MSTAR: A High Precision Laser Range Sensor

Serge Dubovitsky and Oliver Lay

1. Novelty – Describe what is new and different about your work and its improvements over the prior art

Our invention enables unambiguous measurement of range with nanometer accuracy. Existing methods, e.g. pulsed laser rangers, can perform unambiguous range measurements but with only millimeter accuracy. Other methods, such as optical interferometers, measure changes in range with nanometer resolution, but do not measure the range itself. Currently there are no range sensors that can perform unambiguous measurements with nanometer accuracy. Figure 1 illustrates this point

A. What other methods are there for performing the function of the invention?

Existing methods, e.g. pulsed laser rangers, can perform unambiguous range measurements but with only millimeter accuracy. Other methods, such as optical interferometers, measure changes in range with nanometer resolution, but do not measure the range itself. Currently there are no range sensors that can perform unambiguous measurements with nanometer accuracy. Figure 1 illustrates this point

B. Differentiate your innovation over other methods and, if possible, discuss your advantages/disadvantages

Our method achieves what is currently impossible with existing practical methods. For more detailed explanation please see Serction 2. Technical Disclosure.

2. Technical Disclosure

A. Problem – Motivation that led to development or problem that was solved

The precision of *formation-flying control* will only be as good as the precision of the formation-flying sensor. The required position control accuracy of future distributed spacecraft missions will be at the micron or even nanometer levels over inter-spacecraft distances of 1-100 km, posing unprecedented challenges for ranging precision and dynamic range. Figure 1 illustrates the challenge. Existing state-of-the-art sensors cover both the "fine" and "coarse" regions of sensor performance: pulse-based time-of-flight sensors provide cm-level accuracy, and optical interferometric systems provide nanometer-level precision, but with an ambiguity range[1] of ~1 micron. There is no sensor technology that bridges the gap between the "fine" and "coarse" regions. Not only is micron-level range accuracy not possible, but the existing coarse and fine sensors cannot be combined into an ultra-high dynamic range sensor system. *No current technology meets the requirements for both long-range precision and high dynamic range* and an innovation is required.

[1] A sensor with an ambiguity range of 1 μm cannot distinguish between distances separated by a multiple of 1 μm. For example, it will read 0.123 μm if the actual distance is 1.123, or 2.123, or even 90003456.123 μm.

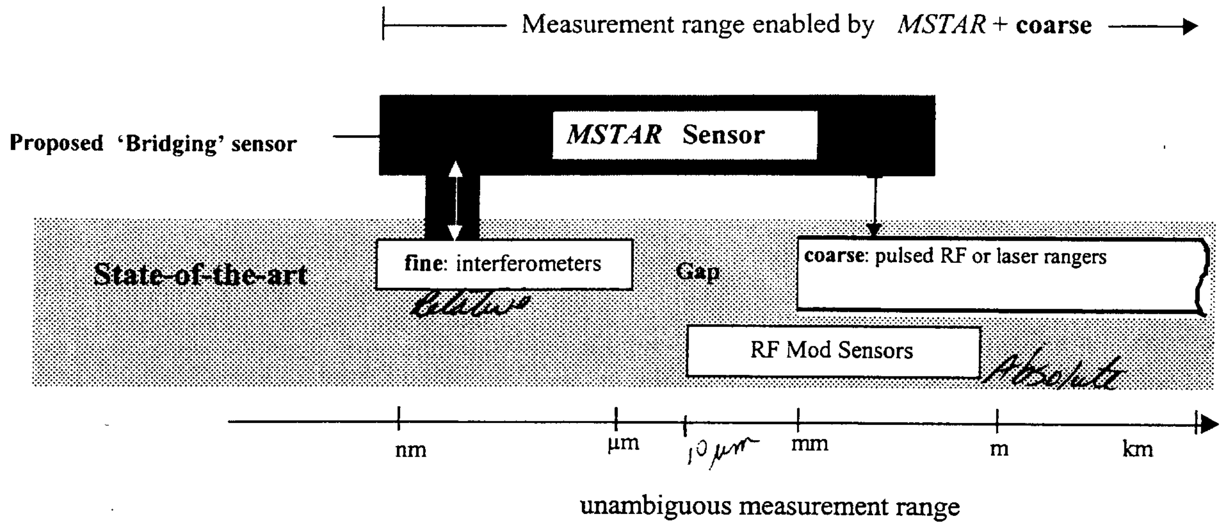

Figure 1. Performance ranges of various range measurements techniques. The left end of each bar marks the resolution of the technique and the right end of the bar marks the ambiguity range of the technique. Length of the bar is indicative of the dynamic range.

