Investigation of the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber-A Ground Based Program

James D. Trolinger, PI
MetroLaser Incorporated

Roger Rangel, Co-I
University of California Irvine
Dept. of Mechanical & Aerospace Eng.

William Witherow, Co-I Jan Rogers, Co-I
Marshall Spaceflight Center,

Ravindra B. Lal, Co-I
Alabama A&M University,
Dept. of Physics

S110-29

Presented at the Microgravity Materials Science Conference
July 14-16-1998
Huntsville Alabama

Background and Introduction

In January 1992, the IML-1 FES experiment produced a set of classic experimental data and a 40 hour holographic "movie" of an ensemble of spheres in a fluid in microgravity[1]. Because the data are in the form of holograms, we can study the three-dimensional distribution of particles with unprecedented detail by a variety of methods and for a wide variety of interests. The possession of the holographic movie is tantamount to having a complex experiment in space while working in an easily accessible laboratory on earth[2]. The movie contains a vast amount of useful data, including residual g, g-jitter, convection and transport data, and particle fluid interaction data. The information content in the movie is so great that we have scarcely begun to tap into the data that is actually available in the more than 1000 holograms, each containing as much as 1000 megabytes of information. This ground-based project is exploiting this data and the concept of holographic storage of spaceflight data to provide an understanding of the effects of microgravity in materials processing. This paper provides the foundation, objectives, and status of the ground based project.

Objectives

The primary objective of this project is to advance the understanding of microgravity effects on crystal growth, convection in materials processing in the space environment, and complex transport phenomena at low Reynolds numbers. This objective is being achieved both experimentally and theoretically. Experiments are making use of existing holographic data recorded during the IML-1 spaceflight. A parallel theoretical effort is providing the models for understanding the particle fields and their physics in the microgravity environment.

Virtual Spaceflight Chamber Concept:

Certain spaceflight experiments can be recorded in holograms in such a manner that having the holograms on earth is optically equivalent to being back in space with unlimited time to view the experiment[3]. Properly exploited, this concept can save a significant amount of experiment time in space by effectively bringing the experiment optically back to earth

Figure 1 illustrates the concept. Holograms of the space flight chamber are produced in space with a time resolution that is sufficient to capture any movement that is of interest to the investigator. In this case the chamber includes a growing TGS crystal surrounded by a fluid that has been seeded with polystyrene tracer particles of three sizes, 200, 400, and 600 micron diameters.

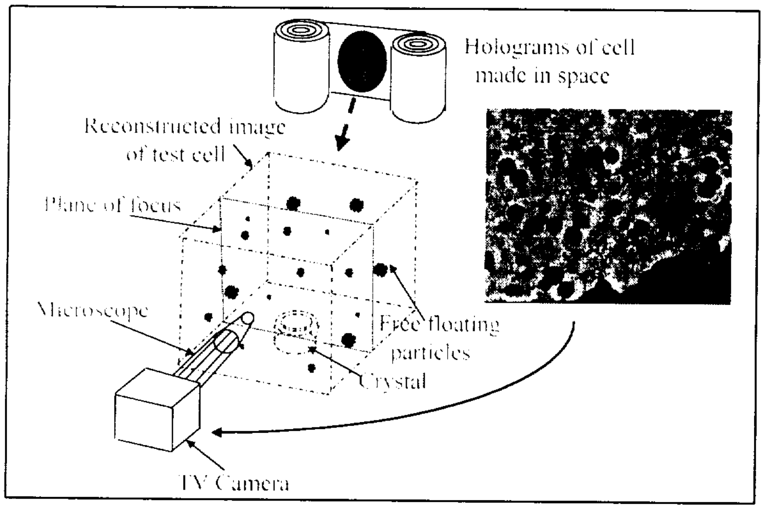

Figure 1-Virtual Space Flight Chamber Concept

When particle field data are in the form of holograms, we can study the three-dimensional distribution of particles with unprecedented detail by a variety of methods and for a wide variety of interests. The possession of the holographic movie is tantamount to having a complex experiment in space while working in an easily accessible laboratory on earth. The holographic movie contains a vast amount of useful data, including residual g, g-jitter, convection and transport data, and particle fluid interaction data. This project is further exploiting this data as well as the concept of holographic storage of spaceflight data, and is illustrating the effects of microgravity on materials processing.

