Contour mapping of Europa using frequency diverse, spatial heterodyne imaging

R. L. Kendrick*[a] , Thomas Höft[b] , J. C. Marron[b] , Joe Pitman [a], Nathan Seldomridge[b]
[a] Lockheed Martin Advanced Technology Center, 3251 Hanover St., Palo Alto, CA 94304
[b] Lockheed Martin Coherent Technologies, 135 Taylor Avenue, Louisville CO 80027

ABSTRACT

Three dimensional imaging of planetary and lunar surfaces has traditionally been the purview of Synthetic Aperture Radar payloads. We propose an active imaging technique that utilizes laser frequency diversity coupled with spatial heterodyne imaging. Spatial heterodyne imaging makes use of a local oscillator which encodes pupil plane object information on a carrier frequency. The object information is extracted via Fourier analysis. Snapshots of the encoded pupil plane information are acquired as the frequency of the illumination laser is varied in small steps (GHz). The resulting three-dimensional data cube is processed to provide angle-angle-range information. The range resolution can be adjusted from microns to meters simply by adjusting the range over which the illuminator laser frequency is varied. The proposed technique can provide fine resolution contour maps of planetary surfaces having widely varying characteristics of importance to science exploration, such as the search for astrobiological habitat niches near the surface of heavily irradiated Europa. This information can be used to better understand the geological processes that form the surface features, and help characterize candidate potential habitat sites on the surface of Europa and other planetary bodies of interest. In this paper we present simulations and experimental data that demonstrate the concept.

Keywords: Spatial Heterodyne imaging, Holographic Laser Radar, Inter-planetary imaging

1. INTRODUCTION

The advent of long coherence length lasers has enabled many interferometric measurement techniques that were previously difficult or impossible to perform. Lasers with mega-meter coherence lengths are now readily available as off-the-shelf items. In this paper we consider an interferometric measurement technique known as spatial heterodyne detection for measuring interferometric data. Additionally, we use Holographic Laser Radar[1] (HLR) for acquiring three-dimensional object information. HLR was originally demonstrated by mapping small (millimeter) surface contours of objects over short ranges. Long coherence length lasers enable HLR to obtain large or small surface contour information over ranges of 100s of Kilometers. We propose using HLR for measuring the surface contours of Europa from science orbits ranging from 100-200 km during a mission to the Jovian system. In this paper we will describe the HLR technique and show example data from laboratory experiments on samples that are scaled models of Europa's surface. We will also describe parameters that define the key characteristics of our HLR instrument concept for use on a mission to Europa.

A recent study released by the NASA Outer Planet Assessment Group (OPAG)[2] defined six objectives for a mission to Europa. Three of these objectives can be addressed directly with an HLR system. These are:

1) Characterize the ocean through its effects on potential fields and dynamic relationship with the ice shell.

2) Characterize processes operating within the ice shell, and the nature of ice-ocean exchange.

3) Understand the formation of surface features, including sites of recent or current activity, and identify candidate sites for *in situ* exploration.

*rick.kendrick@lmco.com, 650-424-2085

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Objective #1 can be addressed by measuring the relative surface motion of the ice shell over the tidal cycles that will distort the ice shell, as many have suggested are present.[3,4,5] Surface contour maps taken at various times during the tidal cycle can be subtracted to determine if any large scale deformations have occurred. The OPAG lists four sub-objectives for Europa objective #2. One of these - "Correlate surface features and subsurface structure"- can be addressed with HLR. Very fine resolution (millimeter to micron) contour maps can be examined to determine the nature of fine surface features. This information can be used in modeling the subsurface structure and processes that formed the surface and subsurface features. OPAG's Europa objective #3 also has four sub-objectives that can be investigated using HLR:

1) Characterize magmatic, tectonic, and impact features.

2) Search for areas of recent or current geological activity.

3) Assess surface ages.

4) Assess processes of erosion and deposition.