To bridge the gap one can either drastically improve the resolution of the RF or pulsed laser range sensors or extend the ambiguity range of optical interferometers. Improving the resolution of the RF modulation sensor due to problems inherent in trying to measure very small displacements with a comparatively long RF wavelength. An alternative approach is to extend the ambiguity range of the optical interferometer by a well known two-color interferometry technique that requires interferometric measurements at two different wavelengths. That is our approach.

Traditionally two-color absolute interferometers are implemented with two lasers detuned from each other by the required frequency. The required frequency detuning is easy to achieve with semiconductor lasers, but the semiconductor lasers do not have the narrow linewidth and high frequency stability required for range measurements over long target distances. Almost invariably when frequency stability is required, Nd:YAG Nonplanar Ring Oscillator (NPRO) lasers, further stabilized to an external cavity, are used. These lasers cannot be detuned by the needed amount (~120 GHz).

B. Solution

We plan to produce the required frequency separation by using a novel Modulation Sideband Technology for Absolute Range (*MSTAR*) architecture that uses modulation sidebands generated by a high-speed electro-optic phase modulators, an item used in telecommunications industry. The proposed *MSTAR* sensor architecture achieves large frequency separation, but uses a *single* very-frequency-stable source which does not need to be tuned or stabilized relative to a second laser.

C. Detailed Description and Explanation

An implementation of the MSTAR system is shown in Figure 2. It can be best explained by first considering its fundamental building block: a **heterodyne interferometer**, represented by the unshaded components in Figure 2. Interferometry is a displacement measurement method in which pathlength change between two fiducial points manifests itself as phase change of the carrier wave. The heterodyne interferometer is a particular implementation [1, 2] in which the optical carrier phase is transferred onto the phase of a low frequency electronic signal. Because the phase of this low frequency heterodyne signal can be measured very precisely, heterodyne interferometers are invariably used for high-precision applications.

Two closely separated optical frequencies, the 'Target' frequency and the 'Local' frequency, are generated by the frequency shifters and form a 'heterodyne pair'. The Target frequency makes the return trip between two retro-reflectors that define the distance to be measured, L. Small changes in L cause a change in the phase of the Target beam. The Local frequency mixes with the Target frequency at the photodetectors, and is used to down-convert the optical frequency ν to the much lower heterodyne frequency δf.

The phase meter compares the phase of the heterodyne signal from the 'Signal' Photodetector to that generated by the 'Reference' Photodetector. The measured phase ϕ is equal to the optical phase delay between the Target and Local beams and contains the desired distance information, $\phi = 4\pi\nu L / c$. This equation has solutions for L that repeat at intervals of the **ambiguity range**, $\Delta_L \approx c\ /\ (2\nu)$, which is 0.65 μm for a 1.3 μm laser. Standard heterodyne metrology does not distinguish between these many possible solutions, and is therefore only useful as a differential metrology system that measures *changes* in length.

This limitation can be overcome with a **"two-color" interferometer**[3], where standard heterodyne phase measurements are made using two different optical frequencies, ν_1 and ν_2:

$$\phi_1 = 4\pi\nu_1 L/c\,,\ \phi_2 = 4\pi\nu_2 L/c\,.$$

The difference in the phases,

$$\phi_1 - \phi_2 = 4\pi(\nu_1 - \nu_2)L/c = 4\pi F_S L/c\,,$$

is analogous to a single heterodyne measurement made at 'synthetic' frequency F_S. The ambiguity range for this difference measurement is increased to $\Delta_L = c\,/\,2F_S$, and the range resolution is $\sigma_L = \rho c\,/\,2F_S$. Existing implementations of the two-color interferometer use two separate lasers to generate ν_1 and ν_2. It is necessary to make **independent measurements** of the two phases, ϕ_1 and ϕ_2. This is straightforward when two lasers are used, since the two optical frequencies can be given different heterodyne frequencies, which can be separated after photodetection. An alternative is to switch rapidly between the two optical frequencies.

