particularly acute in regions of the hologram which are insufficiently dense, as the background noise level is then relatively high. For these reasons analysis of cloud droplets is best performed in the region between 5 and 15 cm from the minipod, in the high magnification region of the optical bench. Images are then sufficiently large on the screen to be sized with reasonable accuracy, and relatively easier to distinguish from background noise.

4.3.2 Particles situated close to zone boundaries

Particles which lie close to the z-axis limits will come into focus just as the hologram is brought to a halt by the automatic scanning facility. In such cases the operator may be in some doubt as to whether the image lies within the current analysis zone or not. He should however always attempt to record the image data as the recording routine itself will reject any image that lies outside the zone limits, and there is thus no possibility of erroneously including images from outside the current zone.

5. Instructions for the Operation of the System

This section is intended to provide a practical guide to the operation of the system. Topics will be presented as far as possible in the order in which they would be encountered in the course of an analysis session.

5.1 Switching on the equipment

Two circuit-breakers mounted on the wall by the lab door and over the optical bench must first be switched on. The various components of the system (computer, disc-drive, monitor, printer, DIGIPLAN electronics box, TV camera and He-Ne laser) may then be switched on in any order. It should be noted that the computer power supply is also used for the datum sensor system. This has four LED indicators mounted on the right-hand panel of the DIGIPLAN electronics box, all of which should be illuminated when the computer is switched on. If for any reason one of the indicators is not lit then there may be a fault with the system and further advice should be sought.

5.2 Data and program discs

In its current form, two floppy discs are needed to run the system. The first, labelled "HOL-3.2-USER" contains all the necessary programs including some to perform simple analyses of the recorded data. This disc is loaded into DRIVE 0 or the right-hand one of the pair. Recorded data from the hologram are held on a separate disc. In normal use the file containing image data will be extended in the course of an analysis session as further images are recorded. There must therefore be sufficient free space on the disck to allow this extension to take place. This is most easily achieved if separate data discs are kept for each hologram currently undergoing analysis. Several data files from completed holograms may be archived on a single disc at a later stage. The appropriate data disc for the hologram to be analysed, or in the case of a new hologram a blank disc, should be loaded in DRIVE 1.

5.3 The Main Menu

The main menu may be entered by pressing and releasing the "BREAK" key on the computer with the 'SHIFT' key held down. It presents four choices:

A. Continue analysis of a hologram.

B. Begin analysis of a new hologram.

C. Copy a data file to back-up disc.

D. Perform analysis of recorded data.

The required choice may be selected by pressing the appropriate key. In each case the system will prompt the operator to ensure that a data disc is loaded in DRIVE 1.

5.4 Beginning analysis of a new hologram

From option 'B' in the main menu the system will check the disc in DRIVE 1 to ensure that it is blank. If it is not then the operator must exchange it for a blank disc before being able to continue. The following five tasks will then be presented in order.

i) Enter the flight number, 'Hnnn'
and frame number, 'mmm'
of the hologram to be analysed. The data file created will have the filename "Hnnnmmm" and directory letter "D".

ii) Set system parameters. A menu is presented which allows the operator to alter the default values of five basic parameters of both the hologram formation and reconstruction systems, these being Uo, the recording length; d, the reconstruction length; the x/y position of the hologram centre; and the distance from the spatial filter to the z-axis datum on the optical bench. For a normal aircraft hologram there will be no need to alter the default values, therefore select option 'F'.

iii) Select the magnification region in which analysis of the hologram is to be performed. This is necessary for the operation of the automatic scanning facility and the choice depends on the particle size range of interest. Select 'H' or 'L' as appropriate.

iv) Select the limit positions for the x, y and z-axes to define the first analysis zone. Appropriate default values are supplied in a menu, and may be altered within an allowable range as required. If a value is entered which falls outside this range then it will automatically revert to the default. For more information on the definition of analysis zones, see section 3.2.1. Exit from this routine is not possible until $x_{max} > x_{min}$.

v) Ensure that the y-axis micrometer is correctly set to the value which will then be displayed on the screen. This value will be the y-axis minimum position as entered in the previous section. It should be noted that all axis positions are held by the computer in centimetres, but the y-axis setting is displayed and entered in millimetres for ease of comparison with the actual scale markings.

5.5 Continuing analysis of a hologram

Selecting option 'A' from the main menu will display the flight number and frame number of the data file on DRIVE 1 with a message to ensure that these are correct. If they do not correspond to those of the hologram mounted on the bench then reply 'N' and insert the correct disc. If they are correct then reply 'Y'. The system will then read the values of the system parameters and zone limits which are held on the data file and prompt the operator to ensure that the y-axis micrometer is correctly set to the value displayed on the screen. This will be the last value set on the micrometer during the previous analysis session for this hologram.

5.6 Initializing the x- and z-axis positions

Once the micrometer position has been correctly set, the system will perform an automatic routine to move the hologram to the correct starting position for analysis. The hologram is first moved to its datum position on the x- and z-axes and then either to (x_{min}, z_{min}) if starting a new zone, or to the saved positions (x_{sav}, z_{sav}) from a previous analysis session. The motion system will then be set in 'RUN' mode, with automatic scanning on, and the speed set to 100 steps/sec.

5.7 The Auxiliary Keyboard

A 16-key auxiliary keyboard has been connected to the computer via the BEEBEX expansion interface. This provides a compact means of entering the single-key commands which operate the major functions of the hologram analysis system. The keyboard has been programmed to emulate the 16 user-defined function keys of the computer. The layout of the keyboard is shown in Fig 12, and a description of the key commands will now be given.

i) 'Y, N, 1, 2, 3, 4'. These are used to respond to the various choices which may be made during either movement of the hologram or the sizing and classification routine.

ii) 'G'. Display a menu of alternatives for moving the hologram to defined positions on the x- and z-axes. The options available are:

1. Move to the last (x,z) saved position
2. HILO go to opposite magnification.
3. Any specified (x,z) position.
4. Alter y-micrometer setting.
5. Go to datum position.

Option 2 may be used to move the hologram from an image focus position in one magnification zone to the focus position in the other zone. This might be used to examine images which are larger than the screen size in high magnification or examine smaller particles in more detail than can be obtained in low magnification. If option 3 is selected, the desired x- and z-axis positions must be input from the main keyboard. If it is wished to move only the z-axis then simply press 'RETURN' when the x-axis position is requested, and vice versa. Option 4 also requires a temporary setting of the y-micrometer to be entered from the main keyboard, and might be used to move an image which is only partly visible on the monitor. Moves of the hologram using any of these options are not made in automatic scanning mode.

iii) 'P'. Enter the particle sizing and classification routine (see sections 3.3 and 5).

iv) 'A' Selects auto-scanning mode on or off.

'R' Selects RUN or INDEX mode for axis moves.

Both of these keys operate by changing to the alternative state from whatever is currently selected.

v) 'I' Increase the current speed setting.

'D' Decrease the curent index length setting.

Both speed and index length may be selected from a range of 7 different values which are currently:

SPEED (steps/sec) = 100, 500, 1000, 1500, 2000, 3000, 4000
INDEX LENGTH (steps) = 20, 50, 100, 500, 1000, 2000 or a variable value.

The desired value may be selected by pressing the appropriate key to move through the list until it is displayed on the monitor. In normal operation it is likely that one particular speed will be found most suitable for 'RUN' moves in the current analysis zone. This speed will be selected at the start of analysis of the zone and will only be altered infrequently. The index length will normally be decreased from high to low values as INDEX moves are made to bring an image into focus, and successively smaller movements are required. The variable value of the index length is used to hold the value required for various pre-defined INDEX moves, e.g. moving from high to low magnification or incrementing the x-axis position at the end of a scan on the z-axis.

vi) 'X' and 'W'. These are used to initiate INDEX moves on the x-axis, in the positive-x direction (X) or negative-x direction (W).

vii) '+' and '-'. These are used to initiate moves on the z-axis in the positive or negative-z directions respectively. The move will be made in the currently selected mode (RUN or INDEX). In RUN mode, the axis will remain in motion as long as the key remains depressed.

5.7 The standard screen display during hologram motion

The layout of the screen display when the system is being used for movement of the hologram is shown in Fig 13. The top two lines display the current positions in centimetres of the x- anx z-axes relative to their datum positions, and also the current values of speed (in steps/sec) and index length (in steps). Line three shows four status indicators in the following order across the screen:

i)	Magnification region.	HIGH or LOW
ii)	z-axis motion mode.	RUN or INDEX.
iii)	Direction to move on the z-axis to reach the end of the current scan.	+ ← or → -
iv)	Automatic-scanning on or off.	AUTO-SCAN or [blank].

