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US010148352B1

(12) **United States Patent**
Yang et al.

(10) **Patent No.: US 10,148,352 B1**
(45) **Date of Patent: Dec. 4, 2018**

(54) **CONTINUOUS CARRIER OPTICAL PHASE OPTOMETRIC MEASUREMENT OVER COHERENT OPTICAL COMMUNICATION LINK**

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(73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/646,687**

(22) Filed: **Jul. 11, 2017**

(51) **Int. Cl.**

H04B 10/08	(2006.01)
H04J 14/00	(2006.01)
H04B 10/079	(2013.01)
H04B 10/61	(2013.01)
H04L 7/00	(2006.01)
H04B 7/185	(2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***H04B 10/079*** (2013.01); ***B64G 3/00*** (2013.01); ***G01S 17/36*** (2013.01); ***G01S 17/933*** (2013.01); ***H04B 7/18506*** (2013.01); ***H04B 10/071*** (2013.01); ***H04B 10/503*** (2013.01); ***H04B 10/61*** (2013.01); ***H04J 14/00*** (2013.01); ***H04L 7/0075*** (2013.01); *G08B 13/08* (2013.01)

(58) **Field of Classification Search**
CPC . H04L 7/0075; H04B 10/079; H04B 7/18506; H04B 10/503; H04B 10/61; H04B 1/40; H04B 7/00; G01S 17/933; G01S 17/36; G01S 1/00; B64G 3/00; G01C 3/06; G01P 3/36; A61B 8/00; G01N 29/44; H04J 3/16; H04W 64/00
USPC 398/25, 66, 70
See application file for complete search history.

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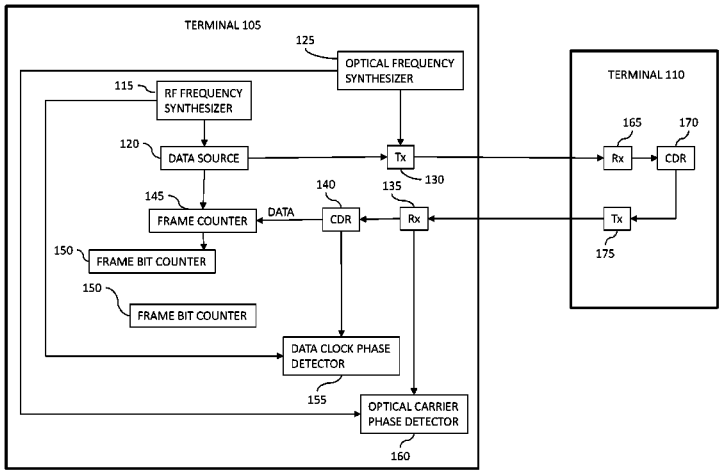
(57) **ABSTRACT**

An apparatus for measuring a distance between a first and second terminal includes a frame counter for determining a number of data frames traversing a distance between the first terminal 105 and the second terminal, a frame bit counter for determining a number of data clock bits offset between a transmitted data frame and a concurrently received data frame, a data clock phase detector for determining a phase difference between an RF data clock for the transmitted data frame and an RF data clock for the concurrently received data frame, and an optical carrier phase detector for determining a phase difference between an optical carrier used to transmit the transmitted data frame and an optical carrier for the concurrently received data frame. The distance between the first and second terminal is determined from a round trip transit time T between the first and second terminals.

18 Claims, 4 Drawing Sheets



(51) **Int. Cl.**

H04B 10/50	(2013.01)
G01S 17/36	(2006.01)
G01S 17/93	(2006.01)
B64G 3/00	(2006.01)
H04B 10/071	(2013.01)
G08B 13/08	(2006.01)

