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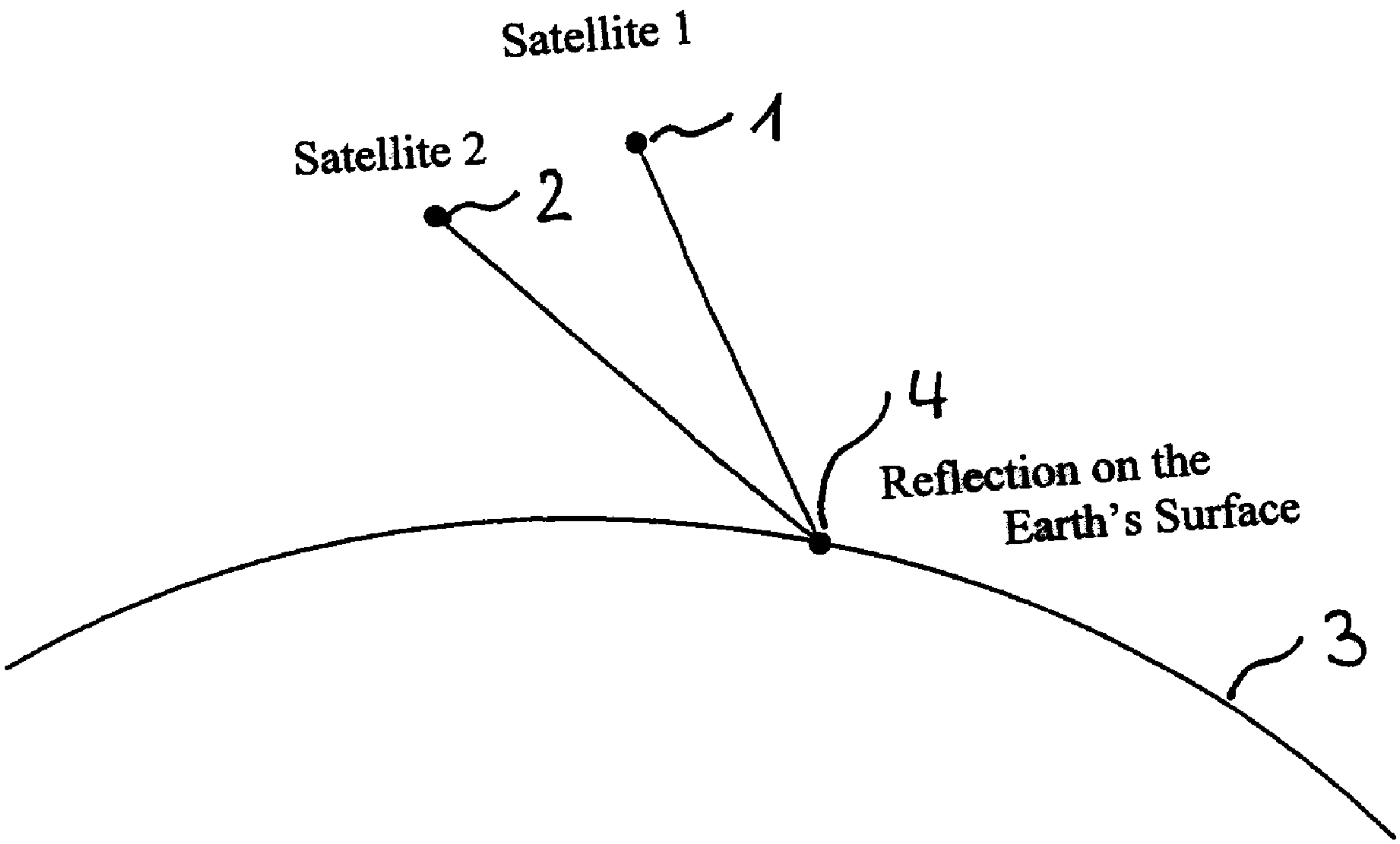
(54) **Titre :** METHODE ET APPAREIL D'INTERFEROMETRIE RADAR
(54) **Title:** METHOD AND APPARATUS FOR INTERFEROMETRIC RADAR MEASUREMENT



(57) **Abrégé/Abstract:**
In a method for interferometric radar measurement, at least two synthetic aperture radar (SAR) systems on satellite and/or missile-supported platforms illuminate a common surface area by means of microwave signals. A first SAR system sends a first radar signal on a first transmit frequency, and at least a second SAR system sends at least a second radar signal on at least a second transmit frequency. At least one of the at least two SAR systems receives the at least two interfering radar signals reflected on the common surface area, determines difference phases of the received radar signals from the interferograms, determines therefrom a drift of a system clock of the at least two SAR systems, and compensates the determined drift.

ABSTRACT OF THE DISCLOSURE

In a method for interferometric radar measurement, at least two synthetic aperture radar (SAR) systems on satellite and/or missile-supported platforms illuminate a common surface area by means of microwave signals. A first SAR system sends a first radar signal on a first transmit frequency, and at least a second SAR system sends at least a second radar signal on at least a second transmit frequency. At least one of the at least two SAR systems receives the at least two interfering radar signals reflected on the common surface area, determines difference phases of the received radar signals from the interferograms, determines therefrom a drift of a system clock of the at least two SAR systems, and compensates the determined drift.