Line four is used to display various messages to the operator, the meanings of which are described below.

a) 'READY' Indicates that the system is ready to receive a command.

b) 'Move not allowed!' Indicates that an attempt has been made to initiate a RUN move on the z-axis that would cause it to move beyond its current limits.

c) 'Index is too long'. Indicates that an attempt has been made to initiate an INDEX move on the x- or z-axes, with an index length that would take the axis beyond its current limits.

d) 'Move to next x-axis scan position? (Y/N)'. The hologram has been moved through a full scan along the z-axis. To move the hologram on the x-axis to the position of the next scan then reply 'Y'. This will automatically initiate an INDEX move with the index length corresponding to the scan-box width. Reply 'N' will leave the x-axis position unaltered, and might be used to move back along a scan to re-examine a particular image.

The remainder of the screen area is available for viewing images. The limits of the scan box are shown by four corner markers. It will be seen that the scan box fills the image viewing area when the hologram is at its z-axis lower limit position.

5.8 Bringing images into focus

In normal operation, the hologram will be moved along a z-axis scan in 'RUN' mode at a convenient speed. Out-of-focus images will normally be recognised by a characteristic pattern of circular or almost-circular concentric bands. As the image is brought closer to focus, the diameter of thse bands will decrease and it may be possible to discern the non-spherical nature of small ice particles. When the image is judged to be close to focus, the RUN move may be stopped by releasing the key, and the z-axis switched to INDEX mode. A series of moves may then be made to bring the hologram to the sharpest focus position, using decreasing index lengths as successively smaller position adjustments are required. The degree of precision with which an image can be focussed depends on the magnification and the brightness and contrast of the image against the background noise. In practice, it should normally be found that the 20 step setting can be used for sharp focussing in high magnification and the 100 step setting in low magnification.

If the image is of a large particle then it may be only partly visible on the screen. In this case temporary adjustments to the (x,y) position of the hologram may be made using the x-axis motion commands or the temporary y-micrometer setting (key 'G', option 4). In the case of particles with a radius ≥ 1 mm being analysed in high magnification, it may be necessary to move temporarily to the low magnification region in order to view the complete image.

5.9 Sizing and recording image data

When an image has been brought to focus, press key 'P' to enter the particle classification, sizing and recording routine. There are basically four stages involved:

i) Classification of the image.
ii) Superposition of the cursor over the image.
iii) Calculation and display of particle true size and position.
iv) Checking of displayed data for coincidence with previously recorded images, followed by recording of the new data.

If the motion system is not in auto-scanning mode then only stages ii) and iii) are performed and it is thus not possible to record image data.

In stage i), the top four lines of the screen are used to display the various menus which comprise the image classification scheme (see Fig 8). The final particle description IP% is developed using keys Y,N,1,2,3,4 to select the appropriate choices. It should be noted that continued use of key N will lead out of the routine and return control the hologram motion system.

Stage ii) is entered as soon as the particle classification is complete. The horizontal and vertical positions of the cursor are controlled using the potentiometers labelled 'X' and 'Y' respectively, and its radius by the one labelled 'R'. The cursor is moved using these controls until it spans the appropriate dimension of the image. For water droplets this will be their diameter, for column- or needle-type ice crystals their length, and for other types of ice particle their maximum chord.

Stage iii) is entered by pressing any key once the cursor has been correctly set. The screen will now display the true position of the object particle relative to the surface of the minipod, its true size (radius for water droplets, length or maximum chord for ice crystals), and its particle type classification.

At any time during stages ii) and iii) pressing the 'ESCAPE' key on the main keyboard will cause an immediate exit from the sizing and recording routine and a return to the hologram motion display. Use of this facility might be made if for example the cursor has for any reason been incorrectly set or an incorrect type classification has been assigned.

If the information displayed by stage iii) is correct, then stage iv) is entered by again pressing any key. The position data for the current image will then be compared with that of all images recorded in the current and preceding slices. If any image is found which lies within 0.3 cm of current image in the z-direction and within 5 particle radii in the x/y plane then current and recorded positions will be displayed on the screen with the warning message "Are these the same particle? (Y/N)". A reply of 'N' to this question may be given if there are genuinely two particles lying very close together, a situation which will be clearly visible on the screen. A reply of 'Y' will cause a return to the hologram motion display without recording the data for the current image.

If no position coincidences are detected in stage iv) then the position, size and type of the current image will be recorded on disc. The screen display will now also show the total number of images counted in the current analysis zone. Pressing any key will cause a return to the hologram motion display.

5.10 End of slice

When sufficient scans along the z-axis have been made to move the hologram between the x-axis limits of the current analysis zone then one slice has been completed (see 3.2.1 and Fig 7). The screen display will now show the accumulated sample volume and image count for all slices in the current zone, together with the message:

"Continue analysis in this zone? (Y/N)"

If the reply is 'Y' then the hologram will automatically be moved back to the (x,z) lower limit position, the y-axis position incremented by the correct amount and the operator prompted to ensure that this new value is correctly set on the y-axis micrometer. The hologram is then ready to resume scanning.

If, however the operator decides that a sufficient sample volume and/or particle count has been reached then a reply of 'N' should be given. A further message will then be displayed:

"Do you wish to define a new analysis zone? (Y/N)"

A reply of 'N' will cause exit from the program via the termination routine described below. If however a reply of 'Y' is given then the program will return to the menu for selecting zone limits (section 5.4, para iv).

5.11 Ending an analysis session

An analysis session may be terminated at any time when the screen is showing the hologram motion display by pressing key 'Q' on the main keyboard. The current hologram position and the current auto-scanning saved position are written to the main header of the data file, together with the values of pointers to the start of data in the current and preceding slices (it should be noted that upon resuming analysis of this hologram the system will initially restore the hologram to the auto-scanning saved position). The data file will then be closed and control returned to the main menu.

5.12 Copying the data file

Whilst floppy discs are a reasonably robust form of data storage, it is nevertheless a good precaution to keep backup copies of data files. The system currently records 47 bytes of data for each image thus a single disc can accommodate about 2000 individual images. Option 'C' in the main menu provides a facility for copying the data file for the hologram under analysis onto a master backup disc which may contain data from a number of different holograms (up to a maximum of 31, or until the disc is full). The data is first copied to a temporary file on the program disc in DRIVE 0. The master backup disc is then inserted into DRIVE 1 and the data file copied to it.

5.13 The analysis of recorded image data

Option 'D' on the main menu provides a further menu which gives access to various data processing programs. Users wishing to add their own programs to this option should SAVE them on the program disc with a filename having the directory letter D (see BBC DFS manual). There are currently programs available to produce scatter plots of particle radius or x- or y-coordinate against z, and also to plot histograms of particle counts in either FSSP or 2D-cloudprobe size ranges. Each of these programs plots results on the screen which may be dumped to the printer if required. Examples of the output of two of these programs are shown in Figs. 14 and 15. Fig. 14 clearly shows the limited resolution of the screen cursor described in section 4.2.1.

References

1. 'An Introduction and Guide to the Met O 15 Holographic Particle-Measuring System'
C. N. Taylor.
Met O 15 Internal Report No. 40.

2. 'Optical Holography'
R. J. Collier, C.B. Burckhardt, and L. H. Lin
Academic Press.

Appendix A

Disc datafile format

This section is intended for the guidance of users who wish to write programs to process the recorded image data. The data file has a main header with a length of 158 bytes. This contains the flight and frame numbers of the hologram, the values of a number of variables required by the program at the start of a further analysis session, and a set of pointers which point to the start positions on disc of data for the various analysis zones. Data for each zone is preceded by a sub-header section containing the zone limits, the number of images recorded in the zone, and a pointer to an end-of-zone terminator which follows the last image record in the zone. This terminator has the value 2222 if scanning of the zone is incomplete, or 3333 if the zone has been completely scanned. In the detailed description of the file format which follows, the variable names given correspond to those used by the main system-controlling program.

