МИНИСТЕРСТВО ОБРАЗОВАНИЯ И НАУКИ РОССИЙСКОЙ ФЕДЕРАЦИИ

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(ФГБОУ ВПО «СГГА»)

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ORAL PRACTICE FOR SCIENCE STUDENTS
INTERFEROMETRY

Учебное пособие

Новосибирск
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The essence of the manual lies in the fact that majority of Master and PhD students of non-English speaking countries face problems connected with their inability to carry out oral and written communication in this language. The manual is intended to help all of the interested parties to develop the mentioned above skills as the advanced stage of group training of communication in the sphere of their professional activity.

Apart from Master and PhD students the manual can also be used by research and technical staff wishing to improve skills of oral and written speech independently on the basis of scientific lexicon.

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ПРЕДИСЛОВИЕ

Цели и задачи курса «Интерферометрия»

Предлагаемое учебное пособие предназначено для работы по развитию навыков устной речи в группах аспирантов и научных сотрудников неязыковых специальностей вузов в качестве продвинутого этапа группового обучения общения на английском языке в сфере своей профессиональной деятельности. Оно также может быть использовано студентами и аспирантами технических вузов, научными сотрудниками и инженерами, желающими самостоятельно овладеть навыками устной речи на базе научной лексики.

В настоящем пособии использованы оригинальные научные тексты, взятые из современных научных журналов и научно-популярных книг. Автором были отобраны тексты, так или иначе связанные с научной работой и новыми технологиями в области интерферометрии. При разработке курса автор стремился отобрать фабульные тексты, поддающиеся обсуждению и пересказу и содержащие лексический материал, характерный для научной речи.

Таким образом, тексты пособия содержат не только необходимый языковой материал, но, одновременно, и расширяют знания обучающихся представляя определенный интерес, что является условием успешной работы при изучении языка.

В каждом уроке курса для всех текстов разработаны упражнения, цель которых закрепить необходимый лексический и грамматический материал и стимулировать устную речь. При составлении упражнений автор руководствовался следующими принципами: были отобраны готовые речевые модели, которые закрепляются путем многократного и разнообразного повторения тренировочного характера в различных видах упражнений. Сначала обучающимся предлагаются упражнения тренировочного характера, затем идут упражнения полутворческого характера и, наконец, упражнения творческого характера, стимулирующие высказывание по какому-либо вопросу, связанному с тематикой основного текста или пройденного материала.

Пособие построено на базе отобранного лексического материала объемом около 1300 лексических единиц и рассчитан на 68 – 72 учебных часа (30 – 36 часов из которых аудиторные). Он может быть реализован в различной учебной сетке часов, однако рекомендуется проводить не менее 6 – 8 часов занятий в неделю.

По окончанию курса обучаемый должен уметь:

- общаться в рамках тематики учебного пособия (понимать речь в естественном темпе и говорить с достаточной степенью грамматической корректности);
- читать научную литературу в области интерферометрии с общим пониманием смысла прочитанного;
- составлять и представлять презентации научных выступлений и лекций на английском языке.

При работе над данным пособием автор учитывал трактовку и иллюстративный материал, представленный в следующих работах:

1. *A. Ferretti, A. Monti-Guarnieri, C. Prati, F. Rocca, D. Massonnet*. **InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation**. ESA Publications, 2007.

2. *Matthew E. Pritchard*. **InSAR, a Tool for Measuring Erath's Surface Deformation**. American Institute of Physics, 2006.
3. *M. Simons, P. A. Rosen*. **Interferometric Synthetic Aperture Radar Geodesy**. California Institute of Technology, 2007.
4. *P. A. Rosen*. **Principles and Theory of Radar Interferometry**. UNAVCO Short Course, Jet Propulsion Laboratory, 2009.

Автор выражает большую благодарность за рекомендации и помощь, оказанную при разработке и апробации курса его первым слушателям, аспирантам и научным сотрудникам Сибирской государственной геодезической академии *А. Чермошенцеву, Л. Липатникову, М. Алтынцеву, П. Кикину, А. Трояну* и *А. Семенцову*.

Отдельная благодарность *Екатерине Долгушиной* за разработку компьютерной программы по запоминанию и контролю усвоенного лексического материала курса.

Unit 1

InSAR

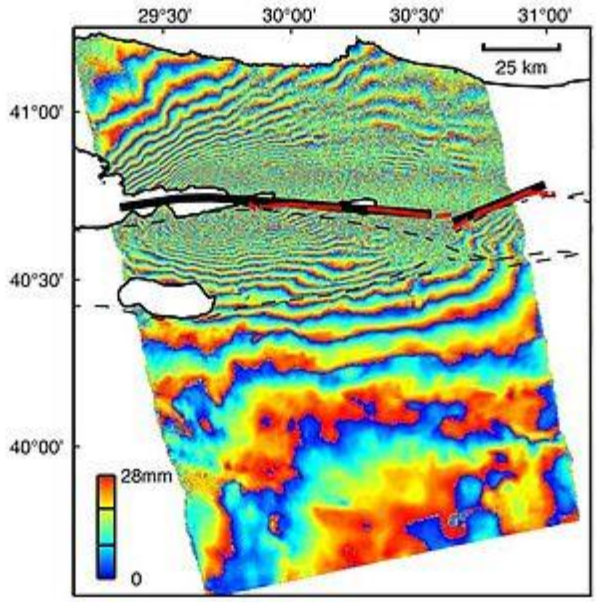
Phrases to learn:

ambient illumination – *окружающее освещение*
outgoing wave – *исходящая волна*
phase difference – *разность фаз*
phase shift – *изменение фазы*
summed contribution – *суммированный вклад*,
adjacent pixels – *смежные пиксели*
altitude of ambiguity – *неоднозначность высоты*
two-pass method – *метод с двумя проходами*
externally derived – *полученный извне*
residual phase – *остаточная фаза*
incidence angle – *угол падения*
poor coverage – *слабое покрытие*
partial pressure – *парциальное давление*
spurious signal – *ложный сигнал*

Interferometric synthetic aperture radar

Interferometric synthetic aperture radar, also abbreviated **InSAR** or **IfSAR**, is radar technique used in geodesy and remote sensing. This geodetic method uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the satellite or aircraft.

SAR amplitude image of Kilauea(NASA/JPL-Caltech)



Interferogram produced using ERS-2data from 13 August and 17 September 1999, spanning the 17 August Izmit (Turkey) earthquake. (NASA/JPL-Caltech)

The technique can potentially measure centimeter-scale changes in deformation over time spans of days to years. It has applications for geophysical monitoring of natural hazards, for example earthquakes, volcanoes and landslides, and also in structural engineering, in particular monitoring of subsidence and structural stability.

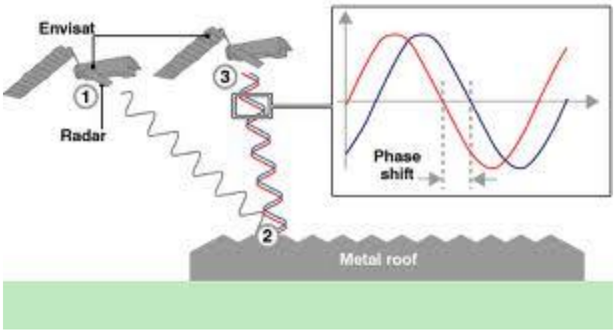
Technique

Synthetic aperture radar

Synthetic aperture radar (SAR) is a form of radar in which sophisticated processing of radar data is used to produce a very narrow effective beam. It can only be used by moving instruments over relatively immobile targets. It is a form of active remote sensing - the antenna transmits radiation which is then reflected from the target, as opposed to passive sensing, where the reflection is detected from ambient illumination. The image acquisition is therefore independent of the natural illumination and images can be taken at night.

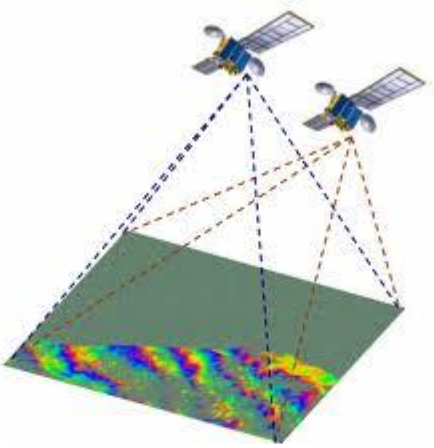
Radar uses electromagnetic radiation with microwave frequencies; the atmospheric absorption at typical radar wavelengths is very low, meaning observations are not prevented by cloud cover.

Phase



Most SAR applications make use of the amplitude of the return signal, and ignore the phase data. However interferometry uses the phase of the reflected radiation. Since the outgoing wave is produced by the satellite, the phase is known, and can be compared to the phase of the return signal. The phase of the return wave depends on the distance to the ground, since the path length to the ground and back will consist of a number of whole wavelengths plus some fraction of a wavelength.

Phase difference



This is observable as a phase difference or phase shift in the returning wave. The total distance to the satellite (i.e. the number of whole wavelengths) is not known, but the extra fraction of a wavelength can be measured extremely accurately.

In practice, the phase is also affected by several other factors, which together make the raw phase return in any one SAR image essentially arbitrary, with no correlation from pixel to pixel.

To get any useful information from the phase, some of these effects must be isolated and removed. Interferometry uses two images of the same area taken from the same position (or for topographic applications slightly different positions) and finds the difference in phase between them, producing an image known as an interferogram. This is measured in radians of phase difference and, due to the cyclic nature of phase, is recorded as repeating fringes which each represent a full 2π cycle.

Factors affecting phase

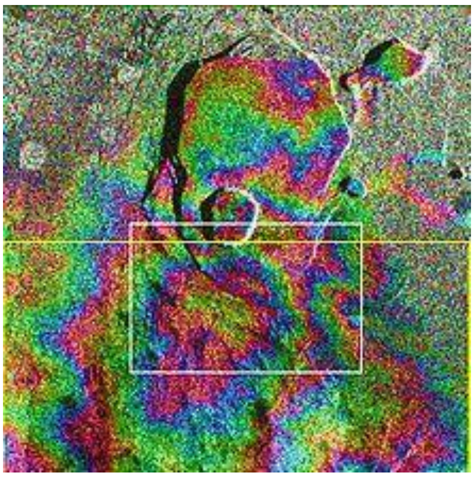
The most important factor affecting the phase is the interaction with the ground surface. The phase of the wave may change on reflection, depending on the properties of the material. The reflected signal back from any one pixel is the summed contribution to the phase from many smaller 'targets' in that ground area, each with different dielectric properties and distances from the satellite, meaning the returned signal is arbitrary and completely uncorrelated with that from adjacent pixels. Importantly though, it is consistent - provided nothing on the ground changes the contributions from each target should sum identically each time, and hence be removed from the interferogram.

Once the ground effects have been removed, the major signal present in the interferogram is a contribution from orbital effects. For interferometry to work, the satellites must be as close as possible to the same spatial position when the images are acquired. This means that images from two different satellite platforms with different orbits cannot be compared, and for a given satellite data from the same orbital track must be used. In practice the perpendicular distance between them, known as the *baseline*, is often known to within a few centimeters but can only be controlled on a scale of tens to hundreds of meters. This slight difference causes a regular difference in phase that changes smoothly across the interferogram and can be modelled and removed.

The slight difference in satellite position also alters the distortion caused by topography, meaning an extra phase difference is introduced by a stereoscopic effect. The longer the baseline, the smaller the topographic height needed to produce a fringe of phase change - known as the altitude of ambiguity. This effect can be exploited to calculate the topographic height, and used to produce a digital elevation model (DEM).

If the height of the topography is already known, the topographic phase contribution can be calculated and removed. This has traditionally been done in two ways. In the two-pass method, elevation data from an externally-derived DEM is used in conjunction with the orbital information to calculate the phase contribution. In the three-pass method two images acquired a short time apart are used to create an interferogram, which is assumed to have no deformation signal and therefore represent the topographic contribution. This interferogram is then subtracted from a third image with a longer time separation to give the residual phase due to deformation.

Once the ground, orbital and topographic contributions have been removed the interferogram contains the deformation signal, along with any remaining noise. The signal measured in the interferogram represents the change in phase caused by an increase or decrease in distance from the ground pixel to the satellite, therefore only the component of the ground motion parallel to the satellite line of sight vector will cause a phase difference to be observed.



Corresponding interferogram of Kilauea, showing topographic fringes (NASA/JPL-Caltech)

For sensors like ERS with a small incidence angle this measures vertical motion well, but is insensitive to horizontal motion perpendicular to the line of sight (approximately north-south). It also means that vertical motion and components of horizontal motion parallel to the plane of the line of sight (approximately east-west) cannot be separately resolved.

One fringe of phase difference is generated by a ground motion of half the radar wavelength, since this corresponds to a whole wavelength increase in the two-way travel distance. Phase shifts are only resolvable relative to other points in the interferogram.

Absolute deformation can be inferred by assuming one area in the interferogram (for example a point away from expected deformation sources) experienced no deformation, or by using a ground control (GPS or similar) to establish the absolute movement of a point.

Difficulties with InSAR

A variety of factors govern the choice of images which can be used for interferometry. The simplest is data availability - radar instruments used for interferometry commonly don't operate continuously, acquiring data only when programmed to do so. For future requirements it may be possible to request acquisition of data, but for many areas of the world archived data may be sparse. Data availability is further constrained by baseline criteria. Availability of a suitable DEM may also be a factor for two-pass InSAR; commonly 90m SRTM data may be available for many areas, but at high latitudes or in areas of poor coverage alternative datasets must be found.

A fundamental requirement of the removal of the ground signal is that the sum of phase contributions from the individual targets within the pixel remains constant between the two images and is completely removed. However there are several factors that can cause this criterion to fail. Firstly the two images must be accurately co-registered to a sub-pixel level to ensure that the same ground targets are contributing to that pixel. There is also a geometric constraint on the maximum length of the baseline - the difference in viewing angles must not cause phase to change over the width of one pixel by more than a wavelength. The effects of topography also influence the condition, and baselines need to be shorter if terrain gradients are high. Where co-registration is poor or the maximum baseline is exceeded the pixel phase will become incoherent - the phase becomes essentially random from pixel to pixel rather than varying smoothly, and the area appears noisy. This is also true for anything else that changes the contributions to the phase within each pixel, for example changes to the ground targets in each pixel caused by vegetation growth, landslides, agriculture or snow cover.

Another source of error present in most interferograms is caused by the propagation of the waves through the atmosphere. If the wave travelled through a vacuum it should theoretically be possible (subject to sufficient accuracy of timing) to use the two-way travel-time of the wave in combination with the phase to calculate the exact distance to the ground. However the velocity of the wave through the atmosphere is lower than the speed of light in a vacuum, and depends on air temperature, pressure and the partial pressure of water vapour. It is this unknown phase delay that prevents the integer number of wavelengths being calculated. If the atmosphere was horizontally homogeneous over the length scale of an interferogram and vertically over that of the topography then the effect would simply be a constant phase difference between the two images which, since phase difference is measured relative to other points in the interferogram, would not contribute to the signal. However the atmosphere is laterally heterogeneous on length scales both larger and smaller than typical deformation signals. This spurious signal can appear completely unrelated to the surface features of the image, however in other cases the atmospheric phase delay is caused by vertical inhomogeneity at low altitudes and this may result in fringes appearing to correspond with the topography.

Data Sources

Seasat (NASA/JPL-Caltech)

Early exploitation of satellite-based InSAR included use of Seasat data in the 1980s, but the potential of the technique was expanded in the 1990s, with the launch of ERS-1 (1991), JERS-1 (1992), RADARSAT-1 and ERS-2 (1995). These platforms provided the stable, well-defined orbits and short baselines necessary for InSAR. More recently, the 11-day NASA STS-99 mission in February 2000 used a SAR antenna mounted on the space shuttle to gather data for the Shuttle Radar Topography Mission. In 2002 ESA launched the ASAR instrument, designed as a successor to ERS, aboard Envisat.

While the majority of InSAR to date has utilized the C-band sensors, recent missions such as the ALOS PALSAR, TerraSAR-X and COSMO SKYMED are expanding the available data in the L- and X-band.

I. Vocabulary

absorption (n) – *поглощение*
acquisition (n) – *сбор (данных)*
alter (v) – *изменять, менять*
arbitrary (adj) – *произвольный*
availability (n) – *доступность*
baseline (n) – *базис*
beam (n) – *луч*
constraint (n) – *ограничение*
ERS – *European Resource Sensor*
establish (v) – *устанавливать*
expand (v) – *распространять*
fringe (n) – *цветовая линия, полоса*
homogeneous (adj) – *однородный*
incoherent (adj) – *несогласованный*
infer (v) – *выводить*
inhomogeneity (n) – *неоднородность*
insensitive (adj) – *нечувствительный*
integer (adj) – *целый*
interaction (n) – *взаимодействие*
isolate (v) – *отделять*
laterally (adv) – *латерально (в стороне от)*
observation (n) – *наблюдение*
prevent (v) – *предотвращать*
propagation (n) – *распространение*
random (adj) – *случайный*
resolvable (adj) – *разрешимый*
sparse (adj) – *редкий*
sub-pixel (adj) – *подпиксельный*
subsidence (n) – *понижение*
transmit (v) – *передавать*
vapour (n) – *пар*
velocity (n) – скорость

II. Reading

absorption [əb'zɔ:pʃ(ə)n], acquisition [ˌækwi'ziʃ(ə)n], alter ['ɔ:ltə], arbitrary ['ɑ:bitr(ə)ri], availability [əˌveilə'biləti], beam [bi:m], constrain [kən'streint], establish [is'tæbliʃ], expand [ik'spænd], fringe [frindʒ], homogeneous [ˌhɔmə'dʒi:niəs], incoherent [ˌinkəu'hiər(ə)nt], infer [in'fə:], insensitive [in'sen(t)sətiv] integer ['intidʒə], interaction [ˌintər'ækʃ(ə)n], isolate ['aisəleit], laterally ['læt(ə)r(ə)li], observation [ˌɔbzə'veiʃ(ə)n], prevent [pri'vent], propagation [ˌprɔpə'geiʃ(ə)n], random ['rændəm], resolvable [rɪ'zɒlvəbᵊl], sparse [spɑ:s], subsidence [səb'said(ə)n(t)s], transmit [trænz'mit], vapour ['veipə], velocity [vi'lɔsəti], baseline ['beislain].

III. Comprehension check

1. What do abbreviations InSAR or IfSAR mean?
2. Where InSAR technique can be applied?
3. How does the SAR work?
4. What is the atmospheric absorption of typical radar wavelengths?
5. What factors affect the phase?
6. What is the most important condition to make interferometry work?
7. What effect can be exploited to produce a digital elevation model?
8. Which methods are used to calculate the topographic phase contribution?
9. What does the measured signal represent in the interferogram?
10. What factors are crucial when choosing the images used for interferometry?
11. How effects of topography can influence the baselines?
12. What influences the velocity of the wave when travelling in atmosphere?

IV. Repeat the following statements after the teacher, then change them to questions supplying short answers.

1. The technique can measure centimeter-scale changes in deformation.
2. It has applications for geophysical monitoring of natural hazards.
3. SAR is a form of radar in which sophisticated processing of radar data is used.
4. Most SAR applications make use of the amplitude of the return signal.
5. The phase of the return wave depends on the distance to the ground.
6. This means that images from two different satellite platforms with different orbits cannot be compared.
7. The slight difference in satellite position also alters the distortion caused by topography.
8. This effect can be exploited to calculate the topographic height.
9. The signal measured in the interferogram represents the change in phase caused by an increase or decrease in distance from the ground pixel to the satellite.
10. Another source of error present in most interferograms is caused by the propagation of the waves through the atmosphere.

V. Remake the following sentences according to the given pattern.

A. Interferometric synthetic aperture radar is abbreviated as InSAR or IfSAR.
*Interferometric synthetic aperture radar **will be** abbreviated as InSAR or IfSAR*

1. SAR is a form of radar in which sophisticated processing of radar data **is** used.
2. The image acquisition **is** taken at night.
3. The atmospheric absorption is very low if observations **are** not prevented by cloud cover.
4. The most important factor affecting the phase **is** the interaction with the ground surface.
5. In the two-pass method, elevation data from an externally-derived DEM **is** used in conjunction with the orbital information to calculate the phase contribution.

B. The technique can potentially measure centimeter-scale changes in deformation.
*Centimeter-scale changes in deformation can **be** potentially **measured** by the technique.*

1. Radar uses electromagnetic radiation with microwave frequencies.
2. Several factors affect the phase of the returned signal.

3. You can’t compare images from two different satellite platforms with different orbits.
4. The signal measured in the interferogram represents the change in phase caused by an increase or decrease in distance from the ground pixel to the satellite.
5. Vertical inhomogeneity at low altitudes causes spurious signals completely unrelated to the surface features of the image.

C. Observations are not prevented by cloud cover.
Cloud cover does not prevent observations.

1. The total distance to the satellite is not known.
2. To get any useful information from the phase, some of these effects must be isolated and removed.
3. This effect can be exploited to calculate the topographic height, and used to produce a DTM.
4. One fringe of phase difference is generated by a ground motion of half the radar wavelength.
5. The two images must be accurately co-registered to a sub-pixel level to ensure that the same ground targets are contributing to that pixel.