All of these sub-objectives can be addressed with HLR by, again, carefully examining the very high topographic resolution data that is acquired. The HLR technique is, of course, not limited to long range measurements. The technique also lends itself to a landed science package or rover mission where sub-micron range resolutions would be of interest. One of the main strengths of the HLR concept is the ability to vary the range resolution by varying the wavelength of the illumination laser during science operations.

2. CONCEPT DESCRIPTION

The HLR technique is an extension of traditional holography and is described in detail in references 1 and 6. We will give a very brief overview in this paper. With traditional holography, a coherent source is used to illuminate an object. Part of the coherent source is split from the illuminator beam and used as a reference. The reference beam and object wavefront interfere and the interference pattern is recorded using a 2D detector array. This data then yields a complex-valued image by computing the Fourier transform and extracting a single image term. This process is often referred to as spatial heterodyne detection. In HLR, a series of these holograms are recorded as the wavelength of the illuminator is shifted in very small increments. The result is a three dimensional data cube with angle, angle and wavelength as the coordinates. The data cube is then Fourier transformed in three dimensions to extract angle, angle and range information. The angular resolution of an HLR system is defined by the typical optical resolution equation.

$$\text{Resolution}_{\text{angle}} = R\,\lambda/D \tag{1}$$

Where λ is the illuminator wavelength, D is the limiting aperture of the optical system and R is the range to the target. The range resolution of an HLR system is given by

$$\text{Resolution}_{\text{range}} = \lambda^2 / (2\,\Delta\lambda) \tag{2}$$

Where λ is the wavelength of the illuminator laser and $\Delta\lambda$ is the total wavelength range over which the illuminator laser is tuned. The "unambiguous" range is given by

$$\text{Range}_{\text{unambiguous}} = \lambda^2 / (2\,\Delta\lambda_{\text{inc}}) \tag{3}$$

Where again, λ is the wavelength of the illuminator laser and $\Delta\lambda_{inc}$ is the wavelength step size that is taken when the illuminator laser is scanned in wavelength as defined for equation 2. The unambiguous range is the range over which there will be no 2π ambiguities. There will be phase wrapping if the unambiguous range is exceeded. This in itself is not a problem for smooth surfaces but it will complicate the analysis for objects that have sharp discontinuities. Equations 1, 2 and 3 can be used to estimate the basic parameters for a HLR system.

We will use the following parameters for a Jovian mission that will image Europa. The range for high resolution 3-d laser remote sensor imaging will be from the assumed 100 km science orbit[7,8]. The reference aperture will be the 1.5

meter diameter MIDAS payload concept[9] selected by NASA/HQ in 2004 for study as a candidate science payload on a mission to Europa[10]. Figure 1 shows the MIDAS payload concept. The wavelength of the illuminator laser will be set as 1.55 µm. Given these parameters the angle resolution given by equation 1 is 10 cm. The range resolution given by equation 2 is governed by the wavelength range. For example to have a range resolution of 1 centimeter the wavelength scan range must be 0.12 nanometers. The step size for an unambiguous range of 1 meter is 1.2 picometers. In frequency units this would be a step size of 0.15 Ghz. A variety of range resolutions can be obtained simply by changing the wavelength step size and range.

The MIDAS concept provides an adaptable payload concept which can easily accommodate a payload instrument that includes an illuminator laser. The apertures can time share between illuminate and receive operations, or one (or more) of the apertures can be used as the transmit channel while the remainder are used as collectors.