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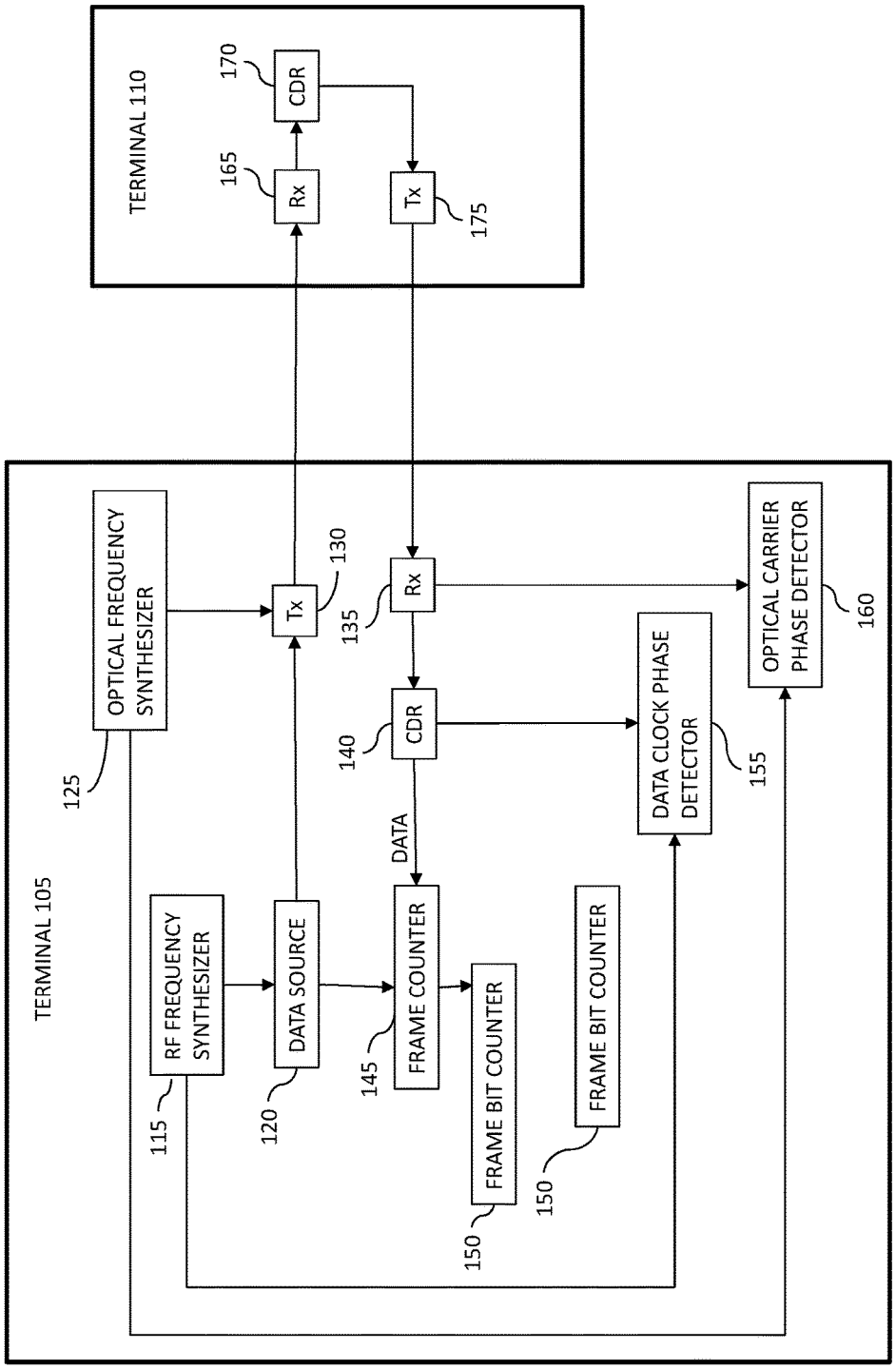
TERMINAL 110
170
CDR
165
Rx
Tx
175
TERMINAL 105
OPTICAL FREQUENCY SYNTHESIZER
125
Tx
130
Rx
135
OPTICAL CARRIER PHASE DETECTOR
160
CDR
140
DATA CLOCK PHASE DETECTOR
155
DATA
RF FREQUENCY SYNTHESIZER
115
DATA SOURCE
120
FRAME COUNTER
145
FRAME BIT COUNTER
150
FRAME BIT COUNTER
150