D. Change the sentences into negative.

1. It can only be used by moving instruments over mobile targets.
2. The atmospheric absorption at typical radar wavelengths is very high.
3. Most SAR applications make ignore the amplitude of the return signal.
4. Vertical motions and components of horizontal motion parallel to the plane of the line of sight can be separately resolved.
5. The atmosphere is laterally homogeneous on length scales both larger and smaller than typical deformation signals.

VI. Ask questions to which the following sentences could be answers.

1. Geodetic method uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation.
2. The technique can potentially measure centimeter-scale changes in deformation over time spans.
3. The total distance to the satellite is not known.
4. Interferometry uses two images of the same area taken from the same position to produce an image known as an interferogram.
5. A slight difference in satellite position alters the distortion caused by topography.
6. The signal measured in the interferogram represents the change in phase caused by an increase or decrease in distance from the ground pixel to the satellite.
7. If the height of the topography is already known, the topographic phase contribution can be calculated and removed.
8. The effects of topography influence the accuracies, so baselines need to be shorter if terrain gradients are high.
9. The velocity of the wave through the atmosphere is lower than the speed of light in a vacuum.
10. The atmospheric phase delay is caused by vertical inhomogeneity at low altitudes.

VII. Correct the wrong statements using the given phrases.

on the contrary; I do not believe that; to my mind; as is known; as far as I know; it is considered that; it seems to be wrong; I am afraid you are mistaken; I can't agree with you; it seems unlikely that; in my opinion.

1. Geodetic and remote sensing methods do not use synthetic aperture radar images to generate maps of surface deformation or digital elevation.
2. The SAR technique can't measure centimeter-scale changes in deformation over time spans of days.
3. The image acquisition is dependent of the natural illumination and images can't be taken at night.
4. The reflected signal back from any one pixel is only its individual contribution to the phase.
5. In practice the perpendicular distance between two satellites, known as the *baseline*, is often known to within a few metres.
6. Only two factors govern the choice of images which can be used for interferometry.
7. An optional requirement of the removal of the ground signal is that the sum of phase contributions from the individual targets within the pixel remains different between the two images and is completely removed.
8. There is no geometric constraint on the maximum length of the baseline.
9. The velocity of the wave through the atmosphere is much higher than the speed of light in a vacuum.
10. Phase shifts are impossible to observe when making an interferogram.

VIII. Give Russian equivalents to the following phrases.

geodetic method, remote sensing, digital elevation, geophysical monitoring, processing of radar data, relatively immobile, passive sensing, microwave frequencies, essential arbitrary, summed contribution, adjacent pixels, ground effects, stereoscopic effect, slight difference, digital elevation model, phase difference, data acquisition, poor coverage, varying smoothly, vegetation growth, deformation signal.

IX. Give English translation of the following phrases. Use them in your own sentences.

исходящая волна; смежные пиксели; метод с двумя проходами; слабое покрытие территории; псевдо сигнал; разность фаз; промежуток времени; дистанционное зондирование; отраженная волна; плавно изменяться; сбор данных; неоднородность атмосферы; основное требование.

X. Put a proper preposition if necessary.

1. The SAR technique can measure centimeter-scale changes … deformation over time spans … days to years.
2. It can be used … moving instruments over relatively immobile targets.
3. The image acquisition is independent … the natural illumination and images can be taken … night.
4. The phase of the return wave depends … the distance to the ground.
5. Another source of error present … most interferograms is caused by the propagation of the waves … the atmosphere.

6. The slight difference causes a regular difference … phase that changes smoothly … the interferogram.
7. In the two-pass method, elevation data from a DEM is used … conjunction … the orbital information to calculate the phase contribution.
8. There is also a geometric constraint … the maximum length of the baseline.
9. The difference in viewing angles must not cause phase to change … the width of one pixel … more than a wavelength.
10. The velocity of the wave … the atmosphere is lower than the speed of light … a vacuum, and depends … air temperature, pressure and the partial pressure … water vapour.

XI. Put the words from the brackets in the right order.

1. The signal measured in the interferogram (*caused by, the change in, increase, represents, an, phase, or decrease, in distance*) from the ground pixel to the satellite.
2. (*in which, data, form of radar, is, a, radar, sophisticated, is used, SAR, processing of*) to produce a very narrow effective beam.
3. The phase of the return wave depends on (*length to, the since, distance, to, path, the ground, the*) the ground and back will consist of (*wavelengths, some, of, whole, plus, a number, fraction*) of a wavelength.
4. Phase shifts (*relative to, points, only resolvable, are, in, the interferogram, other*).
5. The SAR technique can potentially measure (*years, centimeter-scale, in, days, over, deformation, spans of, time, to, changes*).

XII. Choose the correct form from the two, given in the brackets.

1. It can only (*be used, is used*) by moving instruments over relatively immobile targets.
2. When the height of the topography (*knows, is known*), its phase contribution can be calculated and removed.
3. Another source of error present in most interferograms (*is caused, will cause*) by the propagation of the waves through the atmosphere.
4. One fringe of phase difference (*generated, is generated*) by a ground motion of half the radar wavelength, since this corresponds to a whole wavelength increase in the two-way travel distance.
5. This slight difference causes a regular difference in phase that changes smoothly across the interferogram and can (*modelled, be modelled*) and removed.

XIII. Translate the texts into English using the words and phrases supplied below.

A. Интерферометр — измерительный прибор, принцип действия которого основан на явлении интерференции. Принцип действия интерферометра заключается в следующем: пучок электромагнитного излучения (света, радиоволн и т. п.) с помощью того или иного устройства пространственно разделяется на два или большее количество когерентных пучков. Каждый из пучков проходит различные оптические пути и возвращается на экран, создавая интерференционную картину, по которой можно установить смещение фаз пучков.

Интерферометры применяются как при точных измерениях длин, в частности в станкостроении и машиностроении, так и для оценки качества оптических поверхностей и проверки оптических систем в целом.

интерферометр – *interferometer*
измерительный – *measuring*
оптический – *optical*
экран – *screen*
применять – *apply*
точный – *accurate*
машиностроение – *machine-building*
оценка качества – *quality control*
поверхность – *surface*

B. Самый простой способ оценки смещений и временных изменений состоит в использовании пары спутниковых изображений, сделанных с некоторым интервалом времени.

Две интерферограммы позволяют увидеть любые изменения, которые произошли в поверхности Земли. Дифференциальная интерферометрия позволяет определять на малых масштабах смещение земной поверхности (оползни и предвестники землетрясений), а также отслеживать изменение характеристик радиосигналов из-за смены влажности почвы (проблемы подтопления).

Для получения достоверных результатов необходимо выполнение некоторых условий, таких, как выведение спутника для повторной экспозиции в область космического пространства, близкую к первому снимку; один сезон съемки (хоть и в разные годы) для соблюдения сходного состояния отражающей поверхности (растительный покров, гидрогеологические условия). Эти проблемы в большей мере решаются с помощью специальной программы «Тандем» на базе двух спутников, которые работают по одним и тем же орбитам с временным интервалом пролета ровно 24 часа.

оползень – *landslide*
почва – *soil*
затопление – *floods*
достоверный – *reliable*
снимок - *snapshot*

XIV. Translate the text into Russian.

Applications of InSAR

Tectonic

InSAR can be used to measure tectonic deformation, for example ground movements due to earthquakes. It was first used for the 1992 Landers earthquake, but has since been utilized extensively for a wide variety of earthquakes all over the world. In particular the 1999Izmit and 2003 Bam earthquakes were extensively studied. InSAR can also be used to monitor creep and strain accumulation on faults.

Volcanic

InSAR can be used in a variety of volcanic settings, including deformation associated with eruptions, inter-eruption strain caused by changes in magma distribution at depth, gravitational spreading of volcanic edifices, and volcano-tectonic deformation signals. Early work on volcanic InSAR included studies on Mount Etna, and Kilauea, with many more volcanoes being studied as the field developed. The technique is now widely used for academic research into volcanic deformation, although its use as an operational monitoring technique for volcano observatories has been limited by issues such as orbital repeat times, lack of archived data, coherence and atmospheric errors. Recently InSAR has also been used to study rifting processes in Ethiopia.

DEM generation

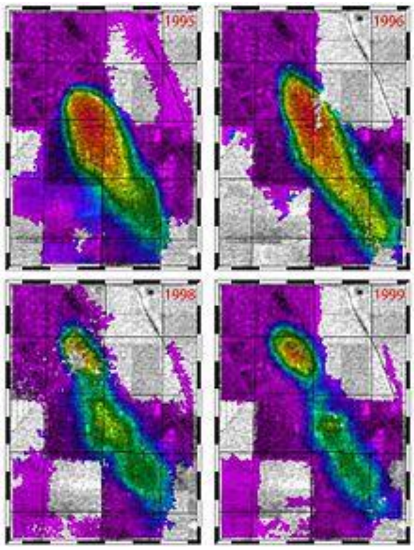
Interferograms can be used to produce digital elevation maps (DEMs) using the stereoscopic effect caused by slight differences in observation position between the two images. When using two images produced by the same sensor with a separation in time, it must be assumed other phase contributions (for example from deformation or atmospheric effects) are minimal.

In 1995 the two ERS satellites flew in tandem with a one-day separation for this purpose. A second approach is to use two antennas mounted some distance apart on the same platform, and acquire the images at the same time, which ensures no atmospheric or deformation signals are present. This approach was followed by NASA's SRTM mission aboard the space shuttle in 2000. InSAR-derived DEMs can be used for later two-pass deformation studies, or for use in other geophysical applications.

Kamchatka Peninsula, Landsat data draped over SRTM digital elevation model (NASA/JPL-Caltech)

Subsidence

Ground subsidence from a variety of causes has been successfully measured using InSAR, in particular subsidence caused by oil or water extraction from underground reservoirs, subsurface mining and collapse of old mines. It can also be used for monitoring the stability of built structures, and landscape features such as landslides.



Rapid ground subsidence over the Lost Hills oil field in California. (NASA/JPL-Caltech)

Ice Flow

Glacial motion and deformation have been successfully measured using satellite interferometry. The technique allows remote, high-resolution measurement of changes in glacial structure, ice flow, and shifts in ice dynamics, all of which agree closely with ground observations.

Persistent Scatterer InSAR

Persistent or Permanent Scatterer techniques are a relatively recent development from conventional InSAR, and rely on studying pixels which remain coherent over a sequence of interferograms.

In 1999, researchers at Politecnico di Milano, Italy, developed a new multi-image approach in which one searches the stack of images for objects on the ground providing consistent and stable radar reflections back to the satellite. These objects could be the size of a pixel or, more commonly, sub-pixel sized, and are present in every image in the stack.

Politecnico di Milano patented the technology in 1999 and created the spin-off company Tele-Rilevamento Europa – TRE in 2000 to commercialize the technology and perform ongoing research.

Some research centres and other companies, like the Dutch TU Delft spin-off Hansje Brinker, were inspired to develop their own algorithms which would also overcome InSAR's limitations. In scientific literature, these techniques are collectively referred to as Persistent Scatterer

Interferometry or PSI techniques. The term Persistent Scatterer Interferometry (PSI) was created by ESA to define the second generation of radar interferometry techniques.
Commonly such techniques are most useful in urban areas with lots of permanent structures, for example the PSI studies of European cities undertaken by the Terrafirma project. The Terrafirma project (led by Fugro NPA) provides a ground motion hazard information service, distributed throughout Europe via national geological surveys and institutions. The objective of this service is to help save lives, improve safety, and reduce economic loss through the use of state-of-the-art PSI information. Over the last 5 years this service has supplied information relating to urban subsidence and uplift, slope stability and landslides, seismic and volcanic deformation, coastlines and flood plains.

XV. Read the text and ask your group mates several questions.

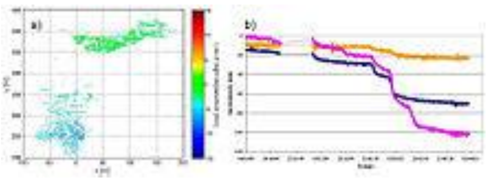
Producing interferograms

The processing chain used to produce interferograms varies according to the software used and the precise application, but will usually include some combination of the following steps.

Two SAR images are required to produce an interferogram; these may be obtained pre-processed, or produced from raw data by the user prior to InSAR processing. The two images must first be co-registered, using a correlation procedure to find the offset and difference in geometry between the two amplitude images. One SAR image is then re-sampled to match the geometry of the other, meaning each pixel represents the same ground area in both images. The interferogram is then formed by cross-multiplication of each pixel in the two images, and the interferometric phase due to the curvature of the Earth is removed, a process referred to as flattening. For deformation applications a DEM can be used in conjunction with the baseline data to simulate the contribution of the topography to the interferometric phase, this can then be removed from the interferogram.

Once the basic interferogram has been produced, it is commonly filtered using an adaptive power-spectrum filter to amplify the phase signal. For most quantitative applications the consecutive fringes present in the interferogram will then have to be *unwrapped*, which involves interpolating over the 0 to 2π phase jumps to produce a continuous deformation field. At some point, before or after unwrapping, incoherent areas of the image may be masked out. The final processing stage involves geocoding the image, which resamples the interferogram from the acquisition geometry (related to direction of satellite path) into the desired geographic projection.

Terrestrial SAR Interferometer (TInSAR)



a) 2D interferometric displacement map; b) displacement time series of pixel

Terrestrial SAR Interferometry (TInSAR)

Terrestrial SAR Interferometry (TInSAR) is a remote sensing technique for the displacement monitoring of slopes, rock scarps, volcanoes, landslides, buildings, infrastructures etc. The TInSAR technique is based on the same operational principles of the Satellite SAR Interferometry, but the Synthetic Aperture of the Radar is obtained by an antenna moving on a rail instead of satellite moving around an orbit. SAR technique allow 2D radar image of the investigated scenario to be achieved, with a high range resolution (along the instrumental line of sight) and cross-range resolution (along the scan direction). The antenna emits and receives microwave impulses, and by the measurement of the phase difference between two images it is possible to compute the displacement of all the pixel of the SAR image. The accuracy in the displacement measurement is on the scale of millimeters or less than a millimeter, depending on the specific local and atmospheric conditions.

XVI. Read and learn the dialogue by heart, then enlarge it with your own phrases.

a.

M.: Hello, Dr Hart. Do you happen to know anything about SAR?

H.: ….

M.: I've also read several articles. But it was difficult to understand them completely. How can I get a DEM using SAR?

H.: ….

M.: Can we use various types of satellites?

H.: ….

M.: But can we use the satellite with a single antenna for deriving a DEM?

H.: ….

M.: So what is the sense of using two antennas?

H.: ….

M.: I heard that SAR could be used for decoding vegetation. It was in one TV-program on "National geographic". What type of SAR should be used in this case?

H.: ….

M.: Then where can we apply SAR images?

H.: ….

M.: Did you hear about persistent scatterer InSAR?

H.: ….

M.: I think SAR is a rather perspective kind of survey. So I will try to do something with SAR data in my research work.

H.: ….

M.: Ok. Agreed, Thank you, Dr Hart.

H.: ….

b.

L.: Probably, the most important thing of any technique is the field where it can be used. Since we have been studying InSAR, …?

A.: There are various fields in which InSAR is applied. In fact, all fields of application can be divided into two: …. The second field comprises tectonic deformation and volcanic studies, ice flow monitoring. Can you add anything?

L.: And I would also add subsidence monitoring. In my opinion … not only for scientific or economic purposes but also for hazards mitigation. I read about persistent scatter InSAR (or PSI), which is used particularly in the frame of Terrafirma project for providing a ground motion hazards information service. Have you heard about PSI?

A.: Yes, I have heard about it too. In fact, PSI is …, such as Politecnico di Milano and Technical University of Delft. The technique implies use of multiple images of objects on the ground providing consistent and stable reflections back to the satellite.

L.: You are right. Commonly such techniques ….

XVII. Dialogue of the Unit. Learn the dialogue in roles, then change them and learn it again.

P.: Dear friends, today I would like to discuss such an issue as Interferomerty and its historic background. As far as I remember your home task was to find some preliminary information on InSAR. So, who is ready to start? Ah, Bill, the floor is yours?

B.: Thank you, professor. In 1993, Goldstein presented the first satellite-based interferometric synthetic aperture radar map showing large strains of the Earth's solid surface.

P.: Please, specify the details. What was mapped?

B.: In this case, the deforming surface was an ice stream in Antarctica. The same year, Massonnet showed exquisitely detailed and spatially continuous maps of surface deformation associated with the 1992 Landers earthquake in the Mojave Desert in southern California. These papers heralded a new era in geodetic science, whereby we can potentially measure three-dimensional surface displacements with nearly complete spatial continuity, from a plethora of natural and human-induced phenomena. An incomplete list of targets to date includes all forms of deformation on or around faults (interseismic, aseismic, coseismic, and postseismic) aimed at constraining the rheological properties of the fault and surrounding crust, detection and quantification of changes in active magma chambers aimed at understanding a volcano's plumbing system, the mechanics of glaciers and temporal changes in glacier flow with obvious impacts on assessments of climate change, and the impact of seasonal and anthropogenic changes in aquifers.

P.: Thank you, Bill. Who will continue the topic? Leo, please.

L.: Beyond detection of coherent surface deformation, InSAR can also provide unique views of surface disruption, through measurements of interferometric decorrelation, which could potentially aid the ability of emergency responders to respond efficiently to many natural disasters.

P.: So, that InSAR can take advantage of a satellite's perspective of the world permits one to view large areas of Earth's surface quickly and efficiently. In solid Earth geophysics, we are frequently interested in rare and extreme events (e.g., earthquakes, volcanic eruptions, and glacier surges). Go on, Leo.

L.: Therefore, if we want to capture these events and their natural variability, we cannot simply rely on dense instrumentation of a few select areas; instead, we must embrace approaches that allow global access. Given
easy access to data (which is not always the case), this inherently global perspective provided by satellitebased InSAR also allows one the luxury of going on geodetic fishing trips, whereby one essentially asks ''I wonder if …?'', in search of the unexpected.

P.: In essence we must not limit ourselves to hypothesis testing, but rather tap the inherently exploratory power of InSAR. Fine, thanks Leo. Now, who will give us a short overview of InSAR? Alex.

A.: Well, operating at microwave frequencies, SAR systems provide unique images representing the electrical and geometrical properties of a surface in nearly all weather conditions.

P.: Since they provide their own illumination, SARs can image in daylight or at night. Alex.

A.: SAR mapping systems typically operate on airborne or spaceborne platforms following a linear flight path. Raw image data are collected by transmitting a series of coded pulses from an antenna illuminating a swath offset from the flight track. The echo of each pulse is recorded during a period of reception between the transmission events. When a number of pulses are collected, it is possible to perform 2-D matched-filter compression on a collection of pulse echoes to focus the image.

P.: Correct. This technique is known as SAR because in the along-track, or azimuth, direction, a large virtual aperture is formed by coherently combining the collection of radar pulses received as the radar antenna moves along in its flight path. Continue, please.

A.: Although the typical physical length of a SAR antenna is on the order of meters, the synthesized aperture length can be on the order of kilometers. Because the image is acquired from a side-looking vantage point (to avoid left-side/rightside ambiguities), the radar image is geometrically distorted relative to the ground coordinates.

P.: Well, Bill, do you want to add something?

B.: Yes, thank you. By coherently combining the signals from two antennas, the interferometric phase difference between the received signals can be formed for each imaged point. In this scenario, the phase difference is essentially related to the geometric path length difference to the image point, which depends on the topography.

P.: Well done. Are you aware that with knowledge of the interferometer geometry, the phase difference can be converted into an altitude for each image point? In essence, the phase difference provides a third measurement, in addition to the along- and cross-track location of the image point, or 'target', to allow a reconstruction of the 3-D location of the targets. Alex, sorry for interruption.

A.: Bill, professor Higgins, thank you for your help. I will continue. The InSAR approach for topographic mapping is similar in principle to the conventional stereoscopic approach. In stereoscopy, a pair of images of the terrain are obtained from two displaced imaging positions. The 'parallax' obtained from the displacement allows the retrieval of topography because targets at different heights are displaced relative to each other in the two images by an amount related to their altitudes.

P.: Sure, but the major difference between the InSAR technique and stereoscopy is that, for InSAR, the 'parallax' measurements between the SAR images are obtained by measuring the phase difference between the signals received by two InSAR antennas. These phase differences can be used to determine the angle of the target relative to the baseline of the interferometric SAR directly. Does anybody know what accuracies we can speak about when discussing InSAR parallax measurement?

L.: The accuracy of the InSAR parallax measurement is typically several millimeters to centimeters, being a fraction of the SAR wavelength, whereas the parallax measurement accuracy of the stereoscopic approach is usually on the order of the resolution of the imagery, several meters or more.

P.: Thank you, Leo. Typically, the postspacing of the InSAR topographic data is comparable to the fine spatial

resolution of SAR imagery, while the altitude measurement accuracy generally exceeds stereoscopic accuracy at comparable resolutions. What else can you add Alex?

A.: The registration of the two SAR images for the interferometric measurement, the retrieval of the interferometric phase difference, and subsequent conversion of the results into digital elevation models of the terrain can be highly automated, representing an intrinsic advantage of the InSAR approach.

P.: We are going to discuss that in detail in later seminars, but I will mention in passing. The performance of InSAR systems is largely understood both theoretically and experimentally. These developments have led to airborne and spaceborne InSAR systems for routine topographic mapping. The InSAR technique we have just described, using two apertures on a single platform, is often called 'crosstrack interferometry' or XTI in the literature. Other terms are 'single-track' and 'single-pass' interferometry. Have you came across any other SAR technique when getting ready for the seminar?