METHOD AND APPARATUS FOR INTERFEROMETRIC RADAR MEASUREMENT

[0002] The present invention relates to a method and apparatus for interferometric radar measurement.

[0003] In synthetic aperture radar (SAR) systems, a highly precise time reference is of considerable importance for exact measuring results. If several SAR systems are used, for example, on different satellites, a mutual balancing of the individual time references of the SAR systems is also important for a precise radar measurement.

[0004] European Patent Document EP 1 065 518 discloses a radar system which has a number of SAR systems on satellite- or missile-supported platforms. In order to avoid drift of the internal oscillators of the SAR systems, which are used as a time reference, a microwave or laser connection between the individual SAR systems is used to transmit an oscillator frequency from a main oscillator to the other oscillators, and thereby to synchronize these oscillators.

[0005] The essay "Oscillator Clock Drift Compensation in Bistatic Interferometric SAR", M. Eineder, IGARSS 2003, Toulouse, IEEE Proceedings of

IGARSS'03, describes the compensation of the drift of time references in SAR systems. The transmitters and receivers of the radar signal are spatially separated, and the oscillator frequency is exchanged between the receiving satellites via an inter-satellite connection in order to achieve a synchronization of the time references.

[0006] Drift compensation in such systems requires additional inter-satellite connections for transmission of the oscillator frequency. Moreover, additional measuring-relevant parameters cannot be determined by this method, and other compensation methods require additional components for implementing control mechanisms. However, the use of these control mechanisms requires time which is lost during the actual radar measurement. The scanning for the referencing thus remains limited to a few hertz.

[0007] It is therefore an object of the present invention to provide a method and apparatus for interferometric radar measurement, which permits drift compensation during radar measurements by means of SAR interferometry, without the use of high-expenditure inter-satellite connections.

[0008] This object is achieved by means of the method and apparatus for interferometric radar measurement according to the invention, in which, when several SAR systems are used, each of the SAR systems receives the radar signals sent by the other SAR systems and reflected on the ground. Interferograms created by the overlapping of the various spectral ranges of the received radar signals can be used to determine a drift of the system clocks of the

SAR systems which can be taken into account, particularly compensated, during further processing of the radar signals. This permits drift compensation, without the use of an inter-satellite connection.

[0009] More specifically, the invention relates to a method for interferometric radar measurement by means of at least two synthetic aperture radar (SAR) systems on satellite or missile-supported platforms, which systems illuminate a common surface area by means of microwave signals. For this purpose, a first SAR system sends a first radar signal on a first transmit frequency, and a second SAR system sends at least a second radar signal on at least a second transmit frequency. In this case, at least one of the at least two SAR systems receives the at least two interfering radar signals reflected on the common surface area, determines difference phases of the received radar signals from the interferograms, determines a drift of a system clock of the at least two SAR systems from the difference phases, and compensates the determined drift. An additional connection between the platforms is therefore no longer necessary for synchronizing the systems clocks.

[0010] In a preferred embodiment of the method, the first and the at least a second SAR system receives the at least two interfering radar signals of the at least two SAR systems reflected on the common surface area, determines difference phases of the received radar signals from the interferograms, determines a drift of a system clock of the at least two SAR systems from the difference phases, and compensates the determined drift, preferably by means of corresponding measures for the drift compensation.

[0011] In particular, the process can derive a first interferogram from the first radar signal received by the first SAR system and from at least a second radar signal received by the at least a second SAR system. In comparison to further interferograms, this interferogram has a base length which is twice as effective.

[0012] In addition, the process can derive a second interferogram from the first radar signal received by the first SAR system and from the first radar signal received by the at least a second SAR system. This interferogram derived in the range of the first transmit frequency contains a difference phase which is a result of a phase error of the second SAR system minus a phase error of the first SAR system.

[0013] Furthermore, the process can derive a third interferogram from the at least a second radar signal received by the first SAR system and the at least a second radar signal received by the at least a second SAR system. This interferogram derived in the range of the second transmit frequency contains a difference phase, which also is a result of a phase error of the second SAR system minus a phase error of the first SAR system.

[0014] In order to determine a difference phase (which is a result of a phase error of the first SAR system minus a phase error of the second SAR system), the process can derive a fourth interferogram from the first radar signal received by the first SAR system and at least a second radar signal. This interferogram, which is crossed in the microwave frequency range, is created by the overlapping of the spectral ranges of the first and second radar signal because of a displacement of the spectrum of the received radar signals.

[0015] The process can also derive a fifth interferogram from the first radar signal received by the at least a second SAR system and the at least a second radar signal, in order to determine a difference phase which is equal to the determined difference phase in the case of the fourth interferogram. This interferogram is also created by an overlapping of the spectral ranges of the first and second radar signal.