The ***MSTAR*** system generates multiple colors (ν_1 , ν_2, etc.) by modulating the light from a single laser. The recent development of high speed electro-optic modulators enables the generation of sidebands that are separated by tens of gigaHertz, and the problems associated with offset-locking two lasers are avoided. Both phase and intensity modulation can be used. The challenge is to make the separate phase measurements for each color, since neither of the techniques described above can be applied to a modulated single laser.

The implementation shown in Figure 2 adds two high-speed phase modulators and a second phase meter to the conventional heterodyne interferometer (shaded regions of Fig. 2). Consider the Target beam. The phase modulator applies a sinusoidal phase modulation $\Delta\Phi \sin(2\pi F_T t)$ to the carrier frequency ν, producing a series of sidebands spaced by $\pm F_T$, $\pm 2F_T$, $\pm 3F_T$, ..., with amplitudes given by Bessel functions[4]. The carrier and all the sidebands are then frequency shifted by f_T. Similar modulation is applied to the Local beam. The resulting optical spectrum is shown in Figure 2b, for both the Target and Local beams (second and higher sidebands have been omitted for clarity). The upper sidebands form one heterodyne pair (A) and lower sidebands form another (B). The 3 lowest frequency products after photodetection are shown in Figure 2c.

The primary innovation of the ***MSTAR*** architecture is the use of frequency shifters *together with* phase (or intensity) modulators in such a way that every sideband order (m) forms a heterodyne pair with a distinct heterodyne frequency, $m\Delta F - \delta f$, where $\Delta F = F_T - F_L$ and $\delta f = f_T - f_L$. The signal from each heterodyne pair can be isolated by appropriate filtering.

At this point we propose to use the first upper ($m = +1$) and the first lower ($m = -1$) sidebands to generate a synthetic frequency $F_S = 2F_T$. Filters isolate heterodyne frequencies A ($= \Delta F + \delta f$) and B ($= \Delta F - \delta f$). The phase meter outputs are:

$$\phi_A = 2\pi\left(\nu + f_T + F_T\right)\left(\frac{2L}{c}\right) \quad \text{and} \quad \phi_B = 2\pi\left(\nu + f_T - F_T\right)\left(\frac{2L}{c}\right)$$

The individual measurements have the same range resolution and ambiguity range as the standard heterodyne interferometer, and constitute the "fine" sensor. The difference between the two outputs forms the "bridging" sensor output:

$$\phi_A - \phi_B = 4\pi F_T\left(\frac{2L}{c}\right).$$

The ambiguity range is now extended to $(c / 4_T)$. Switching to a lower modulation frequency allows the ambiguity range to be extended further as needed.

The analysis above assumes that only the mixing products of the first sidebands are used for measurement. It is also possible to use the carrier and/or the mixing products of the second sidebands. Use of the carrier would extend the ambiguity range by a factor of 2. Use of the second sidebands would lower the required phase modulation frequency by a factor of 2.