B.: Another interferometric SAR technique was advanced by Goldstein and Zebker in 1987 for measurement of surface motion by imaging the surface at multiple times. The time separation between the imaging can be a fraction of a second to years. The multiple images can be thought of as 'time-lapse' imagery. A target movement will be detected by comparing the images.

P.: Unlike conventional schemes in which motion is detected only when the targets move more than a significant fraction of the resolution of the imagery, this technique measures the phase differences of the pixels in each
pair of the multiple SAR images. Bill.

B.: If the flight path and imaging geometries of all the SAR observations are identical, any interferometric phase difference is due to changes over time of the SAR system clock, variable propagation delay, or surface motion in the direction of the radar line of sight (LOS). In the first application of this technique described in the literature I found, Goldstein and Zebker augmented a conventional airborne SAR system with an additional aperture, separated along the length of the aircraft fuselage from the conventional SAR antenna. Given an antenna separation of roughly 20m and an aircraft speed of about 200 ms^{-1}, the time between target observations made by the two antennas was about 100 ms. Over this time interval, clock drift and propagation delay variations are
negligible.

P.: Thank you, Bill. This technique has been dubbed 'along-track interferometry' or ATI because of the arrangement of two antennas along the flight track on a single platform. In the ideal case, there is no cross-track separation of the apertures, and therefore no sensitivity to topography. Is there anybody here who can cast light on ATI? Wow, so Leo first, and then Alex will continue.

L.: ATI is merely a special case of space 'repeat-track interferometry' also known as RTI, which can be used to generate topography and motion. The orbits of several spaceborne SAR satellites have been controlled in such a way that they nearly retrace themselves after several days. Aircraft can also be controlled to accurately repeat flight paths. If the repeat flight paths result in a cross-track separation and the surface has not changed between observations, then the repeat-track observation pair can act as an interferometer for topography measurement. For spaceborne systems, RTI is usually termed 'repeat-pass interferometry' in the literature you gave us. If the flight track is repeated perfectly such that there is no cross-track separation, then there is no sensitivity to topography, and radial motions can be measured directly as with an ATI system. However, since the temporal separation between the observations is typically days to many months or years, the ability to detect small radial velocities is substantially better than the ATI system we have just discussed above.

P.: Do you happen to know that the first demonstration of RTI for velocity mapping was a study of the Rutford ice stream in Antarctica? The radar aboard the ERS-1 satellite obtained several SAR images of the ice stream with near-perfect retracing so that there was no topographic signature in the interferometric phase, permitting measurements of the ice stream flow velocity of the order of 1 m yr-1 (or 3 x 10^{-8} ms^{-1}) observed over a few days. Alex.

A.: Most commonly for repeat-track observations, the track of the sensor does not repeat itself exactly, so the interferometric time-separated measurements generally comprise the signature of topography and of radial motion or surface displacement. The approach for reducing these data into velocity or surface displacement by removing topography is generally referred to as 'differential interferometric SAR.' The first proof of concept experiment for spaceborne InSAR using imagery obtained by the SeaSAT mission was conducted in 1988. In the latter portion of that mission, the spacecraft was placed into a near-repeat orbit every 3 days.

P.: I will make an example. In 1989 Gabriel and his colleagues used data obtained in an agricultural region in California, to detect surface elevation changes in some of the agricultural fields of the order of several cm over approximately a 1-month period. By comparing the areas with the detected surface elevation changes with irrigation records, they concluded that these areas were irrigated in between the observations, causing small elevation changes from increased soil moisture. They were actually looking for the deformation signature of a small earthquake, but the surface motion was too small to detect. These early studies were then followed by the aforementioned seminal applications to glacier flow and earthquake induced surface deformation.

All civilian InSAR-capable satellites to date have been right-looking in near-polar sun-synchronous orbits. This gives the opportunity to observe a particular location on the Earth on both ascending and descending orbit passes. With a single satellite, it is therefore possible to obtain geodetic measurements from two different directions, allowing vector measurements to be constructed. Who has any idea how it can be done?

B.: The variety of available viewing geometries can be increased if a satellite has both left- and right-looking capability. Similarly, neighboring orbital tracks with overlapping beams at different incidence angles can also provide diversity of viewing geometry.

P.: Good. In an ideal mission scenario, observations from a given viewing geometry will be acquired frequently and for a long period of time to provide a dense archive for InSAR analysis. The frequency of imaging is key in order to provide optimal time resolution of a given phenomena, as well as to provide the ability to combine multiple images to detect small signals. Of course, many processes of interest are not predictable in time, thus we must continuously image the Earth in a systematic fashion in order to provide recent 'before' images. But what will happen if the data on the area of interest is not viable?

L.: For a given target, not all acquisitions are necessarily viable for InSAR purposes. The greatest nemesis for

InSAR geodesy comes from incoherent phase returns between two image acquisitions. This incoherence can be driven by observing geometry, I mean the baseline is too large, or by physical changes of the Earth's surface, for example, snowfall. Thus any InSAR study begins with an assessment of the available image archive.

P.: Thank you, guys. I am afraid out time is up. We will continue our discussion next week. Please, be ready for discussing InSAR related techniques.

Unit 2

Interferometric SAR image processing and interpretation

Phrases to learn:

operational capability – *эксплуатационные качества*
accurate measurements – *точные измерения*
operational control – *управление полётами*
to be in orbit – *находиться на орбите*
in combination with – *в сочетании с*
look angle – *угол обзора*
to be acceptable for – *быть приемлемым для*
ascending (descending) orbit – *восходящая (нисходящая) орбита*
to be foreshortened – *укорачиваться (выглядеть короче)*
a wealth of information on – *большой объем информации о*
factors contributing to – *факторы вносящие вклад в*
a number of smth – *ряд чего-либо*
mode of operation – *режим работы, рабочий режим*
primary objectives – *главные цели*
factors affecting smth – *факторы оказывающие воздействие на что-либо*
due to the curvature of – *ввиду кривизны чего-либо*
incidence angle – *угол падения*
to be associated with – *относится к, ассоциироваться с*
resolution cell dimension – *разрешение размера ячейки*

Introduction

Synthetic Aperture Radar (SAR) is a microwave imaging system. It has cloud-penetrating capabilities because it uses microwaves. It has day and night operational capabilities because it is an active system. Finally, its 'interferometric configuration', Interferometric SAR or InSAR, allows accurate measurements of the radiation travel path because it is coherent. Measurements of travel path variations as a function of the satellite position and time of acquisition allow generation of **Digital Elevation Models (DEM)** and measurement of centimetric surface deformations of the terrain. This part of the InSAR principles manual is dedicated to beginners who wish to gain a basic understanding of what SAR interferometry is. Real examples derived from ESA satellites, ERS-1, ERS-2 and Envisat, will be exploited to give a first intuitive idea of the information that can be extracted from InSAR images, as well as an idea of the limits of the technique.

Introduction to ERS

The European Remote Sensing satellite, ERS-1, was ESA's first Earth Observation satellite; it carried a comprehensive payload including an imaging Synthetic Aperture Radar (SAR). With this launch in July 1991 and the validation of its interferometric capability in September of the same year, an ever-growing set of interferometric data became available to many research groups. ERS-2, which was identical to ERS-1 apart from having an extra instrument, was launched in 1995.

Shortly after the launch of ERS-2, ESA decided to link the two spacecraft in the first ever ‘tandem’ mission, which lasted for nine months, from 16 August 1995 until mid-May 1996. During this time the orbits of the two
spacecraft were phased to orbit the Earth only 24 hours apart, thus providing a 24-hour revisit interval. The huge collection of image pairs from the ERS tandem mission remains uniquely useful even today, because the brief 24-hour revisit time between acquisitions results in much greater interferogram coherence. The increased frequency and level of data available to scientists offered a unique opportunity to generate detailed elevation maps (DEMs) and to observe changes over a very short space of time. Even after the tandem mission ended, the high orbital stability and careful operational control allowed acquisition of more SAR pairs for the remainder of the time that both spacecraft were in orbit, although without the same stringent mission constraints.

The near-polar orbit of ERS in combination with the Earth’s rotation (E-W) enables two acquisitions of the same area to be made from two different look angles on each satellite cycle. If just one acquisition geometry is used, the accuracy of the final DEM in geographic coordinates strongly depends on the local terrain slope, and this may not be acceptable for the final user.

Combining DEMs obtained from ascending (S-N) and descending (N-S) orbits can mitigate the problems due to the acquisition geometry and the uneven sampling of the area of interest, especially on areas of hilly terrain. The ERS antenna looks to the right, so for example a slope that is mainly oriented to the West would be foreshortened on an ascending orbit, hence a descending orbit should be used instead.

In March 2000 the ERS-1 satellite finally ended its operations. ERS-2 is expected to continue operating for some time, although with a lower accuracy of attitude control since a gyro failure that occurred in January 2001.

Introduction to Envisat

Launched in 2002, Envisat is the largest Earth Observation spacecraft ever built. It carries ten sophisticated optical and radar instruments to provide continuous observation and monitoring of the Earth’s land, atmosphere, oceans and ice caps. Envisat data collectively provide a wealth of information on the workings of the Earth system, including insights into factors contributing to climate change.

Furthermore, the data returned by its suite of instruments are also facilitating the development of a number of operational and commercial applications. Envisat’s largest single instrument is the Advanced Synthetic Aperture Radar (ASAR), operating at C-band. This ensures continuity of data after ERS-2, despite a small (31 MHz) central frequency shift. It features enhanced capability in terms of coverage, range of incidence angles, polarisation, and modes of operation. The improvements allow radar beam elevation steerage and the selection of different swaths, 100 or 400 km wide.

Envisat is in a 98.54° sun-synchronous circular orbit at 800 km altitude, with a 35-day repeat and the same ground track as ERS-2.

Its primary objectives are:

- to provide continuity of the observations started with the ERS satellites, including those obtained from radar-based observations;
- to enhance the ERS mission, notably the ocean and ice mission;
- to extend the range of parameters observed, to meet the need for increasing knowledge of the factors affecting the environment;

- to make a significant contribution to environmental studies, notably in the area of atmospheric chemistry and ocean studies (including marine biology).

SAR images of the Earth's surface

What is a strip-map SAR imaging system?

A SAR imaging system from a satellite (such as ERS or Envisat) is sketched in Figure 1. A satellite carries a radar with the antenna pointed to the Earth's surface in the plane perpendicular to the orbit (in practice this is not strictly true, because it is necessary to compensate for the Earth's rotation).

The inclination of the antenna with respect to the nadir is called the off-nadir angle and in contemporary systems is usually in the range between 20° and 50° (it is 21° for ERS). Due to the curvature of the Earth's surface, the incidence angle of the radiation on a flat horizontal terrain is larger than the off-nadir (typically 23° for ERS). However, for the sake of simplicity we assume here that the Earth is flat, and hence that the incidence angle is equal to the off-nadir angle, as shown in the figure.

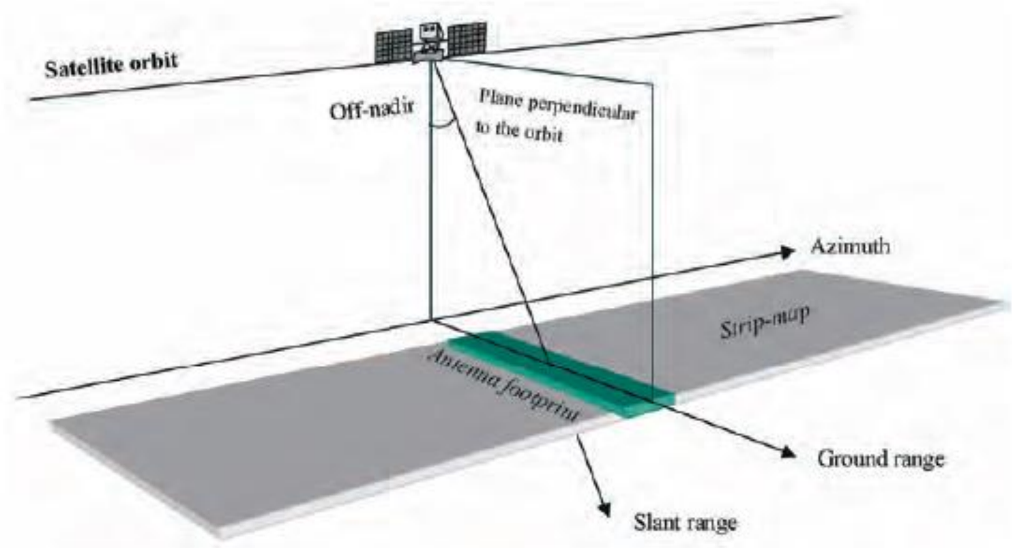


Figure 1. A SAR imaging system from a satellite.

Currently, operational satellite SAR systems work in one of the following microwave bands:

• C band – 5.3 GHz (ESA's ERS and Envisat, the Canadian Radarsat, and the US shuttle missions)

• L band – 1.2 GHz (the Japanese J-ERS and ALOS)

• X band – 10 GHz (the German-Italian X-SAR on the shuttle missions)

In the case of ERS, the illuminated area on the ground (the **antenna footprint**) is about 5 km in the **along-track direction** (also called the **azimuth direction**) and about 100 km in the **across-track direction** (also called the **ground range direction**).

The direction along the **Line of Sight (LOS)** is usually called the **slant-range** direction.

The antenna footprint moves at the satellite speed along its orbit. For ERS, the satellite speed is about 7430 m/s in a quasi-polar orbit that crosses the equator at an angle of 9° and an elevation of about 800 km. The footprint traces a **swath** 100 km wide in ground range on the Earth's surface, with the capability of imaging a strip 445 km long every minute (strip map mode).

What is a complex SAR image?

A digital SAR image can be seen as a mosaic (i.e. a two-dimensional array formed by columns and rows) of small picture elements (pixels). Each pixel is associated with a small area of the Earth's surface (called a **resolution cell**). Each pixel gives a complex number that carries amplitude and phase information about the microwave field backscattered by all the scatterers (rocks, vegetation, buildings etc.) within the corresponding resolution cell projected on the ground. Different rows of the image are associated with different azimuth locations, whereas different columns indicate different slant range locations. The location and dimension of the resolution cell in azimuth and slant-range coordinates depend only on the SAR system characteristics.

In the ERS case, the SAR resolution cell dimension is about 5 metres in azimuth and about 9.5 metres in slant-range. The distance between adjacent cells is about 4 metres in azimuth and about 8 metres in slant range. The SAR resolution cells are thus slightly overlapped both in azimuth and in slant-range.

I. Vocabulary.

acceptable (adj) – приемлемый, допустимый
accuracy (n) – точность
altitude (n) – высота
antenna footprint – контур диаграммы направленности антенны
apart from (adv) – помимо, за исключением
assume (v) – принимать
azimuth direction (n) – азимутальное направление
backscattered (adj) – рассеянный в обратном направлении
C-band (n) – диапазон частот, выделенный для частной и служебной связи
circular (adj) – круглый, округлый
cloud-penetrating (adj) – проникающий сквозь облака
comprehensive (adj) – всесторонний, полный
dedicate to (v) – посвящать
enhance (v) – усиливать, улучшать
environment (n) – окружающая среда
equator (n) – экватор
ever-growing (adj) – неуклонно растущий
extract (v) – извлекать
facilitate (v) – способствовать
generation (n) – генерирование, создание
ground range (n) – горизонтальная дальность
gyro failure – ошибка гироскопа
image pair (n) – стереопара
improvement (n) – улучшение
inclination (n) – наклон
insight (into) (n) – представление (о чем-либо)
L-band (n) – диапазон сверхвысоких частот (от 300 до 1550 мегагерц)
launch (v) – запускать (в космос)
line of sight (LOS) – линия прямой видимости
microwave (adj) – микроволновый
mitigate (v) – уменьшать, смягчать
mosaic (n) – мозаика
near-polar (adj) – околополярный
overlap (v) – перекрывать
path (n) – путь
payload (n) – полезная нагрузка
phase (v) – поэтапно осуществлять (что-л.)
plane (n) – плоскость
point out (v) – отмечать
quasi-polar (adj) – околополярный
resolution (n) – разрешающая способность
revisit time (n) – период повторной съемки
sampling (of) (n) – образец, выборка
set of (n) – набор чего-либо
slant-range (n) – наклонная дальность
slope (n) – уклон, наклон
steerage (n) – управление
stringent (adj) – строгий, точный
strip (n) – полоса

strip-map (n) – карта маршрута
suite (of) (n) – комплект, набор (чего-либо)
sun-synchronous orbit – орбита солнечно-синхронного спутника
swath (n) – полоса обзора
terrain (n) – местность, территория
two-dimensional array (n) – двухмерный массив
validation (n) – проверка достоверности
X-band (n) – (частотный) диапазон X (от 5,2 до 11 ГГц)

II. Reading.

acceptable [ək'septəbl], accuracy ['ækjərəsi], altitude ['æltitju:d], assume [ə'sju:m], circular ['sə:kjələ], dedicate ['dedikeit], enhance [in'hɑ:n(t)s], gyro ['dʒaiərəu], inclination [,inkli'neiʃ(ə)n], launch [lɔ:ntʃ], microwave ['maikrəweiv], mitigate ['mitigeit], mosaic [məu'zeiik], payload ['peiləud], slant [slɑ:nt], steerage ['stiəridʒ], stringent ['strindʒənt], synchronous ['siŋkrənəs], swath [swɔ:θ], extract [ik'strækt].

III. Comprehension check.

1. What kind of an imaging system Synthetic Aperture Radar is?
2. Why does InSAR allow accurate measurements of the radiation travel path?
3. What does ERS mean?
4. What did ESA decided to do shortly after the launch of ERS-2?
5. What factors offered scientists a unique opportunity to generate detailed elevation maps and to observe changes over a very short space of time?
6. When does the accuracy of the final DEM in geographic coordinates strongly depend on the local terrain slope?
7. What can lead to the foreshortening of a slope in the image?
8. How the inclination of the antenna with respect to the nadir is called?
9. What does LOS stand for?
10. How can the SAR system characteristics affect the location and dimension of the resolution cell in azimuth and slant-range coordinates?

IV. Repeat the following statements after the teacher, then change them to questions supplying short answers.

1. A satellite carries a radar with the antenna pointed to the Earth's surface in the plane perpendicular to the orbit.
2. Operational satellite SAR systems work in one of C, L, and X microwave bands.
3. The footprint traces a swath 100 km wide in ground range on the Earth's surface.
4. The SAR resolution cell dimension is about 5 metres in azimuth and about 9.5 metres in slant-range.
5. One of its primary objectives is to provide continuity of the observations started with the ERS satellites, including those obtained from radar-based observations.
6. A digital SAR image can be seen as a two-dimensional array formed by columns and rows of pixels.
7. The distance between adjacent cells is about 4 metres in azimuth and about 8 metres in slant range.
8. The two spacecraft were phased to orbit the Earth only 24 hours apart, providing a 24-hour revisit interval.

9. Measurements of travel path variations as a function of the satellite position and time of acquisition allow generation of DEM.
10. Each pixel is associated with a small area of the Earth's surface called a resolution cell.

V. Remake the following sentences according to the given pattern.

A. InSAR showed that ***it*** *had very good cloud-penetrating capabilities.*

It *was found to have very good cloud-penetrating capabilities*.

1. They wanted that ERS-1 carried a comprehensive payload including an imaging Synthetic Aperture Radar (SAR).
2. ESA decided that two spacecraft could be linked in the first ever 'tandem' mission.
3. They know that these two satellites will allow them to extract some additional information from InSAR images.
4. They were certain that the near-polar orbit of ERS in combination with the Earth's rotation would enable two acquisitions of the same area to be made from two different look angles on each satellite cycle.
5. They expect that the data returned by ERS-1 and ERS-2 instruments are facilitating the development of a number of operational and commercial applications.

B. **Restate the following sentences beginning each one with** *on the one hand …. … on another*

Measurements of travel path variations allow generation of DEM and measurement of centimetric surface deformations of the terrain.

On the one hand measurements of travel path variations allow generation of DEM on another they allow measurement of centimetric surface deformations of the terrain.

1. The SAR system characteristics affect location and dimension of the resolution cell in azimuth and slant-range coordinates.
2. ERS-2 is expected to continue operating for some time, although with a lower accuracy of attitude control since a gyro failure that occurred in January 2001.
3. The signal measured in the interferogram represents the change in phase caused by an increase or decrease in distance from the ground pixel to the satellite.
4. It carries sophisticated optical instruments and an InSar to provide continuous observation and monitoring of the Earth's land.
5. Combining DEMs obtained from ascending (S-N) and descending (N-S) orbits can mitigate the problems due to the acquisition geometry and the uneven sampling of the area of interest, especially on areas of hilly terrain.

C. **Restate the following sentences according to the pattern:**

It did not show cloud-penetrating capabilities.

No cloud-penetrating capabilities were shown by it.

1. They do not know the total distance to the satellite.
2. They could not obtain any useful information from the images.
3. This effect cannot be exploited to calculate the topographic height.
4. They do not make a significant contribution to environmental studies.
5. The increase of data available to scientists did not offer a unique opportunity to generate detailed elevation maps.

D. *The increased frequency as well as level of data available to scientists offered a unique opportunity to generate detailed elevation maps.*
Both the increased frequency and level of data available to scientists offered a unique opportunity to generate detailed elevation maps.