[0016] The invention also relates to a system for interferometric radar measurement having at least two synthetic aperture radar (SAR) systems on satellite- and/or missile-supported platforms, which illuminate a common surface area by means of microwave signals. A first SAR system can send a first radar signal on a first transmit frequency and at least a second SAR system can send at least a second radar signal on at least a second transmit frequency. In this case, at least one of the at least two SAR systems is constructed for receiving the at least two interfering radar signals reflected on the common surface area, for determining difference phases of the received radar signals from the interferograms, for determining a drift of a system clock of the at least two SAR systems from the difference phases, and for compensating the determined drift.

[0017] In a preferred embodiment, the first and the at least a second SAR system are constructed for receiving the at least two interfering radar signals of the at least two SAR systems, which are reflected on the common surface area, for determining difference phases of the received radar signals from the interferograms, for determining a drift of a system clock of the at least two SAR systems from the difference phases, and compensating the determined drift. The system preferably contains devices for the drift compensation which are activated as a function of the determined drift.

[0018] In particular, the first SAR system has a steeper incidence angle with respect to the illuminated surface area than that of the at least a second SAR system.

[0019] In this case, the first transmit frequency should be higher than the at least a second transmit frequency. In order to obtain a high resolution transversely to the flight direction of the satellites, a higher transmit frequency is assigned to the SAR system with the steeper incidence angle than to the SAR system with the flatter incidence angle.

[0020] Furthermore, the system can be constructed such that the first and the at least a second SAR system send radar signals on more than one transmit frequency. The different and partially mutually supplementing information content of the radar image data, which are recorded in different frequency ranges, yields an improvement of the interpretation of these radar image data.

[0021] In addition, the system can be constructed such that the first and the at least a second SAR system send radar signals with more than one polarization. As with the use of several frequencies, the use of different polarizations permits a higher yield of information when the radar images are interpreted.

[0022] In particular, the first and the at least a second radar signal can be either frequency-modulated continuous signals or frequency-modulated pulses. When frequency-modulated pulses are used, for example, data concerning the distance or the scattering of the radar signal (which, in turn, provides information on the surface condition) can be obtained from the transit time of the pulse, the slope of its edges and the energy of the pulse response.

[0023] The system can also be constructed for sending the first and the at least a second radar signal in a time-staggered manner within a pulse interval. Since processing of the radar image data is computationally very intensive, staggering the radar signals can reduce the image resolution, and hence the data transmission rate.

[0024] In the description, in the claims, in the abstract and in the drawings, the terms used in the attached list of reference symbols and the assigned reference symbols are used.

[0025] Other objects, advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] Figure 1 is a view of an embodiment of the system according to the invention having two SAR systems on a satellite-supported platform;

[0027] Figure 2 is a spectral diagram of the received radar signals in the microwave frequency range with a view of their position along a geometrical base line; and

[0028] Figure 3 is a spectral diagram of the received radar signals with their position displacement due to reflection on the illuminated surface area, and the resulting overlapping spectral ranges for forming the interferograms.

DETAILED DESCRIPTION OF THE DRAWINGS

[0029] In the following, the same and/or functionally identical elements may be provided with the same reference numbers.

[0030] Figure 1 shows an embodiment of the system according to the invention with two SAR systems 1 and 2, each on a satellite-supported platform. Both SAR systems 1 and 2 illuminate a surface area 4 of the earth's surface 3, with the first satellite and the first SAR system 1 situated over the illuminated surface area 4 at a steeper incidence angle than the second satellite and the second SAR system 2. The first SAR system 1 sends with a first transmit frequency f_1, while the second SAR system 2 sends with a second transmit frequency f_2 which is lower than the first transmit frequency f_1. (In order to obtain a high resolution transversely to the flight direction of the satellites, a higher transmit frequency is assigned to the SAR system with the steeper incidence angle than to the SAR system with the flatter incidence angle.)

[0031] The reflected radar signals of the first and second SAR systems are in each case received by both SAR systems. The sent radar signals may be frequency-modulated pulses as well as frequency-modulated continuous signals. When frequency-modulated pulses are used, among others, data concerning the distance or the scattering of the radar signal (which in turn provides information on the surface condition) can be obtained (for example, from the transit time of the pulse, the slope of its edges and the energy of the pulse response).

[0032] In addition, it becomes possible for the first and second SAR system 1 and 2 to send radar signals on, in each case, more than one transmit frequency. Incident radar signals are reflected differently by the surface depending on the frequency. Different frequency bands exhibit different backscatter characteristics as a function of the surface condition. The intensity of the backscattered signal is high dependent on, among other things, the surface inclination or the incidence angle of the radar signal.

[0033] The different and partially mutually supplementary information content of the radar image data which are recorded in different frequency ranges, leads to an improvement of the interpretation of these radar image data. Likewise, the use of different polarizations permits a higher yield of information when interpreting the radar images.

[0034] Since the processing of the radar image data is very computation-intensive, time-staggered transmission of the radar signals within one pulse interval can be used to reduce the image resolution, and hence the data transmission rate.

