

**RAMOS (Russian American Observational Satellites) Experiments  
to Obtain a Three Dimensional Background Data Base**

VI-4355

**A.T. Stair, V. Abramov, A. Sidorin, T. Stephens, J.W. Carpenter,  
A.J. LePage, V. Sinelshchikov, V. Misnik, T. Humpherys,  
P. Gretzkowski**

**Paper for  
2003 Multinational BMD Conference & Exhibition  
9-12 June, 2003  
Kyoto, Japan**

# RAMOS (Russian American Observational Satellites) Experiments to Obtain a Three Dimensional Background Data Base

A.T. Stair<sup>a</sup>, V. Abramov<sup>b</sup>, A. Sidorin<sup>b</sup>, T. Stephens<sup>a</sup>, J.W. Carpenter<sup>a</sup>, A.J. LePage<sup>a</sup>, V. Sinelshchikov<sup>b</sup>, V. Misnik, T. Humpherys<sup>c</sup>, P. Gretzkowski<sup>d</sup>

<sup>a</sup>Visidyne, Inc., Burlington, MA; <sup>b</sup>TsNPO Kometa, Moscow, RF; <sup>c</sup>Utah State University/Space Dynamics Laboratory, Logan, UT; <sup>d</sup>MDA/CF, Arlington, VA

## ABSTRACT

Space-based launch detection and tracking, including post boost warm body tracking, must operate with Earth backgrounds in the sensors' fields of view. The primary technology to accomplish these functions is the use of passive infrared sensors. The primary limitation to performance is solar scattering from clouds which result in major signals (clutter) which can overwhelm the system capabilities at some scattering angles and/or lead to false alarms. It is in the joint security interests of the US and Russia that both jointly have confidence in early warning and tracking so that false alarms and false targets are minimized, recognized, and not perceived as threats. The MDA-sponsored RAMOS program (joint between US and Russia) plans to obtain a multi-spectral, three dimensional, background data base so that future designs for detection and tracking can be optimized.

The RAMOS program plans to launch two co-orbiting satellites with similar electro-optical sensors covering the infrared, visible and ultraviolet spectral regions. In order to obtain a 3D data base the satellites must operate with some significant angular separation to extract the vertical dimension. For example, the optimum separation for a point source is 90 degrees. This paper presents our joint modeling of this problem using a radiometrically validated computer simulation of three dimensional clouds, Cloudscape<sup>®</sup>, for cloud backgrounds as observed from space as a function of separation angle. Preliminary results, modeled in the visible, limit the separation angle because of the requirement for common recognizable features as seen from the different lines of sight. Vertical resolution as a function of separation angle and the approach used to derive three dimensions are discussed.

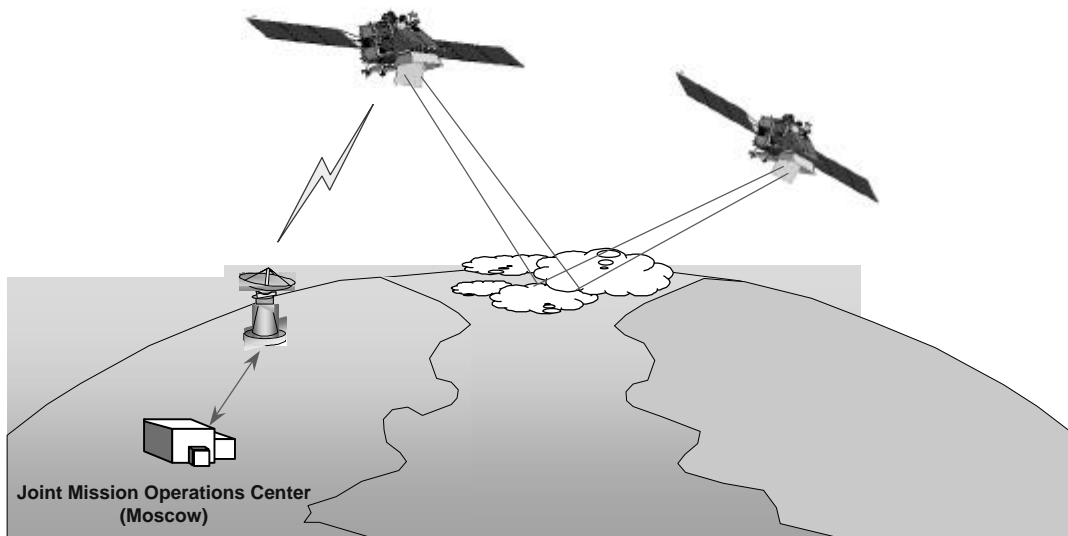
**Keywords:** remote stereo sensing, backgrounds, tracking, international cooperation.

## 1. INTRODUCTION

The scientific objective of the RAMOS program is to employ simultaneous stereo-optical techniques using a pair of co-orbiting satellites to address problems associated with space-based launch detection and tracking as well as global environmental issues (Figure 1). This stereo capability will enable multi-spectral stereo measurements of a variety natural Earth backgrounds including time-varying phenomena such as hurricanes, volcanic plumes and fires, polarization measurements of solar glints, 3-D wind velocity measurements, 3-D water vapor soundings and numerous other experiments. Our goal is to obtain data with 100-meter spatial resolution and stereo reconstructions with an altitude accuracy on the order of 100 meters. The results of these experiments will point the way toward improving existing technologies and developing new technologies for spaced-based defense-related and global environmental monitoring systems. A joint Russian-American science team is active in defining the objectives and preparing detailed plans for the experiments<sup>1</sup>.

Underlying this program is the goal of demonstrating the ability of the American and Russian defense agencies and their contractors to cooperate in important space-based experiments and compare independent analyses. Exchanging scientific data between the users in the two countries is a key component of RAMOS. A Joint Mission Operation Center (JMOC) in Moscow, Russia, will coordinate the functions of communication, spacecraft constellation maintenance, experiment execution, data collection and data distribution. The JMOC will be responsible for directing the satellites to perform an average of two experiments or data collection events (DCEs) per day over the life of the mission. Each DCE can be as long as 10 to 12 minutes of continuous

observations. The science data will be downlinked to the JMOC from the satellites, quickly validated, and distributed to both Russian and American science teams for further processing and analysis.



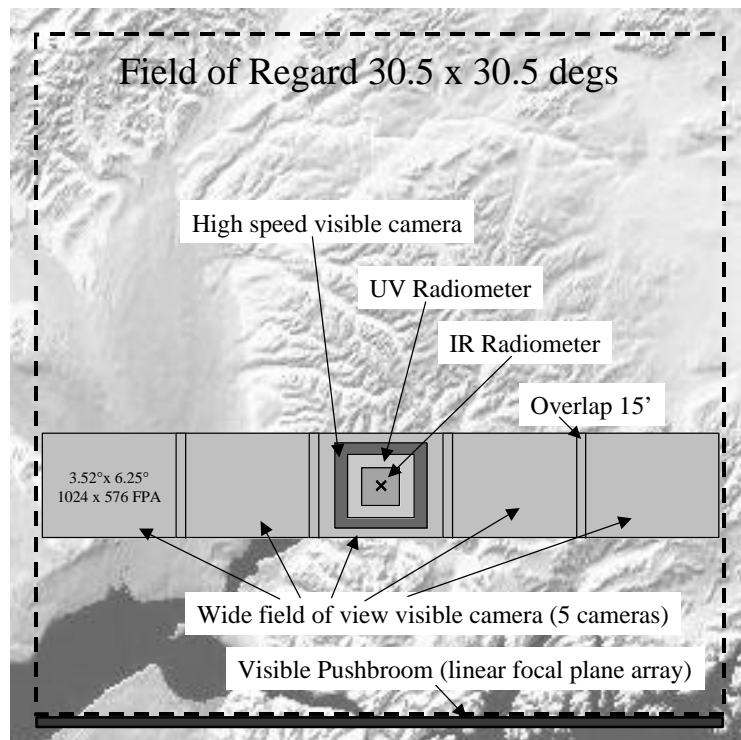
**Figure 1:** Orbiting approximately in the same plane at the altitude of 500 km, the pair of RAMOS satellites are designed to use their on-board passive electro-optical IR, visible, and UV sensors for near-simultaneous stereo-optical measurements in a variety of environmental and defense-related experiments.