1. Measurements of travel path variations as a function of the satellite position and time of acquisition allow generation of Digital Elevation Models as well as measurement of centimetric surface deformations of the terrain.
2. The satellites carry sophisticated optical instruments as well as an InSar.
3. InSars make a significant contribution to environmental studies, notably in the area of atmospheric chemistry as well as ocean studies.
4. The improvements allow radar beam elevation steerage as well as the selection of different swaths, 100 or 400 km wide.
5. Due to the fact that InSAR is an active system it has day as well as night operational capabilities.

VI. Ask questions to which the following sentences could be answers.

1. Synthetic Aperture Radar is a microwave imaging system.
2. The technique can allow generation of Digital Elevation Models (DEM).
3. Because it uses microwaves.
4. The SAR resolution cell dimension is about 5 metres in azimuth.
5. The inclination of the antenna in contemporary systems is usually in the range between 20° and 50°.
6. In the case of ERS, the antenna footprint is about 5 km in the along-track direction.
7. Each pixel associated with a small area of the Earth’s surface is called a resolution cell.
8. It carries ten sophisticated optical and radar instruments.
9. Operational satellite SAR systems work in one of C, L, or X bands.
10. The footprint traces a swath 100 km wide on the Earth’s surface.

VII. Give Russian equivalents to the following phrases.

A number of image pairs, to be in orbit, cloud-penetrating systems, set of phases, Earth’s surface, total distance, contemporary InSAR system, to be acceptable for, mode of operation, resolution cell, primary objectives, factors contributing to, accurate measurements, in combination with, to be foreshortened, factors affecting the accuracy, due to the curvature of the orbit, incidence angle.

VIII. Correct the wrong statements using the given phrases.

on the contrary; I do not believe that; to my mind; as is known; as far as I know; it is considered that; it seems to be wrong; I am afraid you are mistaken; I can’t agree with you; it seems unlikely that; in my opinion .

1. A satellite carries a radar with the antenna pointed to the Earth’s surface in the plane parallel to the orbit.
2. A considerable time after the launch of ERS-2, ESA decided to link the two spacecraft in the first ever ‘tandem’ mission, which lasted for nine months.
3. The inclination of the antenna with respect to the nadir is called the off-nadir angle and in contemporary systems is usually in the range between 80° and 90°.

4. Due to the curvature of the Earth's surface, the incidence angle of the radiation on a flat horizontal terrain is smaller than the off-nadir.
5. With this launch and the validation of interferometric capability, an ever-growing set of interferometric data became unavailable to many research groups.
6. SAR resolution cells are largely overlapped both in azimuth and in slant-range.
7. The direction along the Line of Sight (LOS) is usually called the ground range direction.
8. Each pixel gives a complex number that carries amplitude and phase information about the microwave field backscattered by rocks or buildings.
9. All operational satellite SAR systems work in one microwave C band.
10. A digital SAR image can be seen as an integrated image of small picture elements.

IX. Give English translation of the following phrases. Use them in your own sentences.

уменьшать, способствовать, извлекать, полоса, контур диаграммы, уклон, ошибка гироскопа, полоса обзора, наклон, создание, местность, проверка достоверности, высота, главные цели, оползень, точность, разрешение размера ячейки, большой объем информации о местности, разрешающая способность радара, распространение сигнала, околополярный.

X. Put a proper preposition if necessary.

1. A digital SAR image can be seen … a mosaic … small picture elements (pixels).
2. The SAR resolution cell dimension is about 5 metres … azimuth and about 9.5 metres … slant-range.
3. Measurements of travel path variations … a function of the satellite position and time … acquisition allow generation of DEM.
4. The direction … the Line of Sight is usually called the slant-range direction.
5. The antenna footprint moves … the satellite speed … its orbit.
6. Each pixel is associated … a small area of the Earth's surface.
7. A satellite carries a radar … the antenna pointed … the Earth's surface in the plane perpendicular … the orbit.
8. The inclination … the antenna … respect … the nadir is called the off-nadir angle.
9. Envisat is … a 98.54° sun-synchronous circular orbit … 800 km altitude.
10. The near-polar orbit … ERS in combination … the Earth's rotation (E-W) enables two acquisitions of the same area to be made … two different look angles … each satellite cycle.

XI. Translate the texts into English.

A. Энвисат (англ. Environmental Satellite) — спутник, построенный Европейским Космическим Агентством для исследования Земли из космоса. Спутник запущен 1 марта 2002 года ракетой-носителем Ариан-5 на солнечно-синхронную полярную орбиту высотой 790±10 километров. Один оборот делает за 101 минуту. На данный момент (середина 2007) он является самым крупным спутником, запущенным Европейским космическим агентством (ЕКА).

На борту Энвисат несёт девять инструментов, собирающих информацию о суше, воде, льде и атмосфере, используя различные способы измерения.

- ASAR (Advanced Synthetic Aperture Radar) наблюдает Землю в микроволновом спектре от 4 до 8 ГГц. Этот инструмент позволяет отслеживать изменение высоты поверхности с субмиллиметровой точностью.
- MERIS (MEdium Resolution Imaging Spectrometer) — спектрометр, исследующий свет, отражаемый Землёй (поверхностью и атмосферой). Основная цель спектрометра — изучать цвет океана, например для того, чтобы дать оценку концентрации хлорофила и твёрдых частиц.
- AATSR (Advanced Along Track Scanning Radiometer) измеряет температуру морской поверхности.
- RA-2 (Radar Altimeter 2) — радар, наблюдающий два электромагнитных диапазона: Ku-диапазон и S-диапазон (2-4 ГГц); служит цели изучения океанской топографии, наблюдения за льдом и измерения высот суши.
- MWR (Microwave Radiometer) измеряет количество водяного пара в атмосфере и содержание жидкой воды в облаках.
- DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) — микроволновая следящая система, выполняющая задачу точного позиционирования спутника.
- GOMOS (Global Ozone Monitoring by Occultation of Stars) наблюдает за звёздами сквозь атмосферу Земли; по изменению их цвета можно много сказать о количестве различных газов, например озона, и их распределению по высоте.
- MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) —фурье-спектрометр для среднего инфракрасного диапазона; этот диапазон важен для слежения за газами, играющими большую роль в климате Земли.
- SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) — спектрометр, который сравнивает свет, идущий от Солнца, со светом, отражаемым Землёй; это позволяет получить информацию об атмосфере, через которую проходит отражённый свет.

B. Интерферометрия

Радиолокация с синтезированной апертурой фиксирует амплитуду и фазу отраженного сигнала. Одно изображение, полученное с помощью РСА, в большинстве случаев не имеет практического значения, тогда как два снимка РСА (интерференционная пара), полученные под различными углами, могут быть использованы для получения цифровой модели рельефа, которая, в свою очередь, может дать информацию об изменениях ландшафта и улучшить разрешение.

Как известно, плоская монохроматическая волна распространяется таким образом, что вектор электрического поля E, вектор магнитного поля H и волновой вектор k образуют ортогональную систему. Для этой волны уравнения Максвелла имеют вид: $\nabla \times E(r) = -j\omega\mu H(r)$ $\nabla \times H(r) = j\omega\mu E(r)$, $(\nabla \times k^2)E = 0$, из которых следует, что распространение плоской монохроматической волны может быть описано в виде $E(r,t) = E_0 e^{j(\omega t - kr)}$ с фазой k*r, где j – мнимая единица, r – радиус-вектор наблюдаемой точки, ε и μ – диэлектрическая и магнитная проницаемости среды соответственно, ω – частота распространения волны, а $|k| = \omega\sqrt{\varepsilon\mu}$.

Интерферометрия комбинирует комплексные изображения, зафиксированные антеннами под различными углами наблюдения или в разное время. По результатам сравнения двух снимков одного и того же участка местности получают интерферограмму, представляющую собой сеть цветных полос, ширина которых соответствует разности фаз по обоим экспозициям. Благодаря высокой частоте излучения подвижки регистрируются с точностью миллиметры-первые сантиметры. Все данные съемок представляются в цифровом виде, что обеспечивает объективность и однозначность интерпретации.

XII. Put each word from the first group with a suitable word from the second one.

1. Ever, look, poor, summed, spurious, operational, sun-synchronous, resolution cell, two-pass, ambient, cloud-penetrating, adjacent, azimuth, incidence, primary, accurate.
2. System, illumination, dimension, measurements, coverage, method, capability, objectives, pixels, direction, contribution, growing, angle, signal, orbit.

XIII. Read the text and put the proper sentences into the gaps, then translate it into Russian.

The detected SAR image


Figure 2: ERS SAR detected image of Milan (Italy). The image size is about 25 km in ground range (vertical) and 25 km in azimuth (horizontal).

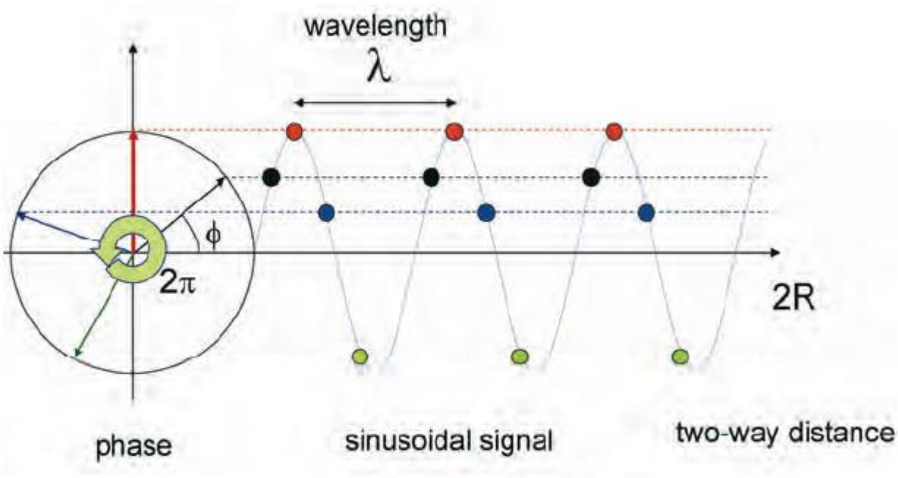
The detected SAR image contains a measurement of the amplitude of the radiation ____________the radar by the objects (**scatterers**) contained in each SAR resolution cell. This amplitude depends more on the roughness than on the chemical composition of the scatterers on the terrain. Typically, exposed rocks and urban areas show strong amplitudes, whereas smooth flat surfaces (like quiet water basins) show_________, since the radiation is mainly mirrored away from the radar. The detected SAR image is generally visualised by means of grey scale levels as shown in the example of Figure 2. Bright pixels correspond to areas of strong backscattered radiation (e.g. urban areas), whereas __________ correspond to low backscattered radiation (e.g. a quiet water basin).

The phase SAR image

The radiation transmitted from the radar has to reach the scatterers on the ground and then come back to the radar in order to __________ (two-way travel). Scatterers at different distances from the radar (different slant ranges) introduce different delays between transmission and reception of the radiation.

Due to the almost ___________ nature of the transmitted signal, this delay τ is equivalent to a phase change φ between transmitted and received signals. The phase change is thus proportional to the two-way travel distance $2R$ of the radiation divided by the transmitted wavelength λ . This concept _________ in Figure 3.

Figure 3: A sinusoidal function sin φ is periodic with a 2π radian period. In the case of a relative narrow-band SAR (i.e. ERS and Envisat), the transmitted signal can be assimilated, as a first approximation, to a pure sinusoid whose angle or phase φ has the following linear dependence on the slant range coordinate r: φ = 2π r /λ (where λ is the SAR wavelength). Thus, assuming that the phase of the transmitted signal is zero, the received signal that covers the distance 2R travelling from the satellite to the target and back, shows a phase φ = 4πR/λ radians.



$$\phi = \frac{2\pi}{\lambda} 2R = \frac{4\pi}{\lambda} R$$

However, due to the __________of the signal, travel distances that differ by an integer multiple of the wavelength introduce exactly the same phase change. In other words the phase of the SAR signal is a measure of just the last fraction of the two-way travel distance __________ than the transmitted wavelength. In practice, due to the huge ratio between the resolution cell dimension (of the order of a few metres) and wavelength (~5.6 cm for ERS), the phase change passing from one pixel to another within a single SAR image looks random and is of___________.

a. dark pixels
b. backscattered toward
c. that is smaller
d. form the SAR image
e. is illustrated
f. reflected radiation
g. purely sinusoidal
h. low amplitudes
i. periodic nature
j. no practical utility

XIV. Read the text and ask your group mates several questions.

Speckle

The presence of several scatterers within each SAR resolution cell generates the so-called 'speckle' effect that is common to all coherent imaging systems. Speckle is present in SAR, but not in optical images. Homogeneous areas of terrain that extend across many SAR resolution cells (imagine, for example, a large agricultural field covered by one type of cultivation) are imaged with different amplitudes in different resolution cells. The visual effect is a sort of 'salt and pepper' screen superimposed on a uniform amplitude image. This speckle effect is a direct consequence of the superposition of the signals reflected by many small **elementary** scatterers (those with a dimension comparable to the radar wavelength) within the resolution cell. These signals, which have random phase because of multiple reflections between scatterers, add to the directly reflected radiation. From an intuitive point of view, the resulting amplitude will depend on the imbalance between signals with positive and negative sign. An example of speckle is shown in Figure 4. Here the 'salt and pepper' effect is clearly visible on the homogenous fields that surround the Linate Airport as seen by ERS-2. The same area as seen from the SPOT optical system is shown in Figure 5. Here no speckle is present and the fields that surround the Linate Airport appear homogeneous. Speckle has an impact on the quality and usefulness of detected SAR images. Typically, image segmentation suffers severely from speckle. However, by taking more images of the same area at different times or from slightly different look angles, speckle can be greatly reduced: averaging several images tends to cancel out the random amplitude variability and leave the uniform amplitude level unchanged. An example of speckle reduction is shown in Figure 7. Here the average of 60 separate ERS-1 and ERS-2 SAR images of the area surrounding the Linate airport in Milan is shown. A comparison between this image and the single SAR image shown in Figure 5 gives an idea of the speckle reduction achieved and of the improved visibility of detail. SAR resolution cell projection on the ground

Figure 5: ERS-2 SAR detected image of the Linate Airport in the eastern part of Milan: the speckle effect on the homogeneous fields surrounding the airport is clearly visible

The terrain area imaged in each SAR resolution cell (called the ground resolution cell) depends on the local topography.

It strongly depends on the terrain slope in the plane perpendicular to the orbit (ground range direction), and on the terrain slope in the azimuth direction. The dimension of the ground resolution cell in azimuth is related to that of the SAR resolution cell by the usual perspective deformation we experience every day looking at surfaces from different angles (e.g. a postcard seen at 90 degrees is a line).

The dimension of the ground resolution cell in range is related to that of the SAR resolution cell by an unusual perspective deformation.

As the terrain slope increases with respect to a flat horizontal surface (i.e. as the normal to the terrain

Figure 6: Optical image of Linate Airport taken from the SPOT satellite. No speckle is visible and the fields that surround the airport look homogeneous

On the other hand, when the terrain slope decreases with respect to the flat horizontal reference surface, the resolution cell dimension decreases. The minimum resolution cell dimension (i.e. equal to the slant range resolution) is reached when the terrain is parallel to the LOS. This is also the lower slope limit that can beimaged at all by a SAR system, since beyond this angle the terrain is in shadow. It should be pointed out that foreshortening has a strong impact on the amplitude of the detected SAR image. Foreshortened areas are brighter on the image because the resolution cell is larger (hence more power is backscattered towards the satellite) and the incidence angle is steeper. An example that illustrates this effect is shown in Figure 8 with reference to the area of Mount Vesuvius (Italy) as seen by ERS-1. It should be pointed out that foreshortening has a strong impact on the amplitude of the detected SAR image.

Foreshortened areas are brighter on the image because the resolution cell is larger (hence more power is backscattered towards the satellite) and the incidence angle is steeper.

Referring to the same area, Figure 9 shows how the regular resolution grid in SAR coordinates (azimuth and slant-range) is deformed by the topography when projected on the ground.

Geometric deformation from ascending and descending ERS passes. With ERS there is the possibility to observe the same scene with incidence angles of both plus and minus 23 degrees. Observation of the whole of the Earth's surface is achieved by combination of the orbital satellite motion along the meridians (almost polar orbits) and the Earth's rotation in the equatorial plane.

This possibility comes from the fact that during orbits that go from South to North (**ascending passes**) and from North to South (**descending passes**), the SAR antenna pointing is usually fixed to the same side of the orbital plane with respect to the velocity vector (e.g. the radar antenna is always pointed to the right side of the track for ERS and Envisat).

Thus, the same scene on the ground is observed by the SAR antenna from the east during the descending passes and from the west during the ascending passes.

Here two detected ERS images of Mount Etna (Italy) taken from ascending and descending passes are shown together with an elevation model of the imaged area. A comparison of these two images clearly shows the effect of the different perspective: the summit is shifted away from the coastline in the ascending (left) ERS SAR image and towards it in the descending (right) image. From these images it is also evident that high resolution details of the western flank of the volcano are obtained from ERS ascending passes, whereas the eastern flank is 'squeezed' into a few pixels of the SAR image; the opposite happens with descending ERS passes.

Figure 7: Average of multiple ERS SAR images of Linate airport: the speckle effect on the homogeneous fields around the airport has disappeared.

Figure 8: ERS-2 SAR image of Mount Vesuvius (Italy), as detected. The slant range direction is vertical on the image (near range is in the upper part of the image). Brighter levels correspond to stronger backscattered radiation.

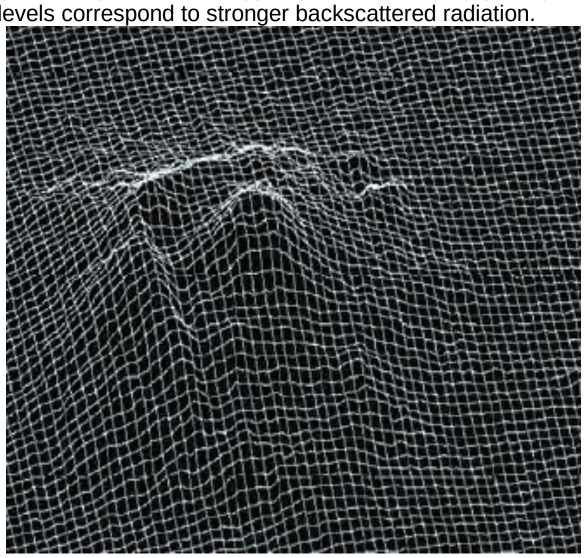


Figure 9: Deformation of the regular resolution grid on the ground when projected in SAR coordinates. The deformation is due to topography.

Thus, both ascending and descending passes should be exploited to get a high resolution SAR image of the whole area. It is necessary, however, to resample both images on a common reference grid in order to be able to make such a combination.

XV. Explain the meaning of following words in English.

Cloud-penetrating system, active system, digital elevation model, orbit, look angle, radar, atmosphere, elevation, satellite, resolution, slant-range direction, swath.

XVI. Complete the dialogue with proper sentences, then reproduce it with your partner.

A.: Hello Professor! I heard that ERS-2 differs from ERS-1. It has much better resolution. It is possible to

P.: I can’t agree with you. ERS-2 is identical to ERS-1. It has the same resolution but there are some extra instruments not influencing on the SAR images.

A.: So what ERS-2 was launched for?

P.: It was launched to get a greater interferogram coherence, because ERS-2 was linked to ERS-1. It was a so called “tandem” mission.

A.: Do you remember what orbit ERS operates in?

P.: ERS operates in the near-polar orbit.

A.: How does this orbit influence the acquisition geometry?

P.: It influences the final DEM. It strongly depends on the local terrain slope. We should combine DEM’s obtained from ascending and descending orbits.

A.: And what can you say about foreshortening in the hilly terrain for these two orbits. Which one is more

P.: If a slope is mainly oriented to the west, a descending orbit should be used. If not, then an ascending orbit should be taken into consideration.

A.: I heard these satellites finished their mission. Is it true?

P.: Yes. It’s true. ERS-1 finished its operations in 2000 and ERS-2 stopped its mission in 2011.

A.: What

P.: Envisat is the largest Earth Observation spacecraft. It has better resolution and other parameters.

A.: How many instruments does it carry?

P.: There are 9 instruments collecting information about land, water, ice and the atmosphere using various methods of measurements.

A.: Ok. That is all I wanted to know. Thank you a lot.

P.: I am glad I could help you. Have a nice day.

A.: Good bye, professor.

XVII. Dialogue of the Unit. Learn the dialogue in roles, then change them and learn it again.

P.: Good morning. A week has passed and I am glad to see you all again at the seminar. Today we are going to speak about InSAR related techniques. Who wants to be the first? You are welcome Alex.

A.: InSAR and other space geodetic techniques are primarily designed to measure the displacement of Earth’s surface over time. The particular characteristics of the measurements are tied to the specific implementation of the InSAR instrument and the mission characteristics. Clearly, there is a close link between the science that can be done with an InSAR mission and the design of that mission. It is important for the research community to understand this link in order to accomplish their goals. A simple example of this would be avoiding the use of data from a mission that provides an image over an area once per month, when the phenomenon of interest has changes that occur on timescales of days.

P.: Thanks, Alex. Today I would like you all had a better understanding of the discussed subject. So, who is able to give us the flow from scientifically driven measurement needs to the basic parameters of an InSAR mission. With such an understanding, it is then possible to characterize the performance of existing missions and productively discuss the design trades for future systems. Leo, please, do start.