FIGURE 1

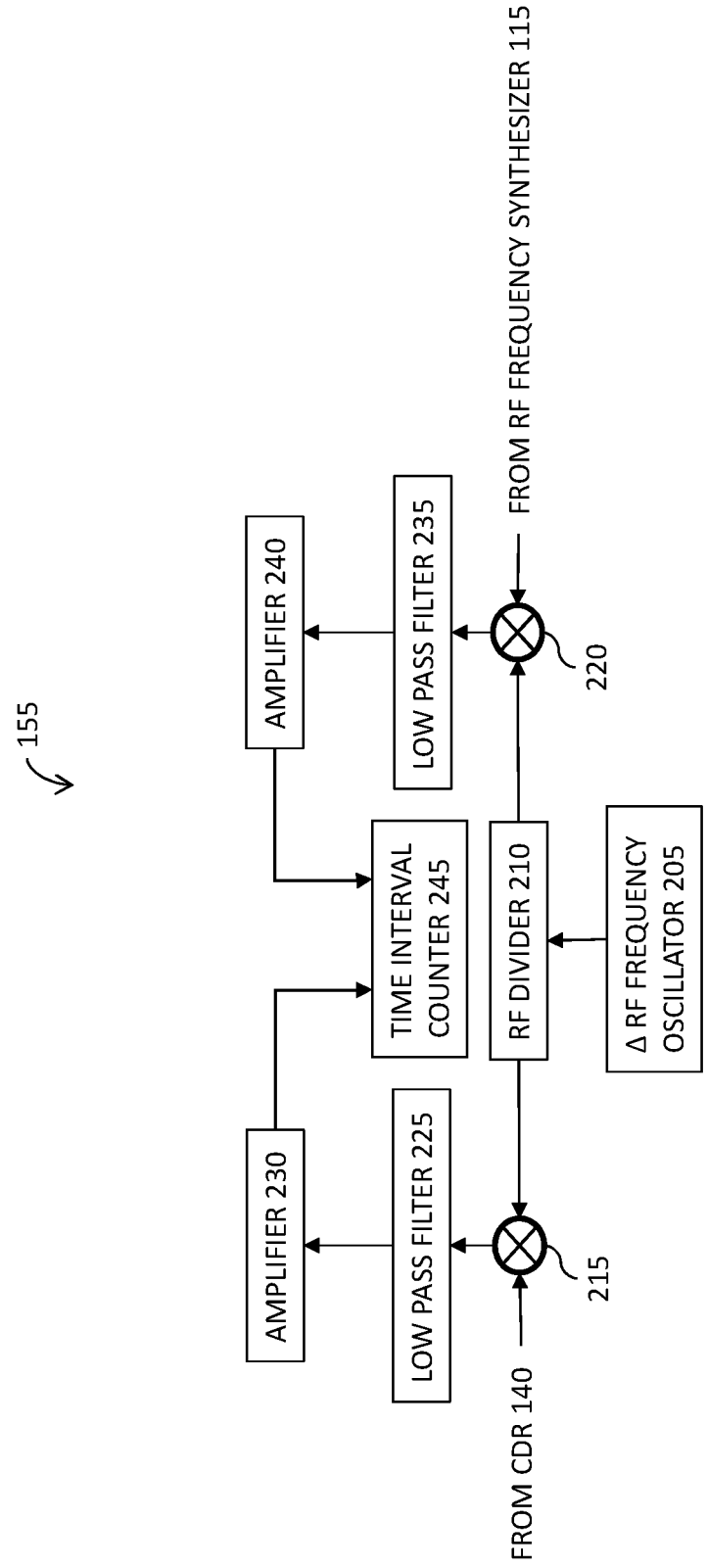
155
AMPLIFIER 240
LOW PASS FILTER 235
FROM RF FREQUENCY SYNTHESIZER 115
220
TIME INTERVAL COUNTER 245
RF DIVIDER 210
Δ RF FREQUENCY OSCILLATOR 205
AMPLIFIER 230
LOW PASS FILTER 225
215
FROM CDR 140

FIGURE 2

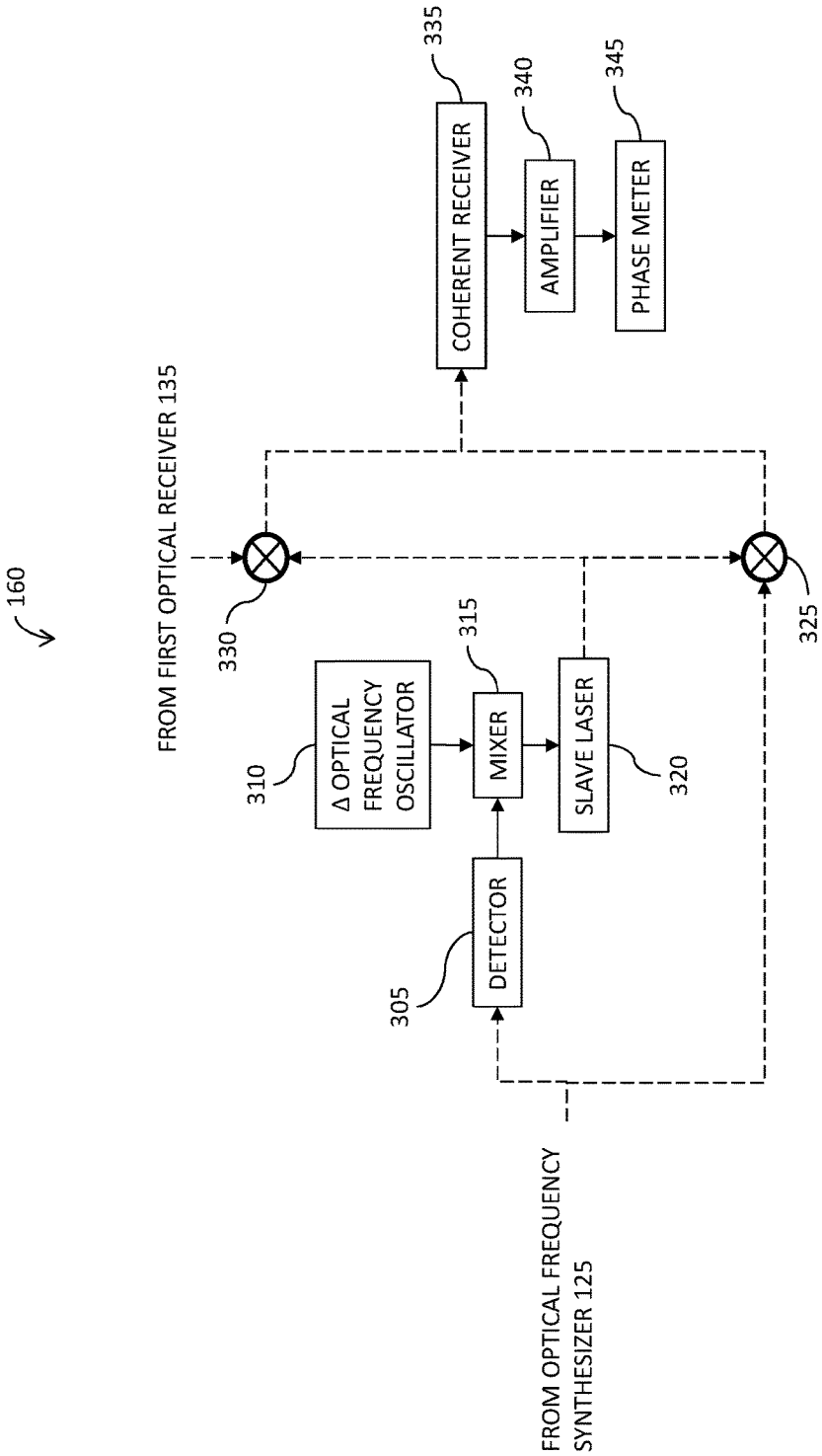
160
FROM FIRST OPTICAL RECEIVER 135
330
325
335
COHERENT RECEIVER
340
AMPLIFIER
345
PHASE METER
310
Δ OPTICAL FREQUENCY OSCILLATOR
315
MIXER
SLAVE LASER
320
305
DETECTOR
FROM OPTICAL FREQUENCY SYNTHESIZER 125