Main header	variable name or value	No. of bytes
Flight number	FLT$	6
Frame number	FRN%	5
Current position of hologram in bench coordinate system.	ZPS XPS YPS	3 x 6
Last position reached whilst in automatic-scanning mode.	ZSV XSV YSV	3 x 6
Recording length, Uo	U0	6
Camera-to-z-axis datum position.	TVD	6
Spatial filter-to-z-axis datum position.	ZSF	6
Bench (x,y) coordinates of hologram centre.	XC,YC	2 x 6
Number of analysis zones to follow (maximum 10)	NZ%	5
Disc start pointers for all following zones.	PT% (n) n = 1 to 10	10 x 5
Number of slices in the zone under analysis.	NS%	5

Disc start pointer of preceding slice.	OSP%	5
Disc start pointer of current slice.	NSP%	5
End of main header indicator.	EOD% (= 1111)	5
		158

Zone sub-header	Variable name or value	No. of bytes
Number of this zone.	NZ%	5
Pointer to end-of-zone terminator.	IPT%	5
Number of images recorded in this zone.	NP%	5
Zone limits in the bench coordinate system	ZMN, ZMX	2 x 6
and increments applied to x- and y-axes by	XMN, XMX, DX	3 x 6
auto-scanning system.	YMN, YMX, DY	3 x 6
z-axis limits in recording coordinate system.	VOMN, VOMX	2 x 6
		75

Image records		
Position of particle in recording coordinate system.	VO, XCRD, YCRD	3 x 6
True radius	RDS	6
Type classification	IP%	5
Position of hologram in bench coordinate system.	ZPS, XPS, YPS	3 x 6
		47

End-of-zone terminator	EOD%	5

Fig 1. RECORDING STAGE

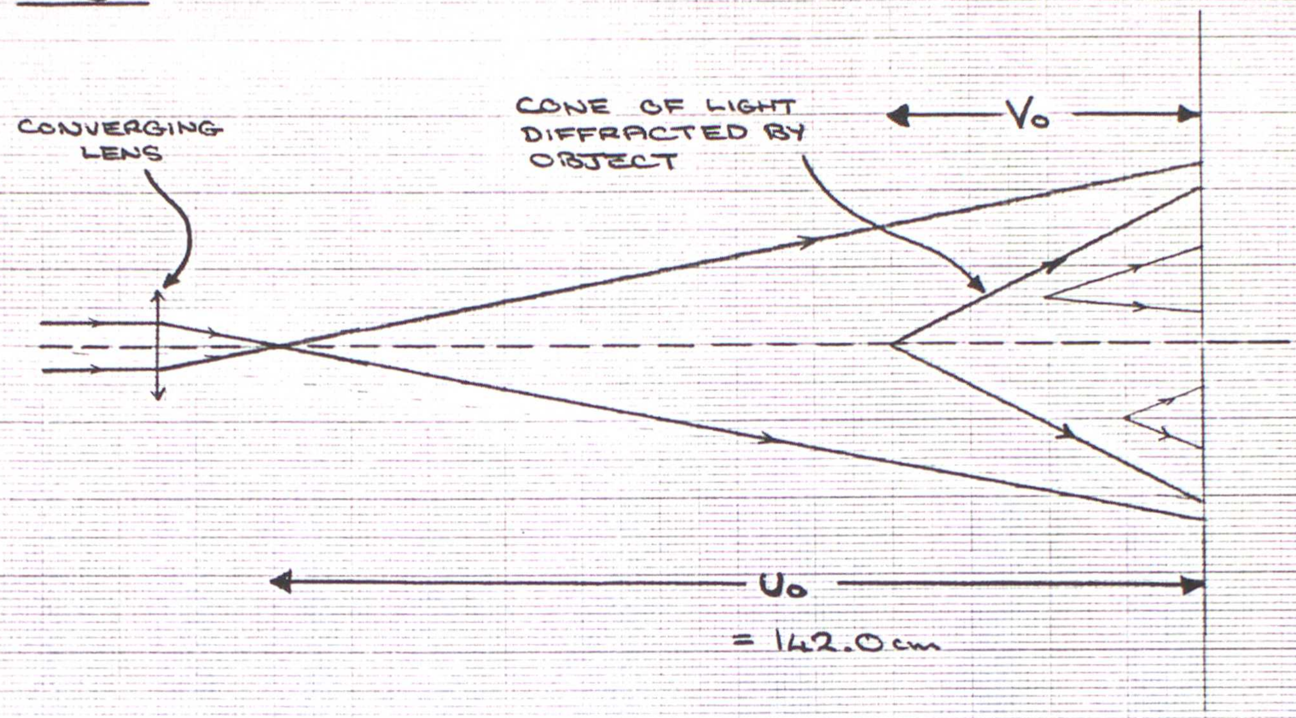
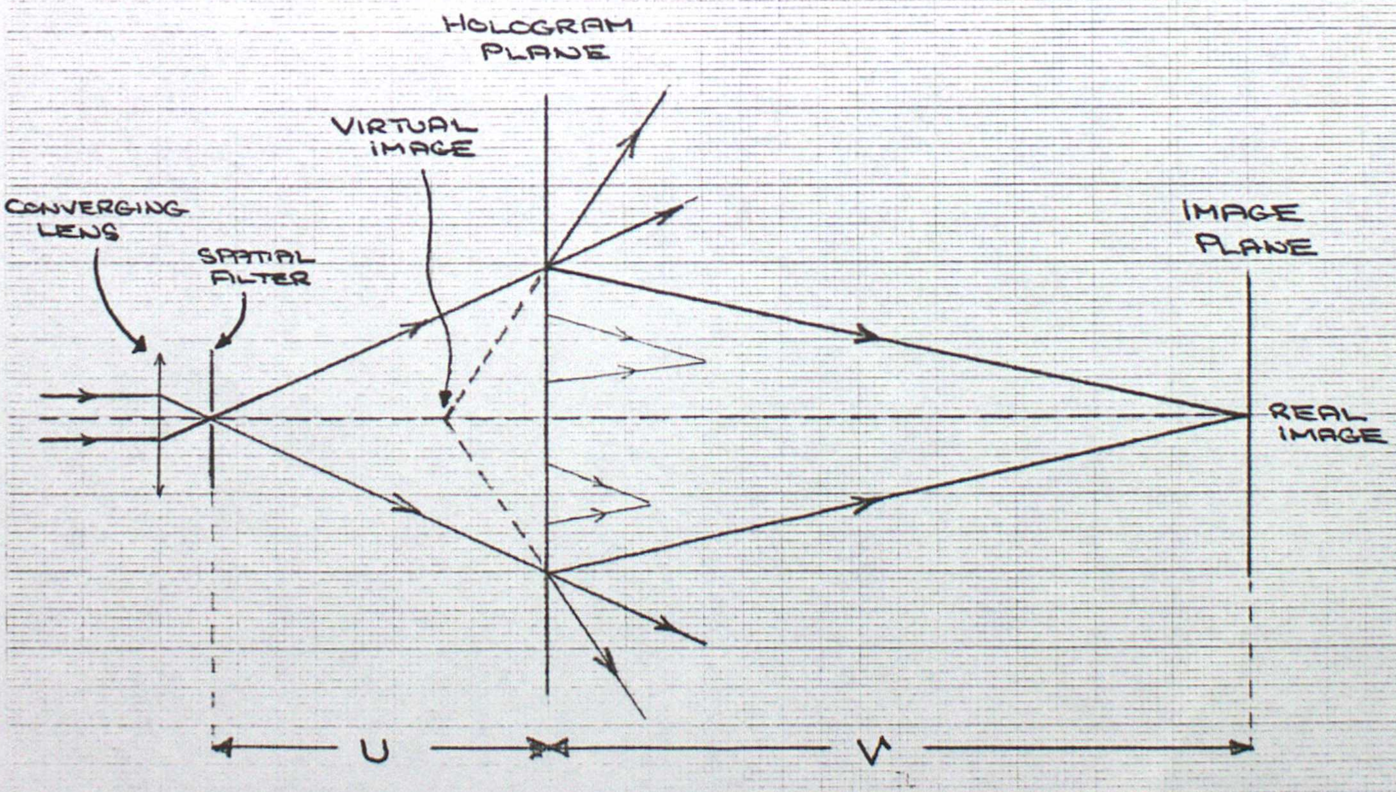
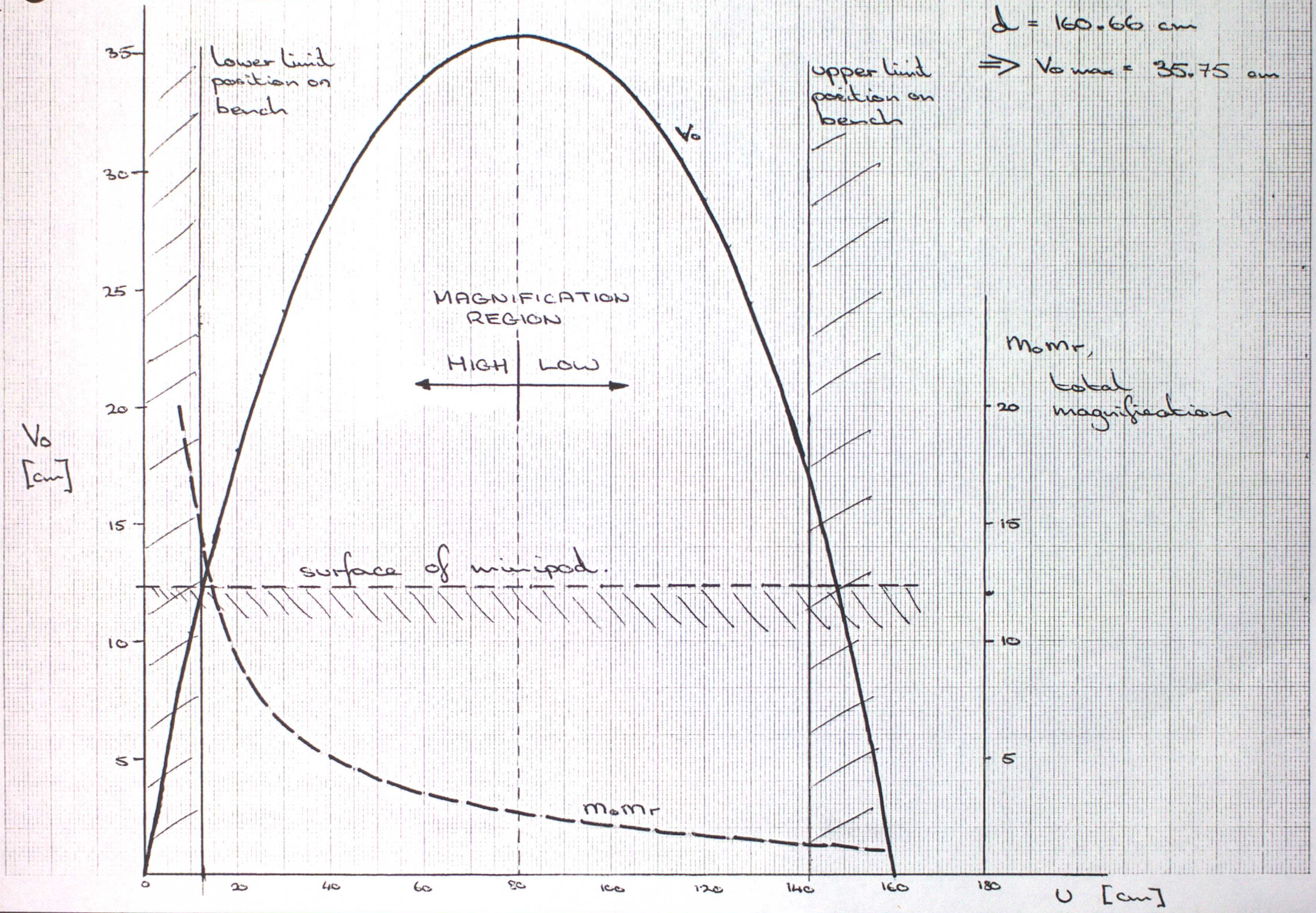