RAMOS has a distinct advantage compared to earlier efforts that have carried out stereo measurements from orbit. Past programs made use of a single satellite to make observations from two vantage points relying on the satellite's orbital motion over time to provide a stereo baseline. This approach works well for static scenes where the features of interest are essentially motionless such as in topographic mapping of terrain. One of our goals in the RAMOS program is to make stereo measurements at ~100-meter accuracy level of temporally dynamic scenes containing clouds, plumes, and other atmospheric phenomena moving at speeds as great as 100 meters per second. The motion of features in such scenes can easily be great enough to totally mask the stereo-induced parallax signature we need to measure even if the pair of observations needed for stereo are separated in time by only a few seconds. In order to meet our measurement accuracy goals, it is necessary that the stereo observations be made virtually simultaneously. This can only be done with a pair of satellites making simultaneous measurements that are physically separated to produce the stereo baseline.

The two satellites, using the Russian Yacht universal space platform, will be placed into nearly identical 500-kilometer, high inclination orbits. The satellites will be capable of accurate pointing, attaining and maintaining the desired inter-satellite separation over a range of distances, accurately determining their respective positions, and conducting simultaneous observation of scenes of interest. The satellites will be equipped with American- and Russian-built instruments which can conduct radiometric, spectrometric, and polarimetric measurements. The nearly identical sets of instruments on the two satellites are grouped behind two pointing mirrors. The first mirror will point the SMWIR/MLWIR radiometer and the second mirror, slaved to the IR-instruments' mirror for co-registration, will support the wide field of view (FOV) matrix camera, the visible camera and the UV radiometer. In addition, a body-mounted visible push-broom scanner camera will make polarization measurements and cloud top height estimates with kilometer-level accuracy (less than  $1/10^{\text{th}}$  of the expected accuracy of the RAMOS stereo measurements).

The payload sensors can be pointed anywhere within  $30.5^\circ$  by  $30.5^\circ$  field of regard to provide flexible simultaneous measurements (Figure 2). The field of regard can be located over  $4\pi$  steradians by changing the attitudes of the satellites. The instrument suite on each satellite consists of the following:

- 1) A SMWIR/MLWIR radiometer, the primary instrument, with a pair of 128×128 detector arrays each with about 150 μrad/pixel IFOV (~ 1.1° total field of view) capable of operating in the 1.5 to 7.5 μm band;
  - a) Satellite 1: radiometer has multiple spectral filters and a polarization capability
  - b) Satellite 2: radiometer will be able to provide both image and spectral observations in SWIR to MLWIR bands (1.5 to 7.5 μm).
- 2) A co-aligned 3°×3°, high speed (=100 Hz) visible camera with a pixel scale similar to the SMWIR/MLWIR radiometer
- 3) A co-aligned wide field 3°×30° visible camera system consisting of five cameras featuring red, green, blue filters and other selected passbands on demand that provide adjacent, overlapped images for continuous wide field reconstruction
- 4) A multi-filtered, two-channel ultraviolet radiometer. One channel covers 200 to 300 nm with a 2.0°×2.6° field of view, and the other covers 300 to 400 nm with a 1.4°×1.4° field of view
- 5) A 30° wide FOV visible push-broom sensor designed to cover a wide swath of space with its linear detector arrays as the satellites move providing SWIR polarization and cloud top altitude data.



**Figure 2:** The payload sensor footprints can be pointed anywhere in a 30.5° by 30.5° field of regard, form a configuration with (1) 1° x 1° IR radiometer in the center, (2) a co-aligned variable FOV ultraviolet photometer, (3) a co-aligned 3° x 3° high speed visible camera, (4) a co-aligned wide field 3.52° x 30.5° visible camera system consisting of 5 cameras, and (5) a 30° wide FOV visible push-broom sensor that will cover the entire field of regard if the satellite moves in vertical direction on this figure.

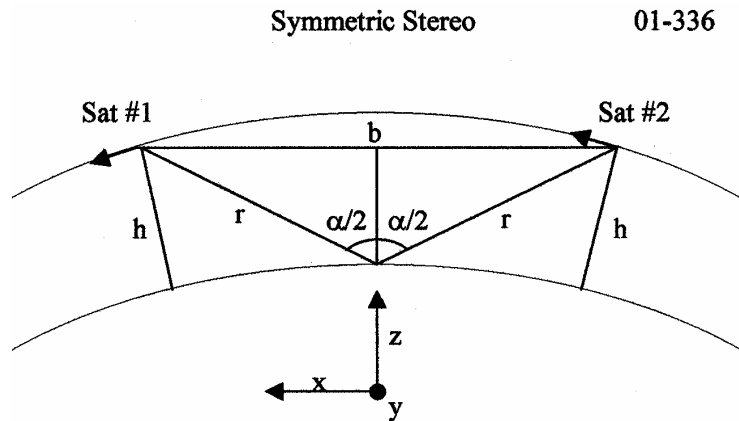
In principle, any matching set of instruments on the pair of satellites can be used to produce data for stereo analysis. At this time our plans are to use the SMWIR/MLWIR radiometer and the high speed visible camera as the primary instruments for gathering stereo data for the three-dimensional reconstruction of scenes.

## 2. CONSIDERATIONS FOR SELECTION OF OPTIMUM STEREO ANGLE

The accuracy of a stereo reconstruction is dependent on many factors including the size of the stereo angle. Here we define the stereo angle,  $\mathbf{a}$ , to be the full angle between the two lines of sight of the satellites as they observe a common point. This dependence can be illustrated by a simplified example of symmetric stereo where two observers triangulate on an object that is the same distance  $r$  from each observer. Assuming that the positions of the observers are precisely known, the uncertainty in the range from the observers to the object,  $\mathbf{D}r$ , can be approximated by the following equation:

$$\Delta r \approx \frac{r\Delta f}{\sqrt{2} \sin \mathbf{a}}$$

where  $\mathbf{D}f$  is the pointing knowledge uncertainty in radians. With this symmetric viewing geometry it can be seen that for a given range,  $\mathbf{D}r$  is a minimum when the stereo angle is equal to  $90^\circ$ . This angle is considered the optimum stereo angle when the goal is to minimize the uncertainty of a range determination from the observers.