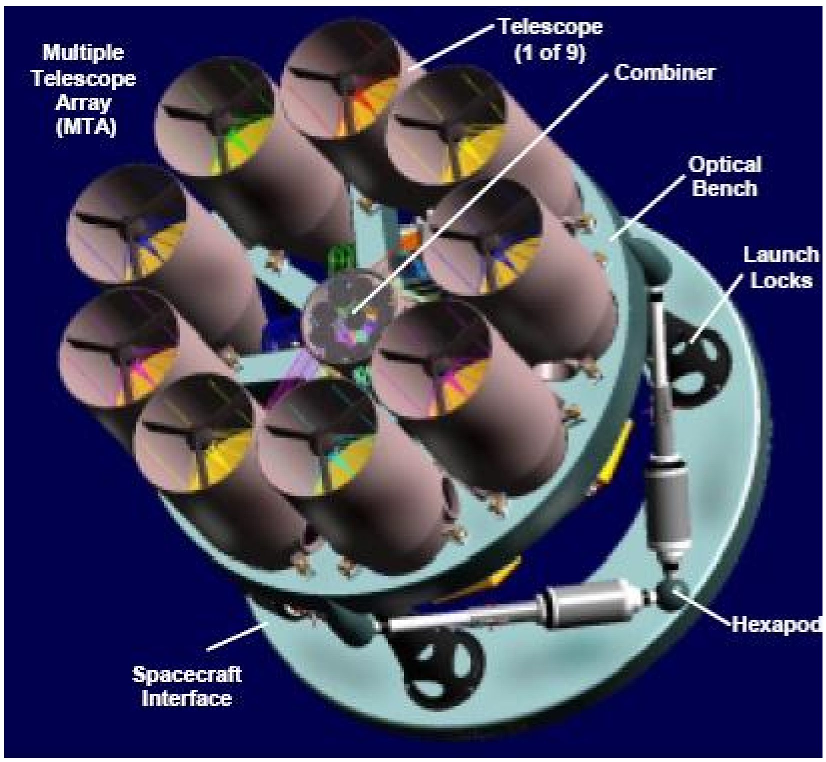


Fig. 1. A schematic of the MIDAS concept is shown. The multiple apertures can be grouped into transmit and receive channels.

3. EXPERIMENT

Figure 2 is a schematic of the laboratory experiment. The laser diode beam is collimated into a two cm by one cm beam that is split into a Local Oscillator (LO) and the object beam. The object beam illuminates the object and returns off of the second beam splitter into the CMOS array. This beam manifests itself as a speckle pattern on the focal plane. The local oscillator reflects off a mirror and onto the CMOS array and combines with the object speckle pattern. The LO beam has a prescribed amount of tilt with respect to the object beam. This results in a fine fringe pattern across the object beam speckle. There are approximately two fringes per speckle.

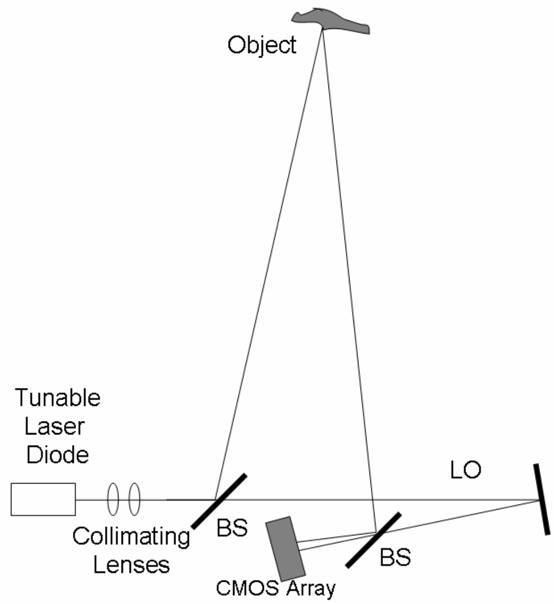


Fig. 2. A schematic of the laboratory experiment is shown with the major components labeled. BS is a non-polarizing beam-splitter. LO is the local oscillator leg of the interferometer.

A New Focus tunable diode laser is used as the source. The laser power is approximately 4 mW. The laser was tuned from 769.83 nm to 770 nm for these experiments. Various step sizes up to the full tuning range were used for the experiments described in this paper. A Lumenera L250 CMOS array was used to acquire the data. This array is a 1280 by 1024 pixel CMOS chip that uses a USB2 connection for control and data transfer. The exposure times are ~70 msecs in order to freeze any turbulence. The data acquisition and analysis are performed using MATLAB. All of the equipment items in the test bed are commercial-off-the-shelf components.

4. RESULTS

Figure 3 is a photograph of a rock that was imaged in the test bed. A small area has been gouged out of the surface, a few millimeters deep. The rest of the features on the rock are under 1 mm in size.