FIGURE 3

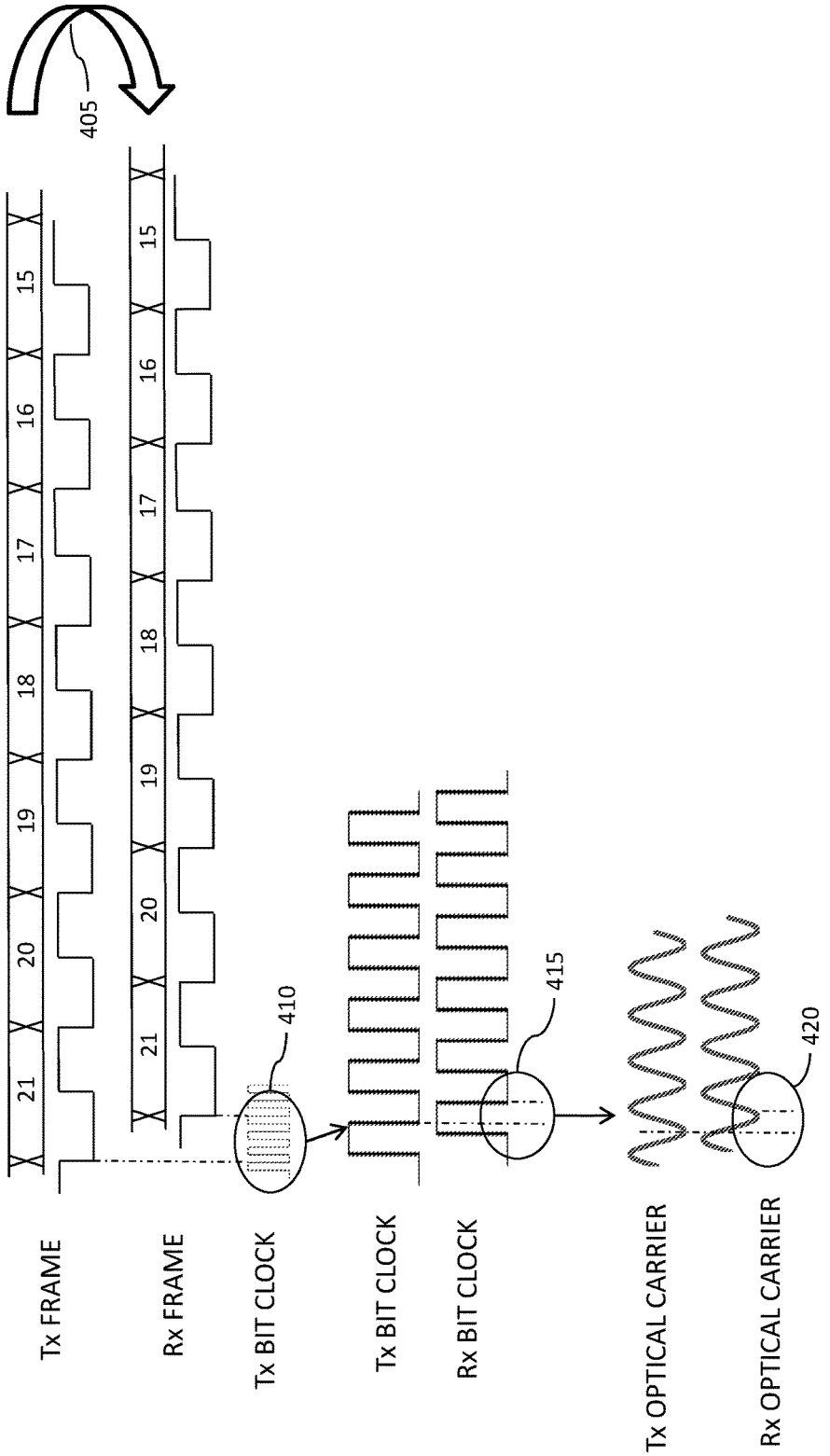
405
21
20
19
18
17
16
15
Tx FRAME
Rx FRAME
Tx BIT CLOCK
Tx BIT CLOCK
Rx BIT CLOCK
Tx OPTICAL CARRIER
Rx OPTICAL CARRIER
410
415
420