L.: It is worth stating that InSAR measurements are a poor proxy for what scientists really would like to know about geophysical systems. The desired starting point to address larger geophysical questions – for example, what are the mechanics of earthquakes and how do fault systems interact? – would be measurements of the state of the crust, its pressure, temperature, and distribution of material properties throughout medium, to use as input to geophysical models. These *in situ* measurements at depth are impossible to obtain, so scientists model them through observations of the motions of Earth's surface.

P.: Thus, you want to say that it is important initially to understand the sensitivity relationship between model parameters and surface displacements, don't you, Leo?

L.: Yes, that is exactly what I want to say. For example, if any reasonable change in a model parameter changes the modelled surface displacement by 1mm, there is limited value in measuring deformation to only 1 cm accuracy.

A.: May I ask a question?

P.: Sure, what is it?

A.: The question is: what can we reasonably expect to measure with an InSAR system, and conversely, what is required of that system in order to advance science?

P.: Leo, I see you know the answer, but let Bill do it.

B.: A repeat-pass InSAR system measures the range displacement of any image element through a differencing of the phase from one epoch to another. Using a time series of observations, a repeatpass InSAR system measures a spatial distribution of range displacements in discrete time intervals. To use InSAR displacement measurements in geophysical models, the measurements must have adequate displacement accuracy, both absolute and relative, spatial resolution, spatial coverage, and temporal sampling. These requirements differ for each specific scientific investigation.

P.: For a given system, we have seen that the accuracy of the range displacement measurement is determined by noise induced by decorrelation of the radar echoes, by random phase delays introduced by propagation effects through the time-variable atmosphere, and by systematic knowledge uncertainties in the radar path delays and orbit. In addition, the incidence angle and azimuth angle of the observation can affect the accuracy of the measurement greatly; measuring a horizontal displacement with a system that looks steeply down toward nadir is not desirable. Go on, Leo.

L.: As it was already said earlier, decorrelation is comprised of principally three components: thermal decorrelation that is related to the noise level relative to the signal level of the radar system; geometric decorrelation which is related to the arrangement of scatterers on the surface and how they change with differences in time or viewing geometry; and other decorrelation terms that derive from noise, for example quantization, ambiguities, or sidelobes, that is dependent on the signal level itself.

P.: I should note that there is a strong functional dependence of these decorrelation terms on system parameters such as power, antenna size, wavelength, etc., and great interplay among them. So, Bill, do you have anything to add?

B.: I would say that the range resolution of a SAR system is inversely proportional to waveform bandwidth. The required range resolution is usually set by the scale size of the ground feature that is being mapped. For InSAR systems, however, there is a relationship between system bandwidth and desirable interferometric baselines. Finer resolution implies less decorrelation due to nonzero baselines. Thus, even if the final map resolution desired is only 100 m, one might require a system to have 10m resolution in range so that the constraints on the repeat-orbit accuracy are manageable.

P.: Good, what about you Alex?

A.: The along-track resolution of a conventional strip map SAR system is equal to half the along-track length of the antenna, independent of range and wavelength. I can illustrate it schematically in the blackboard. Here the antenna size is grossly exaggerated in size relative to the antenna beam width and the range, so that the salient characteristics can be viewed on a single page. The resolution alongtrack is determined by the spread in frequency content a given surface element experiences as the SAR beam illuminates it.

P.: Do you know that because of its beam width, the radar signal experiences Doppler shifts across its beam, such that the received echo contains a spectrum of information. Leo, you must be good at it, can you describe us this phenomenon?

L.: Certainly. The beam width is given by $\varphi_D=\lambda/L$, where λ is the wavelength of the radar tone and L is the length of the antenna along-track. The frequency bandwidth associated with the Doppler shifts within this beam width is given by $\Delta f_{D,t}=2v\varphi_D/\lambda=2v/L$. In spatial coordinates, the spatial frequency bandwidth is $\Delta f_{D,x}=2/L$, which implies a resolution of $L/2$. Thus, while wavelength and antenna length determine the beam width of the antenna, the spatial frequency content is not dependent on the wavelength in SAR.

P.: Thank you, Leo. For ScanSAR systems the resolution is determined by the length of the burst of pulses in a given scan, which is generally related to the number of ScanSAR beams. For spotlight SAR systems, the resolution is determined by the length of time over which the observation is made. But what about other noises met in radar systems?

B.: In addition to the thermal noise present in a radarsystem, there are a number of noise sources that play a significant role in the design of a radar and the accuracy one can expect to achieve for InSAR displacements. SAR systems point to an angle off nadir to avoid echoes from both sides of the nadir track: such echoes would be ambiguously combined in the SAR receiver and could not be distinguished from each other. Even with off nadir pointing, the transmitted and received energy cannot be completely localized in time as the signal spreads throughout the illumination area, resulting in a wide range of time over which a given echo can return, as well as some energy from the opposite side of nadir in some cases.

A.: Also, because the radar transmits pulses of energy over 1000 times per second for typical space borne systems in order to properly sample the Doppler spectrum, it can often occur that energy from time intervals outside the area of interest defined by this sampling rate, for example, from a previous or later pulse, arrives at the receiving antenna at the same time as the desired echo energy. These corrupting echoes, generally occurring at much lower amplitude, are called range ambiguities. The magnitude of these are controlled by the pulse rate – generally lower pulse rate allows more time to collect all echoes from a pulse – and by shaping the illumination area by manipulating the shape of the antenna pattern.

P.: On the other hand one cannot lower the pulse rate below the point where the along-track pulses become undersampled. As we have seen earlier, to create a narrow Doppler spectrum, we desire a long antenna in the along-track direction. Physical constraints on the size of the flight system, as well as a common desire for reasonably high resolution, limit this size, and therefore limit the minimum pulse rate. The illumination pattern in the along-track direction also has extent beyond the nominal beam width (antenna sidelobes), so the pulse sampling rate will naturally cause aliasing of some energy from beyond the along-track antenna main beam extent. To first order, then, if a wide swath is desired, then a low pulse rate must be chosen to allow enough time between pulses for the received echo to be unambiguously acquired. This then requires that the Doppler bandwidth, and hence the antenna beam width, be narrow, which then mandates a long antenna in the along-track direction. Furthermore, the antenna must be limited in size in the elevation direction to create a wide-enough beam to receive energy from the wide swath of interest. How can we determine the swath size for a particular satellite altitude?

L.: For a particular spacecraft altitude, the swath size is determined by these ambiguity constraints for most practical spaceborne systems. As the radar antenna of fixed beam width is pointed at greater distances off nadir, the swath illuminated on the ground becomes broader from projection effects, but the usable swath extent is usually narrower because of ambiguities. This then means that the antenna must be larger in the elevation dimension to limit the swath to maintain performance.

B.: These effects then influence mission design for an InSAR system. Scientists studying deformation want to be able to observe any point on the Earth at some regular interval. They also would like rapid repeat coverage to be able to track rapid changes of the Earth.

P.: Ok, guys, but suppose the mission requirement is to repeat an orbit every 8 days. For exact repeat, this requires an integer number of orbits in this time. There is an 8-day repeat polar orbit at about 760 km altitude that contains 115 orbits in 8 days.

A.: This then implies that the separation of the orbit tracks at the equator will be $2\pi 378/115 \approx 340$ km. Thus, the SAR must be able to cover 340 km of swath, either all at once with a very wide swath from a very long and skinny antenna (giving very low resolution), or using multiple smaller beams with smaller swaths covering different angles off nadir at different times.

L.: ScanSAR, where the radar sends a collection of pulses illuminating one subswath, then electronically steers the antenna to the next subswath off nadir and sends the next collection of pulses, and so on with multiple beams, allows full coverage of the wide swath in one pass again, at the expense of resolution, and somewhat degraded ambiguity performance.

P.: These design space possibilities – frequency, resolution, antenna size, orbit altitude and control, system power, viewing angle, repeat period, observation modality – are the playground of scientists, working with system designers, to optimize a mission to capture meaningful geophysical signals in the presence of the noise sources that are present in radar measurements. Space faring nations are increasingly relying on SAR and InSAR for scientific discovery and monitoring, with the trend moving away from large multimode systems to simpler instruments that do a few things well.

One of these missions will no doubt be dedicated InSAR mission, a true geodetic instrument in the model of GPS, but with global reach and dramatically improved denser coverage of the Earth.
That is all for today. Thank you all for a well done work. Next time we will discuss ScanSAR or Wide Swath Interferometry. The list of literature for the next meeting is in the screen. Have a good, but fruitful week.

Unit 3

SAR interferometry: applications and limits

Phrases to learn:

slightly different – *слегка отличающийся*
cross-multiplying – *поперечное перемножение*
dominant point scatterer – *точка, вносящая максимальный рассеивающий эффект*
it should be noted that – *следует заметить*
adjacent discontinuities – *смежные неоднородности*
the higher … the more … – *чем выше…тем больше*
temporal change – *временные изменения*
a comparison between – *сравнение между*
take into consideration – *принимать во внимание*
draw attention – обращать внимание

Introduction

A satellite SAR can observe the same area from slightly different look angles. This can be done either simultaneously (with two radars mounted on the same platform) or at different times by exploiting repeated orbits of the same satellite. The latter is the case for ERS-1, ERS-2 and Envisat. For these satellites, time intervals between observations of 1, 35, or a multiple of 35 days are available.

The distance between the two satellites (or orbits) in the plane perpendicular to the orbit is called the **interferometer baseline** (Figure 1) and its projection perpendicular to the slant range is the **perpendicular baseline**.

The SAR interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second. Thus, the interferogram amplitude is the amplitude of the first image multiplied by that of the second one, whereas its phase (the **interferometric phase**) is the phase difference between the images.

Terrain altitude measurement through the interferometric phase

Let us suppose we have only one dominant point scatterer in each ground resolution cell that does not change over time. These point scatterers are observed by two SARs from slightly different look angles as shown in Figure 1. In this case the interferometric phase of each SAR image pixel would depend only on the difference in the travel paths from each of the two SARs to the considered resolution cell. Any possible phase contribution introduced by the point scatterers does not affect the interferometric phase since it is cancelled out by the difference.

Once a ground reference point has been identified, the variation of the travel path difference Δr that results in passing from the reference resolution cell to another can be given by a simple expression (an approximation that holds for small baselines and resolution cells that are not too far apart) that depends on a few geometric parameters shown in Figure 2.

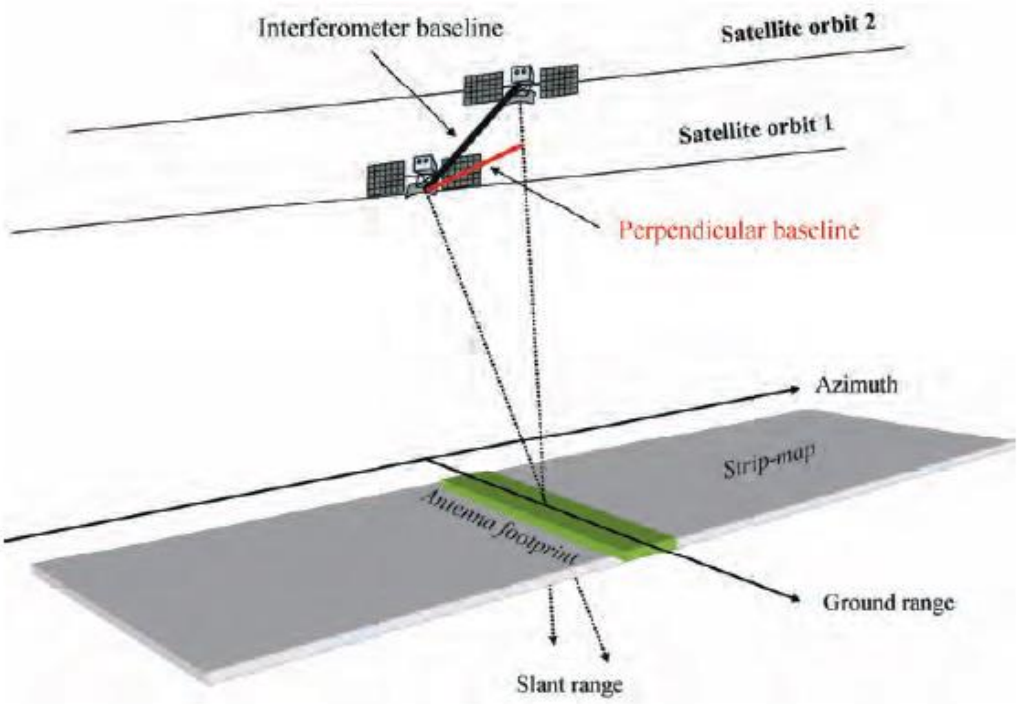


Figure 1: Geometry of a satellite interferometric SAR system. The orbit separation is called the interferometer baseline, and its projection perpendicular to the slant range direction is one of the key parameters of SAR interferometry.

The parameters are:

1. The perpendicular baseline *Bn*
2. The radar-target distance *R*
3. The displacement between the resolution cells along the perpendicular to the slant range, *qs.*

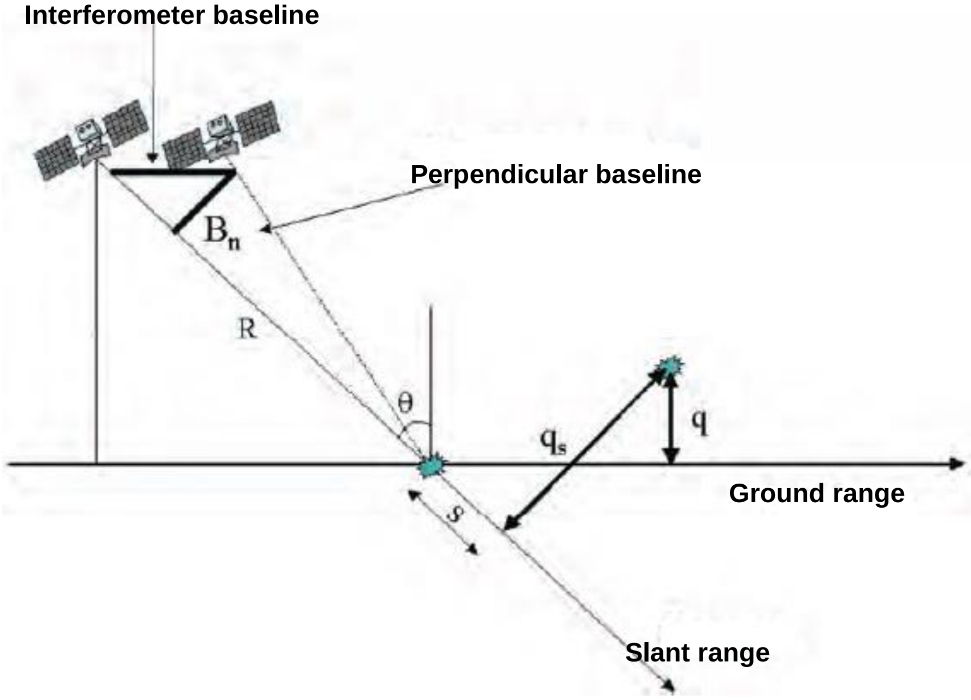


Figure 2: Geometric parameters of a satellite interferometric SAR system

The following approximated expression of Δ*r* holds:

$$\Delta r = -2\frac{B_n q_s}{R} \quad 1$$

The interferometric phase variation Δφ is then proportional to Δr divided by the transmitted wavelength λ:

$$\Delta\varphi = \frac{2\pi\Delta r}{\lambda} = \frac{2\pi}{\lambda}\frac{B_n q_s}{R} \quad 2$$

Interferogram flattening

The interferometric phase variation can be split into two contributions:

1. A phase variation proportional to the altitude difference q between the point targets, referred to a horizontal reference plane
2. A phase variation proportional to the slant range displacement s of the point targets

$$\Delta\varphi = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} - \frac{4\pi}{\lambda}\frac{B_n S}{R\tan\theta} \quad 3$$

where θ is the radiation incidence angle with respect to the reference.

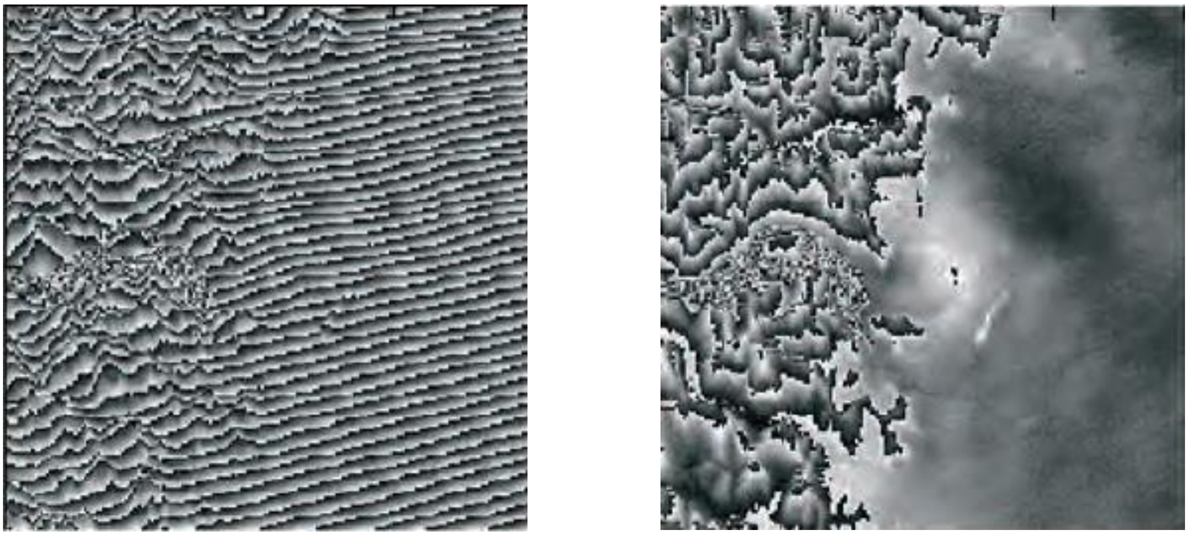


Figure 3: Left**:** interferogram of a portion of the Italian Alps and the Pianura Padana that has been obtained from ERS data. Right: flattened interferogram. Here the phase discontinuities resemble the contour lines.

It should be noted that the perpendicular baseline is known from precise orbital data, and the second phase term can be computed and subtracted from the interferometric phase. This operation is called **interferogram flattening** and, as a result, it generates a phase map proportional to the relative terrain altitude.

An example of interferogram flattening is shown in Figure 3. An interferogram of a portion of the Italian Alps and the Pianura Padana that has been obtained from ERS-1 and ERS-2 data (taken one day apart with a normal baseline of about 30 metres) is shown on the left. The flattened interferogram is shown on the right side. Here the phase discontinuities resemble the contour lines. The altitude between two adjacent discontinuities is called the **altitude of ambiguity** (symbol h_a) and can be computed from the interferometer parameters.

Altitude of ambiguity

The altitude of ambiguity h_a is defined as the altitude difference that generates an interferometric phase change of 2π after interferogram flattening. The altitude of ambiguity is inversely proportional to the perpendicular baseline:

$$h_a = \frac{\lambda\, R \sin\theta}{2B_n} \quad 4$$

In the ERS case with λ = 5.6 cm, θ = 23º, and *R* = 850 km, the following expression holds (in metres):

$$h_a \approx \frac{9300}{B_n} \quad 5$$

As an example, if a 100 metre perpendicular baseline is used, a 2π change of the interferometric phase corresponds to an altitude difference of about 93 metres. In principle, the higher the baseline the more accurate the altitude measurement, since the phase noise is equivalent to a smaller altitude noise. However, it will be shown later that there is an upper limit to the perpendicular baseline, over which the interferometric signals decorrelate and no fringes can be generated. In conclusion there is an optimum perpendicular baseline that maximises the signal to noise power ratio (where the signal is terrain altitude). In the ERS case, such an optimum baseline is about 300–400 metres.

Phase unwrapping and DEM generation

The flattened interferogram provides an ambiguous measurement of the relative terrain altitude due to the 2π cyclic nature of the interferometric phase. The phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation, after deleting any integer number of altitudes of ambiguity (equivalent to an integer number of 2π phase cycles). The process of adding the correct integer multiple of 2π to the interferometric fringes is called **phase unwrapping**.

An example of phase unwrapping is shown in Figure 4, in which the SAR interferometric phase, its unwrapped version and a map with the correct integer multiple of 2π added to the original phase are shown together.