[0035] Figure 2 is a spectral diagram of the received radar signals in the microwave frequency range illustrating their position along a geometrical base line. Here, s_{11} indicates a radar signal sent and received by the first SAR system; s_{12} indicates a radar signal sent by the first SAR system and received by the second SAR system. Analogously, s_{21} is a radar signal sent by the second SAR system and received by the first SAR system; and s_{22} is a radar signal sent and received by the second SAR system. Furthermore, δ_1 is defined as the phase error in the sent signal of the first SAR system based on a drift of the system clocks; $-\delta_1$ is to be the phase error in the received signal of the first SAR system. Analogously, δ_2 is the phase error of the sent signal of the second SAR system based on a drift of the system clocks; $-\delta_2$ is the phase error in the received signal of the second SAR system.

[0036] Thus, the received signals contain the following phase errors:

s_{11}, s_{11}^*, s_{22} and s_{22}^*	0
s_{12} and s_{21}^*	δ_1-δ_2
s_{21} and s_{12}^*	δ_2-δ_1

[0037] The spectral diagram shows the spectral lines of the different radar signals 13 reflected on the surface. The first SAR system receives the signals s_{11} and s_{12} with a signal bandwidth 12 in the frequency range 11. Analogously thereto, the second SAR system receives the signals s_{21} and s_{22} with the signal bandwidth 12 in the frequency range 10.

[0038] As illustrated in Figure 3, five interferograms can be formed from the four received radar signals s_{11}, s_{12}, s_{21} and s_{22}. The interferograms are formed as the product of a first of the four received radar signals s_{11}, s_{12}, s_{21} and s_{22} with another complexly conjugated radar signal of the four received radar signals s_{11}^*, s_{12}^*, s_{21}^* and s_{22}^*.

[0039] The interferograms derived around f_1 and f_2 (always the same transmitter)

$i_{|1} = s_{11}\, s_{12}^*$ and

$i_{|2} = s_{21}\, s_{22}^*$

each contain the same differential phase error $\delta_2 - \delta_1$, which is based on a drift between the systems. This measurement corresponds to a doubling of a single bistatic SAR system in which the transmitter and receiver are separate, without any drift compensation but with a multiplied signal intensity.

[0040] The displacement of the spectrum of the reflected radar signals results in an overlapping of the spectral ranges which permits a formation of interferograms i_{x1} and i_{x2} within these overlapping ranges, which interferograms are crossed in the microwave range. In this case, the radar signals around f_1 interfere coherently with radar signals around f_2 in:

$i_0 = s_{11}\, s_{22}^*$ with an effective base length doubled with respect to the other interferograms, and

$i_{x1} = s_{11}\, s_{21}^*$ and

$i_{x2} = s_{12}\, s_{22}^*$ with the same differential phase errors $\delta_2 - \delta_1$ which,however, compared with $i_{|1}$ and $i_{|2}$, have an opposite preceding sign.

[0041] These interferograms are used for the measurement and compensation of the differential phase error. The signal fractions pertaining to the geometry, such as altitude information during topographical measurements are extracted from the differences between these interferograms. The following phase errors therefore remain:

$i_{|1}\ i_{x2}\ ;\ i_{|2}\ i_{x1}$ $2\,(\delta_2 - \delta_1)$

$i_{|1}\ i_{|2}\ i_0^*$ $2\,(\delta_2 - \delta_1)$

[0042] It is sufficient for at least one of the crossed interferograms i_{x1} or i_{x2} to be present in a reduced slant range resolution (in a small spectral width) because the determination of the differential phase error of a low order is independent of the slant range (for example, constant within a pulse or a modulation period). For example, if the differential phase drifts between SAR systems are to be compensated, the determined differential phase errors can be determined by averaging the interferograms in the slant range direction for different positions in the flight direction. In the case of phase errors which vary rapidly with time, either the synthetic aperture has to be shortened correspondingly, or the occurring displacement of the image data along the flight direction must be detected, on the basis of the different phases of the SAR pictures situated above one another geometrically, but not with respect to time. At pulse rates in the range of 5 kHz, phase drift measurements of a rate of up to 500 Hz are expected.

[0043] The displacement of the ground spectrum on the basis of the interferometric measuring arrangement permits the computation of an interferogram between the two microwave frequency ranges also in the case of an arrangement in which only one receiver is used. However, a phase error compensation as in the case of a multireceiver arrangement is not possible here. Thus, for example, when the first SAR system is used as a receiver, a crossed interferogram

$$i_{x1} = s_{11}\, s_{21}^{*}$$

can be determined. This method of operation can also be implemented in combination with the multireceiver variant, in which case the time reception windows of the participating receivers are situated in a displaced manner with respect to one another, for example, with a small overlap in order to be able to detect expanded surface widths or in order to have to detect lower data quantities.

[0044] The foregoing disclosure has been set forth merely to illustrate the invention and is not intended to be limiting.