FIGURE 4

CONTINUOUS CARRIER OPTICAL PHASE OPTOMETRIC MEASUREMENT OVER COHERENT OPTICAL COMMUNICATION LINK

INVENTION BY GOVERNMENT EMPLOYEE(S) ONLY

The invention described herein was made by one or more employees of the U.S. Government, and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND

The disclosed embodiments generally relate to laser optical ranging, and in particular, to using a coherent optical communication link for laser optical ranging and range rate measurements.

Ranging and range rate measurements are important parameters in spacecraft navigation and tracking. Because of the distances between space craft, between a terrestrial body and a spacecraft, or between terrestrial bodies, for example, Earth and Mars, accurate range and range rate measurements are difficult to achieve. Traditionally, these measurements are accomplished by measuring a Doppler shift of a microwave carrier that provides a target velocity along a line of sight. An exemplary Doppler tracking system may utilize a two-way X band (7.2-8.4 GHz) radio link to achieve average measurement accuracy ranges from 100 to 20 um/s at a 60 s integration time. Such RF based systems are subject to interference from various types of noise, in particular, the solar wind and plasma scintillation noise.

It would be advantageous to improve provide a system that provides communication at a high data rate, accurate pointing capability, and more precise ranging and range rate measurements with lower interference, while adding minimal cost over existing optical communication systems.

SUMMARY

The disclosed embodiments are directed to an apparatus for measuring a distance between a first and second terminal. The apparatus includes a frame counter for determining a number of data frames traversing a distance between the first terminal **105** and the second terminal, a frame bit counter for determining a number of data clock bits offset between a transmitted data frame and a concurrently received data frame, a data clock phase detector for determining a phase difference between an RF data clock for the transmitted data frame and an RF data clock for the concurrently received data frame, and an optical carrier phase detector for determining a phase difference between an optical carrier used to transmit the transmitted data frame and an optical carrier for the concurrently received data frame. The distance between the first and second terminal is determined from a round trip transit time T between the first and second terminals expressed as:

$$T=N_{frame}\times T_{frame}+N_{bit}\times T_{bit}+\Delta\text{Data Clock Phase}+\Delta\text{Carrier Phase},$$

where N_{frame} is the number of frames traversing the distance between the first terminal **105** and the second terminal **110**, T_{frame} is the frame period, N_{bit} is the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame, T_{bit} is the period of the RF data clock, Δ Data Clock Phase is the phase difference between the transmitted RF data clock and the received data clock, and Δ Carrier Phase is the phase difference between the transmitted optical carrier and the received optical carrier.

The apparatus may include an RF frequency synthesizer for generating the RF data clock.

The apparatus may also include a pattern generator for generating data for the data frames.

The apparatus may further include a source of communication data for generating data for the data frames.

The apparatus may still further include an optical frequency synthesizer for generating the optical carrier.

The optical carrier may be a coherent optical communications carrier.

The first terminal may be a ground terminal and the second terminal may be a space terminal.

The first and second terminals may be located on different space craft.

The first and second terminals may be located on different terrestrial bodies.

The disclosed embodiments are also directed to an method for measuring a distance between a first and second terminal. The method includes determining a number of data frames traversing a distance between the first terminal **105** and the second terminal, determining a number of data clock bits offset between a transmitted data frame and a concurrently received data frame, determining a phase difference between an RF data clock for the transmitted data frame and an RF data clock for the concurrently received data frame, determining a phase difference between an optical carrier used to transmit the transmitted data frame and an optical carrier for the concurrently received data frame, and calculating the distance between the first and second terminal from a round trip transit time T between the first and second terminals expressed as:

$$T=N_{frame}\times T_{frame}+N_{bit}\times T_{bit}+\Delta\text{Data Clock Phase}+\Delta\text{Carrier Phase},$$

where N_{frame} is the number of frames traversing the distance between the first terminal **105** and the second terminal **110**, T_{frame} is the frame period, N_{bit} is the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame, T_{bit} is the period of the RF data clock, Δ Data Clock Phase is the phase difference between the transmitted RF data clock and the received data clock, and Δ Carrier Phase is the phase difference between the transmitted optical carrier and the received optical carrier.