**Figure 3:** Simplified diagram of symmetric stereo viewing geometry with  $h$  indicating the altitude of the pair of satellites,  $r$  is the slant range from the satellites to the point being observed,  $b$  is the stereo baseline and  $\mathbf{a}$  is the stereo angle.

For many RAMOS experiments the goal is not necessarily to accurately measure the range to a point in a scene. Instead we wish to accurately determine the height,  $z$ , of a cloud or other feature of interest above the Earth's surface so that various properties of objects in a scene can be correlated with their height. A simplified example of a symmetric stereo viewing geometry for this situation using satellites is shown in Figure 3. Here a pair of satellites, #1 and #2, in a common circular orbit around a spherical Earth at an altitude  $h$  and separated by a baseline distance  $b$  (resulting in a stereo angle  $\mathbf{a}$ ) are observing a common point on or near the Earth's surface halfway between the sub-satellite points in the orbital plane. Assuming that the positions of the satellites are known exactly, the uncertainty in the height determination of the observed point,  $\mathbf{D}z$ , can be approximated by the following equation:

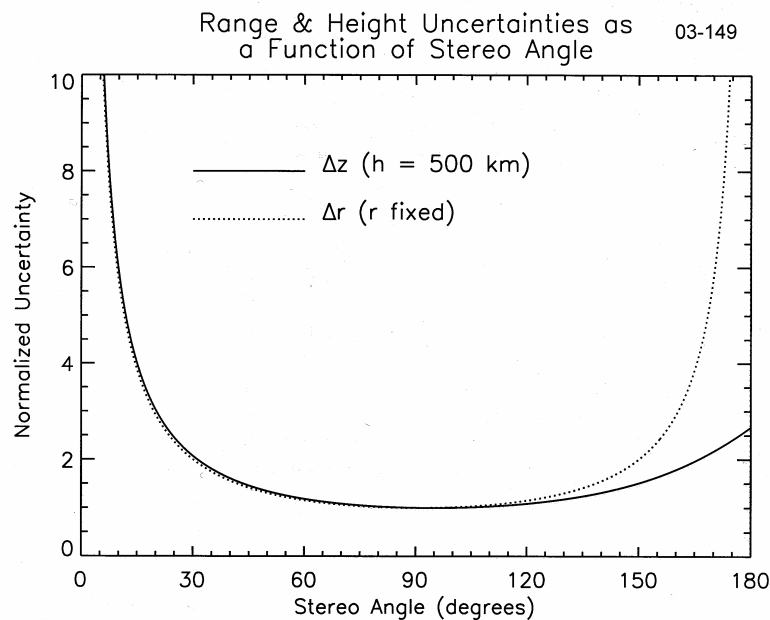
$$\Delta z \approx \frac{r\Delta f}{\sqrt{2} \sin(\mathbf{a}/2)}$$

The slant range,  $r$ , for this example is given by the following relation:

$$r = \sqrt{(R_e + h)^2 + R_e^2 - 2R_e(R_e + h) \cos\left(\frac{\mathbf{a}}{2} - \sin^{-1}\left(\frac{R_e \sin(\mathbf{a}/2)}{R_e + h}\right)\right)}$$

where  $R_e$  is the radius of the Earth.

The problem of making an accurate height determination is geometrically different from this first case where we wished to make an accurate range determination. With the satellite altitude,  $h$ , fixed, the range to the point being observed now varies as the stereo angle,  $\alpha$ , is changed. Before  $r$  remained constant as  $\alpha$  was varied. More importantly, the quantity we wish to measure,  $z$ , is not necessarily along the lines of sight of the observers as before but at an angle  $\alpha/2$  to the lines of sight. As the stereo angle opens up to towards  $180^\circ$  resulting in the observed object being seen closer and closer to the horizon, the determination of the object's height above the Earth's surface is less dependent on the results of range determination via stereo analysis. Instead the determination of the location of the object in the image plane (which is dependent on the stereo angle driven changes in  $r$ ) becomes the driver for the uncertainty in height. The differences in the results for these two cases are illustrated in Figure 4. The plot of normalized range and height uncertainties (where the plots have been scaled so that the minimum theoretical measurement uncertainty is equal to 1) shows that there are only minor differences between these two cases at stereo angles less than  $\sim 120^\circ$ . At larger stereo angles, the differences between these two cases become quite pronounced.



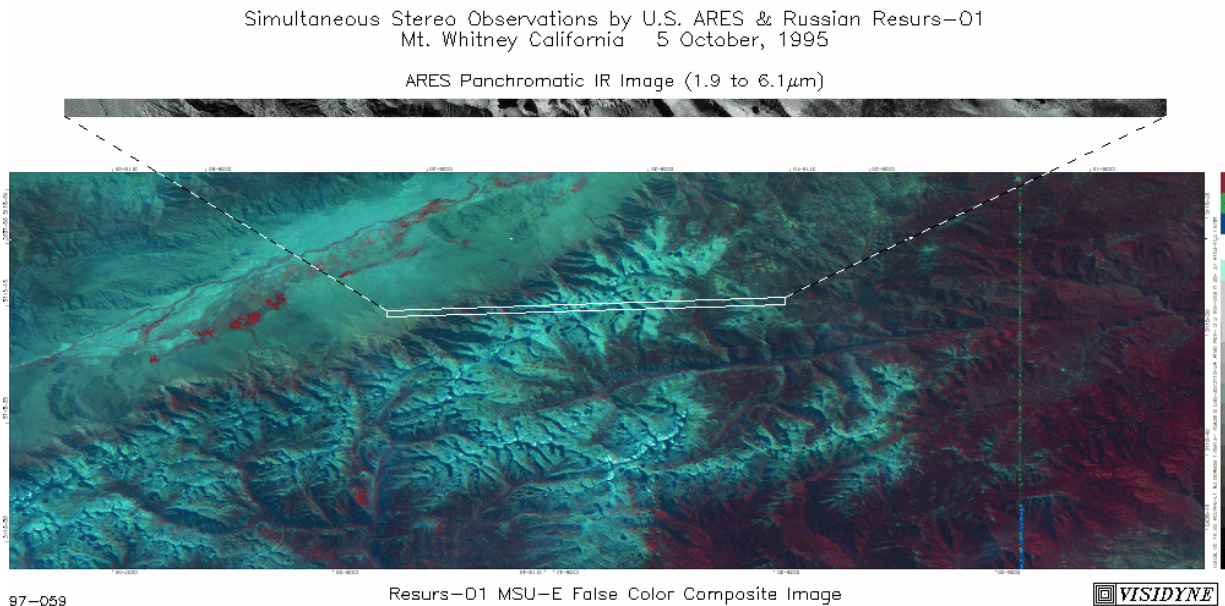
**Figure 4:** This plot illustrates the difference between the normalized uncertainties as a function of stereo angle for the determination of range (with a fixed range between the satellites and the observed target) and height (with the satellites' altitude fixed at 500 kilometers). The disparity between the plots, especially at stereo angles  $>120^\circ$ , are the result of the differences of what is actually being measured (range versus height) and, to a lesser extent, the subtle differences in the viewing geometries between the two cases.