[0045] Reference Symbols

1	First SAR system on a first satellite
2	second SAR system on a second satellite
3	earth's surface
4	illuminated surface area
f_1	first transmit frequency of the first SAR system
f_2	second transmit frequency of the second SAR system
10	transmit range of the first SAR system
11	transmit range of the second SAR system
12	bandwidth of the received radar signals
13	spectrum of the radar signals reflected on the illuminated surface
s_{11}	radar signal sent and received by the first SAR system
s_{12}	radar signal sent by the first SAR system and received by the second SAR system
s_{21}	radar signal sent by the second SAR system and received by the first SAR system
s_{22}	radar signal sent and received by the second SAR system
δ_1	the phase error of the first SAR system based on a drift of the system clocks
δ_2	the phase error of the second SAR system based on a drift of the system clocks

i_0 first interferogram from the overlapping spectral ranges of the radar signals s_{11} and s_{22}

i_{l1} second interferogram from the overlapping spectral ranges of radar signals s_{11} and s_{12}

i_{l2} third interferogram from the overlapping spectral ranges of the radar signals s_{21} and s_{22}

i_{x1} fourth interferogram from the overlapping spectral ranges of the radar signals s_{11} and s_{21}

i_{x2} fifth interferogram from the overlapping spectral ranges of the radar signals s_{12} and s_{22}

WHAT IS CLAIMED IS:

1. A method for interferometric radar measurement in which at least two SAR systems, mounted on satellite and/or missile-supported platforms, wherein illuminate a common surface area by means of microwave signals; wherein:

a first SAR system sends a first radar signal on a first transmit frequency;

at least a second SAR system sends at least a second radar signal on at least a second transmit frequency; and

at least one of the at least two SAR systems receives at least two interfering radar signals reflected on the common surface area, and based thereon determines difference phases of the received radar signals by forming interferograms, determines a drift of a system clock of the at least two SAR systems from the difference phases, and compensates the determined drift.

2. The method according to Claim 1, wherein each of the first and at least a second SAR system receives the at least two interfering radar signals reflected on the common surface area, and based thereon determines difference phases of the received radar signals from the interferograms determines a drift

of a system clock of the at least two SAR systems from the difference phases, and compensates the determined drift.

3. The method according to Claim 2, wherein a first interferogram is derived from a radar signal s_{11} sent and received by the first SAR system, and from a radar signal s_{22} sent and received by the at least a second SAR system.

4. The method according to Claim 3, wherein a second interferogram is derived from the radar signal s_{11}, and a radar signal s_{12} sent by the first SAR system and received by the at least a second SAR system.

5. The method according to Claim 4, wherein a third interferogram is derived from a radar signal s_{21} sent by the at least a second SAR system and received by the first SAR system and a radar signal sent s_{22} and received by the at least a second SAR system.

6. The method according to Claim 5, wherein a fourth interferogram is derived from the radar signal s_{11}, and the radar signal s_{21}.

7. The method according to Claim 6, wherein a fifth interferogram is derived from the radar signal s_{12} and the radar signal s_{22}.

8. A system for the interferometric radar measurement having at least

two SAR systems on satellite- and/or missile-supported platforms which illuminate a common surface area by means of microwave signals, including a first SAR system which can send a first radar signal on a first transmit frequency, and at least a second SAR system which can send at least a second radar signal on at least a second transmit frequency; wherein:

at least one of the at least two SAR systems is constructed for receiving at least two interfering radar signals reflected on the common surface area, for determining, based on said interfering radar signals, difference phases of the received radar signals by forming the interferograms, determining a drift of a system clock of the at least two SAR systems from the difference phases, and compensating the determined drift.

9. The system according to Claim 8, wherein the first and the at least a second SAR system are constructed for receiving the at least two interfering radar signals reflected on the common surface area, of the at least two SAR systems, for determining, based on said interfering radar signals, difference phases of the received radar signals from the interferograms, determining a drift of a system clock of the at least two SAR systems from the difference phases, and compensating the determined drift.

10. The system according to Claim 9, wherein the first SAR system has a steeper incidence angle with respect to the illuminated surface areas than the at least a second SAR system.

11. The system according to Claim 10, wherein the first transmit frequency is higher than the at least a second transmit frequency.

12. The system according to Claim 11, wherein both the first and the at least a second SAR system send radar signals on more than one transmit frequency.

13. The system according to Claim 12, wherein the first and the at least a second SAR system send radar signals with more than one polarization.

14. The system according to Claim 13, wherein the first and the at least a second radar signals are frequency-modulated continuous signals.

15. The system according to Claim 13, wherein the first and the at least a second radar signals are frequency-modulated pulses.

16. The system according to Claim 13, wheein the first and the at least a second radar signals are sent within a time-staggered pulse interval.