The microscope scans through the entire volume under computer control, storing images throughout. The images are processed by specially developed software that locates the best focus XYZ position of each particle in each time slot. This data has been collected for all holograms for the entire IML-1 spaceflight, has been archived in CD format, and is available to other researchers who may be interested in such data. Holograms were made approximately 10 minutes apart, representing sufficient time resolution for the overall motion of particles, which is characterized by a velocity of the order of micrometers per minute.

The types of information extractable from these holograms can improve our understanding of the microgravity environment, thereby allowing NASA to better exploit its use in such applications as crystal growth from solution. The early part of this investigation has made use of existing holographic data produced in the IML-1 experiment to produce quantitative measurements of convection in the space shuttle environment, g-jitter effects on crystal growth, residual gravity, and complex transport phenomena in low Reynolds number flows. By knowing the location of all of the particles, we can select particles with specific environments for study, for example, a particle with no nearby neighbors, or a particle near the walls or the growing crystal.

Figure 2 shows an enlargement of the region containing both in-focus and out-of-focus particle images of all three sizes of particles. Particles follow a zigzag type of motion due to g-jitter. They move both under the influence of convection as well as gravity. The movement in the region of the crystal differs from that further away because of the influence of the growing crystal. The particles are used to observe micro-convection near the crystal. In addition we found the experiment useful for measuring g and g-jitter effects as well as fundamental particle/fluid physics.

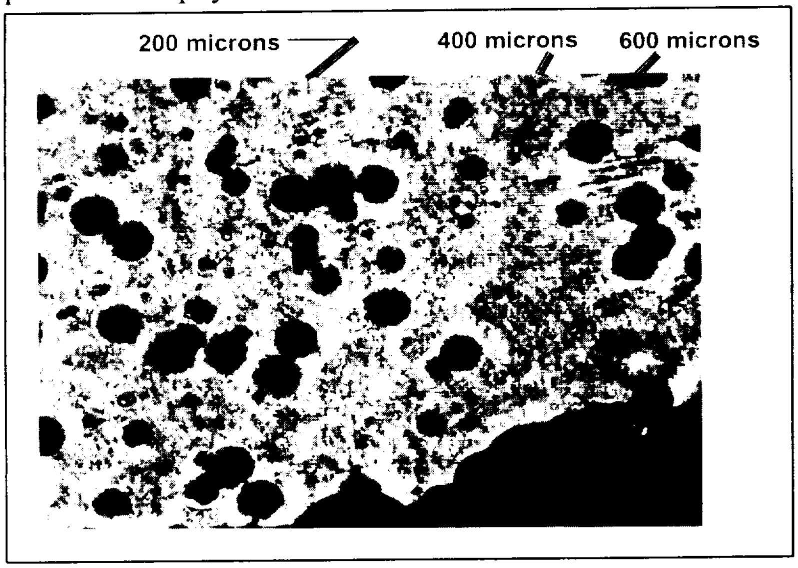

Figure 2-Particles in Microgravity

Discussion

In a microgravity environment, particles of different density can be studied side by side, since the settling rate is extremely low. Those that are denser than the fluid will move in the direction of the residual gravity, while those that are less dense move against the direction of residual gravity. Neutrally buoyant particles move only if the fluid itself moves. The particles actually cause micro-convection in the fluid. At the extremely low Reynolds numbers of these studies, a particle influences its environment out to at least 10 particle diameters. Consequently, the data interpretation requires accounting for the immediate environment of the particle. For fluid velocimetry particles with no nearby neighbors must be used. A neutrally buoyant particle that might otherwise remain motionless may move under the influence of a nearby heavier or lighter particle.

One method for extending the spatial resolution is to employ more than one particle size to reduce confusion between different tracer particles. By using several different particle sizes we improved the spatial resolution as well as the dynamic range of the velocity measurement since the terminal velocity is proportional to the square of the particle diameter, the particle/fluid density ratio, and the acceleration, g. Each factor of two in particle size quadruples the measurable velocity range. Particle size will also be used to distinguish different particle materials. In future experiments particle size can also be used to distinguish different particle materials.