Fig. 2 RECONSTRUCTION STAGE



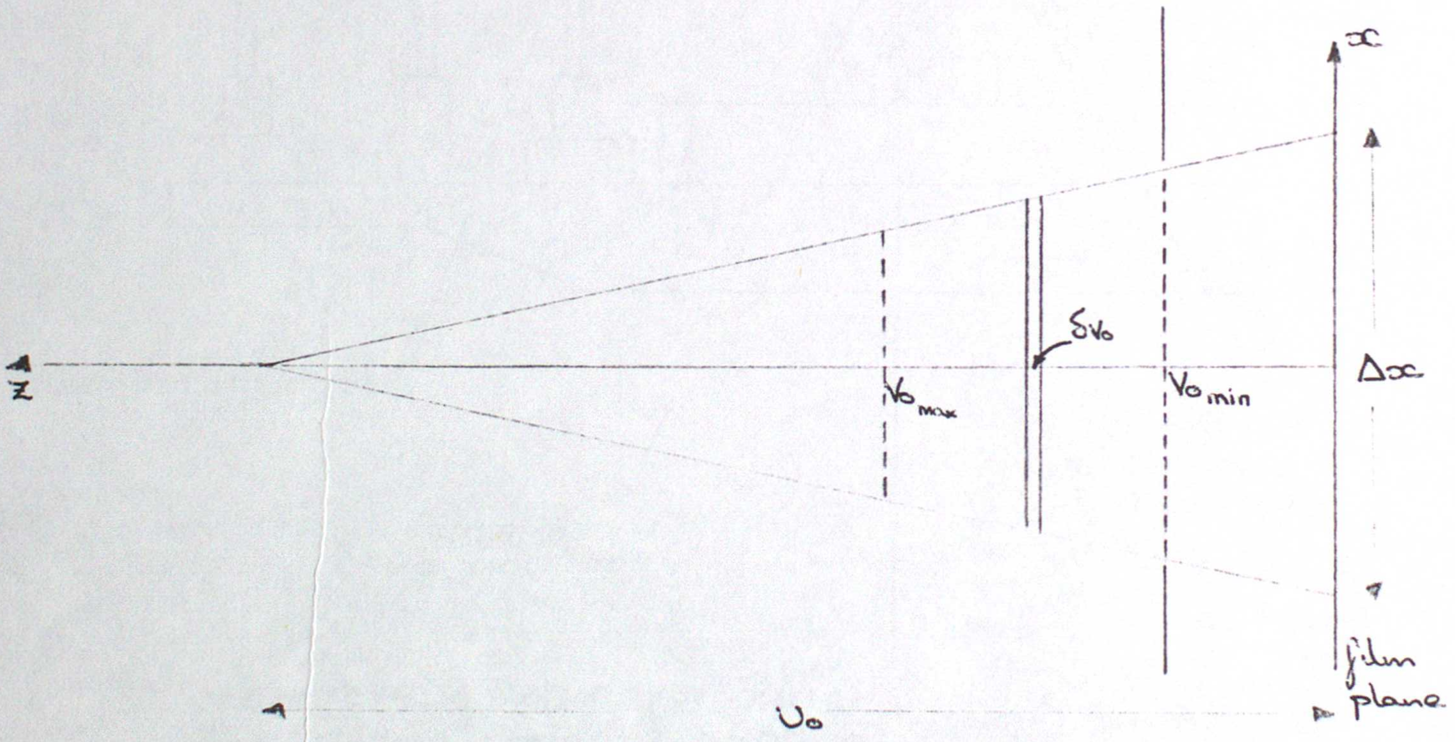
$U + V = d = 160.66$ cm

Fig. 3



d = 160.66 cm
⇒ Vo max = 35.75 cm
Lower limit position on bench
upper limit position on bench
Vo
MAGNIFICATION REGION
HIGH
LOW
surface of minipod.
MoMr
MoMr, total magnification
Vo [cm]
U [cm]
0
20
40
60
80
100
120
140
160
180
5
10
15
20
25
30
35