Fig. 1

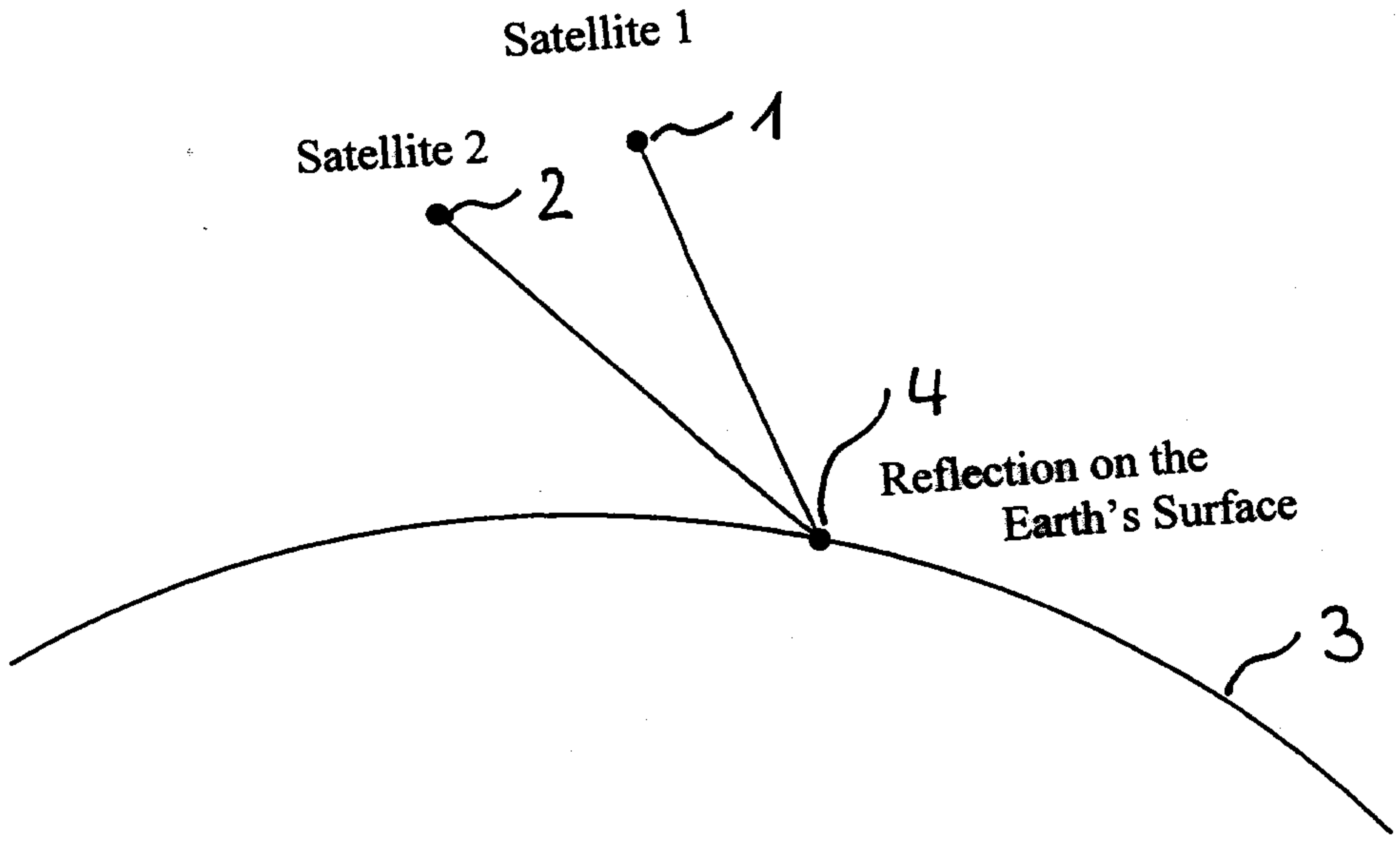
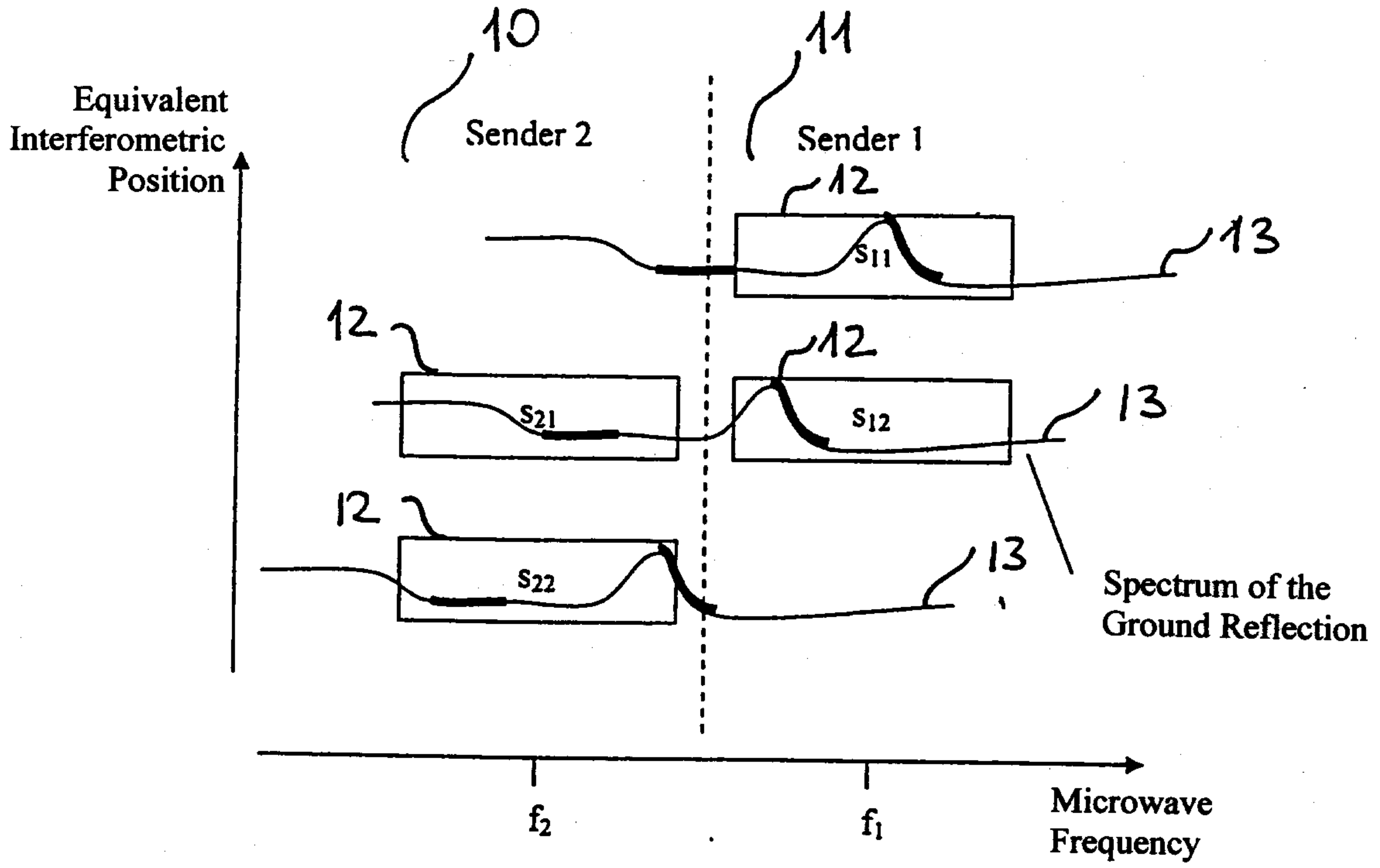