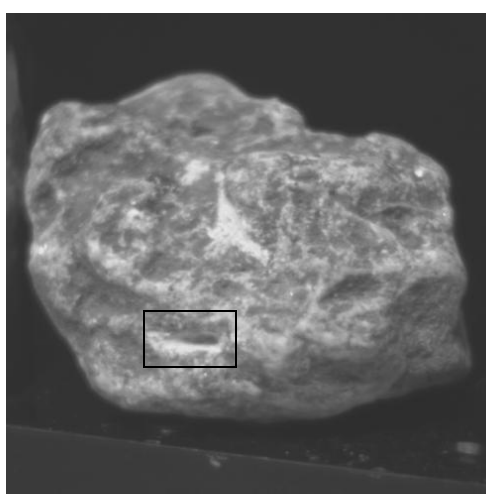
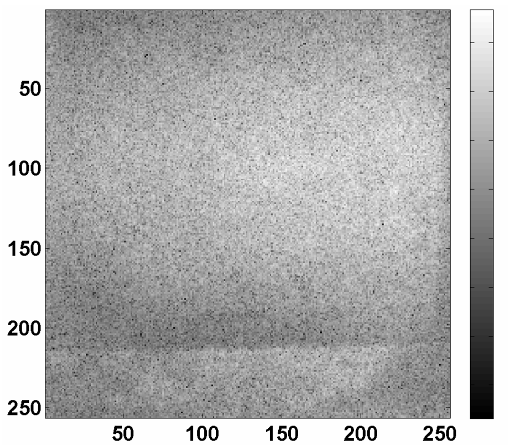


Fig. 3. Photograph of a rock that was imaged in the test bed. A small area was gouged out of the surface as a fiducial for the measurement.

Figure 4a is an intensity map that is produced by taking the Fourier transform of one of the images in the HLR data cube taken for the rock shown in figure 3. The intensity map is used to focus the image. The sharpness or integrated squared intensity is used as a metric for applying focus. The wavefront is minimized when the sharpness is maximized. See reference 11 for a detailed discussion of this technique. Figure 4b is a 3-d map of the surface of the rock shown in figure 3. This map was created using data from the HLR testbed. The color scale to the right runs in increments of mm's. The gouge is clearly visible in the center of the map. The sharp line across the bottom of the map is the metal bracket that supported the sample during the measurement.



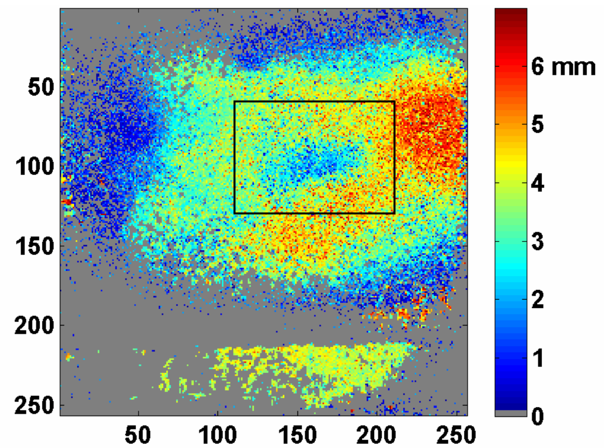


Fig. 4 a) The intensity of one image in the HLR data cube is shown for the object in Fig. 3. b) A surface contour map is shown for the object shown in Fig. 3.

Figure 5 is a photograph of one of a series of wax models generated in an experimental facility at UC Berkeley[1], created as part of the aforementioned award from NASA/HQ for demonstrating MIDAS payload capabilities for science exploration. Theses wax models are formed from first principles in a melting tank with carefully controlled heaters that are used to adjust the viscosity of the wax while the sides of the tank are moved in a such a manner as to create the targeted realistically scaled features similar to the planetary surface of the planetary body of interest, in this case of multi-ridged regions of the surface of Europa[12].