Fig. 4



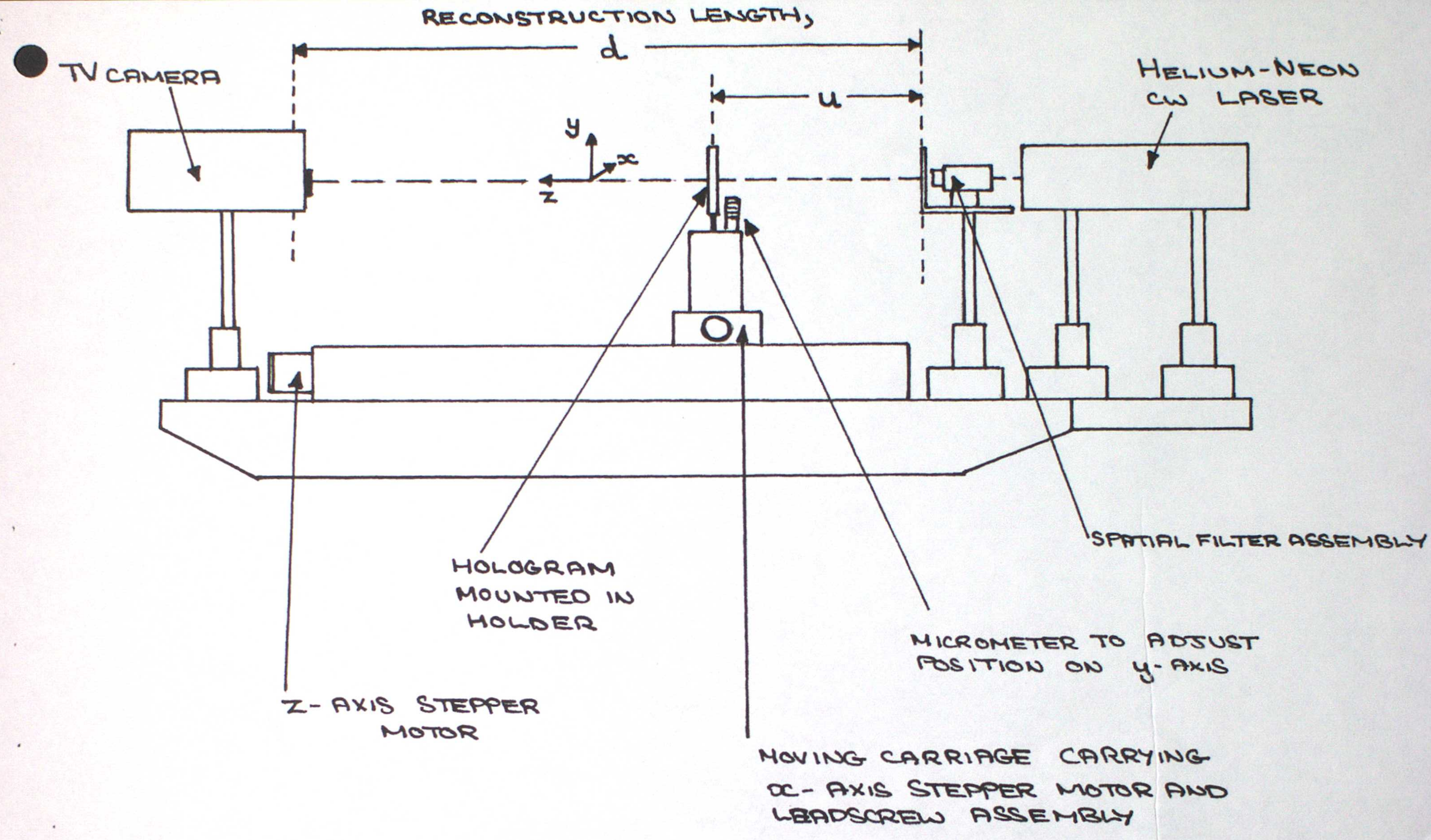
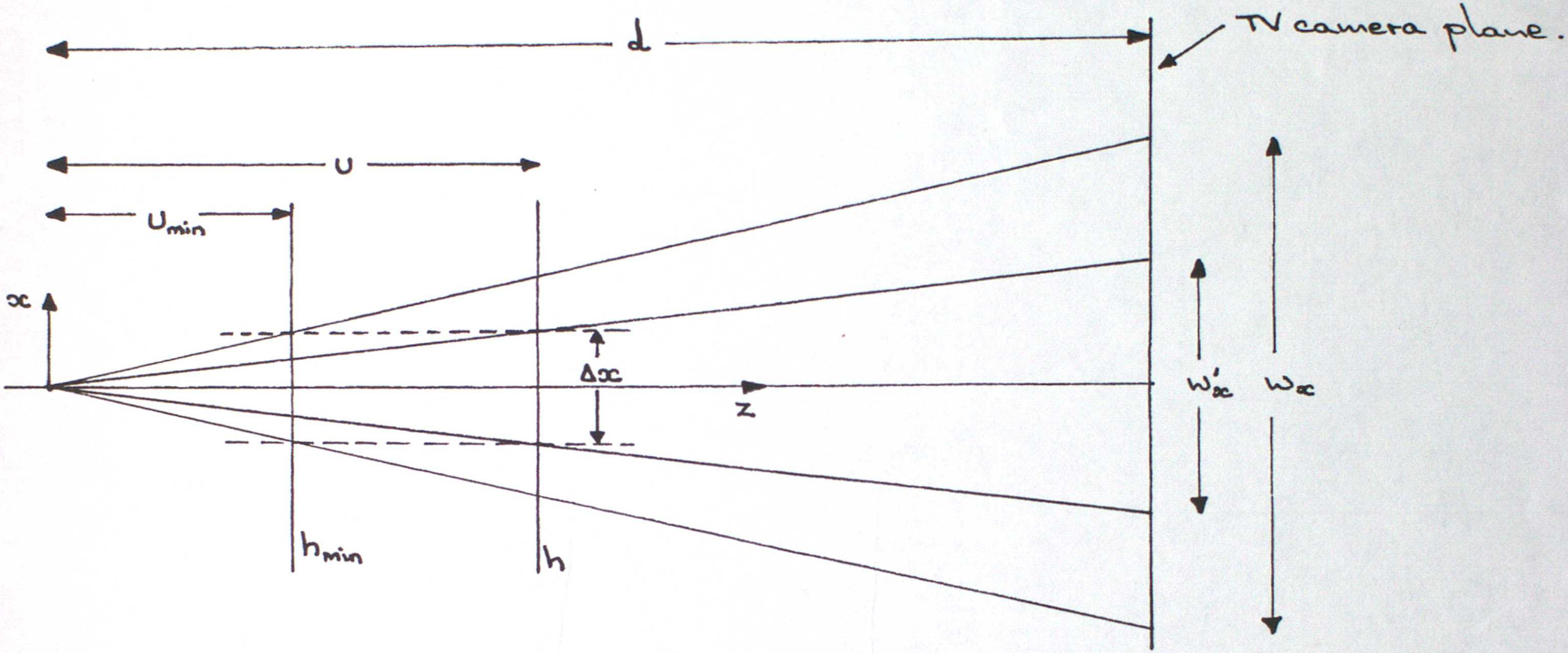


Fig. 5 HOLOGRAM RECONSTRUCTION - OPTICAL BENCH

Fig. 6 **Variation of scan-box size with hologram position**

h_{min} is the hologram plane in its lower-limit position on the z-axis, distance U_{min} from beam divergence point.

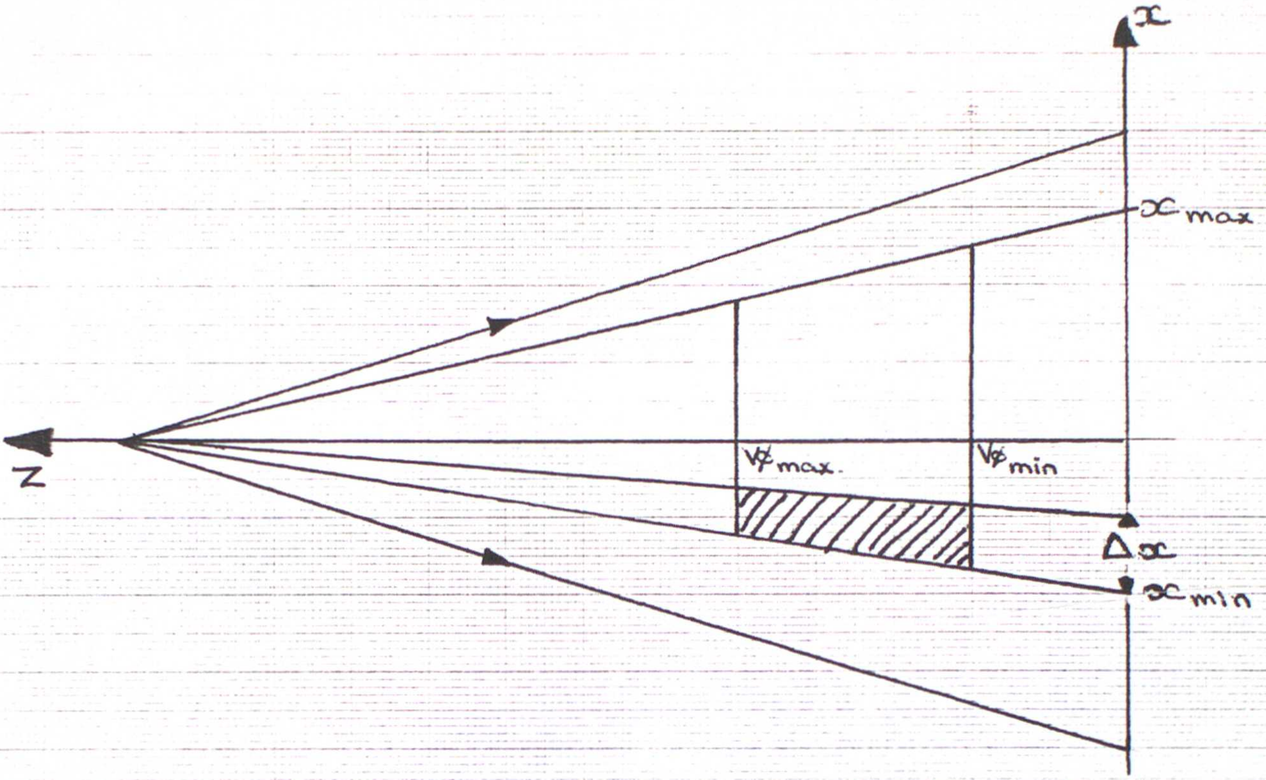


Δx = width of hologram area element corresponding to camera-tube width.

$$= \frac{U_{min} \times W_x}{d}$$

$$\frac{W'_x}{W_x} = \frac{U_{min}}{U}$$

Fig. 7 Definition of analysis zone



Shaded area represents 1 scan, defined by Δx, the width of the hologram area element, and $V\phi_{min}$, $V\phi_{max}$ the limits on the z-axis position of object particles. Successive scans between x_{min} and x_{max} form a slice.