The method may include generating the RF data clock using an RF frequency synthesizer.

The method may also include generating data for the data frames using a pattern generator.

The method may further include generating data for the data frames using a source of communication data.

The method may still further include generating the optical carrier using an optical frequency synthesizer.

The optical carrier may be a coherent optical communications carrier.

The method may include locating the first terminal terrestrially and locating the second terminal in space.

The method may also include locating the first and second terminals on different space craft.

The method may further include locating the first and second terminals on different terrestrial bodies.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and other features of the embodiments are explained in the following description, taken in connection with the accompanying drawings, wherein:

FIG. **1** illustrates an example of an optical system according to the disclosed embodiments;

FIG. **2** illustrates a data clock phase detector according to the disclosed embodiments;

FIG. **3** illustrates an optical carrier phase detector according to the disclosed embodiments; and

FIG. **4** illustrates exemplary parameters that may be measured by the optical system.

DETAILED DESCRIPTION

Although the disclosed embodiments will be described with reference to the embodiments shown in the drawings and described below, it should be understood that these could be embodied in many alternate forms. In addition, any suitable size, shape or type of elements or materials could be used.

The disclosed embodiments are directed to using continuous carrier optical phase measurements over a coherent optical communications link, such as a laser link, to provide improved accuracy on range and range rate, particularly when compared to direct modulated optical ranging, where measurement is performed over a radio frequency (RF) data clock. Optical phase measurements over a coherent optical communications link provide an orders of magnitude improvement in accuracy due to the use of the much higher optical carrier frequency. The optical carrier laser frequency also provides for an increased data rate, while the coherence of the optical link provides a more accurate pointing capability.

FIG. **1** illustrates an example of an optical system **100** according to the disclosed embodiments. The optical system **100** may include a first terminal **105** and a second terminal **110**. In some embodiments, the first terminal **105** may be a ground or terrestrial terminal, and the second terminal **110** may be a space terminal, such as a satellite. In other embodiments, the first and second terminals may be located on different space craft, or may be located on different terrestrial bodies, for example, different planets.

The first terminal **105** may include an RF frequency synthesizer **115**, a data source **120**, an optical frequency synthesizer **125**, and a first optical transmitter **130**. The first terminal may also include a first optical receiver **135**, a first clock data recovery circuit **140**, a frame counter **145**, a frame bit counter **150**, a data clock phase detector **155**, and an optical carrier phase detector **160**.

The second terminal may include a second optical receiver **165**, a second clock data recovery circuit **170**, and a second optical transmitter **175**.

The RF frequency synthesizer **115** in the first terminal **105** may be a digital phase locked loop synthesizer, an analog phase locked loop synthesizer, a multi-loop phase locked loop synthesizer or any other suitable RF frequency synthesizer. The RF frequency generator **115** may generate an RF data clock at a suitable frequency, for example, approximately 622 MHz. One output of the RF frequency synthesizer **115** may be coupled to the data clock phase detector **155** and another output may be connected to the data source **120**. The data source **120** may generate frames of data embedded with the RF data clock. In some embodiments, the data source **120** may be a pattern generator and the data may be a data pattern, while in other embodiments the data source **120** may be a source of communication data and the data may be a communication transmission. The source of communication data may include one or more of a user interface, an automatic control mechanism or processor or any suitable source of commands or data exchanged with the second terminal. The data frames may all have the same period. The data frames embedded with the RF data clock may be converted to a first optical signal by the first optical transmitter **130**, which may be driven by an optical signal from the optical frequency synthesizer **125**. In some embodiments, the optical frequency synthesizer **125** may include a master laser controlled by an atomic cell feedback loop for stability.

The first optical transmitter **130** may then transmit the first optical signal to the second terminal **110**.

In the second terminal **110**, the second optical receiver **165** may receive the first optical signal and may convert the received first optical signal to an electrical signal which is provided to the second clock recovery circuit **170**. The second clock recovery circuit **170** may recover the RF data clock and the data frames, and may realign the data frames with the RF data clock. The realigned data frames and the recovered RF data clock may then be converted to a second optical signal and transmitted back to the first terminal **105** by the second transmitter **175**.

In the first terminal **105**, the first optical receiver **135** may receive the second optical signal and, for one output, may convert the second optical signal to an electrical signal provided to the first clock data recovery circuit **140**. The first optical receiver **135** may have another output that may provide an optical signal corresponding to the received carrier of the second optical signal to the optical carrier phase detector **160**. The first clock recovery circuit **140** may recover received data frames and a received RF data clock from the second optical signal and may provide the received data frames to the frame counter **145**, and may also provide the received RF data clock to the data clock phase detector **155**.