As a result of the different quantities being measured (height instead of range) and a viewing geometry with a fixed satellite altitude where only the baseline length can be changed, the optimum stereo angle approaches  $90^\circ$  only as the altitude of the satellites comes close to the height of the point being observed. A relatively weak dependence on satellite altitude for this case results in an optimum stereo angle of  $\sim 94^\circ$  at the nominal 500 kilometer altitude of the RAMOS constellation. Other situations where the satellites are viewing a point away from the satellite ground track, asymmetric stereo viewing geometries, and cases where we wish to minimize the uncertainties in all three position coordinates of a point with respect to the geoid have also been investigated to determine optimum stereo angles. These will not be discussed in detail here since, as will be seen in the following sections, there are more than just purely geometrical issues that need to be considered when choosing the optimum stereo angle for a given experiment.

### 3. RESULTS OF EARLY STEREO EXPERIMENTS

Between July 1995 and December 1999 a series of joint Russian-American experiments were conducted using several different existing aircraft and spacecraft acting singly or in concert with each other in support of various RAMOS scientific and international objectives. Some of these experiments collected data suitable for stereo analysis. While the high fidelity pointing, position, and goniometric calibration data of the accuracy needed to perform stereo reconstructions with high absolute accuracy were not available, the images and supporting data were of sufficient quality to exercise stereo reconstruction algorithms under development to determine *relative* heights in scenes and begin tests of various data handling and processing procedures using “real” data.

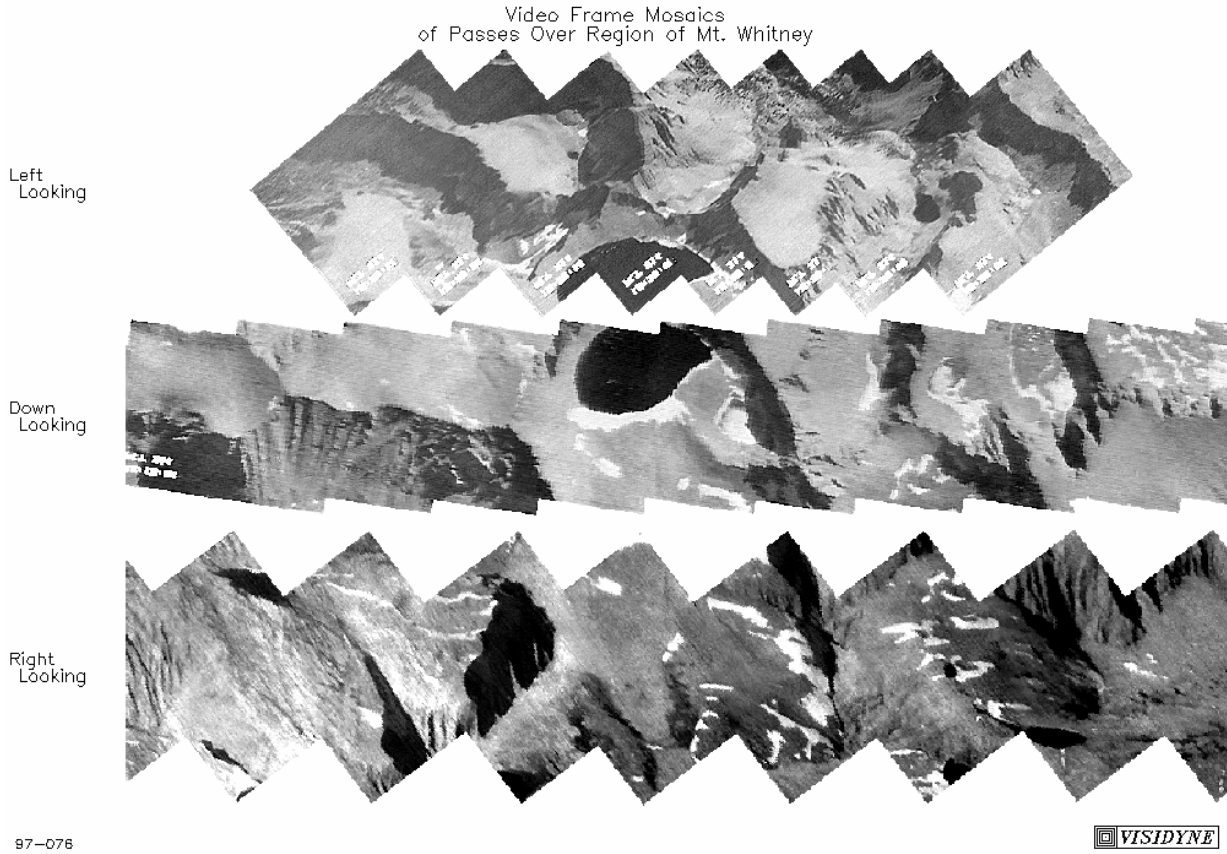
The first experiment to yield usable data for stereo analysis was conducted on October 5, 1995. Nearly simultaneous observations of the area surrounding Mt. Whitney in California were made using the Russian Resurs-O1 Earth resource satellite and the USAF ARES (Airborne Remote Earth Sensing) aircraft<sup>2</sup>. At this early stage of the program, the primary goals of the experiment centered on meeting basic international objectives including developing and demonstrating methods for joint scientific efforts as well as interaction methodologies for future cooperative efforts. Among the scientific objectives was to combine data from the Resurs-O1 MSU-E pushbroom imager and the ARES infrared spectral imager to produce a stereo reconstruction of the jointly observed region. While the international and many other scientific objectives were met, stereo analysis of the combined Resurs-O1 and ARES data sets was not possible as originally envisioned. First, the mismatch in the wavelengths used by the primary Resurs-O1 and ARES instruments (visible and SMWIR, respectively) caused selective contrast reversals in the scenes that complicated automated feature matching between the images. The limited number of spatial pixels in the ARES infrared spectral imager (only 45 pixels) combined with differences in image resolution (~45 meters for Resurs-O1 and ~13 meters for the ARES infrared spectral imager) also made it too difficult to perform meaningful stereo analysis with these data as originally intended (see Figure 5).



**Figure 5:** This is an enhanced-color version of the image taken by the MSU-E pushbroom scanner on the Resurs-O1 satellite with the location of the ARES IR spectral scanner image shown along with a sample image. The target of this experiment, Mt. Whitney in California, is located near the middle of the ARES image swath.

While stereo analysis of the combined ARES and Resurs-O1 data sets was not possible, stereo analysis was possible using ARES data from its three passes over Mt. Whitney during the mission: One with the instruments looking 45° to the port side of the flight path (i.e. “left-looking”), one looking towards nadir (i.e. “down-looking”), and a last run with the instruments looking 45° to the starboard side (i.e. “right-looking”). Since there

were no clouds or other time-variable features visible in the vicinity of Mt. Whitney during the observation period, images from different legs of the ARES flight over the area in principle could be used in a stereo analysis of the region's surface topography. The availability of US Geological Survey topographic maps to check our stereo reconstruction results would also be possible. It was hoped that infrared spectral images from two different legs could be combined to produce image pairs with a stereo angle of 45° or even as much as the optimum 90°. Mosaics of selected visible-light tracking video frames that were boresighted with the infrared spectral imager made during these three passes are shown in Figure 6.