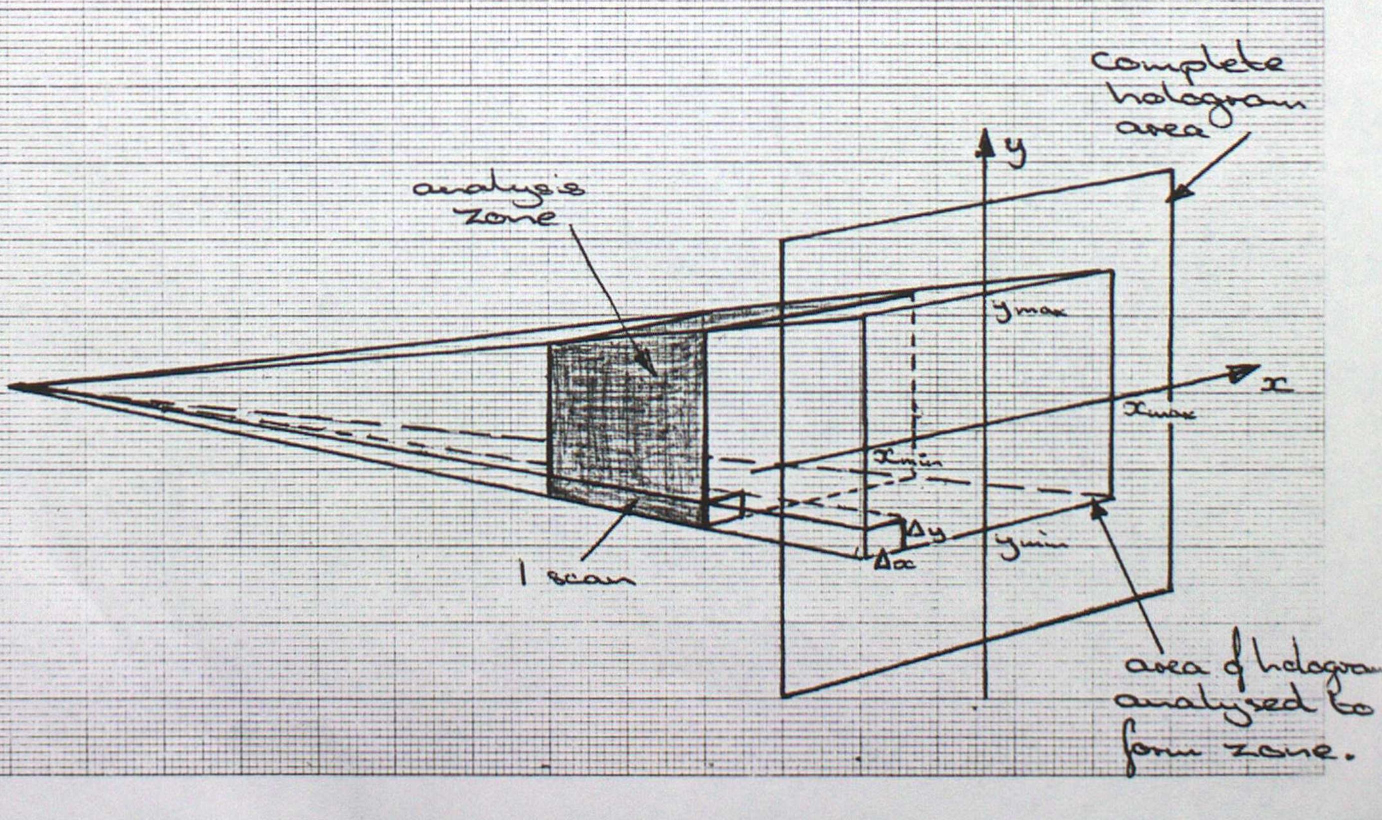


Fig. 8 The Particle Classification Scheme

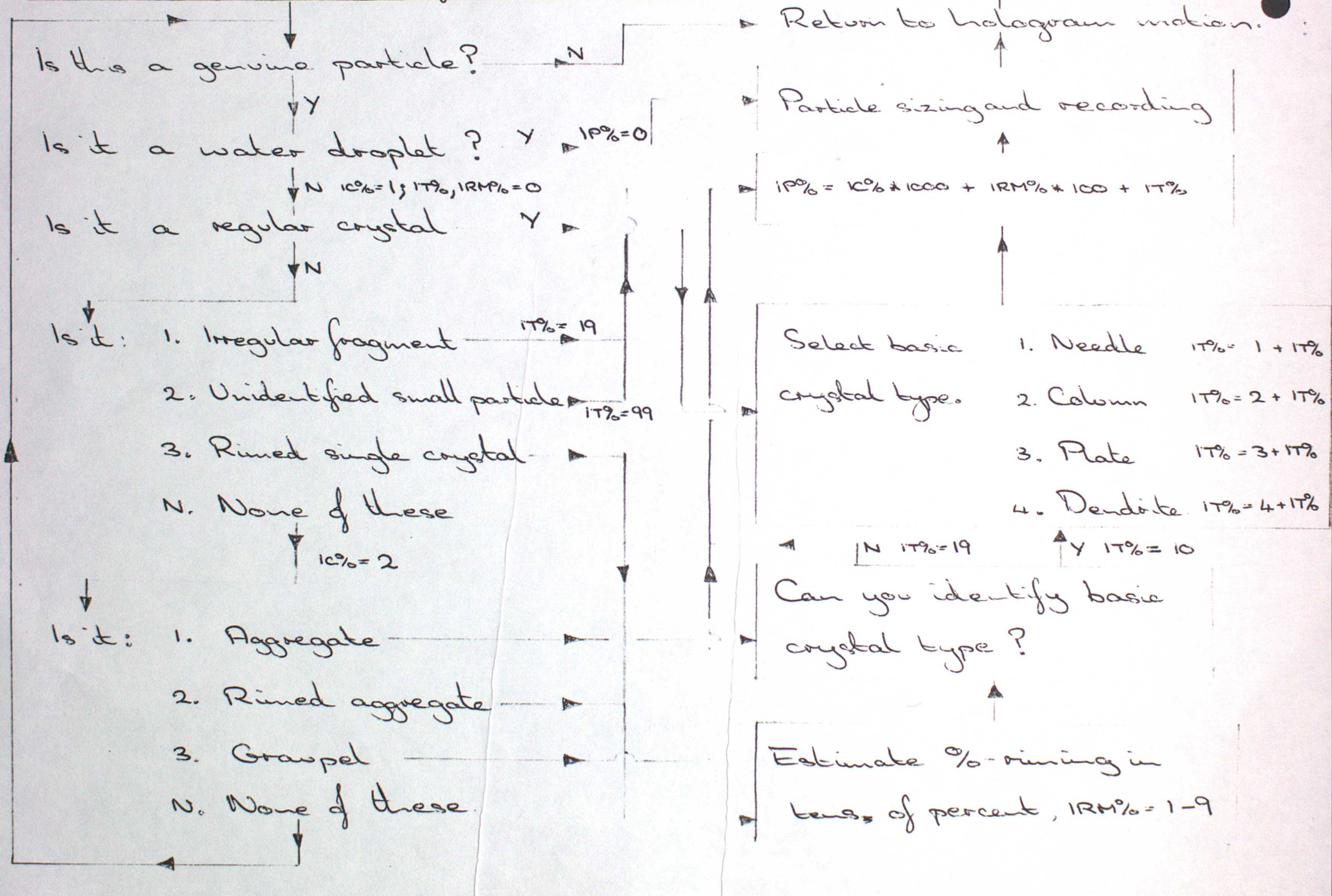