A self-correcting method for measuring effects of g and g-jitter without actually determining velocity of an individual particle is to measure the relative velocity between two different particle sizes (**Figure 3**). The separation of small and large particles located close to each other is proportional to the gravity force and is not affected by registration or by convection. This is a unique way to separate the observance of convection and gravity.

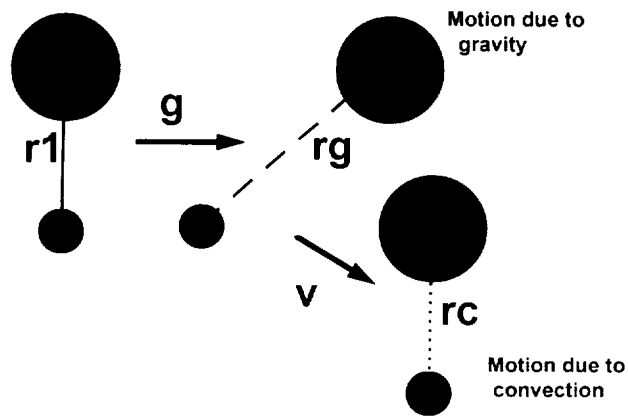

Figure 3. Motion of Large and Small Particle Pairs as Influenced by Gravity and Convection. This procedure has been the most accurate way to measure residual gravity and g-jitter, since the process cancels the effects of convection and minimizes registration errors, and the particle tracks provide a direct measure of residual g.

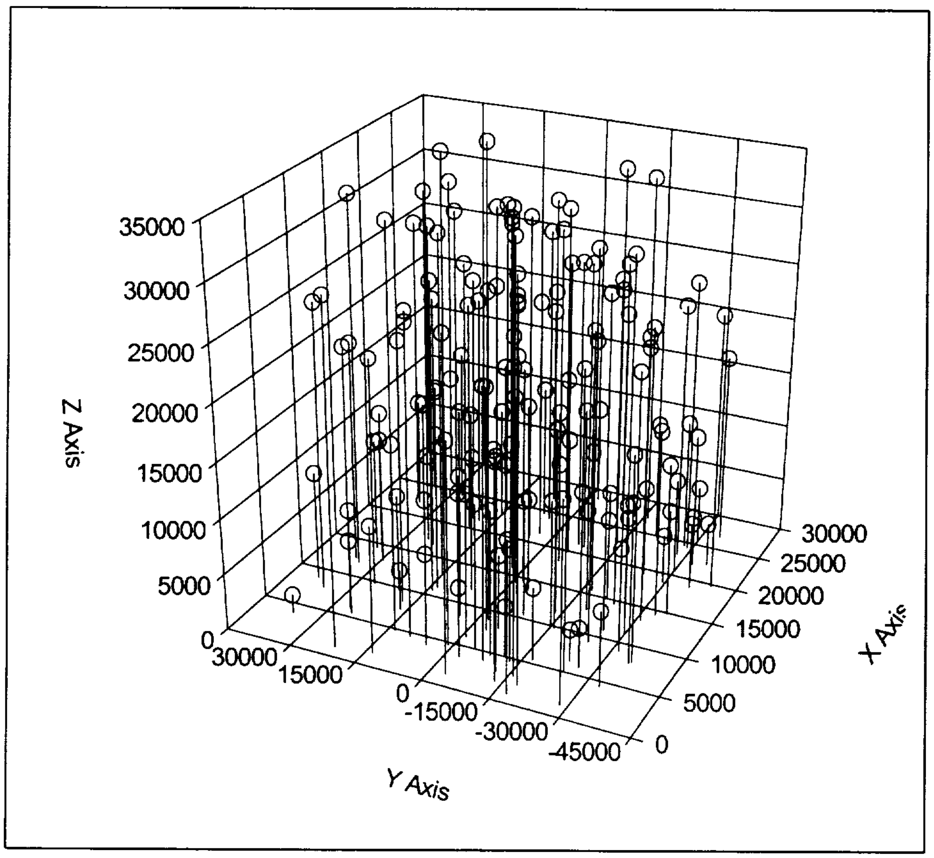

Figure 4-Distribution of Small Particles in the Chamber

Various methods have been devised to analyze and display particle mechanics data. **Figure 4** illustrates the three dimensional positions of all small particles in a hologram. By producing such data for each time slot, particle tracks are created for the entire flight. **Figure 5** illustrates particle tracks in 3D over a 10 hour time period.