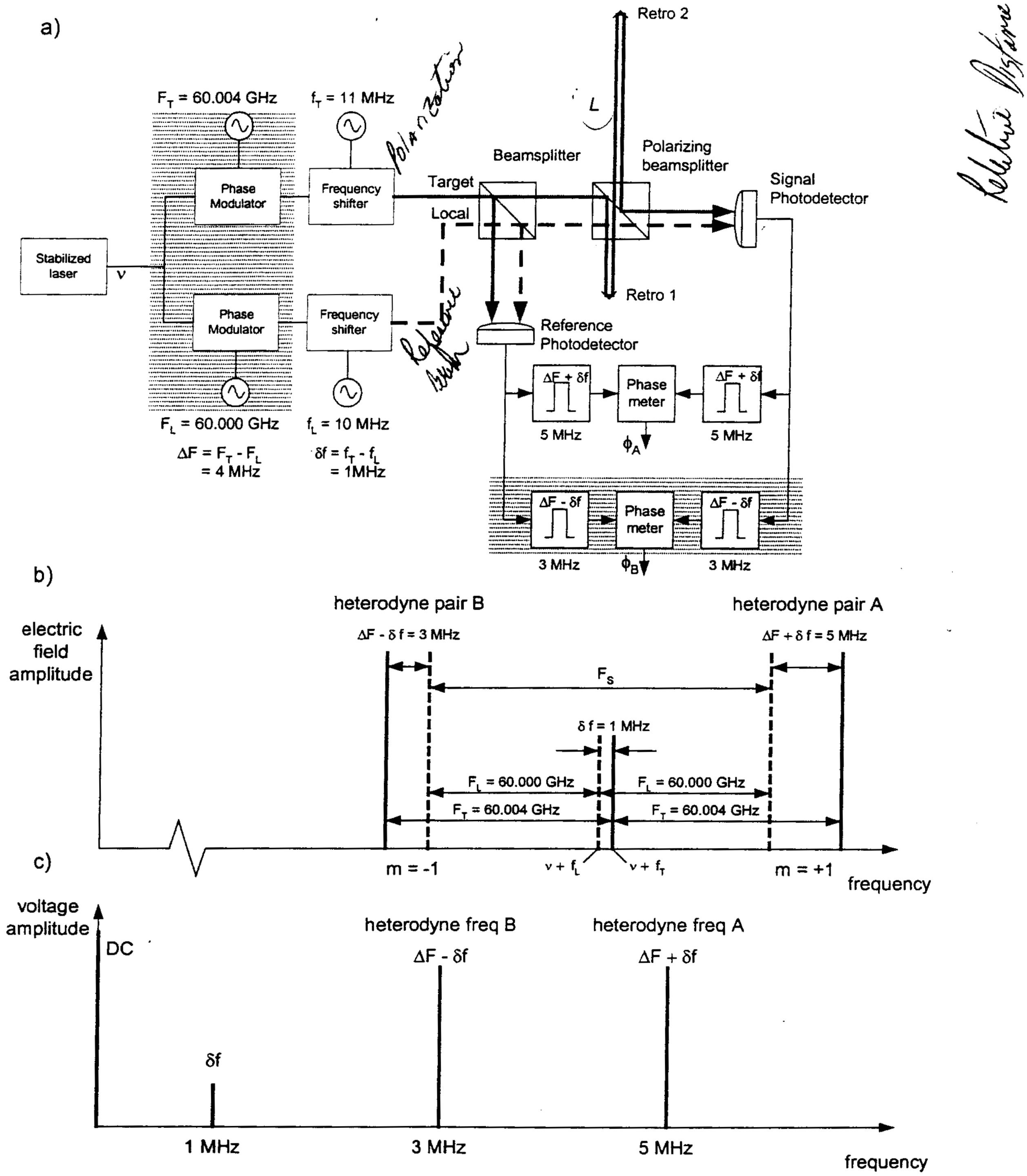

Figure 2. (a) A schematic implementation of the *MSTAR* system. The distance to be measured, *L*, lies between the retro-reflectors 1 and 2. Stated frequencies represent one possible set of values. Shaded components are *MSTAR* additions to a regular heterodyne system. (b) Optical spectrum before photo-detection. Second and higher harmonics have been omitted for clarity. (c) Spectrum of electrical signals after photo-detection.

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MSTAR: A High Precision Laser Range Sensor

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A. Is this invention ready for commercialization in its current form? If not explain. Is the commecialize form different from the invention's current form? In what way(s)?

We believe the invention can be commercialized in its current form, but given it's current low Technology Readiness Level, it is hard to predict what exactly the final implementation will be.

B. At what level of development is this invention? What further development is necessary or ongoing? Prototype developed? Invention fixed in its final form?

The invention is at the TRL 3?. We've build a rough prototype and conducted a proof-of-concept experiment.

Further developments are in progress and include construction of a full-performance prototype the will demonstrate the functional performance goals of the invention

C. Specific applications/markets and estimated use in commercial market place (be very specific, e.g. automobile, semiconductor, etc.)

Semiconductor Industry:

Lithography tools: optical steppers and scanners, e-beam & laser mask writers

Mask, wafer and LCD inspection and measurement tools, CD-SEM's

Process equipment: memory repair tools, probers, die bonders, drilling tools

General Precision positioning

Measurement and calibration of high resolution motions.

High precision machining

D. What companies are developing and marketing products in this technology area? (i.e. possible competitiors to your invention) What are these products?