Fig. 9 Double-count prevention

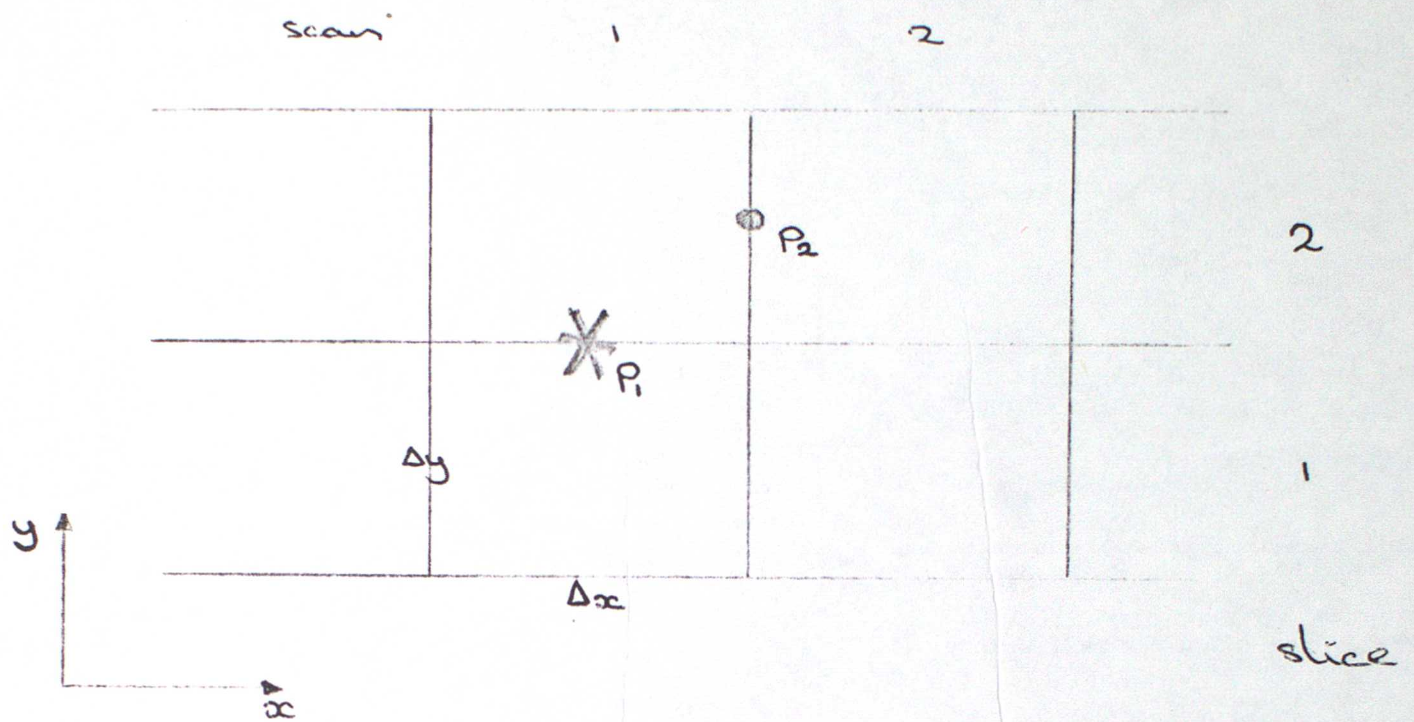
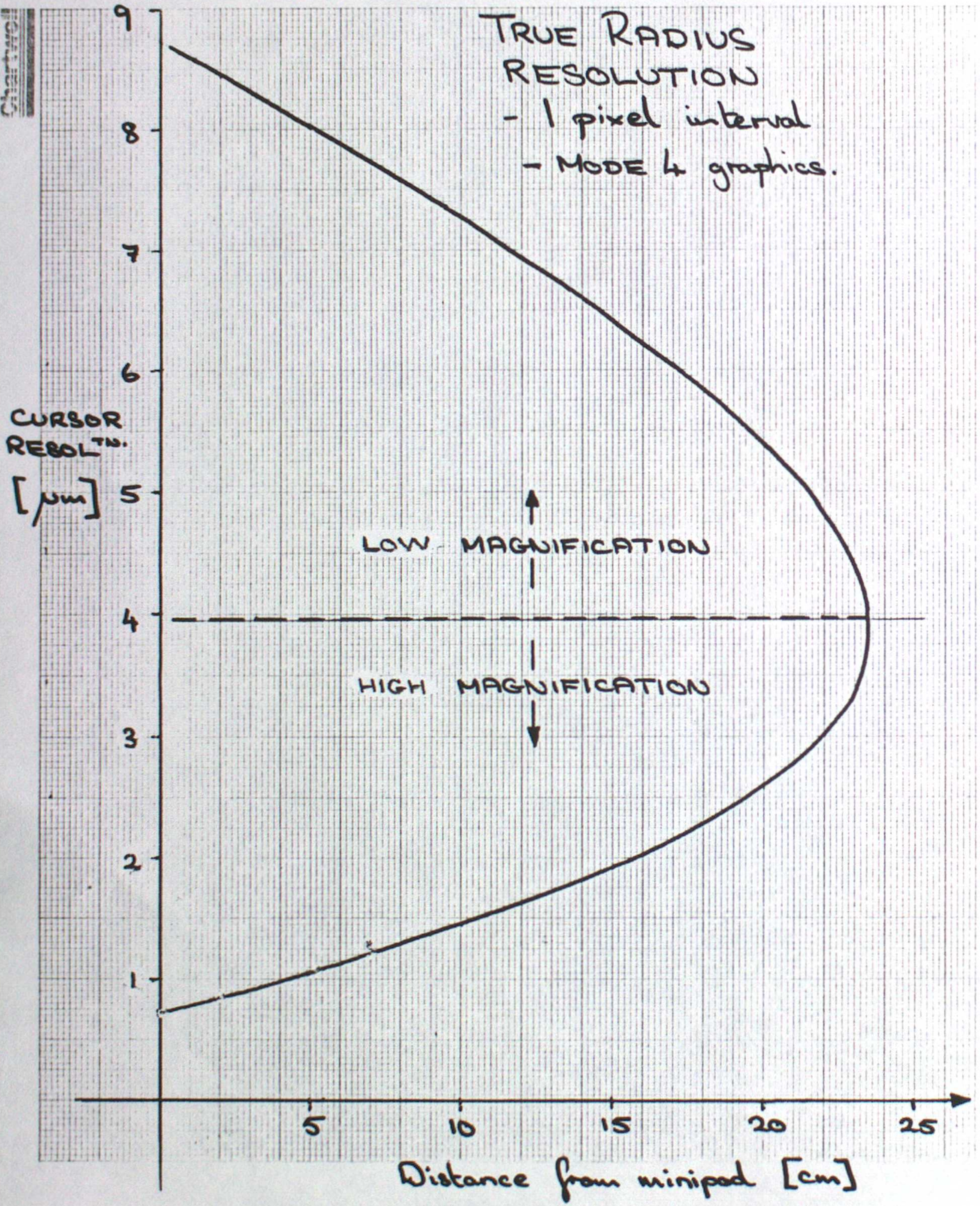