We can locate a particle to within a few microns in the plane normal to viewing direction and to within about one millimeter along the direction of viewing. A major shortcoming in these data is our ability to locate a reference frame from one hologram to the next, which is about 50 microns. We are developing procedures to improve upon this measurement in subsequent experiments.

Drs. Rangel and Coimbra[4,5], using fractional derivative techniques, have discovered a new, analytical solution to the equation of motion of a particle in a fluid under conditions that are especially of interest in a microgravity environment. They applied the work to specific cases of interest for this program and have provided data to support potential flight experiments.

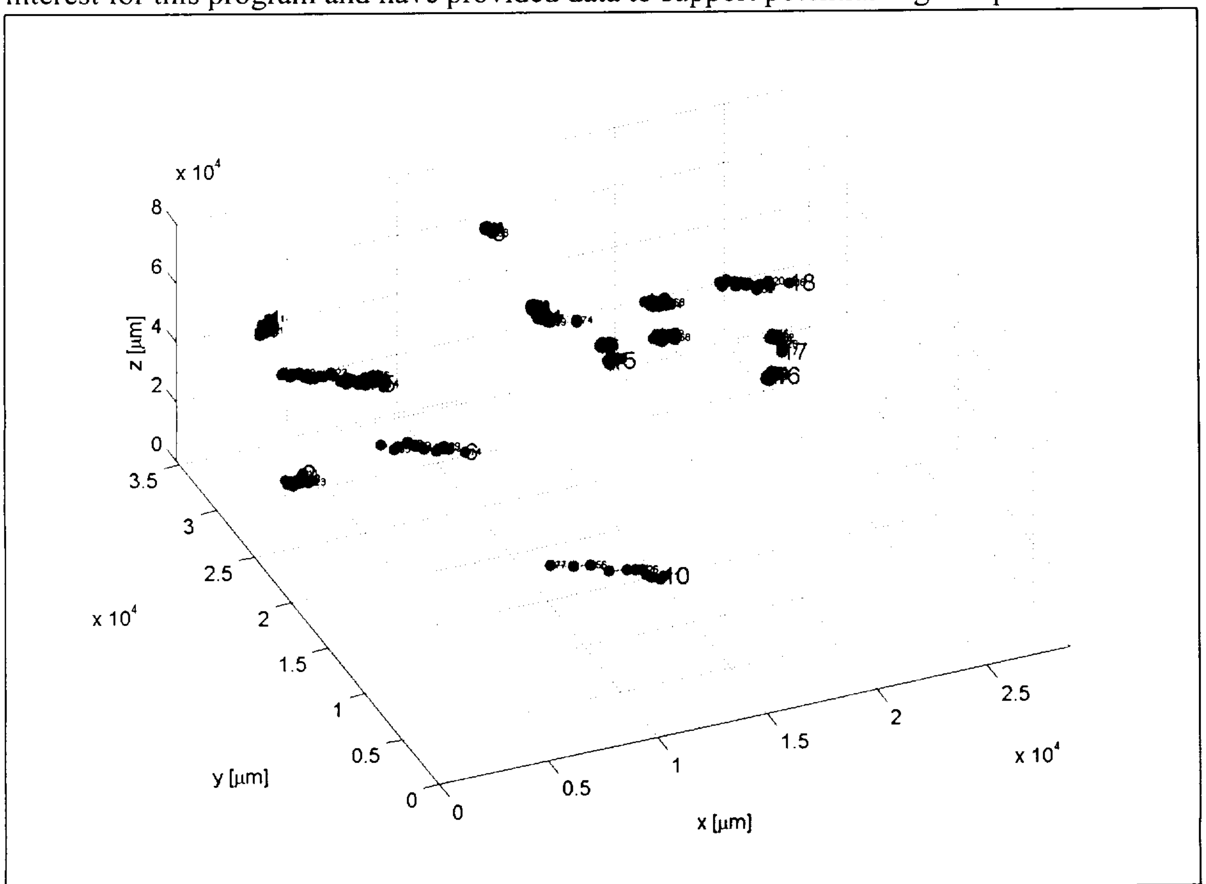

Figure 5-Particle Tracks over an 11-Hour Period

Measurements of residual g are typically in the range of 1 to 2 micro-g's, with large fluctuations of orders of magnitude. Acceleration data correlates well with SAMS on board measurements. Maneuvers are clearly defined with interesting particle movement that can be tracked throughout a maneuver.

Preliminary experiments were conducted in a KC-135 flight to gain experience with a miniaturized holocamera for low-g particle tracking studies. The experiment was designed by the entire project team and was flown by Dr. Rogers

A test cell containing various sized particles and various densities was contained in a solution. When the aircraft was on the upward movement in the parabola where g is highest, particles of density greater than the fluid sank to the "bottom" and particles lighter than the fluid rose to the "top" of the cell. When the aircraft was at the apogee where low g begins, the operator flipped the cell over 180 degrees and inserted it with force into a holder, at which time holograms were recorded continuously for the remainder of the low g portion and well into the high g portion. Based on our theoretical work, we expected that at time zero, when the cell came to a halt at its mount, the heavy particles would move from the top into the fluid and would (depending on density ratio) come to a zero velocity relative to the fluid, while the lighter particles would move upward from the bottom in a similar fashion. Data recorded from these experiments consists of approximately 120 holograms over 25 parabolas.