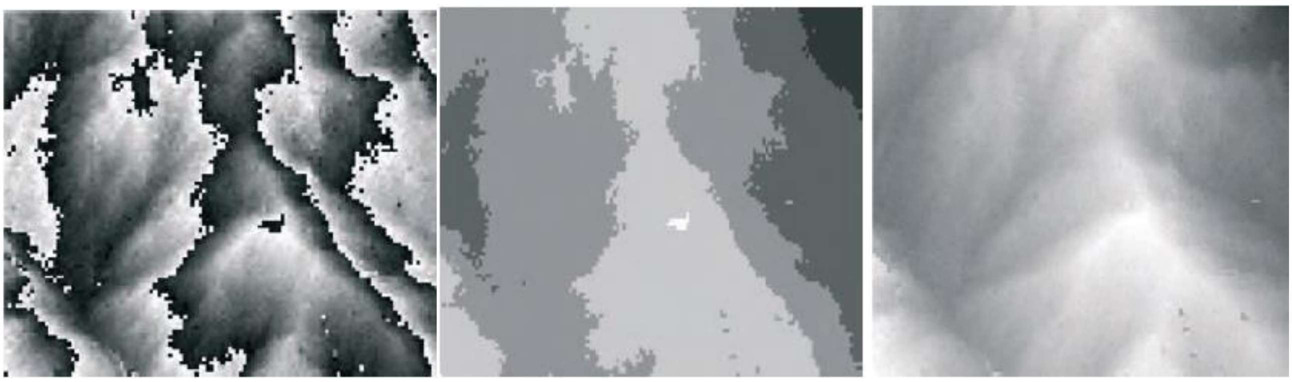


Figure 4: Left: SAR interferometric phase generated by means of two ERS images. The 2π phase discontinuities are clearly visible as black/white transitions. Middle: Unwrapped phase. Right: The 2π phase discontinuities have been eliminated by adding or subtracting an integer multiple of 2π to each pixel of the original interferometric phase image.

There are several well-known phase unwrapping techniques. However it should be noted here that usually phase unwrapping does not have a unique solution, and *a priori* information should be exploited to get the right solution. Once the interferometric phases are unwrapped, an elevation map in SAR coordinates is obtained. This is the first step towards getting a DEM. The SAR elevation map should then be referred to a conventional ellipsoid (e.g. WGS84) and re-sampled on a different grid (for example UTM).

As an example, the flattened interferogram and the relative DEM of Mount Etna obtained through phase unwrapping and re-sampling are shown in Figures 5, 6, 7.

Terrain motion measurement: Differential Interferometry

Suppose that some of the point scatterers on the ground slightly change their relative position in the time interval between two SAR observations (as, for example, in the event of subsidence, landslide, earthquake, etc.). In such cases the following additive phase term, independent of the baseline, appears in the interferometric phase:

$$\Delta\varphi_d = \frac{4\pi}{\lambda} d \qquad 6$$

where d is the relative scatterer displacement projected on the slant range direction.

This means that after interferogram flattening, the interferometric phase contains both altitude and motion contributions:

$$\Delta\varphi = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} + \frac{4\pi}{\lambda} d \qquad 7$$

Moreover, if a digital elevation model (DEM) is available, the altitude contribution can be subtracted from the interferometric phase (generating the so-called **differential interferogram**) and the terrain motion component can be measured. In the ERS case with λ = 5.6 cm and assuming a perpendicular baseline of 150 m (a rather common value), the following expression holds:

$$\Delta\varphi = -\frac{q}{10} + 225\, d \qquad 8$$

From this example it can be seen that the sensitivity of SAR interferometry to terrain motion is much larger than that to the altitude difference. A 2.8 cm motion component in the slant range direction would generate a 2π interferometric phase variation.

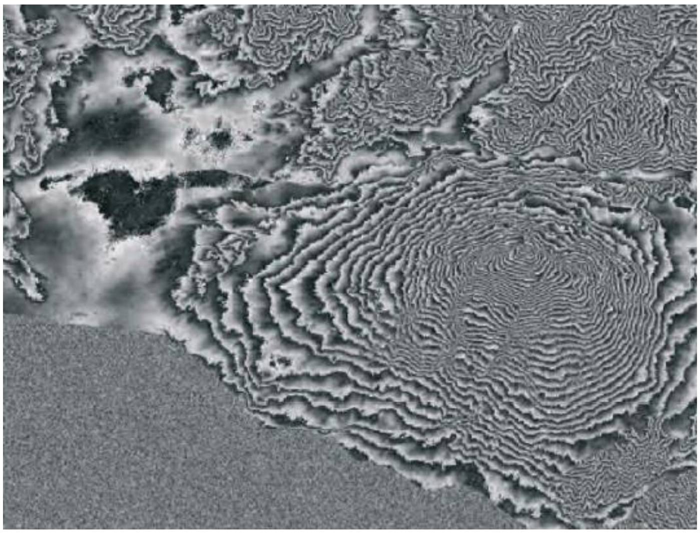


Figure 5: Flattened interferogram of Mount Etna generated from ERS tandem pairs. The perpendicular baseline of 115 metres generates an altitude of ambiguity of about 82 metres.

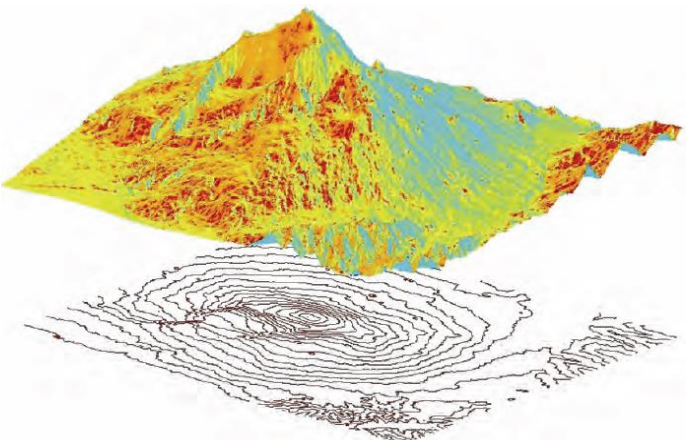


Figure 6: Perspective view of Mount Etna as seen from the Northeast**.** The DEM of Mount Etna has been generated by unwrapping and re-sampling the flattened interferogram of Figure 5: The estimated vertical accuracy is better than 10 metres. Contour lines are shown below the DEM.

Figure 7: Perspective view of Mount Etna as seen from the Northeast. The average of many detected ERS SAR images has been draped on the DEM.

As an example, the differential interferogram showing the surface deformation that occurred during the Mount Etna eruption of July 2001 is shown in Figure 8.

The atmospheric contribution to the interferometric phase

When two interferometric SAR images are not simultaneous, the radiation travel path for each can be affected differently by the atmosphere. In particular, different atmospheric humidity, temperature and pressure between the two takes will have a visible consequence on the interferometric phase. This effect is usually confined within a 2π peak-to-peak interferometric phase change along the image with a smooth spatial variability (from a few hundred metres to a few kilometres). The effect of such a contribution impacts on both altitude (especially in the case of small baselines) and terrain deformation measurements.

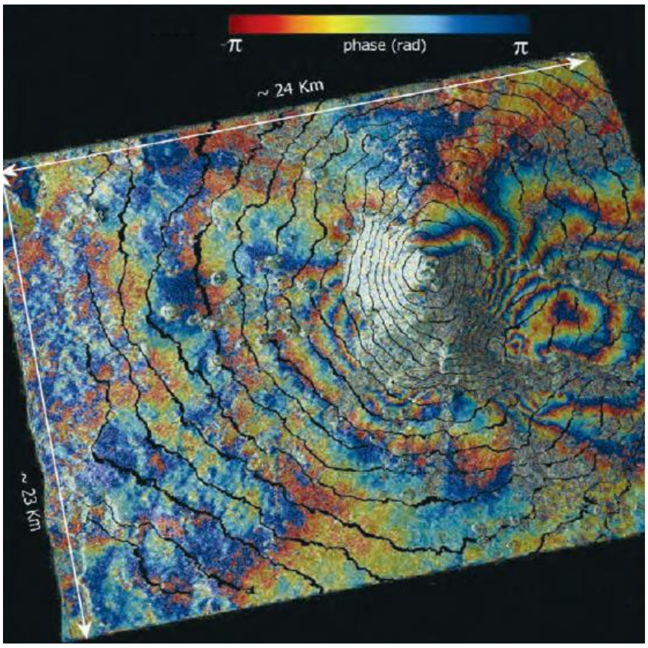


Figure 8: The differential interferogram of the Mt Etna eruption that occurred in July 2001. The interferogram has been generated by means of two ERS images taken before (11 July 2001) and after (15 August 2001) the eruption. The topography has been removed by means of an available DEM. Contour lines of the DEM are shown in black.

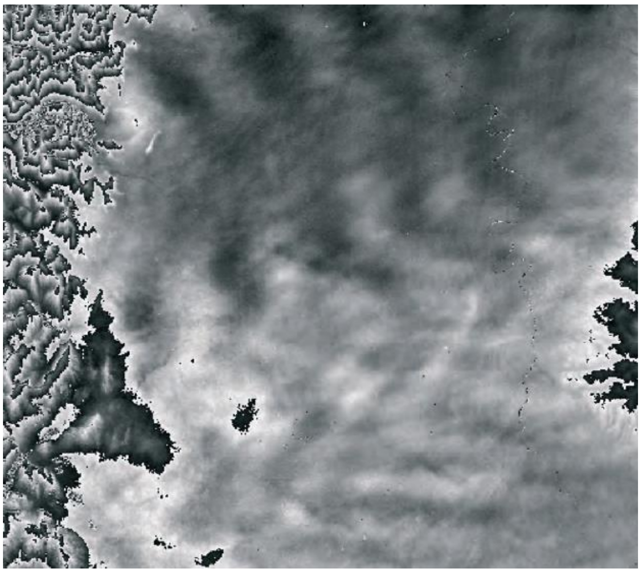


Figure 9: An example of atmospheric phase contribution to the ERS interferogram generated on the Pianura Padana. The perpendicular baseline is about 30 metres and the altitude of ambiguity (from black to white in the grey scale used) is about 300 metres.

As an example, the atmospheric phase contribution to the ERS interferogram generated on the Pianura Padana valley (North Italy) is shown in Figure 9. Here the perpendicular baseline is quite small (30 metres) and the differential turbulence effect is clearly visible on the interferogram where an almost flat phase contribution is expected from the known topography.

Other phase noise sources

In the previous sections it has been hypothesised that only one dominant stable scatterer was present in each resolution cell. This is seldom the case in reality. We should analyse the situation where many elementary scatterers are present in each resolution cell (distributed scatterers), each of which may change in the time interval between two SAR acquisitions. The main effect of the presence of many scatterers per resolution cell and their changes in time is the introduction of phase noise.

Three main contributions to the phase noise should be taken into consideration:

1. Phase noise due to temporal change of the scatterers

In the case of a water basin or densely vegetated areas, the scatterers change totally after a few milliseconds, whereas exposed rocks or urban areas remain stable even after years. Of course, there are also the intermediate situations where the interferometric phase is still useful even if corrupted by change noise.

2. Phase noise due to different look angle

Speckle will change due to the different combination of elementary echoes even if the scatterers do not change in time. The most important consequence of this effect is that there exists a **critical baseline** over which the interferometric phase is pure noise. The critical baseline depends on the dimension of the ground range resolution cell (and thus also on the terrain slope), on the radar frequency, and on the sensor-target distance. In the ERS case, the critical baseline for horizontal terrain is about 1150 metres. It decreases for positive terrain slopes and increases for negative ones.

This phase noise term, however, can be removed from the interferogram by means of a pre-processing step of the two SAR images known as **spectral shift** or **common band** filtering.

3. Phase noise due to volume scattering

The critical baseline reduces in the case of volume scattering when the elementary scatterers are not disposed on a plane surface but occupy a volume (e.g. the branches of a tree). In this case the speckle change depends also on the depth of the volume occupied by the elementary scatterers.

Coherence maps

The phase noise can be estimated from the interferometric SAR pair by means of the local **coherence** γ. The local coherence is the cross-correlation coefficient of the SAR image pair estimated over a small window (a few pixels in range and azimuth), once all the deterministic phase components (mainly due to the terrain elevation) are compensated for. The deterministic phase components in such a small window are, as a first approximation, linear both in azimuth and slant-range. Thus, they can be estimated from the interferogram itself by means of well-known methods of frequency detection of complex sinusoids in noise (e.g. 2-D **Fast Fourier Transform (FFT)**).

The coherence map of the scene is then formed by computing the absolute value of γ on a moving window that covers the whole SAR image.

The coherence value ranges from 0 (the interferometric phase is just noise) to 1 (complete absence of phase noise). As an example, a coherence map of the North East part of Sicily is shown in Figure 10.

Figure 10: Coherence map of the North East part of Sicily

Here the exposed lava on Mount Etna shows a very high coherence value, whereas vegetated areas appear dark, showing lower coherence values. Note the very low coherence value of the sea (dark in the image), which changes completely in the one day interval between the two ERS observations. The exact relation between the interferometric phase dispersion and coherence can be found through complicated mathematical computation.

However, if the number of looks (NL) is greater than four, then independent pixels with the same coherence are averaged after topography compensation (multi-look interferogram) and the following simple approximation holds:

$$\sigma_{\varphi} = \frac{1}{\sqrt{2NL}} \frac{\sqrt{1-\gamma^2}}{\gamma} \qquad 9$$

From a mathematical point of view, this formula is a good approximation of the exact phase dispersion shown in Figure 11 when $\sigma_{\varphi} < 12°$. That is, when *NL* is large and γ close to one. However, for most practical applications of SAR interferometry, the approximated formula can be suitably exploited for coherence values higher than 0.2 and NL > 4.

A comparison between the exact and approximated curves is shown in Figure 12.
The phase dispersion can be exploited to estimate the theoretical elevation dispersion (limited to the high spatial frequencies) of a DEM generated from SAR interferometry:

$$\sigma_{h=\sigma_{\varphi}\frac{R\lambda\sin\theta}{4\pi B}} \tag{10}$$

On the other hand, low spatial frequencies of the DEM error cannot be predicted from the coherence map since the coherence estimation is carried out on small windows. The information carried by the coherence map can be usefully exploited to help image segmentation.

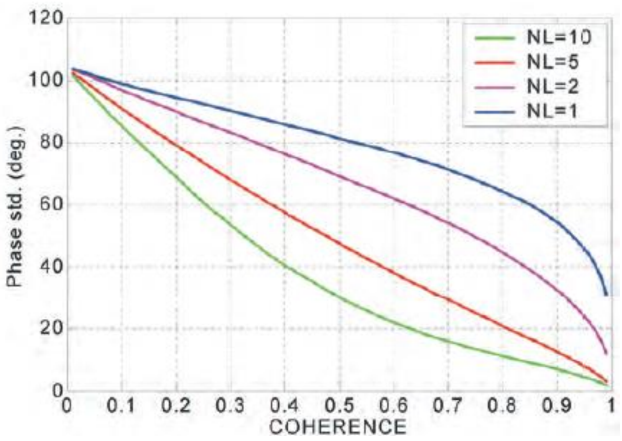


Figure 11: Interferometric phase dispersion (degrees) as a function of the coherence for varying numbers of looks (NL)

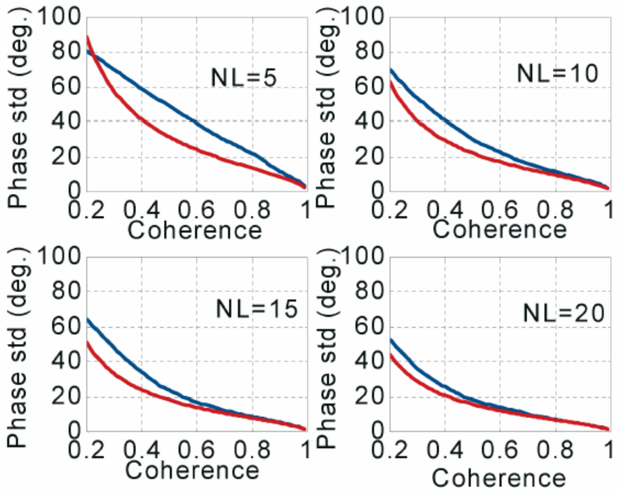


Figure 12: Interferometric phase dispersion exact values (blue curves) and approximated ones (red curves)

I. Vocabulary

ambiguous (adj) – двусмысленный
assume (v) – принимать, допускать
averaged (adj) – усреднённый
black/white transition (n) – черно-белый переход
cancel out (v) – уравновешивать, взаимно уничтожаться
common band (n) – общая полоса частот
complex conjugate (adj) – комплексно-сопряжённый
confine (v) – ограничивать
conjugate (adj) – соединенный, связанный
consequence (n) – результат, последствие
consider (v) – рассматривать
contour lines (n) – контурная линия; горизонталь
conventional ellipsoid (n) – общепринятый эллипсоид
corrupt (v) – искажать
cross-correlation coefficient (n) – коэффициент взаимной корреляции
eliminate (v) – устранять, исключать
far apart – на большом расстоянии друг от друга
flatten (v) – сглаживать; выравнивать
hypothesize (v) – строить гипотезу
inversely proportional (adj) – обратно пропорциональный
multiple (adj) – кратный, неоднократный, повторяющийся
multiple (n) – кратное число
phase discontinuity (n) – скачок фазы
phase unwrapping (n) – развёртывание фазы
pre-processing step (n) – этап предварительной обработки
radar(-resolution) cell (n) – элемент разрешения РЛС
reference plane (n) – базовая плоскость; опорная плоскость; плоскость отсчёта
relative position (n) – взаимное положение, относительное положение, взаимное расположение

simultaneously (adv) – одновременно, синхронно
slant range(n) – наклонная дальность
speckle (v) – спекл (дифракционное пятно изображения)
spectral shift (n) – спектральный сдвиг
split into (v) – разбивать на
subtract (v) – вычитать
wavelength (n) – длина волны

II. Reading

ambiguous [æm'bigjuəs] , averaged ['æv(ə)ridʒd] , transition [træn'ziʃ(ə)n] , conjugate ['kɔndʒugət], confine ['kɔnfain], consequence ['kɔn(t)sikwən(t)s], consider [kən'sidə], conventional [kən'ven(t)ʃ(ə)n(ə)l], ellipsoid [i'lipsɔid] , corrupt [kə'rʌpt] , coefficient [ˌkəui'fiʃ(ə)nt], eliminate [i'limineit], hypothesize [hai'pɔθəsaiz], inversely ['in'və:sli], proportional [prə'pɔ:ʃ(ə)n(ə)l], multiple ['mʌltipl], discontinuity [dɪsˌkɒntɪ'nju:ɪtɪ], simultaneously [ˌsim(ə)l'teiniəsli], slant [slɑ:nt], range [reindʒ], subtract [səb'trækt].

III. Comprehension check

1. What can a SAR satellite observe from different look angles?
2. Which time intervals are available for ERS-1 and ERS-2?
3. What do scientists call the interferometer baseline?
4. How is the SAR interferogram generated?
5. Where is the perpendicular baseline known from?
6. How is the altitude between two adjacent discontinuities called?
7. What is the meaning of phase unwrapping term?
8. What can affect simultaneousness of two interferometric images?
9. What are the three main contributions to the phase noise?
10. What can be estimated when the phase dispertion is exploted?

IV. Repeat the following statements after the teacher, then change them to questions supplying short answers.

1. The information carried by the coherence map can be usefully exploited to help image segmentation.
2. A comparison between the exact and approximated curves is shown in Figure 1.
3. The exact relation between the interferometric phase dispersion and coherence can be found through complicated mathematical computation.
4. A 2.8 cm motion component in the slant range direction would generate a 2π interferometric phase variation.
5. The phase noise can be estimated from the interferometric SAR pair by means of the local coherence γ.
6. Speckle will change due to the different combination of elementary echoes even if the scatterers do not change in time.
7. When two interferometric SAR images are not simultaneous, the radiation travel path for each can be affected differently by the atmosphere.
8. If a digital elevation model (DEM) is available, the altitude contribution can be subtracted from the interferometric phase and the terrain motion component can be measured.
9. The second phase term can be computed and subtracted from the interferometric phase.

10. The SAR interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second.

V. Remake the following sentences according to the given pattern.

A. Applying an InSAR showed very good cloud-penetrating capabilities.
Very good cloud penetrating capabilities were shown by applying an InSAR.

1. A satellite SAR can observe the same area from slightly different look angles.
2. The interferometer baseline is the distance between the two satellites in the plane perpendicular to the orbit.
3. Two SARs observe the point scatterers from slightly different look angles.
4. Figure 3 shows an example of interferogram flattening.
5. The interferometer parameters allow us to compute the altitude of ambiguity.

B. There is an upper limit to the perpendicular baseline.
Is there an upper limit to the perpendicular baseline?
There is not an upper limit to the perpendicular baseline.
There is no upper limit to the perpendicular baseline.

1. There is an optimum perpendicular baseline that maximises the signal to noise power ratio
2. There are some extra instruments carried by ERS-2.
3. There were some instruments collecting information about land, water, ice and the atmosphere using various methods of measurements.
4. However there are several factors that can cause this criterion to fail.
5. There was also a geometric constraint on the maximum length of the baseline.

C. ESA made some ERS-1 images available.
Did ESA make any ERS-1 images available?
ESA made no ERS-1 images available.

1. They had to isolate and remove some of these effects .
2. It will usually include some combinations of the following steps.
3. These two satellites will allow them to extract some additional information from InSAR images.
4. ERS-2 is expected to continue operating for some time.
5. The desert environment raised some hopes that the interferometric comparison of radar images acquired a long time apart could work.

D. Each target should be summed accurately each time, and be removed from the interferogram. (more)
Each target should be summed more accurately each time, and be removed from the interferogram. (much)
Each target should be summed much more accurately each time, and be removed from the interferogram. (as accurately as)
Each time each target should be summed as accurately as possible, and be removed from the interferogram.

1. There are some dominant point scatterers in each ground resolution cell that change slowly.
2. It should be noted that the perpendicular baseline is known from precise orbital data.