FIG. **2** shows a more detailed view of the data clock phase detector **155**. It should be understood that the illustrated data clock phase detector **155** is exemplary and that any suitable structure or technique may be used to measure the difference between the phase of the data clock provided by the RF frequency synthesizer **115** and the data clock recovered from the signal transmitted by the second terminal **110**. In this embodiment, the data clock phase detector **155** may be implemented as a dual mixer time difference measurement apparatus. The dual mixer time difference measurement apparatus may include a Δ RF frequency oscillator **205** having a frequency output offset from the frequency output by the RF frequency synthesizer **115**, for example, approximately 1 KHz. The output of the Δ RF frequency oscillator **205** may be divided by RF divider **210** and both the clock from the first clock recovery circuit **140** and the clock from the RF frequency synthesizer **115** may be mixed with the resulting RF signal, using RF mixers **215** and **220**, respectively. The mixed signal from the first clock recovery circuit **140** may be filtered by low pass filter **225** and amplified by amplifier **230**, while the mixed signal from the RF frequency synthesizer **115** may be filtered by low pass filter **235** and amplified by amplifier **240**. A time interval counter **245** may be used to measure the difference between the phase of the data clock provided by the RF frequency synthesizer **115** and the data clock recovered from the signal transmitted by the second terminal.

FIG. **3** shows a more detailed view of an optical carrier phase detector **160**. The optical carrier phase detector **160** may be implemented using any number of suitable techniques, including but not limited to a phase shift method, a frequency modulation method, and also may be implemented using an interferometer. In the disclosed embodiments, an optical output from the optical frequency synthe-

sizer **125** may be converted to an electrical signal by a detector **305** and may be mixed with an output from a Δ optical frequency oscillator **310** using mixer **315**. The Δ optical frequency oscillator **310** may have a frequency output offset from the frequency output of the optical frequency synthesizer **125**, for example, by approximately 10 MHz. The electrical output of the mixer **315** may be used to drive a slave laser **320**. The slave laser **320** may output an optical signal having the frequency of the optical frequency synthesizer **125** plus the offset. The output of the slave laser **320** may be mixed with the output of the optical frequency synthesizer **125** using optical mixer **325**, and may be mixed with the output of the first optical receiver **135** using optical mixer **330**. The outputs of the optical mixers **325**, **330** may be converted to an electrical output by coherent receiver **335**, which may be amplified by amplifier **340**. The output of amplifier **340** may be provided to phase meter **345** which may determine the phase difference between the optical carrier generated by the optical frequency synthesizer **125** and transmitted by the first optical transmitter **130**, and the optical carrier received by the first optical receiver **135**.

Returning to FIG. **1**, in the first terminal, at least four parameters may be measured: The number of data frames traversing the distance between the first terminal **105** and the second terminal **110**; the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame; the phase difference between the transmitted RF data clock and the received RF data clock, and the phase difference between the transmitted optical carrier and the received optical carrier.

The round trip transit time between the first and second terminals T may be expressed as:

$$T=N_{frame}\times T_{frame}+N_{bit}\times T_{bit}+\Delta\text{Data Clock Phase}+\Delta\text{Carrier Phase},$$

where N_{frame} is the number of frames traversing the distance between the first terminal **105** and the second terminal **110**, T_{frame} is the frame period, N_{bit} is the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame, T_{bit} is the period of the RF data clock, Δ Data Clock Phase is the phase difference between the transmitted RF data clock and the received data clock, and Δ Carrier Phase is the phase difference between the transmitted optical carrier and the received optical carrier.

Referring to FIGS. **1** and **4**, the frame counter **145** may compare the received data frames recovered by the first clock data recovery circuit **140** with the data frames generated by the data source **120** and may determine the number of data frames traversing the distance between the first terminal **105** and the second terminal **110** (**405** FIG. **4**). The number of data frames traversing the distance between the first terminal **105** and the second terminal **110** may provide an exemplary measure of the distance between the first and second terminals within a few hundred meters.

The frame bit counter **150** may determine the number of data clock bits offset between the presently transmitted frame and the presently received frame (**410** FIG. **4**). The determination of the number of data clock bits offset between the presently transmitted frame and the presently received frame may provide further precision of the measurement of the distance between the first and second terminals **105**, **110** to within approximately 30 centimeters.

The data clock phase detector **155** may compare the phase difference between the transmitted RF data clock from the RF frequency synthesizer **115** and the received RF data clock from the first clock data recovery circuit **140** and may utilize the data clock phase difference (**415** FIG. **4**) to provide still further precision of the measurement of the distance between the first and second terminals **105**, **110** to within approximately 50 micrometers.

The optical carrier phase detector **160** may compare the phase difference between the transmitted optical carrier from the optical frequency synthesizer **125** and the optical carrier received by the first optical receiver **135** and may utilize the optical carrier phase difference (**420** FIG. **4**) to provide even further precision of the measurement of the distance between the first and second terminals **105**, **110** to within approximately 60 nanometers.