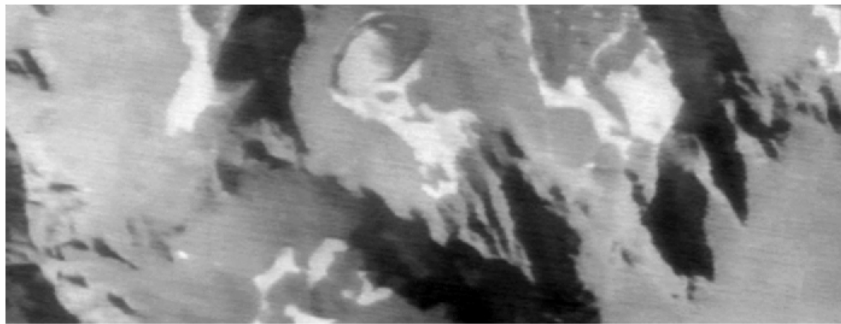
**Figure 6:** Mosaics of video images obtained during the three passes of the ARES aircraft over Mt. Whitney. From the top image swaths are from the left-looking, down-looking, and right-looking passes over the area. Tulainyo Lake is at the center of the image swaths and Mt. Whitney is located about a quarter of the way in from the right edge. The lack of sufficient overlap between the swaths and geometric distortions caused by the 45° stereo angle prevented stereo analysis of images from different legs over Mt. Whitney.

Detailed analysis of the video and infrared data showed that there was no overlap between the side-looking legs near Mt. Whitney eliminating the possibility of analysis of the ARES data with a geometrically optimum 90° stereo angle. In addition, there was little overlap between the left-looking and down-looking swaths. A detailed comparison of the down- and right-looking runs with a stereo angle of 45° did show adequate overlap but revealed a major problem for analysis: The steep gradients in surface elevation combined with the relatively large stereo angle yielded views whose appearance differed too much for semi-automated stereo processing algorithms to match features accurately between stereo pairs. A close examination of the images like those in Figure 6 show that even human observers have a difficult time matching features in the images despite their superior built-in pattern recognition “software”. This analysis clearly demonstrated that more than just purely geometrical arguments need to be considered when choosing an optimum stereo angle for stereo reconstructions of real scenes.

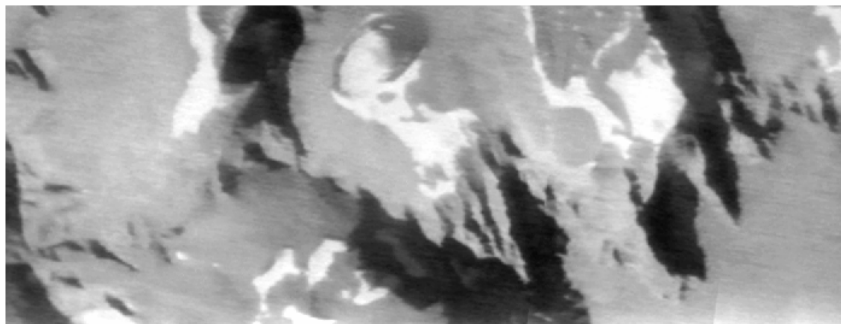
Working against the improvement in stereo reconstruction accuracy expected as the stereo angle increases towards the optimum of  $\sim 90^\circ$  is an increased inability to accurately identify and match up features in stereo pairs of scenes with substantial variations in the altitude of the visible surface. For this particular scene, the optimum stereo angle was not only less than the geometric optimum of  $90^\circ$  but less than even  $45^\circ$ .

To simplify our initial attempt at stereo analysis, video images frame-grabbed directly from the VHS recording of only the down-looking run over Mt. Whitney were used for stereo analysis. The images had a 6.8 degree wide field of view (FOV) yielding an image scale of  $\sim 2$  meters/pixel from the aircraft's nominal altitude of 11.8 kilometers. It was recognized that as a feature moved through the tracking video camera images, we were observing that feature through a range of angles equal to the camera's 6.8 degree FOV. In order to obtain a pair of large stereo images to analyze, two mosaics were assembled from 18 individual video images taken from the mission's VHS recording at approximately one second intervals. A "left" image was assembled using a 80-pixel wide image strip or framelet from the right side of each video frame. A matching "right" image was assembled from 80-pixel wide framelets from the left side of each video frame. These framelet mosaics, shown in Figure 7, yielded a pair of 1050 by 400 pixel stereo images covering an area of approximately 2.0 by 0.8 kilometers with an equivalent stereo angle of about 2.5 degrees. We refer to reconstructions using such data as small-angle stereo.

Small Angle Stereo Mosaics From Down-Looking ARES Video Frames



"Left" Image Mosaic



"Right" Image Mosaic

97-085

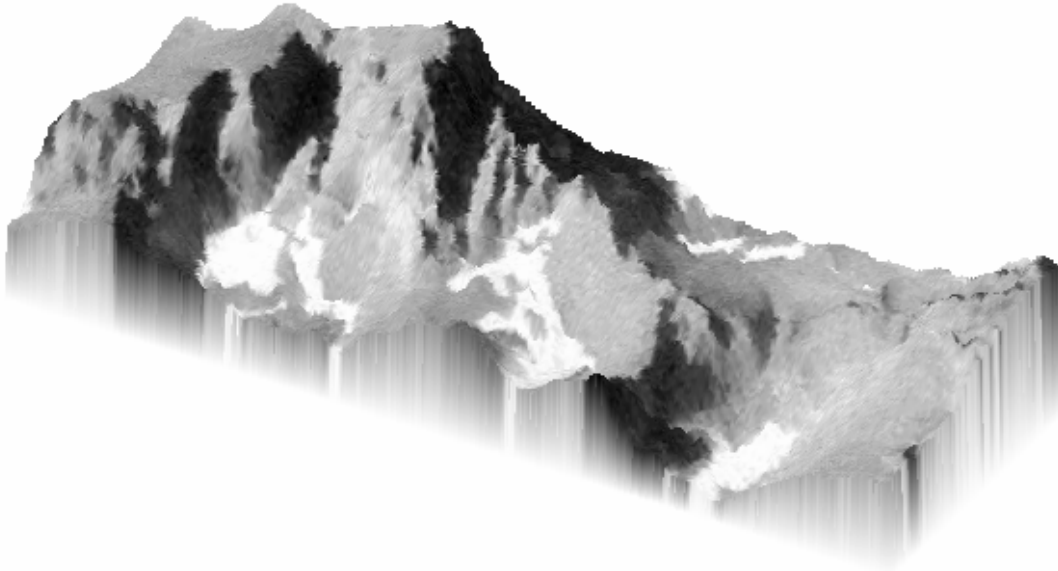


**Figure 7:** This is the stereo image pair used in our initial analysis made by mosaicking sections of individual frame-grabbed video images from the down-looking pass over Mt. Whitney. This yielded images with a stereo angle of  $\sim 2.5^\circ$ . Mt. Whitney is located at the bottom and to the right of the image center and a partially snow-covered Iceberg Lake is located at the top and to the left of the image center.

A visual inspection of the small-angle stereo image pair in Figure 7 shows that they are nearly identical in appearance making it much easier for feature matching algorithms to work properly. Although it is not readily apparent to the eye, parallax effects in the scene resulted in easily measured relative displacements on the order of about a dozen pixels. While there was no goniometric calibration data available and the attitude and pointing information provided did not have the temporal resolution or measurement accuracy needed to determine absolute

heights of features in the scene, the supporting data were of sufficient quality to produce a visually convincing three dimensional reconstruction of Mt. Whitney which provided relative height information with an uncertainty of ~30 meters as shown in Figure 8. While this exercise provided convincing evidence of the utility of small angle stereo, data with significantly larger stereo angles that should yield more accurate results was needed.