Zygo Corp. – diplacement measuring interferometers

Agilent - diplacement measuring interferometers

Veeco – precision metrology

The Cooke Corp. – range sensor

Kelk Corp – absolute displacement trasnducers

LIMAB – noncontact diplacement measurements

Scantron – noncontact measurements

TR Electronic –absolute encoders, linear displacement measurements

OPTRA – high precision positioning

Excel Precision – position measurement

A-Kast – noncontact measurement systems

Windrush Technology – thickness and noncontact measurements

KAMAN – position sensor

above are some that we know or were able to find easily; there are probably many others.

E. List any related/similar government applications which currently utilize similar technology or over which your inventions is an improvement

NASA's separated spacecraft missions, e.g StarLight, LISA, Terrestrial Planet Finder, etc. would benefit from this long range precision metrology.

NASA's Next Generation Space Telescope would also benefit due to greatly expanded capability to measure mirror figure.

E. Is anyone else interested in this innovation? Who? Please list organization names and contact information

At this point nobody knows about it.

G. What other methods are there for performing the function of the invention? Differentiate your invention over the other methods and, if possible, discuss your advantages/disadvantages. Attach any additional pages if necessary.

Our invention enables unambiguous measurement of range with nanometer accuracy. Existing methods, e.g. pulsed laser rangers, can perform unambiguous range measurements but with only millimeter accuracy. Yet other methods, e.g. optical interferometers, can perform measurements of changes in target distance with nanometer resolution, but the measurements are ambiguous in a sense that one does not know the actual distance to the target. Currently there are no range sensors that can perform unambiguous measurements with nanometer accuracy. See "Contributors Report" for more information.

MSTAR: A sub-micron absolute metrology system

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Abstract- **The MSTAR sensor (Modulation Sideband Technology for Absolute Ranging) enables absolute distance measurement with sub-nanometer accuracy, an improvement of 4 orders of magnitude over current techniques. The system uses fast phase modulators to resolve the integer cycle ambiguity of standard interferometers. The concept is described, and demonstrated over target distances up to 1 meter. The design can be extended to kilometer-scale separations.**

High-precision non-contact measurements of distance are required in many areas of science and engineering. Laser interferometry is an established method for displacement measurement; sub-nanometer precision has been achieved [1], but absolute distance is ambiguous, because of the inherent half-wavelength (~0.5 μm) ambiguity range.

A number of methods exist for the unambiguous measurement of target distance, including pulsed time-of-flight [2], intensity-modulated optical beam [3,4], and two-color interferometry [5]. The rms accuracy is currently limited to ~5 μm, although there are examples of higher accuracy in more restricted applications, usually at very short target distances, where the inherent instability of tunable sources is less of an issue [6-8]. These methods are often referred to as "absolute metrology".

Closing the gap between absolute metrology accuracy and the laser interferometer ambiguity has a huge pay-off in increased performance, as the sub-nanometer precision is converted to sub-nanometer accuracy. Resolving the ambiguity requires a 1σ range accuracy of ~0.1 μm (peak-valley error ~0.5 μm), significantly beyond the existing capability.

Two-color interferometry is the most promising approach, in which two laser interferometer measurements are made at different laser wavelengths. Differencing these measurements is equivalent to having a laser interferometer with a much longer synthetic wavelength [5]. High accuracy over large distances imposes four requirements: (1) the coherence length of the laser must be longer than the round-trip distance to be measured; (2) the laser wavelength must be known to the accuracy needed for the measurement (1 nm accuracy at 100 m requires 10^{-11} wavelength knowledge); (3) the combination of synthetic wavelength and phase resolution must be sufficient to achieve the 0.1 μm accuracy; and (4) the synthetic wavelength must be known with high accuracy (0.1 ppm for 1 m distance, 0.01 ppm for 10 m distance, etc.). This combination has not been achieved with existing systems.

In this letter we introduce a new architecture that overcomes the existing limitations, and experimentally demonstrate unambiguous measurements with resolution sufficient to resolve the laser interferometer ambiguity. The technique, Modulation Sideband Technology for Absolute Ranging (MSTAR), implements a two-color heterodyne metrology system using a single narrow-linewidth, frequency-stabilized laser; the multiple wavelengths are produced as phase modulation sidebands using fast integrated-optics modulators. The two-color approach avoids the need for the fast photodetectors and signal processing required for other RF modulation schemes [3,4].