Satellite 1
1
Satellite 2
2
4
Reflection on the
Earth's Surface
3

Fig. 2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11
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Sender 1
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s21
s12
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s22
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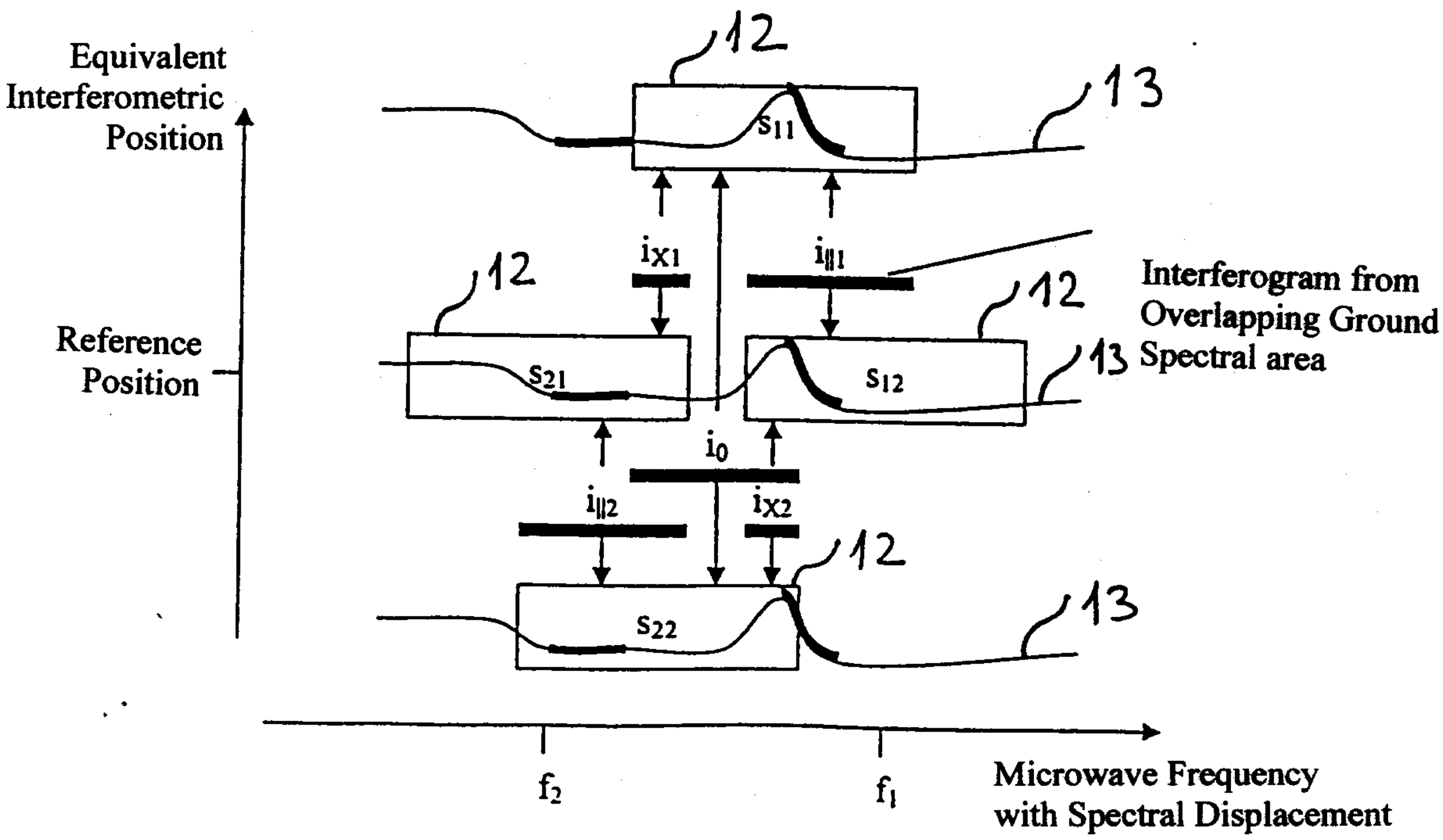
Spectrum of the Ground Reflection
f2
f1
Microwave Frequency