### 3D Reconstruction of Mt. Whitney from ARES Video Images



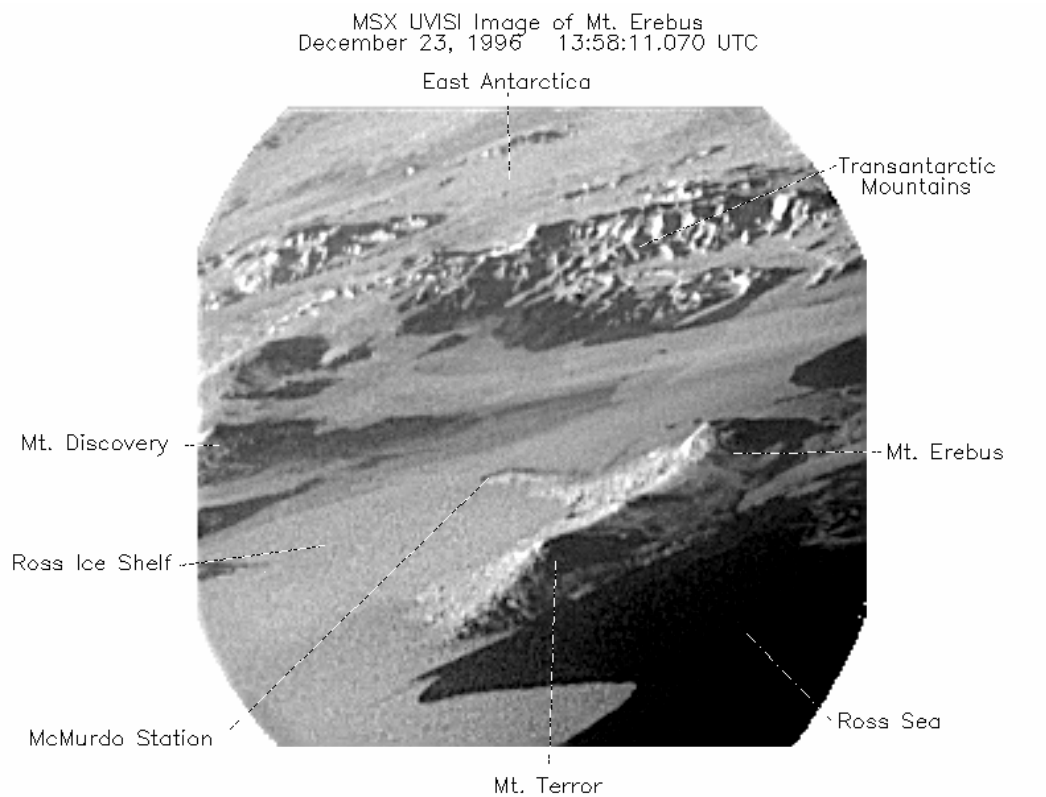
97-089



**Figure 8:** A view of the stereo reconstruction of Mt. Whitney using small-angle stereo measurements from ARES video images.

Based on our initial experiences, another joint stereo experiment was performed using the Russian Resurs-O1 satellite again and, instead of an aircraft, the American MSX satellite<sup>3</sup>. Because of the angle between the orbital planes of these near-polar orbit satellites, conjunctions suitable for stereo experiments would only occur in the polar regions. After an analysis of the orbits of these satellites, it was decided that the target for this experiment would be Mt. Erebus at the edge of the Ross Ice Shelf in East Antarctica. Clouds are typically present in this region and Mt. Erebus, which is an active volcano, usually displays a steam plume coming from its summit. This made Mt. Erebus a desirable target for investigating stereo reconstruction issues with clouds. Orbit predictions showed that the two satellites would be able to simultaneously observe the summit of Mt. Erebus on December 23, 1996 at 13:59:22 GMT.

One of the images taken by the UVISI Camera on MSX, shown in Figure 9, provides oblique view of the region providing context for what was observed at the time of this experiment. Much to our disappointment, there were no clouds visible nor even a plume coming from Mt. Erebus – a rare occurrence indeed. While we were not able to make any stereo measurements of cloud heights as we originally intended, it was possible to do stereo analysis of the topography of Mt. Erebus as we had done with Mt. Whitney 15 months earlier. Unlike the experiment over Mt. Whitney, the satellite images gathered would be of comparable image scale and wavelength band easing data processing issues and use a more modest stereo angle of ~25°

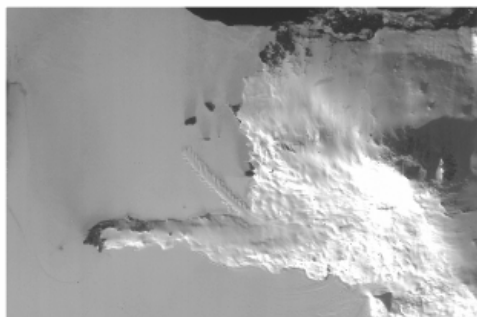


97-122

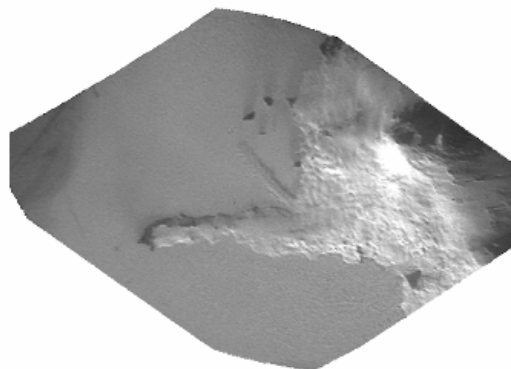


**Figure 9:** An oblique view of the area around Mt. Erebus as it appeared at the time of our stereo observations on December 23, 1996.

Preliminary Mt. Erebus Stereo Pair



Rescaled Resurs-O 1 MSU-E Image



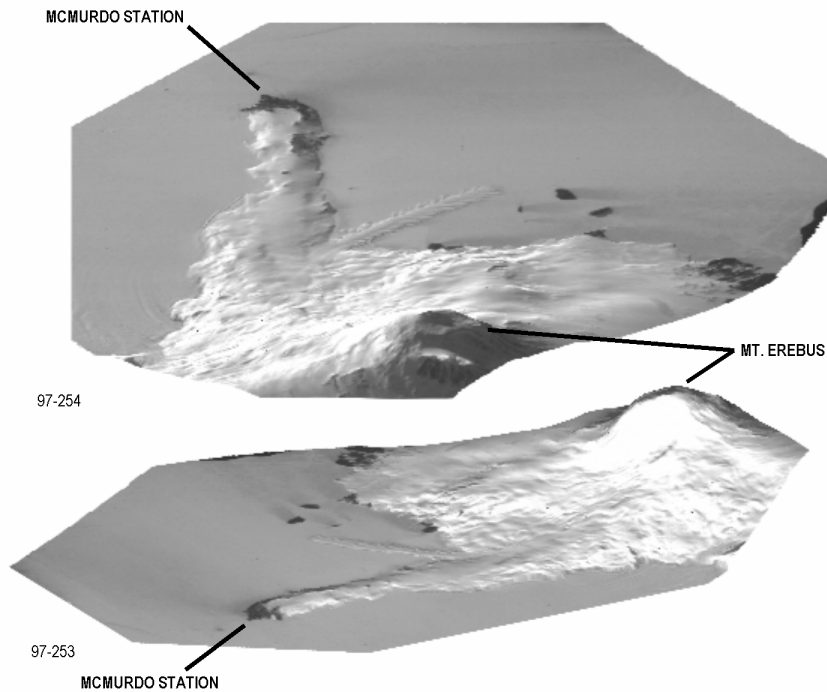
Rectified MSX UVISI Image

97-252



**Figure 10:** Geometrically rectified and rescaled versions of the Resurs-O1 and MSX images used in the stereo analysis of Mt. Erebus.