The system is shown in Fig. 1. The laser light, frequency ν, is split into the Measurement and Local arms. In the Measurement arm; the laser frequency is up-shifted by f_M, and a sinusoidal phase modulation $\Delta\Phi \sin(2\pi F_M t)$ is applied, producing a series of sidebands spaced by $\pm F_M$, $\pm 2F_M$, $\pm 3F_M, \ldots$, with amplitudes given by Bessel functions. Similar modulation, using slightly different frequencies, is applied to the Local arm. The resulting optical spectrum for the Measurement and Local beams is shown in Figure 1b (higher order sidebands have been omitted for clarity). The upper and lower sidebands correspond to the two wavelengths of a two-color interferometer. The Measurement and Local beams mix at the detectors, generating the down-converted frequencies shown in Figure 1c (note that MSTAR does not require high speed photodetectors). These photodetector outputs are bandpass filtered to isolate the sinusoids for the carrier, upper, and lower sidebands. The phase difference in cycles (1 cycle=2π radians) between the carrier sinusoids from the Target and Reference detectors (each with frequency δf) is given by $\Delta\phi_{car} = (\nu + f_M)(2x/c)$ where x is the distance between the reflecting surface of the reference mirror and the vertex of the target retro-reflector, and c is the speed of light. The integer number of cycles is unknown and the resulting estimate of x is ambiguous:

$$x_{car} = \frac{c}{2(\nu + f_M)}(\Delta\phi_{car} \pm m) = L(\Delta\phi_{car} \pm m) \quad (1)$$

where m is an integer. The ambiguity length L is approximately half the laser wavelength. The 1σ-precision of the length measurement (σ_x) depends on the precision of the phase difference ($\sigma_{\Delta\phi}$): $\sigma_x = L\sigma_{\Delta\phi}$. This carrier measurement is equivalent to a standard heterodyne metrology gauge. In addition to making this sub-nanometer measurement, MSTAR uses the sidebands to determine the number of integer cycles *m* in Eq. 1.

The upper sideband has a phase difference of $\Delta\phi_{usb} = (\nu + F_M + f_M)(2x/c)$ between Target and Reference outputs. The lower sideband gives $\Delta\phi_{lsb} = (\nu - F_M + f_M)(2x/c)$. These phase differences are combined to yield

$$x' = \frac{c}{4F_M}(\Delta\phi_{usb} - \Delta\phi_{lsb} \pm n) = L'(\Delta\phi_{usb} - \Delta\phi_{lsb} \pm n) \quad (2)$$

analogous to Eq. 1, but with a substantially longer ambiguity length, $L' = c/(4F_M)$, and precision $\sigma'_x = L'\sqrt{2}\sigma_{\Delta\phi}$. The synthetic wavelength is $c/2F_M$. As an example of how measurement of x' can be used to resolve ambiguity m consider the frequencies shown in Fig. 1. The carrier phase ambiguity length is L = 0.65 μm. With a phase resolution of $\sigma_{\Delta\phi}$ = 5 x 10^{-5} cycles (0.3 mrad), σ_x = 30 pm. The sideband combination has L' = 1.875 mm and σ_x' = 0.12 μm, sufficient to resolve L (and therefore *m*) at a high level of probability. The remaining ambiguity (n) can be resolved by switching to a lower phase modulation frequency. Switching to a phase modulation frequency of 30 MHz gives L'' = 2.5 m and σ_x'' = 0.18 mm, sufficient to resolve *n*.

The above analysis neglects the effects of air dispersion, phase offsets in the detectors and path imbalances within the optics. With strong enough phase modulation, it is also possible to use the higher order sidebands to improve performance. These issues will be addressed in a follow-up paper.

There are two key challenges to implementing MSTAR as an absolute metrology system: (1) generating the high frequency modulation sidebands, and (2) achieving the required precision in phase measurement.

The system in Fig. 1 was implemented on a floating optical table in a laboratory environment. The laser is a Nd:YAG system with linewidth of 10 kHz at 1.32 μm. The wavelength is measured against a HeNe reference laser using a Burleigh WA-1500 wavemeter (accuracy ~0.1 ppm). The light frequency shifted using acousto-optic modulators by ~40 MHz, and then fed into high-frequency phase modulators operating at ~40 GHz.