Fig. 3


Equivalent Interferometric Position
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12
12
Interferogram from Overlapping Ground Spectral area
Reference Position
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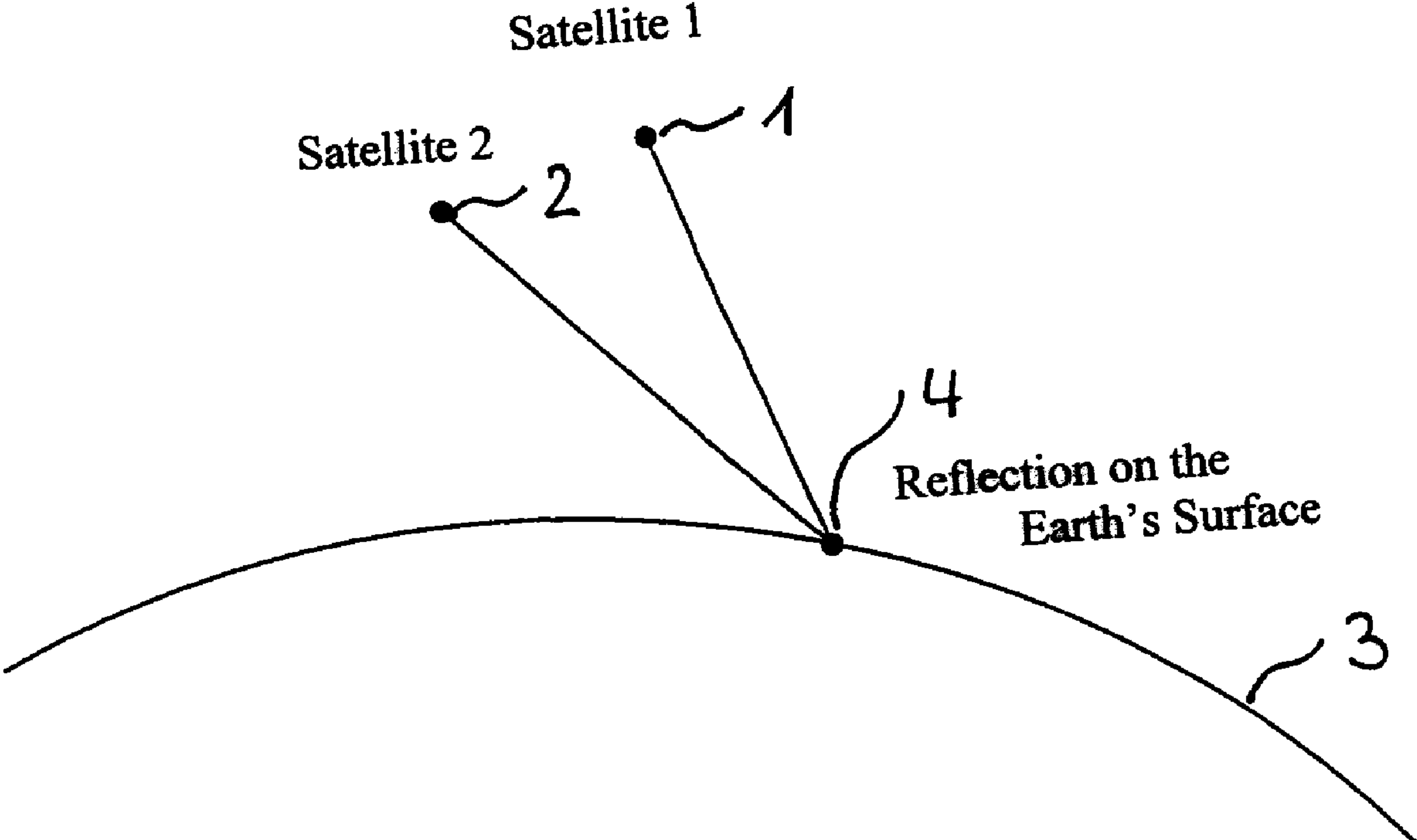
i||2
ix2
12
s22
13
f2
f1
Microwave Frequency with Spectral Displacement



Satellite 1
Satellite 2
1
2
4
Reflection on the
Earth's Surface
3