.Resurs-O1 made its observations from the south of Mt. Erebus and the MSU-E images had an image scale of 34 meters/pixel along the ground track and 62 meters/pixel perpendicular to it. MSX obtained data using several of its instruments but the visible-light images obtained from the UVISI Camera were deemed most useful for the stereo analysis. Of the 795 usable images secured by the UVISI camera during its pass over Mt. Erebus, one of the near-nadir viewing images with an image scale of ~120 meters/pixel was used for the stereo analysis. These images were geometrically rectified and remapped to a common image projection and scale, as shown in Figure 10, for analysis using the available orbit ephemeris and pointing data.



**Figure 11:** Two views of the stereo reconstruction of Mt. Erebus using images obtained by Resurs-O1 and MSX during their joint observation made on December 23, 1996.

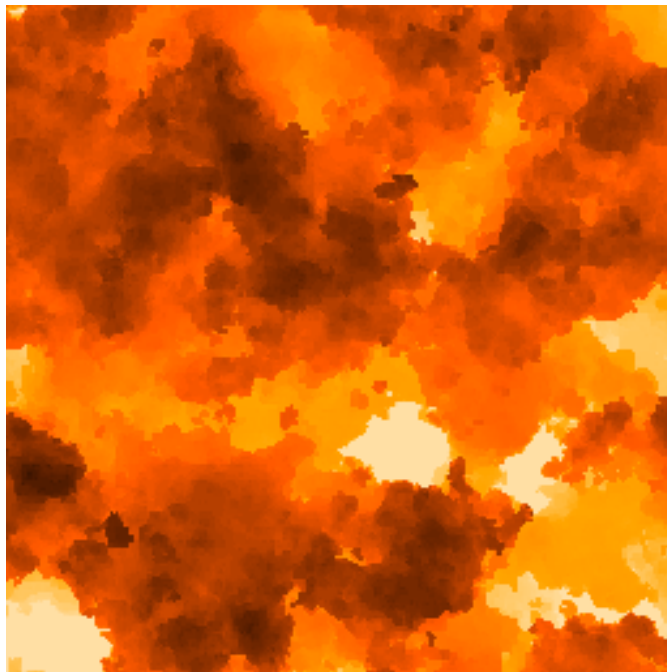
A lack of detailed goniometric calibration, precision pointing and position data for both satellites made it impossible to do a meaningful quantitative analysis of the Mt. Erebus stereo reconstruction as was done for Mt. Whitney. The instruments employed for this experiment were simply not intended for this kind of work. However, the images were of excellent quality which allowed us to exercise portions of our stereo reconstruction algorithms and map the relative displacement of features in the stereo pair. The results of this analysis, where the relative feature displacements were scaled to yield an approximation of a bona fide stereo reconstruction, is shown in Figure 11. Despite the shortcomings in the availability of ancillary data needed to do a quantitative stereo analysis, the experiment did provide valuable experience in joint planning of experiments, demonstrated that many of the problems in sharing data encountered earlier had been overcome, and provided qualitatively useful data for development of stereo reconstruction algorithms.

This experiment also clearly demonstrated that scenes displaying a large range of relief over short distances, as would be observed in thunderstorms, hurricanes and other scene-types of interest to RAMOS, could be successfully analyzed with a stereo angle as large as  $25^\circ$  - an angle ten times larger than the small-angle stereo used in the analysis of the ARES data from Mt. Whitney. While intuitively it would seem that the optimum stereo angle for scene reconstruction would depend on the surface gradients in the scene, the experience with the experiments over Mt. Whitney and Mt. Erebus suggests that it could be as large as the  $25^\circ$  but smaller than  $45^\circ$  -

an angle range that is half to one third the size of the geometrically optimum angle of  $\sim 90^\circ$  initially considered for RAMOS stereo experiments.

#### 4. INITIAL RESULTS OF RECENT INVESTIGATIONS

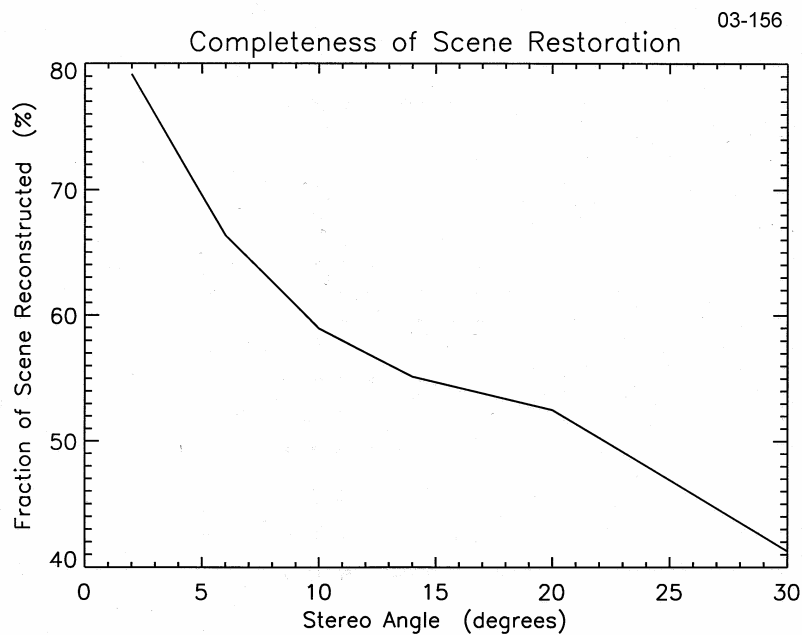
In order to better determine what the optimum stereo angle or range of angles should be for different RAMOS experiments for a variety of scene types over a range of viewing and lighting geometries as well as wavebands, a more detailed and systematic investigation needed to be performed. Available image archives do not have the data needed for such a rigorous study and the required resources associated with gathering the required data using existing aircraft and spacecraft specifically for RAMOS was beyond the scope of the program. Instead it was decided to synthesize realistic images for these detailed studies using CloudScape<sup>®</sup> 4, 5. With a large range of available cloud databases, this program can generate geometrically and radiometrically accurate images of a scene where not only the stereo angle but the waveband, lighting geometry, viewing geometry, season and other important parameters can be varied. Such images allow us to study various stereo reconstruction issues for a range of scene types in a controlled, systematic fashion.



**Figure 12:** A nadir view of the MLWIR scene generated by CloudScape<sup>®</sup> that was used in our initial systematic investigations to determine the optimum stereo angle as a function of various scene and viewing parameters.