The phase modulators are polymer-based integrated optics devices [9] built by USC and Pacific Wave. Polymer-based modulators are more efficient than $LiNbO_3$ devices at high frequencies due to a better velocity match between the RF and optical waves. The packaged modulators have a fiber-to-fiber insertion loss of ~12dB. The phase modulators are driven at ~40 GHz by a pair of Agilent 83650B synthesizers (accurate to ~0.1 ppm) and

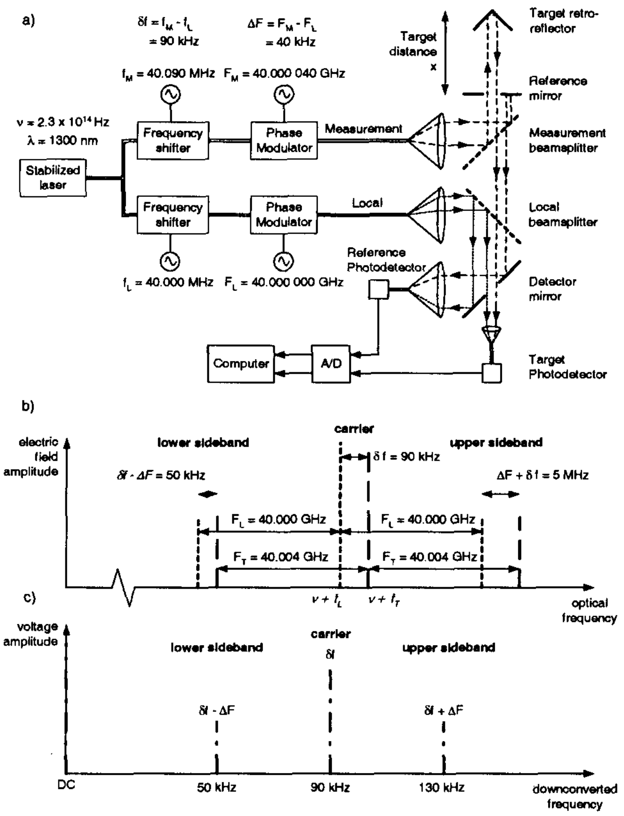

Figure 1: (a) Schematic of the *MSTAR* system. The distance to be measured, *x*, lies between the reference mirror and the target retro-reflector. (b) Optical spectrum before photo-detection. Long-dash = measurement beam; short-dash = local beam (c) Spectrum of electrical signals after photo-detection.

MMIC amplifiers. With +23 dBm of RF input power to the modulators, the first sidebands are 12 dB down from the carrier in the post-detection spectrum.

The Measurement and Local beams are formed by collimating the fiber outputs with 50 mm achromatic lenses. The optics were designed to minimize multi-path effects. A phase accuracy of 5 x 10^{-5} cycles requires an isolation of ~75 dB between the four alternative paths from the laser to the detectors. The dimensions of the annular mirrors were optimized, and a large effort went into minimizing leakages in the system. A set of polarizing optics (not shown in Fig. 1a) was used to increase the isolation to meet the requirement. The target retro-reflector is attached to a 1-meter manual translation slide.

The photodetectors are New Focus 2011 units. The outputs are digitized at 500 kHz and processed in the computer to generate the MSTAR output. Each measurement is based on 60,000 samples (0.12 seconds).

Three types of experiment were conducted to validate performance: (I) a displacement test, (II) a stability test, and (III) a zero test.

(I) *Displacement test.* From an arbitrary starting position the target was moved in small increments along the track. At each position, MSTAR generated a position, x_{MSTAR}, based only on the sideband difference phases; Equation 2 shows that this result depends only on the phase modulation frequency (tied to the synthesizer's frequency reference), and is independent of the laser wavelength. MSTAR switches to a phase modulation frequency of 30 MHz to fully resolve the ambiguity. Before each move, the phase modulation was turned off, and an independent fringe-counting phasemeter (not shown in Fig. 1a), directly connected to the analog outputs of the photodetectors, was used to measure the distance over which the target was moved, relative to the starting position, $x_{TRUTH,0}$. This 'truth' measurement depends only on the accuracy of fringe counting, and the wavelength of the laser light (tied to the wavelength of the HeNe reference laser). An example set of data is shown in Fig. 2, with the MSTAR distance plotted against the 'truth'. The residual, $\sigma'_x = x_{MSTAR} - \Delta x_{TRUTH} - x_{TRUTH,0}$, is shown in Fig. 2b. Note that $x_{TRUTH,0}$ is an offset in the validation measurement and does not reflect any offset intrinsic to the MSTAR system. The standard deviation of this residual (0.12 μm) is typical of the results obtained, and demonstrates that MSTAR can measure *displacements* (as opposed to absolute position) with the accuracy necessary to resolve the number of integer cycles *m*.