[1] http://seismo.berkeley.edu/~manga/labequip.html

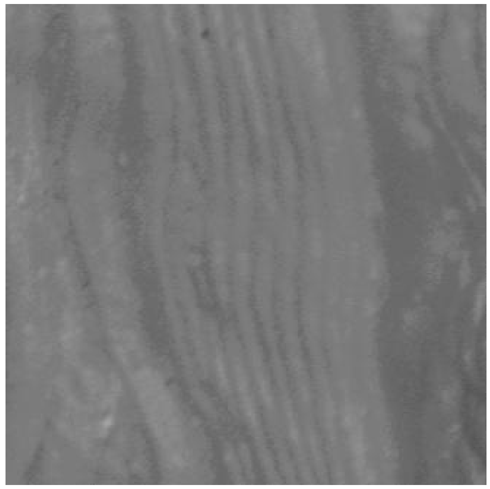


Fig. 5. Paraffin wax samples were constructed with representative features that correspond to the surface of Europa. These samples were provided by UC Berkeley Space Sciences Laboratory.

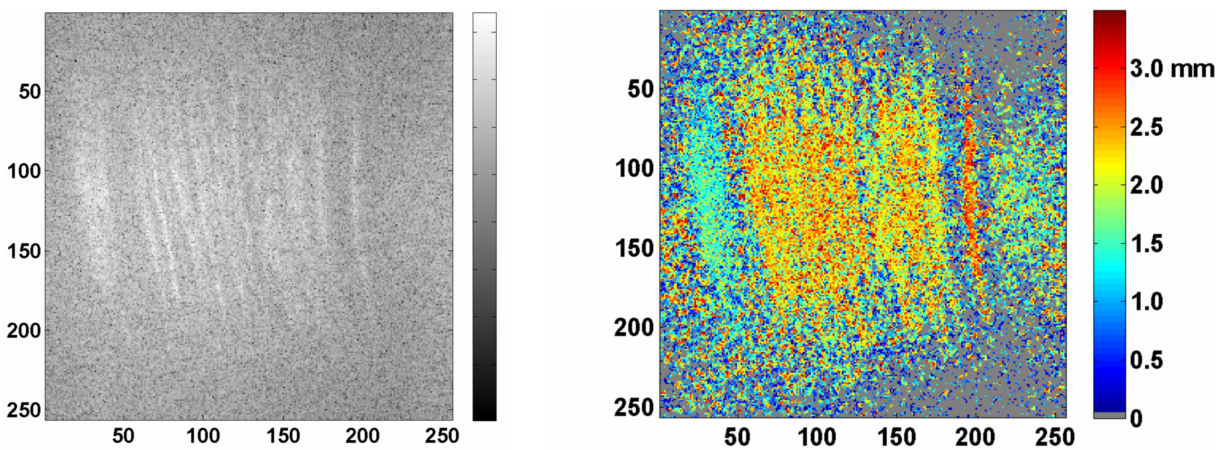


Fig. 6 a) The intensity of one image in the HLR data cube is shown for the object in Fig. 5. b) A surface contour map is shown for the object shown in Fig. 5.

Figure 6a is the intensity map for the object in Fig. 5. Figure 6b is a surface contour map of the sample shown in figure 5. The color coded-scale to the right of the map is in increments of mms. The contours of the surface are clearly visible in the 3-d map. The reflectance of the wax samples is similar to the albedo of Europa which is about 20% in this wavelength regime.

In this experiment the range is on the order of 1 meter and the laser power incident on the sample is about 1 mW over a 2 cm spot. Scaling this to 100 km will require a kw class laser. This size laser is currently available and by the time missions to Europa are realized they will be considered off the shelf components.

5. CONCLUSIONS

We have applied an established laboratory technique to a 3-d mapping mission of Europa. The technique has been clearly demonstrated in the laboratory and the extension to a Jovian mission is now possible due to the availability of long coherence length, ultra-stable, tunable lasers. There remain issues of laser reliability that are currently being addressed world-wide. We suggest that by the time Jovian missions are re-established suitable lasers will be available.

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