For our initial investigations, a highly stressing scene with broken cumulonimbus clouds interleaved at various altitudes ranging from 4.5 to 9.5 kilometers was generated. Stereo pairs in the baseline RAMOS MLWIR band ( $\lambda = 5.4 - 7.2 \mu\text{m}$ ) were the first to be generated using a symmetrical viewing geometry like that shown in Figure 3. Each  $1024 \times 1024$  pixel image was generated for the nominal RAMOS constellation altitude of 500 kilometers with a FOV of  $2^\circ$  for stereo angles ranging from  $0^\circ$  to  $120^\circ$  with the lines of sight for the image centers intersecting at an altitude of 7 kilometers. The cloud database used to generate these images had a horizontal resolution of 50 meters and a vertical resolution of 25 meters – both smaller than the nominal spatial footprint size and stereo reconstruction accuracy expected for RAMOS. A nadir-viewing sample image of the first MLWIR images analyzed is shown in Figure 12.

The first step in our investigation was to determine what fraction of the scene could be reliably reconstructed as a function of stereo angle. The image pairs for each stereo angle were first remapped to a common scale and projection as would be done with actual satellite data. One of the images was then subdivided into a series of subimages large enough to contain at least one distinct feature – typically 15×15 or 25×25 pixels depending on the viewing geometry. A cross correlation algorithm was then used to determine the position where the feature-laden subimage matched the features in the undivided second image. The size of the search zone for the second image used in the feature matching algorithm varied with viewing geometry. For the smaller stereo angles of interest to us, the search zone size, in pixels, was ~5× larger than the stereo angle when measured in degrees. For example, the search zone for a 25×25 pixel subimage when the stereo angle was 20° was 103 pixels. Limiting the size of the search zone not only increases computational efficiency of the image processing but also decreases the likelihood of an erroneous feature match. For this initial analysis, a correlation threshold of at least 0.9 was set as a conservative criterion for a positive match between features in the stereo pair. The fraction of the reconstructed scene that met this criterion as a function of stereo angle for a symmetric stereo geometry is shown in Figure 13.



**Figure 13:** This plot shows the fraction of the generated CloudScape<sup>0</sup> scene shown in Figure 12 that can be reliably reconstructed by stereo analysis. This scene is recognized to be very stressing with clouds interleaved over a range of altitudes. Less structured scenes with a narrower range of cloud altitudes visible should yield even better results.

As expected, the fraction of the scene that yields an accurate feature match is the highest at small stereo angles since the geometrical distortions of three-dimensional features in a stereo pair are the smallest. As the stereo angle increases, the fraction of the scene that can be reliably reconstructed decreases as geometric distortions caused by stereo effects in this complex scene increases. Less than half of this scene under the conditions tested can be reliably reconstructed at stereo angles exceeding 24°. Another factor that contributes to the poorer correlation as the stereo angle increases that was not a major concern during our earlier experiences with Mt. Whitney and Mt. Erebus is the classic problem of hidden surfaces. The lower altitude clouds in this scene are frequently only visible through small breaks in the higher altitude cloud decks. As the stereo angle increases, different parts of the underlying cloud decks are visible to each satellite through these breaks making it more difficult or impossible to match features.

A detailed analysis of the accuracy of the stereo reconstruction is still ongoing but there is evidence for a broad minimum in altitude uncertainty ranging from  $\sim 8^\circ$  to  $>30^\circ$ . The relationship between the accuracy of the stereo reconstruction, stereo angle, and scene type are still being investigated. But based on the completeness of the scene restoration and the initial estimates for accuracy of the reconstruction, a stereo angle in the  $\sim 8^\circ$  to  $\sim 24^\circ$  range would yield a good balance between accuracy and completeness for this scene. This range is in general agreement with the  $15^\circ$  to  $30^\circ$  optimum stereo angle range estimate that we had provisionally adopted earlier (based on results from stereo experiments and the earliest CloudScape<sup>®</sup> image analysis) for the purpose of deriving system requirements and initial experiment plan development.

It should be emphasized that this first scene to be analyzed is recognized by us to be a very stressing example for stereo reconstruction owing to the complexity and scale of the scene structure and the wide range of cloud altitudes interleaved over short distances. A reconstruction of a less stressful scene, such as one with a deck of clouds exhibiting observable structure but more limited variations in altitude would be expected to have a substantially larger fraction of completeness at a given stereo angle than this first scene and could probably be successfully analyzed with larger stereo angles. Additional scenes with different cloud types, structure and altitude ranges have been generated for analysis. Other viewing geometries including symmetric stereo for stare points well away from the satellite ground track and asymmetric stereo will also be investigated. The results of these analyses, in combination with other information that has been and will be gathered, will be used to determine the optimum stereo angle needed to meet RAMOS science objectives for various target scenes types.

## 5. CONCLUSIONS

Based on our initial analysis of synthetic scenes, the results from our experiments over Mt. Whitney and Mt. Erebus and our geometrical studies, we have provisionally adopted a typical optimum stereo angle for scene reconstruction in the  $15^\circ$  to  $30^\circ$  range for the purpose deriving system requirements and initial experiment plan development. This is less than one third of the optimum stereo angle based on geometrical considerations alone. Future results from the stereo analysis of synthesized images of this and other scene types under a wide range of anticipated conditions will allow us to better determine the actual range of ideal stereo angles for individual RAMOS data collection events.

## 6. REFERENCES

1. A.T. Stair, Jr., J. Carpenter, O. Shepard, D. Burt, A. Steed, J. Watson, K. Fielding, S. Goodrich, *RAMOS (Russian American Observational Satellites) and Supporting Joint Experiments*, Proceedings of **1998 IEEE Aerospace Conference**, Volume 5, pp 103 –113, 1998
2. A.J. LePage, A.T. Stair, O. Shepherd, J. Carpenter, A. Savin, V. Sinelshchikov, V. Abramov, *Preliminary Results from Stereo Analysis of EXPRESS Data*, Proceedings of **IRIS TBD Space Surveillance Meeting** (APL/JHU, Laurel, MD, June 4, 1997), 1997
3. C.H. Humphrey, A.J. LePage, R.J. Jordano, A.T. Stair, Jr., O. Shepherd, R.P. Pauliukonis, R. O'Neil, H.A.B. Gardiner, G. Romick, D. Morrison, A. Savin, V. Sinelshchikov, V. Abramov, *Stereo Analysis of EXPRESS and MSX Data Over Mt. Erebus*, Proceedings of **IRIS TBD Space Surveillance Meeting** (APL/JHU, Laurel, MD, June 4, 1997), 1997
4. J.G. DeVore, J.H. Thompson, R.J. Thornburg, *CloudScape<sup>®</sup>: Stochastic Clouds Visualization from Volumetric Descriptions*, Proceedings of **Cloud Impacts on DoD Operations and Systems 1995 Conference** (Phillips Laboratory/GPAA, Hanscom AFB, MA), D. Grantham (ed.), pp 41-44, 1995
5. J.G. DeVore, J.H. Thompson, K.W. Sartor, T.L. Stephens, R.J. Thornburg, *CloudScape<sup>®</sup> VR: Radiometric Visualization of Clouds for Interactive Training and Simulation*, Proceedings of **Cloud Impacts on DoD Operations and Systems Conference** (Phillips Laboratory, Hanscom AFB, MA), 1997