3. The flattened interferogram provides an ambiguous measurement of the relative terrain altitude due to the 2π cyclic nature of the interferometric phase.
4. The radiation travel path for each can be affected differently by the atmosphere.
5. The information carried by the coherence map can be usefully exploited to help image segmentation.

VI. Ask questions to which the following sentences could be answers.

1. The information carried by the coherence map can be usefully exploited to help image segmentation.
2. The exact relation between the interferometric phase dispersion and coherence can be found through complicated mathematical computation.
3. The coherence value ranges from 0 (the interferometric phase is just noise) to 1 (complete absence of phase noise).
4. The phase noise can be estimated from the interferometric SAR pair by means of the local coherence γ.
5. The most important consequence of this effect is that there exists a critical baseline over which the interferometric phase is pure noise.
6. The main effect of the presence of many scatterers per resolution cell and their changes in time is the introduction of phase noise.
7. The effect of such a contribution impacts on both altitude and terrain deformation measurements.
8. A 2.8 cm motion component in the slant range direction would generate a 2π interferometric phase variation.
9. There are several well-known phase unwrapping techniques but usually phase unwrapping does not have a unique solution.
10. The process of adding the correct integer multiple of 2π to the interferometric fringes is called phase unwrapping.
11. The altitude of ambiguity h_a is defined as the altitude difference that generates an interferometric phase change of 2π after interferogram flattening.
12. The SAR interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second.

VII. Give Russian equivalents to the following phrases, then make some sentences using all of the given phrases.

resolution cell dimension, mode of operation, outgoing wave, two-dimensional array, adjacent discontinuities, altitude of ambiguity, look angle, due to the curvature of, summed contribution, incidence angle, residual phase, to be associated with, spurious signal, accurate measurements, to be acceptable for, to be foreshortened, operational capability, factors affecting smth, ever-growing capabilities, take into consideration, slightly different.

VIII. Learn the rules of formula pronunciation, given at Appendixes 1 and 2, then write and read the formulae of the main text of the unit.

a. $$\Delta r = -2\frac{B_n q_s}{R}$$

b. $$h_a = \frac{\lambda\, R \sin\theta}{2B_n}$$

c. $$\Delta\varphi = \frac{2\pi\Delta r}{\lambda} = \frac{2\pi}{\lambda}\frac{B_n q_s}{R}$$

d. $$\Delta\varphi = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} - \frac{4\pi}{\lambda}\frac{B_n S}{R\tan\theta}$$

e. $$\Delta\varphi = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} + \frac{4\pi}{\lambda}d$$

f. $$\sigma_\varphi = \frac{1}{\sqrt{2\mathrm{NL}}}\frac{\sqrt{1-\gamma^2}}{\gamma}$$

g. $$h_{\ a} \approx \frac{9300}{B_n}$$

h. $$\Delta\varphi_d = \frac{4\pi}{\lambda}d$$

j. $$\Delta\varphi = -\frac{q}{10} + 225\,d$$

k. $$\sigma_{h=}\ \sigma_\varphi \frac{R\lambda\sin\theta}{4\pi B}$$

IX. Correct the wrong statements using the given phrases.

on the contrary; I do not believe that; to my mind; as is known; as far as I know; it is considered that; it seems to be wrong; I am afraid you are mistaken; I can't agree with you; it seems unlikely that; in my opinion.

1. Low spatial frequencies of the DEM error can be predicted from the coherence map since the coherence estimation is carried out on small windows.
2. The phase dispersion can be exploited to estimate the real elevation dispersion of a DEM generated from SAR interferometry.
3. The coherence map of the scene is formed by computing the theoretical value of γ on a moving window that covers the whole SAR image.
4. In the ERS case, the critical baseline for vertical terrain is about 1150 metres.
5. Four main contributions to the phase noise should usually be taken into consideration.
6. When two interferometric SAR images are not simultaneous, the radiation travel path for each can be affected equally by the atmosphere.
7. There are several well-known phase unwrapping techniques, and usually phase unwrapping has only unique solution.
8. The flattened interferogram provides a certain measurement of the relative terrain altitude due to the 2π cyclic nature of the interferometric phase.
9. The altitude of ambiguity h_a is defined as the altitude difference that generates an interferometric phase change of $2\frac{3}{4}\pi$ after interferogram flattening.
10. A satellite SAR can observe the same area from equal look angles.

X. Give English translation of the following phrases. Use them in your own sentences.

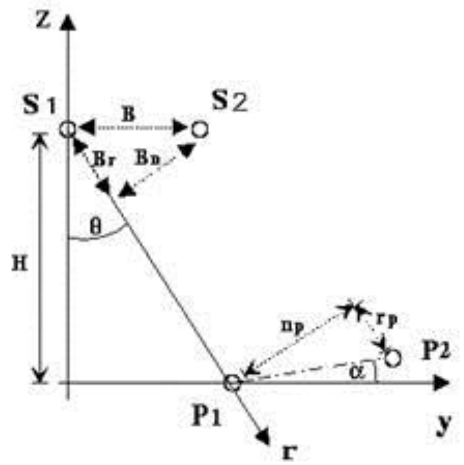
общая полоса частот, этап предварительной обработки, спектральный сдвиг, горизонталь, временные изменения, базовая плоскость, коэффициент взаимной корреляции, наклонная дальность, развёртывание фазы, комплексно-сопряжённый, черно-белый переход, точка, вносящая максимальный рассеивающий эффект, принимать во внимание.

XI. Translate the texts into English.

A. Интерферометрическая РСА (далее – интерферометрия) - это альтернатива традиционной стереофотографической технике для создания топографических карт с высоким разрешением вне зависимости от погодных условий и времени суток при съемке. Конечно, для этого необходимо использовать монохроматический подход, т.е. электромагнитные волны, излучаемые с космического аппарата, должны описываться периодической во времени функцией.

Каждая точка комплексного снимка может быть описана в общем виде как $Z(x, y) = = I(x, y)e^{i\varphi(x,y)}$, где *I* – интенсивность, приходящаяся на нее, φ - фаза точки, x и y – координаты. «Перемножение» снимков в каждой точке дает $p(x, y) = z_1(x, y) \cdot z_2(x, y) = = I'(x, y) \cdot e^{i\Delta\varphi(x,y)}$, где *I'* – интерферометрическая интенсивность точки, $\Delta\varphi(x, y)$ - интерферометрическая фаза. В практике полученные изображения z_1 и z_2 могут различаться из-за вносимых, например, атмосферой, погрешностей. Коэффициент когерентности *g* между ними может быть введен как

$$g(x, y) = \frac{\langle z_1(x, y) \cdot z_2(x, y)\rangle}{\sqrt{\langle|z_1(x, y)|^2\rangle \cdot \langle|z_2(x, y)|^2\rangle}}$$



Разница фаз (интерферометрическая фаза) между двумя соответствующими друг другу точками на интерференционной паре пропорциональна разности хода $2\Delta r_0$ (коэффициент *2* указывает на двойное прохождение пути волнами) и равна $4\frac{\pi}{\lambda}\Delta r_0$, где λ - длина излученной волны. Разность хода волны Δr_0 много больше длины волны (в большинстве практических случаев, различие в пути от спутника может быть порядка нескольких сотен метров, тогда как используемая длина волны имеет длину нескольких сантиметров), и разность фаз может интерпретироваться двусмысленно.

На рисунке изображены положения двух сенсоров РСА (S1 и S2) и их параллельное (B_r) и нормальное (B_n) смещение относительно линии наблюдения. Также там зафиксировано расположение двух точек участка и их смещения, нормальное n_p и параллельное r_p по отношению к линии наблюдения. Основным будем полагать положение S1 с соответствующей точкой P1 с расстоянием между ними Δr_0. Изменяя его положение, расстояние между участком поверхности и датчиком изменится:

$$r = \sqrt{\left(r_0 + r_p - B_r\right)^2 + \left(n_p - B_n\right)^2}. \quad (1)$$

В нашем случае, когда расстояние между двумя антеннами S1 и S2 мало по сравнению с r_0, мы можем записывать изменение интерферометрической фазы в приближении:

$$\Delta\varphi = -\frac{4\pi}{\lambda}\Delta(\Delta r_0) = \frac{4\pi \cdot B_n \cdot n_p}{\lambda \cdot r_0} \ . \quad (2)$$

Этот результат показывает нам, что если мы знаем относительное смещение двух орбит нормально к линии наблюдения Bn, расстояние r0 и длину волны, используемую при локации, тогда величина $\Delta\varphi$ зависит лишь только от n_p.

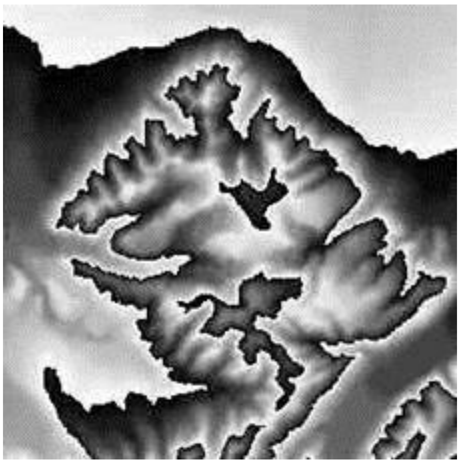
Таким образом, интерференционное изображение фазы представляет собой карту относительного возвышения ландшафта относительно линии наблюдения. После некоторых преобразований, уравнение для 2 можно переписать в виде:

$$\Delta\varphi = \frac{4\pi \cdot B_n \cdot q}{\lambda \cdot r_0 \sin\theta} = 2\pi\frac{q}{q_0} , \quad (3)$$

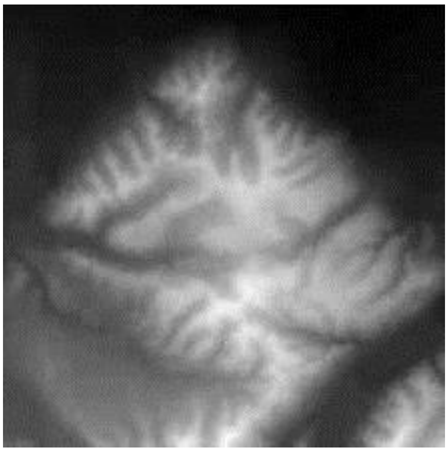
где $q = \Delta z$ есть относительное возвышение и $q_0 = \frac{2Bn}{\lambda \cdot r_0 \cdot sin\theta}$.

Развертка фазы

Очевидно, что уравнение (3) содержит в себе многозначность, связанную с вычислением значения периодической функции $exp(i \cdot \Delta\varphi)$.



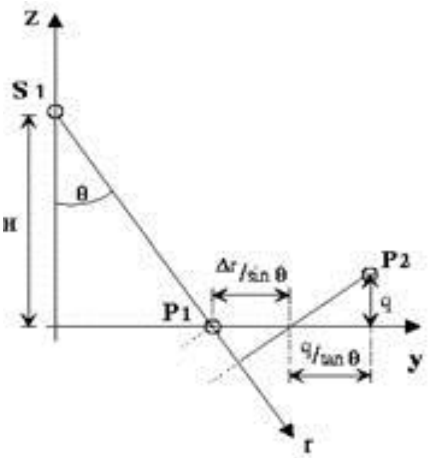
Оригинальная фаза (0pi to 2pi)



Развернутая фаза (0pi to 8pi)

Интерферометрическая фаза может быть обнаружена в интервале от $-\pi$ до π, но ее действительная величина может выходить за эти пределы. Развертка фазы позволяет восстановить истинное ее значение посредством добавления или вычитания кратного 2π числа к фазе $\Delta\varphi$ таким образом, чтобы сделать соответствующую фазовую картину максимально гладкой. Развертку фазы несложно выполнять для участков поверхности с высокой когерентностью. Часто, алгоритмы развертки оставляют «отверстия», где они не могут определить фактическую фазу, но, тем не менее, эта операция позволяет получить весьма точное представление о топографии поверхности.

Ректификация модели рельефа



Из рисунка видно, что горизонтальное положение точек относительно начальной точки отсчета зависит от координат S1P1 и их возвышения относительно начального уровня. Простые геометрические соображения позволяют нам найти между ними связь:

$$y(r,q) = \frac{\Delta r}{\sin\theta} + \frac{q(r)}{\operatorname{tg}\theta}$$

С помощью этой функции строится так называемая цифровая модель рельефа (Digital Elevation Model). К ее построению также применяются корреляционные функции, описывающие влияние атмосферы, температурные эффекты, рассмотрение которых выходит за пределы данной работы.

Следует заметить, что мы получаем карту земной поверхности, включающую в себя строения, леса и т.д.

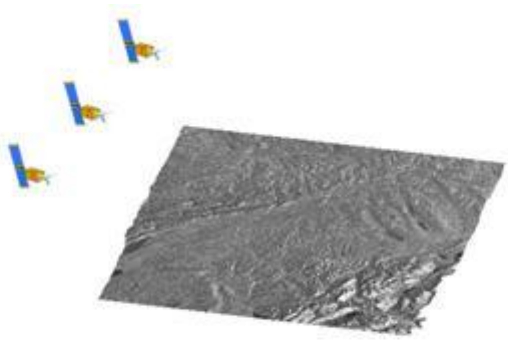
B. Дифференциальная интерферометрия

Известно, что геологические процессы, формирующие ландшафт земной поверхности, проходят на первых стадиях незаметно для большинства общепринятых средств контроля. Но впоследствии, как правило, неожиданно, возникают разломы, подвижки и землетрясения.

Технология спутниковой радиоинтерферометрии обеспечивает измерение вертикального и горизонтального смещения земной поверхности с точностью несколько миллиметров с расстояния сотни километров из космического пространства.

Этот метод с 1992 года реализуется Европейским космическим агентством (ЕКА) и является аналогом стереосъемки и основан на обработке двух радиолокационных снимков, получаемых спутниками на относительно малой базе (расстояние между сенсорами) около 300 м.

Дифференциальная интерферометрия использует два изображения (иногда три) того же самого земельного участка. Проходы спутника (1) и (2) используются, чтобы получить интерферограмму топографии ландшафта, используя основную интерферометрическую методику. Точно так же данные, полученные при прохождении спутников 2 и 3, производят следующую интерферограмму той же самой области.



Разность фаз $\Delta\varphi$, соответствующая измененю рельефа, пропорциональна смещению Δs вдоль линии наблюдения т распространения ЕМ волн, и уравнение (3) может быть переписано в виде

$$\Delta\varphi = \Delta\varphi_t + \Delta\varphi_n = \frac{4\pi \cdot B_n \cdot n_p}{\lambda \cdot r_0} + \frac{2\Delta s}{\lambda} \quad (4).$$

Самый простой способ оценки смещений и временных изменений состоит в использовании пары спутниковых изображений, сделанных с некоторым интервалом времени.

Две интерферограммы позволяют увидеть любые изменения, которые произошли в поверхности Земли. Дифференциальная интерферометрия позволяет определять на малых масштабах смещение земной поверхности (оползни и предвестники землетрясений), а также отслеживать изменение характеристик радиосигналов из-за смены влажности почвы (проблемы подтопления).

Для получения достоверных результатов необходимо выполнение некоторых условий, таких, как выведение спутника для повторной экспозиции в область космического пространства, близкую к первому снимку; один сезон съемки (хоть и в разные годы) для соблюдения сходного состояния отражающей поверхности (растительный покров, гидрогеологические условия). Эти проблемы в большей мере решаются с помощью специальной программы «Тандем» на базе двух спутников, которые работают по одним и тем же орбитам с временным интервалом пролета ровно 24 часа.

XII. Read and translate the text into Russian, then remake it into the dialogue and reproduce it with your partner.

SAR Differential Interferometry basics and examples

Introduction

'Differential interferometry' is the commonly used term for the production of interferograms from which the topographic contribution has been removed. However, the term may occasionally be misleading, because on the one hand interferometry is a differential technique right from the beginning, and on the other hand, the subtraction process can be pushed further as well as in other directions (e.g. subtraction of an expected geophysical contribution through earthquake or volcano dynamic modelling).

Landers co-seismic deformation

On 18 June 1992, a very large earthquake occurred in the desert northeast of the city of Los Angeles. It was named after the small city of Landers, which is nearby this largely unpopulated area. Its magnitude of 7.3 on the Richter scale made it one of the largest of the century in California. The earthquake was strongly felt in the whole area, including Los Angeles, but it caused few casualties and little damage because of its remote location. To geophysicists, the Landers Earthquake was an excellent opportunity to study the mechanisms of a large earthquake using the most recent geodetic and seismological instrumentation, which had previously been put in the field in the area, making it (along with Japan) one of the most densely instrumented areas in the world.

In a much less publicised way, the radar imaging community was eager to demonstrate the power of radar interferometry applied to displacement mapping. The Landers Earthquake was also an excellent opportunity for radar scientists. It took place after ERS-1 had been placed on its 35-day orbit, which was to be maintained for most of the useful life of the satellite and which guaranteed a regular flow of high quality data. The desert environment raised some hopes that the interferometric comparison of radar images acquired a long time apart could work, since the degradation of the soil during the time elapsed might be minimal, despite some previous pessimistic estimations that predicted a decay in a matter of days. Another positive was the availability of a topographic model of the area, of reasonable accuracy. Such a model would allow removal of the effect of topography in the interferograms, so that just two radar images would suffice to catch the displacements. Finally, that the area was so heavily instrumented and being studied was a great benefit, because other geodetic measurements could at the same time confirm the radar measurement and provide the highest level of ‘geodetic competition’ against interferometry.

The study of the Landers Earthquake actually exceeded all expectations. In the first study two images acquired before the earthquake (24 April 1992) and after it (7 August 1992) combined into a nice interferogram despite the 105 days elapsed. A third image (3 July 1992) was used in combination with the 7 August image. This combination did not include the earthquake. It demonstrated the quality of the topographic model used in conjunction with the first interferogram and produced the error bars.

The result of the study went beyond the mere demonstration of interferometry. It was a big surprise for geophysicists, who did not expect such a revolutionary way of looking at the Earth, but it also sets a new aesthetic standard in the geosciences. The cover of the magazine Nature popularised the ‘fringes’ as a new way to look at ground deformation with coloured, and sometimes shaky, contour lines, each amounting to 3 cm or so of additional deformation.

The interferometric image of Figure 1 provides a striking collision of scales: it shows the central part of the 100 km by 300 km area under study, where displacements are recorded with millimetre accuracy from 800 km away in space. The ratio of the width of the scene and the potential accuracy is 10^8. The ratio of the distance of observation and the maximum amplitude of the displacement in the image is 10^6. One year later, another study demonstrated that the fringes were even more robust than anticipated. The interferogram in Figure 1 was actually part of this second study, and was made from two images separated by 18 months. Landers was also a good test site for demonstrating the method using three radar images, which does not need a topographic model and for testing various mixes of geodetic and seismological data to refine earthquake modelling.

Because it created a large surface rupture, the Landers Earthquake could be modelled rather accurately by elastic modelling based on the rupture parameters, which are easier to determine when they are evidenced by fault shifts that reach the surface. The striking resemblance between the artificial fringes inferred from the geophysical elastic modelling and the actual interferogram was crucial to making people simply believe the result. The Big Bear Earthquake that took place three hours after Landers did not create a surface rupture and was much more difficult to model. On the interferogram, it is the set of six or seven large, circular fringes south of Landers. The same interferogram thus proved both the validity of the method (with Landers) and its unique capabilities (with Big Bear).

Figure 1: The Landers Earthquake of 18 June 1992

Small earthquake modelling

Unlike Landers, the earthquake that struck the northern side of the San Bernardino mountain range had nothing spectacular to draw attention. It had a small magnitude of 5.1 and was located far from populated centres. It took place on 4 December 1992, more than five months after the Landers Earthquake. It was, however, well recorded as a small concentric deformation in the southwest part of the previous illustration, which is considerably zoomed on the left panel of Figure 2.

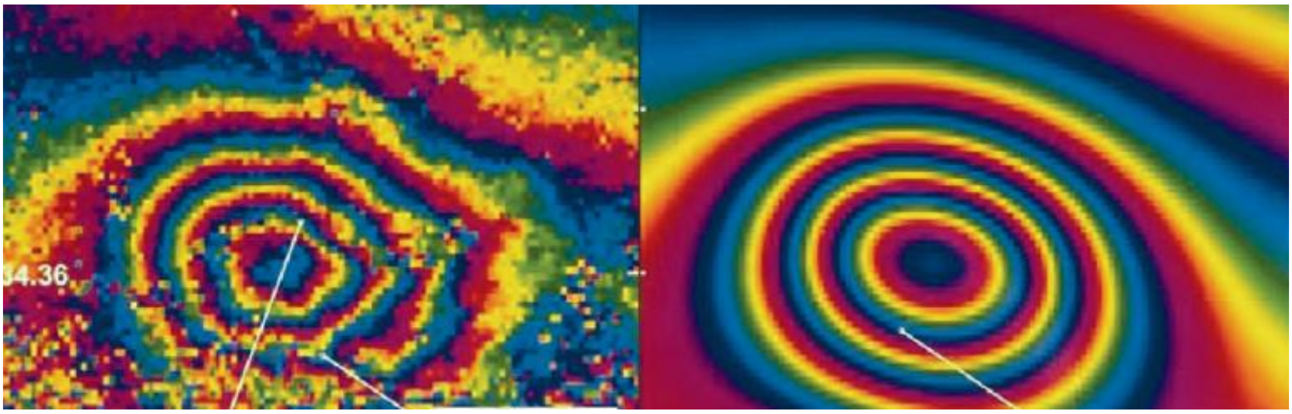


Figure 2: Fawnskin earthquake (left) and its modelling (right)

In interferometry, all the deformations occurring in the time elapsed between the images are stacked together, regardless of their date. The event is therefore superposed on a network of fringes created by the other, more powerful, earthquake in the area. We can see two of the fringes that cross our zoom obliquely. The smaller earthquake created four fringes of its own.