The holograms from the KC-135 were reconstructed to evaluate the image quality and to gain experience with use of the miniaturization techniques. A primary issue is the use of a diode laser and its ability to produce holograms of sufficient quality. These experiments suggest that the diode laser is adequate. Hologram image quality appeared as good as what would be expected from a HeNe laser. The holograms are in-line holographic recordings. Images are characterized by a collapsing diffraction pattern that remains distinct over a large depth of field.

We examined ways to simulate low g in ground-based experiments to test the experiment hardware. High viscosity solutions that have the correct optical properties provide extremely low Reynolds number flows on ground. Methylcellulose in solution can raise the viscosity of the solution by orders of magnitude.

Conclusions and Future Work

We have concluded that extremely useful data can be extracted from holograms of particle fields in microgravity. Residual gravity can be measured with unprecedented accuracy. G-jitter and microconvection can be observed and quantified. Particle interaction can be seen. A new type of particle driven convection at extremely low Reynolds numbers is observable. Improvements in the measurements required to exploit the concept completely have been identified. These include more accurate referencing between holograms, recordings from two views, and improved flexibility on hologram timing. The program is now emphasizing data types that will support the flight definition experiments.

REFERENCES

[1] J.D. Trolinger, R.B. Lal, D. McIntosh and W.K. Witherow *"Holographic Particle Image Velocimetry in the First International Microgravity Laboratory aboard the Space Shuttle Discovery"*, Applied Optics, Vol. 35, No. 4, pp. 681-689 (1 Feb. 96.).

[2] James D. Trolinger, Roger Rangel, and Ravindra Lal, *"Particle Mechanics and G-jitter Observations in the IML-1 Spaceflight"* AIAA 96-0504, 34th Aerospace Sciences Meeting, (January, 1996).

[3] James D. Trolinger, Matthias Rottenkolber, and Frank *"Development and application of holographic particle image velocimetry techniques for microgravity applications"*, Journal of Measurement Sciences and Technology, Vol. 8 (1997) 1573-1583.

[4] C.F.M. Coimbra, (1997). "Analytical Study on the Unsteady Motion and Heat Transfer of Small Particles in Suspension," Ph.D. Dissertation - University of California, Irvine (In preparation).

[5] C.F.M. Coimbra, R. and Rangel *"Analytical Study on the Unsteady Motion and Heat Transfer of Small Particles in Suspension"*, Accepted for publication.