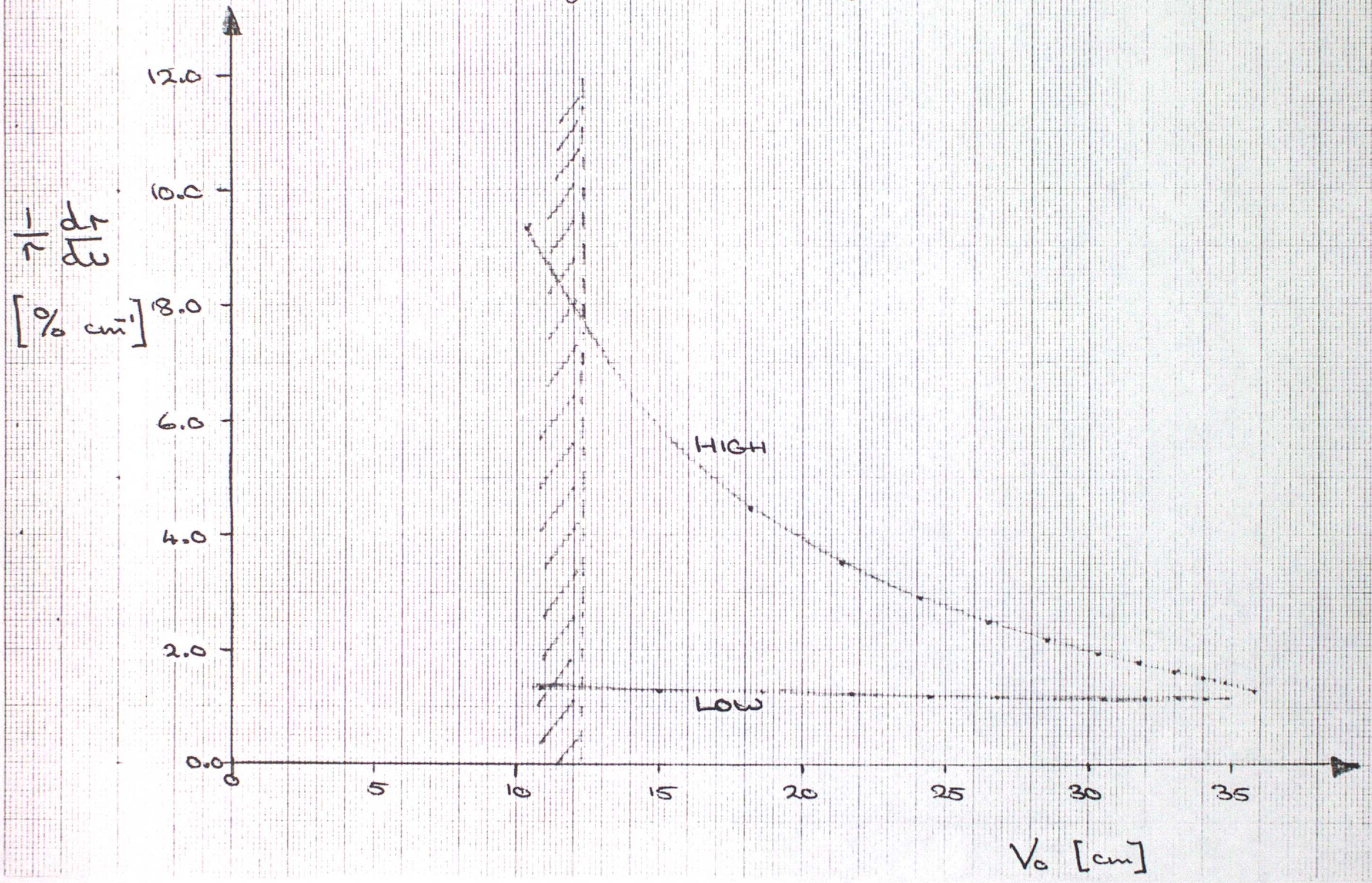
Fig. 10



TRUE RADIUS
RESOLUTION
- 1 pixel interval
- MODE 4 graphics.
CURSOR
RESOL^TN.
[μm]
9
8
7
6
5
4
3
2
1
LOW MAGNIFICATION
HIGH MAGNIFICATION
5
10
15
20
25
Distance from minipad [cm]

Fig. 11

Error in calculated radius due to focus position uncertainty, as a function of object particle distance, for high and low magnification regions.



Y	N	X	W
1	2	3	4
G	P	I	D
A	R	+	—

Fig. 12 Auxiliary keyboard layout

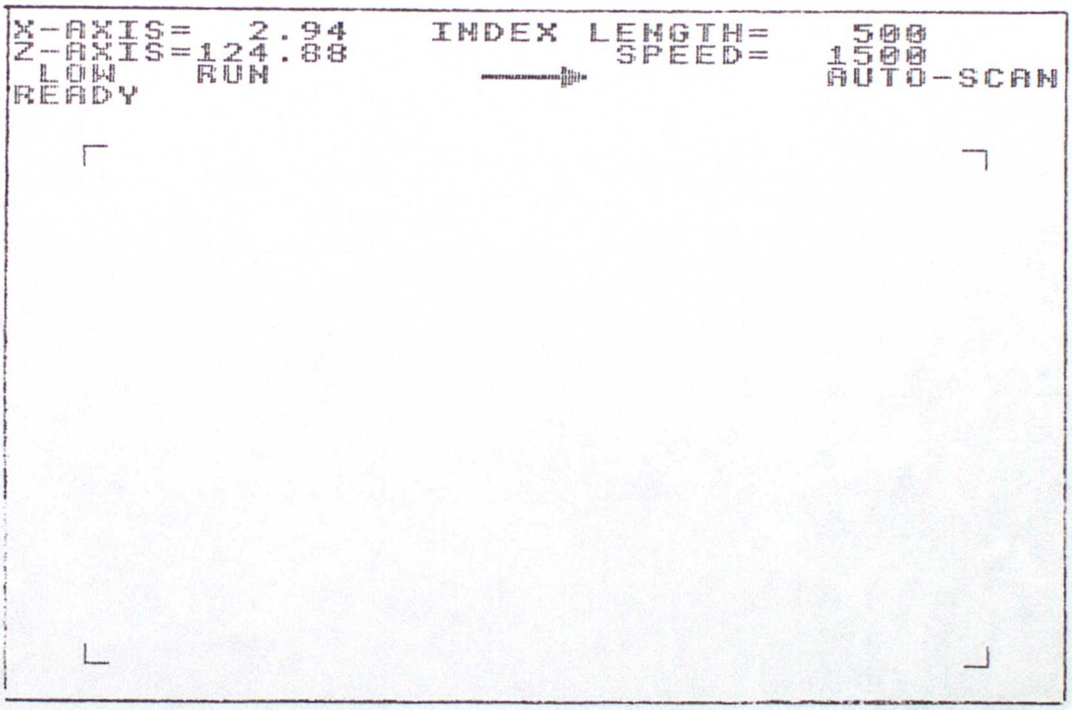


Fig. 13 Screen display during hologram motion.

Fig. 14

>Flight number= H632

Frame number= 76

Zone no.	ZMIN cm.	ZMAX cm.	Volume cm^3	No.	Mean conc.
1	17.3	22.3	6.677	216	32.35
2	22.3	27.3	8.830	224	25.37
3	27.3	32.3	9.213	201	21.82
ZONE NOT COMPLETELY SCANNED					
4	12.6	17.3	4.934	112	22.70

MAXIMUM RADIUS?50

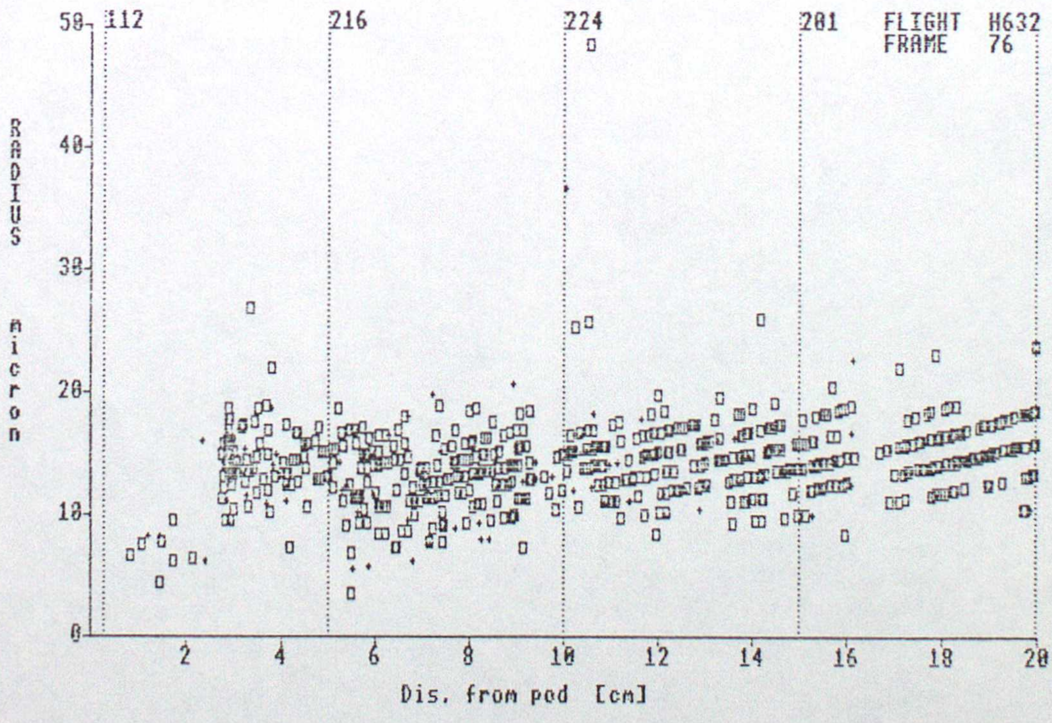


Fig 15

ZONE TO BE ANALYSED?2

BIN	RADIUS	COUNTS
1	1.75	0
2	3.13	0
3	4.59	0
4	6.06	0
5	7.55	2
6	9.00	12
7	10.50	30
8	12.00	39
9	13.50	55
10	15.00	48
11	16.50	27
12	18.00	5
13	19.50	0
14	21.00	0
15	22.50	0
16	24.00	6

MEAN RADIUS 14.1 micron

RATIOS OF PARTICLE TYPES

WATER=	182.0 counts	81.2%
ICE=	12.0 counts	5.4%
UNIDT=	30.0 counts	13.4%