(II) *Stability test*. This test was conducted in the same way as the displacement test, except the target was not deliberately moved (small thermal motions were tracked with the truth measurement). Over a 3 hour period, the standard deviation of the residual was 0.05 μm, demonstrating that MSTAR is stable and calibratable.

(III) *Zero test*. It was not possible to extend the displacement test down to zero separation between the reference mirror and the vertex of the target retro-reflector. The annular reference mirror was instead replaced by a standard plane mirror, giving a target surface that is co-planar with the reference. The MSTAR measurements were consistent with zero to within 0.2 μm.

These validation experiments show that MSTAR resolves the integer number of optical cycles *m* (Eq. 1) and therefore closes the gap between absolute metrology and the laser interferometer ambiguity. With the addition of the built-in standard laser interferometer measurement (Eq. 1), MSTAR is therefore capable of absolute distance measurements with sub-nanometer accuracy, but this capability is not verified in this letter.

It should be noted that this combination of tests does not rule out the possibility of an anomaly in the MSTAR reading between zero and the start point of the displacement test (~18 cm). This issue will be addressed in the follow-up paper.

The MSTAR system was designed to work between spacecraft flying in formation – moving targets at separations of hundred of meters. Maintaining nanometer accuracy σ_x at separation x requires a laser with frequency known to a fraction (σ_x/x), and a phase modulation frequency known to $(10^{-7}\text{m}/x)$. To obtain 1 nm accuracy at a separation of 100 m, requires knowledge at the 10^{-11}

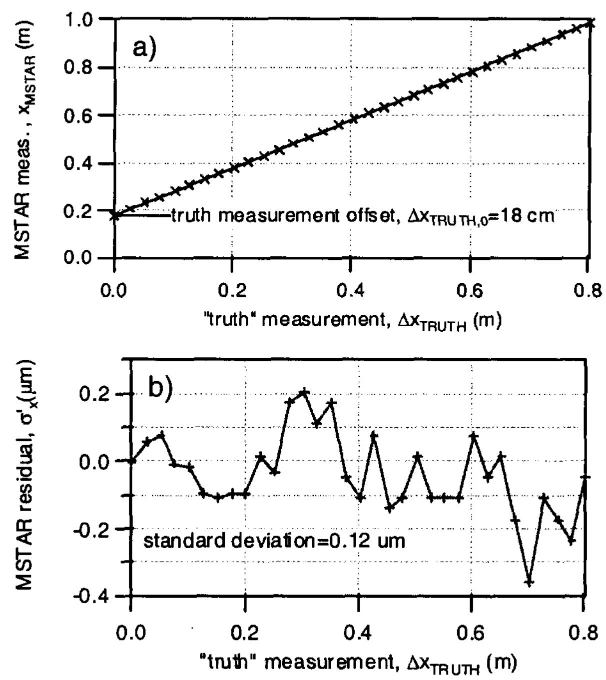

Figure 2. a) MSTAR absolute measurement vs 'true' displacement with respect to starting point, using fringe counting. b) Residual error $\sigma'_x = x_{MSTAR} - \Delta x_{TRUTH} - x_{TRUTH,0}$.

and 10^{-9} level for the laser and phase modulation frequencies, respectively. This is well within the range of current capability. By tracking the optical phase of the carrier (Eq. 1) during an integration, the MSTAR signal processing is able to measure the distance to moving targets without loss of accuracy, with longer integrations to compensate for reduced optical return power.

In conclusion, we have developed a sensor architecture (MSTAR) for measuring absolute distance based on phase modulation of a single laser, in conjunction with standard heterodyne techniques. We have demonstrated in the lab, at separations of up to 1 m, that the MSTAR system can resolve the integer cycle ambiguity, enabling distance measurement with sub-nanometer accuracy. Extending this performance to larger separations requires only that the laser and modulation frequencies be locked to suitable frequency standards.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with a National Aeronautics and Space Administration.

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