The disclosed embodiments thus provide high precision optometric range and ranging measurements which may be advantageous for various applications, for example, space navigation and communications, gravitational based science missions, and also may combine optometric communications and optometric measurements on a single platform.

It is noted that the embodiments described herein can be used individually or in any combination thereof. It should be understood that the foregoing description is only illustrative of the embodiments. Various alternatives and modifications can be devised by those skilled in the art without departing from the embodiments. Accordingly, the present embodiments are intended to embrace all such alternatives, modifications and variances that fall within the scope of the appended claims.

Various modifications and adaptations may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings. However, all such and similar modifications of the teachings of the disclosed embodiments will still fall within the scope of the disclosed embodiments.

Various features of the different embodiments described herein are interchangeable, one with the other. The various described features, as well as any known equivalents can be mixed and matched to construct additional embodiments and techniques in accordance with the principles of this disclosure.

Furthermore, some of the features of the exemplary embodiments could be used to advantage without the corresponding use of other features. As such, the foregoing description should be considered as merely illustrative of the principles of the disclosed embodiments and not in limitation thereof.

The invention claimed is:

1. An apparatus for measuring a distance between a first and second terminal comprising:

a frame counter for determining a number of data frames traversing a distance between the first terminal **105** and the second terminal;

a frame bit counter for determining a number of data clock bits offset between a transmitted data frame and a concurrently received data frame;

a data clock phase detector for determining a phase difference between an RF data clock for the transmitted data frame and an RF data clock for the concurrently received data frame; and

an optical carrier phase detector for determining a phase difference between an optical carrier used to transmit the transmitted data frame and an optical carrier for the concurrently received data frame,

wherein the distance between the first and second terminal is determined from a round trip transit time T between the first and second terminals expressed as:

$$T=N_{frame}\times T_{frame}+N_{bit}\times T_{bit}+\Delta\text{Data Clock Phase}+\Delta\text{Carrier Phase},$$

where N_{frame} is the number of frames traversing the distance between the first terminal **105** and the second terminal **110**, T_{frame} is the frame period, N_{bit} is the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame, T_{bit} is the period of the RF data clock, Δ Data Clock Phase is the phase difference between the transmitted RF data clock and the received data clock, and Δ Carrier Phase is the phase difference between the transmitted optical carrier and the received optical carrier.

2. The apparatus of claim **1**, comprising an RF frequency synthesizer for generating the RF data clock.

3. The apparatus of claim **1**, comprising a pattern generator for generating data for the data frames.

4. The apparatus of claim **1**, comprising a source of communication data for generating data for the data frames.

5. The apparatus of claim **1**, comprising an optical frequency synthesizer for generating the optical carrier.

6. The apparatus of claim **1**, wherein the optical carrier is a coherent optical communications carrier.

7. The apparatus of claim **1**, wherein the first terminal is a ground terminal and the second terminal is a space terminal.

8. The apparatus of claim **1**, wherein the first and second terminals are located on different space craft.

9. The apparatus of claim **1**, wherein the first and second terminals are located on different terrestrial bodies.

10. A method for measuring a distance between a first and second terminal comprising:

determining a number of data frames traversing a distance between the first terminal **105** and the second terminal;

determining a number of data clock bits offset between a transmitted data frame and a concurrently received data frame;

determining a phase difference between an RF data clock for the transmitted data frame and an RF data clock for the concurrently received data frame;

determining a phase difference between an optical carrier used to transmit the transmitted data frame and an optical carrier for the concurrently received data frame; and

calculating the distance between the first and second terminal from a round trip transit time T between the first and second terminals expressed as:

$$T=N_{frame}\times T_{frame}+N_{bit}\times T_{bit}+\Delta\text{Data Clock Phase}+\Delta\text{Carrier Phase},$$

where N_{frame} is the number of frames traversing the distance between the first terminal **105** and the second terminal **110**, T_{frame} is the frame period, N_{bit} is the number of RF data clock bits offset between the presently transmitted frame and the presently received data frame, T_{bit} is the period of the RF data clock, Δ Data Clock Phase is the phase difference between the transmitted RF data clock and the received data clock, and Δ Carrier Phase is the phase difference between the transmitted optical carrier and the received optical carrier.

11. The method of claim **10**, comprising generating the RF data clock using an RF frequency synthesizer.

12. The method of claim **10**, comprising generating data for the data frames using a pattern generator.

13. The method of claim **10**, comprising generating data for the data frames using a source of communication data.

14. The method of claim **10**, comprising generating the optical carrier using an optical frequency synthesizer.

15. The method of claim **10**, wherein the optical carrier is a coherent optical communications carrier.

16. The method of claim **10**, comprising locating the first terminal terrestrially and locating the second terminal in space.

17. The method of claim **10**, comprising locating the first and second terminals on different space craft.

18. The method of claim **10**, comprising locating the first and second terminals on different terrestrial bodies.

* * * * *