The sign of these fringes, which is somewhat obscured because they are represented by an arbitrary colour table, indicates that the deformation brought the terrain closer to the radar during the second pass.

An anticipated limitation of interferometric geodesy that was expected to be serious before actual experiments took place, is that only the line-of-sight displacement is measured. Therefore, deformations that are basically 3-D are projected on 1-D. This limitation was not such a nuisance in practice because, for most events, geophysicists can recognise the nature of the displacement and propose a likely model. The radar data is then used to find the few free parameters of the model. The model starts from hypotheses of what the fault rupture mechanism at depth might be. This is well illustrated by the specific study of Fawnskin earthquake. Using an approach which has become routine since then, ten parameters are required to characterise a rupture on a single planar patch:

- the position of the lower corner of the patch (3 coordinates)
- the two angles for the orientation of the plane (2 coordinates)
- the size of the ruptured rectangle (2)
- the vector indicating the amount of slip in direction and amplitude (3)

In the case of this study, Kurt Feigl and co-workers found that the patch was 2.9 by 3.1 km with an average 2.6 km depth. To infer this information from the radar data, which deals only with the surface deformation, geophysicists consider the Earth as being made of an elastic material like rubber. The rupture at depth, or 'focal mechanism' as it is called, is then equivalent to a cut in the rubber, followed by a relative displacement of the two lips of the cut. Mechanical equations are then used to convert the at-depth displacement into a 3-D surface displacement, using an assumption about the elastic modulus of the crust material. This displacement is itself converted to a line-of-sight displacement and scaled as fringes. The process lasts until the agreement between the model and the result is satisfactory. The best fit obtained is represented on the right of Figure 2.

Amusingly, when these elastic models were refined during the eighties, some approximations were made. The general feeling was that elastic modelling might have some flaws but that no geodetic method would ever provide measurements with sufficient density to reveal these flaws. This opinion was doubly pessimistic, as radar interferometry provided the required 100 or more measurements per square kilometre, and... proved that this modelling is basically sound and flawless!

The quiet but complicated deformation after an earthquake

The excitement over Landers as an ideal test site did not fade after the initial studies. Crucial questions were still unanswered. Is such a large earthquake preceded by geodetic precursors? What precisely happens to the ground in the months or years following the earthquake? For these studies a wealth of data became available as time went by after the earthquake and as ERS-1 and then ERS-2 continued to gather compatible data over the site.

Unfortunately the amount of radar data before the event remained small, and the first of these questions, perhaps the most important in terms of hazard mitigation, remains unanswered.

During the course of these experiments, significant new facts concerning the interferometric technique were uncovered. In particular, the importance of atmospheric artefacts was suspected and fully characterised mainly on the Landers site. Two studies aimed to model the post-seismic displacement that continued to take place on the site after the earthquake. Different mechanisms of post-seismic fault slip were proposed. Radar interferometry is all the more important in this activity since most of these displacements were aseismic, and therefore went unnoticed by conventional seismological records. The scale on the post-seismic interferogram, Figure 3, speaks for itself. It is clear that, to catch the smallest structures of displacement with ground instrumentation such as GPS receivers, it would be necessary to literally cover the ground with instruments.

Such a density is not realistic. On adequate surfaces, such as those that can be found in Iceland, the western United States, Chile and many more places, having a radar archive suffices for study of any upcoming event in the most remote regions. In this regard, an archive such as the global coverage of the land surface gathered by ERS-1 and ERS-2 is a genuine 'memory of the Earth' that can be compared with new acquisitions taking place years later, possibly by another satellite. In a sense, radar interferometry can turn every pebble into a GPS receiver.

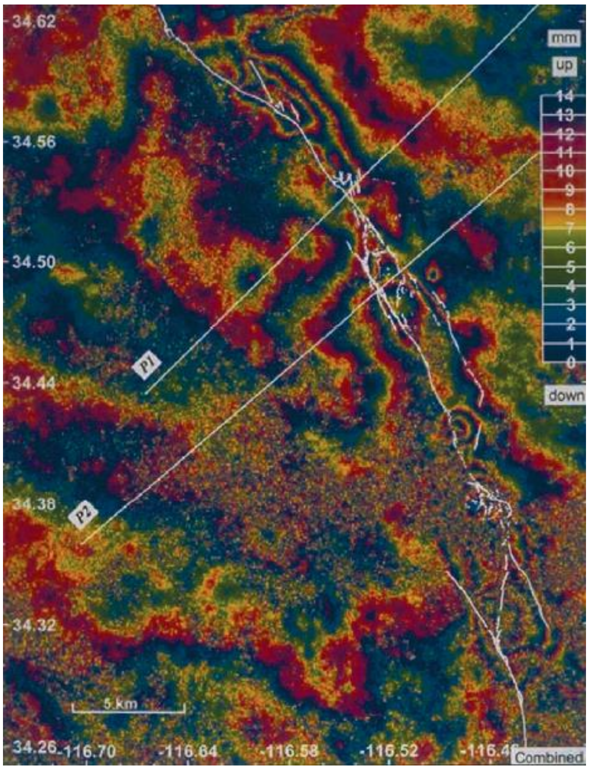


Figure 3: Illustration of post-seismic displacement

A case of coherence loss

One of the drawbacks of the academic way of communicating is that failures are never published. One of these failures are described here.

After the disastrous earthquake of Latur, in India, ESA made some ERS-1 images available.

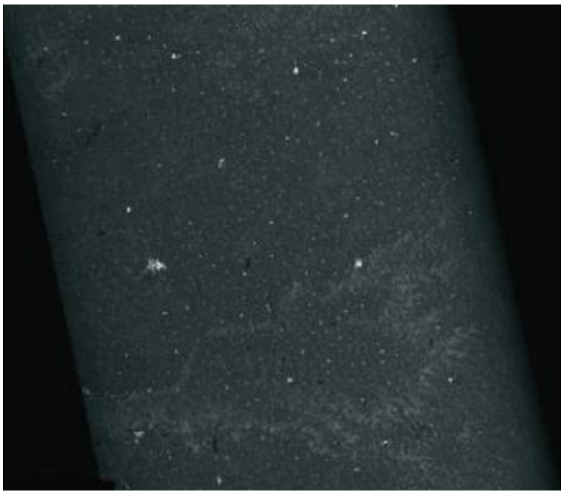


Figure 4a shows the typical landscape: a mostly agricultural landscape with many small cities and villages scattered from place to place. Some mild topography is detectable in the south of this amplitude image.

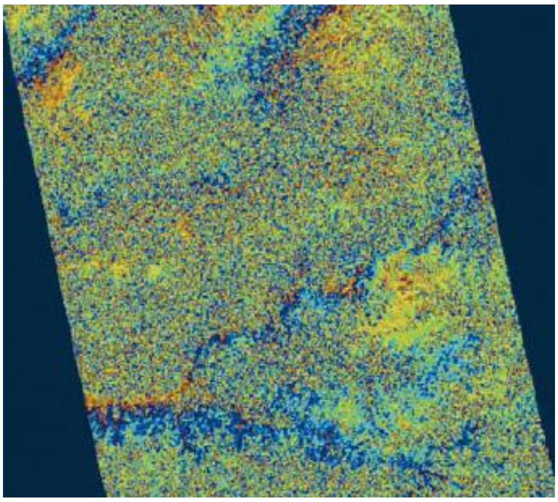


Figure 4b shows a co-seismic interferogram created from ERS-1 orbits 8409 and 11916, i.e. between 23 February 1993 and 26 October 1993. The quality of the interferogram, which includes a negligible topographic component because of a very small orbital separation, does not allow a clear recognition of any ground displacement. The task is further aggravated because no reliable modelling of the expected displacement exists.

Unfortunately, the images show a mostly incoherent result. The area is used mainly for agriculture and located in a monsoon region with heavy rainfalls.

Surprisingly, the only areas that retained coherence are the cities and villages, despite the large-scale destruction they experienced. This is not a unique case; often cities heavily damaged by earthquake remain quite coherent. This might be an indication that the main contributors in the radar signal of a city are not much damaged by earthquakes. In any case, one should not restrict interferometric studies of damaged cities for this reason.

A case of damaged raw data, studying a large earthquake in Chile

Very large events emphasise the usefulness of the wide-area surveying that is possible with radar interferometry. Sometimes, however, the deformation field is so wide that even the wide 100 km swath of ERS cannot catch it entirely. A large earthquake took place in Chile in July 1995, and was studied, among others, by the IPGP (Figure 5).

This example illustrates an unusual error in data management. The large earthquake that struck the Atacama region in Chile on 30 July 1995 was an opportunity for interferometry very similar to the Landers example: a large earthquake in a mostly desert environment. Figure 5 shows the typical behaviour of an interferometric signal (left is amplitude, right is co-seismic phase). The area covered by ocean, around the Mejillones peninsula, is not coherent. The rest of the landscape is exceptionally coherent (except for the interruption of fringe continuity which is explained below). This example illustrates how very big events can actually outspan the size of ERS images, in spite of their being the widest radar images available in standard mode (i.e. not SCANSAR).

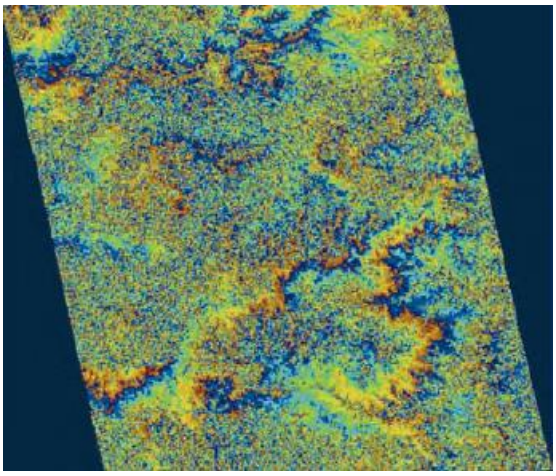


Figure 4c shows another interferogram created from orbits 8409 and 5403, i.e. between 23 February 1993 and 28 July 1992. The quality of the interferogram is similar to the previous one, and includes a topographic signature especially visible in
the south of the image.

Another striking aspect of this example is the very smooth deformation pattern, without any visible surface rupture (again discounting the processing artefacts mentioned above). The data from this site that were processed, analysed in cooperation with the IPG of Paris, were generally made of strips of four or five ERS images in length.

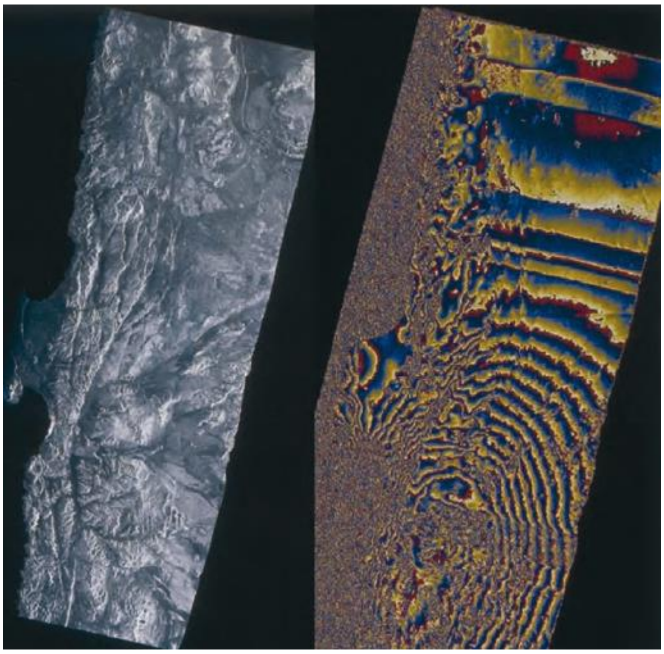


Figure 5: Large deformation field with errors: Chile earthquake

The interruption in the fringe continuity is due to missing lines in the raw data. The interferometric technique relies heavily on the strong self-consistency of the geometry of radar images. Missing lines can break this consistency. There are ways, however, to detect missing lines in raw data. Denoting the complex samples of a data take as A(i,j), where i represents the range pixels (from 1 to N) and j represents the pulse lines, we can form the complex number:

$$\rho(j) = \frac{\sum_{i=1}^{i=N} A(i,j)A(i,j+1)}{\sqrt{\sum_{i=1}^{i=N} A^2(i,j)}\sqrt{\sum_{i=1}^{i=N} A^2(i,j+1)}}$$

This quantity is similar to the one formed on interferograms to compute the coherence. Here the result is a complex number. The phase $\varphi(\rho(j))$ of this complex number is an estimator for the mean Doppler of the scene *D*, once it has been multiplied by the pulse repetition frequency PRF:

$$D(j) = \frac{f(\rho(j))}{2\pi} \cdot PRF$$

The amplitude of ρ (j) is also very interesting because it gives the correlation between adjacent lines of raw data. For ERS, this amplitude should be about 0.3, and if two lines exhibit a lower value (for instance 0.1 or less), it means that the two lines of raw data are not really adjacent, and so there must be at least one missing line between them!

The test is really easy to implement and can be used to check the raw data. Unfortunately, it cannot tell whether there is one or several missing lines between two lines which are found to be not adjacent.

XIII. Put a proper preposition if necessary.

1. This can be done either simultaneously (with two radars mounted on the same platform) or … different times.
2. The distance between the two satellites (or orbits) … the plane perpendicular … the orbit is called the interferometer baseline.
3. The interferogram amplitude is the amplitude … the first image multiplied … that of the second one.
4. The interferometric phase … each SAR image pixel would depend only … the difference in the travel paths from each of the two SARs … the considered resolution cell.
5. A phase variation is proportional … the altitude difference q between the point targets.
6. The perpendicular baseline is known … precise orbital data, and the second phase term can be computed and subtracted … the interferometric phase.
7. An interferogram … a portion of the Italian Alps and the Pianura Padana is shown … the left.
8. Once the interferometric phases are unwrapped, an elevation map … SAR coordinates is obtained.
9. In such cases the following additive phase term, independent … the baseline, appears … the interferometric phase.
10. When two interferometric SAR images are not simultaneous, the radiation travel path … each can be affected differently … the atmosphere.
11. These main contributions … the phase noise should be taken … consideration.
12. Low spatial frequencies of the DEM error cannot be predicted … the coherence map since the coherence estimation is carried out … small windows.

XIV. Put the words from the brackets in the right order.

1. ‘Differential interferometry’ is the commonly used term for the production (*the, from which, topographic, has been, interferograms, contribution, of, removed*).

2. To geophysicists, the Landers Earthquake was (*mechanisms, an, excellent, using, to study, opportunity, the, earthquake, a large, of*) the most recent geodetic and seismological instrumentation.
3. The Landers Earthquake (*an, scientists, also, was, for radar, excellent, opportunity*).
4. This (*include, did, earthquake, combination, the, not*).
5. The (*the, of, of, potential, width, the, the, and, scene, ratio*) accuracy is 10^8.
6. The Big Bear Earthquake that (*place, not, create, three, after, hours, Landers, took, did*) a surface rupture and was much more difficult to model.
7. We can (*fringes, the, two, of, cross, that, see, zoom, our*) obliquely.
8. The radar data (*free, is, find, used, the, parameters, to, few, then*) of the model.
9. The process lasts (*model, result, the, agreement, between, until, the, the, is, and*) satisfactory.
10. The (*on, scale, for, itself, speaks, interferogram, post-seismic, the*).

XV. Choose the correct form from the two, given in the brackets.

1. From this example it can (*be seen, see, seen*) that the sensitivity of SAR interferometry to terrain motion is much larger than that to the altitude difference.
2. The effect of such a contribution (*was impacted, impacts, impacting*) on both altitude and terrain deformation measurements.
3. A 2.8 cm motion component in the slant range direction would (*to generate, generated, generating, generate*) a 2π interferometric phase variation.
4. This is the first step towards getting a DEM. The SAR elevation map should then be (*referring, referred, refer*) to a conventional ellipsoid.
5. The critical baseline (*depends, depending, depend*) on the dimension of the ground range resolution cell, on the radar frequency, and on the sensor-target distance.

XVI. Use the given in the electronic version of Appendix 3 Presentation to make a report.

XVII. Dialogue of the Unit. Learn the dialogue in roles, then change them and learn it again.

P.: Dear friends, I am sorry for being late. The traffic is very busy in the mornings. So, what wasyour task for today?

A.: We are to discuss Wide Swath Interferometry.

P.: Aha, Wide Swath Interferometry, it must be an interesting discussion. Are there any volunteers? Bill is ready to break the ice.

B.: For previously flown SAR systems, the width of the swath has been limited to somewhat less than 100 km. As we discussed last week, SAR antennas must satisfy particular minimum area criteria to ensure noise due to ambiguities below a required level. For wide swath, they must also be quite long, which can be difficult and costly to implement. For example, to achieve a 300 km swath in typical Earth orbits using the typical strip mapping method, the antenna would have to be over 40m in length. To achieve wide swaths with an antenna sized for a swath smaller than 100 km, the ScanSAR technique has been developed.

P.: And what does this technique require?

L.: ScanSAR requires an antenna with rapid electronic steering capability in the elevation direction. In ScanSAR, the antenna is electronically steered to a particular elevation angle and radar pulses are transmitted and echoes received for a time period that is a fraction (say one-tenth) of the synthetic aperture time. After that ‘dwell period,’ also known as the ‘burst period,’ the antenna is electronically steered to another elevation angle (and other radar parameters such as the PRF, bandwidth, and antenna beam shape are changed), and observations are made for another short dwell period. This process is repeated until each of the elevation directions, needed to observe the entire wide swath is obtained at which point the entire cycle of elevation dwell periods is repeated.

P.: Anything else?

A.: For any given elevation direction, or subswath, there are large gaps in the receive echo timeline, yet after processing the data, a continuous strip mode image can be formed.

P.: This is true because the extent of the antenna beam in the along-track direction on the ground is equal to the synthetic aperture length. As long as the dwell periods for any given subswath occur more than once in the synthetic aperture time, there is guaranteed continuous coverage of all points on the ground.

A.: It is important to understand this method of generating radar data because it has strong implications for the quality of the geodetic data that are derived, and for the constraints that are imposed on the use of the data. First we note that the data contained in any given pulse include the full Doppler spectrum of information. We are transmitting over a broad range of angles (the beam width) and that defines the Doppler frequency content.

P.: So each burst of pulses contains the full Doppler spectrum of information, does not it? Bill.

B.: If one were to derive the spectrum in the along-track dimension, the full Doppler bandwidth would be represented. However, we should note that any given scattering element within a burst period only contributes a portion of its full Doppler history because it is not observed over the full synthetic aperture time. Thus each scattering element is only resolved commensurate with the burst period relative to the synthetic aperture time: if the resolution in strip mode is $L/2$, then, the resolution in ScanSAR mode is $(L/2) \cdot T_a/T_b$, where T_a is the synthetic aperture time, and T_b is the burst duration. If one were to attempt to achieve maximal resolution possible, one would divide the synthetic aperture time by the number of subswaths needed, and set the burst duration to this time.

L.: However, it is generally better to create several short bursts within one synthetic aperture. This degrades resolution further, but improves the radiometric characteristics of the data. For interferometry, the most important aspect of ScanSAR is the fact that each scattering element provides in a burst only a small portion of its total Doppler history.

A.: This is equivalent to the statement that each scattering element is observed over a small range of azimuth angles within the beam. In order for interferometry to work, a scattering element must be observed with the same range of Doppler frequencies from one pass to the other. Only then will the images be coherent, with similar speckle patterns.

P.: This implies that from pass to pass, each observation must observe from the same group of angles. What will you say to that?

B.: In the case of strip mode SAR, this implies that the intrinsic pointing of the antenna beam be the same from pass to pass. In this case, the Doppler history of each scattering element will follow the same course. For ScanSAR, this condition also implies a timing constraint on the bursts.

L.: I can also add that each burst must occur at the same location in space relative to a scattering element from pass to pass. This constraint makes it much more challenging for mission operators, particularly with short bursts.

A.: For a satellite in a long repeat period orbit, for example 32 days, the ground swath will be sized to achieve global coverage, around 85 km for the 32-day repeat period orbit. So from an interferometric point of view, using ScanSAR with this period does not improve on the interferometric interval intrinsically.

P.: However, ScanSAR will increase the number of times a given scattering element will be observed by a factor of the number of ScanSAR beams. For a four-beam ScanSAR with 340 km swath in a 32-day repeat orbit, a scattering element will be observed roughly every 8 days, so one could make interleaved 32-day repeat interferograms.

A.: Alternatively, one could place the radar in a shorter repeat period orbit, for example 8 days, and observe always in ScanSAR mode with four beams. This would allow 8-day interferograms with no interleaving.

L.: And the advantage of the latter is that decorrelation will be less of an issue in the basic repeat-pass measurement. The advantage of the former is that there will be greater angular diversity in the measurement, potentially resulting in better constrained models of deformation.

P.: Our lesson has come to its end. See you next time at the exam. Be prepared and good luck.

Stop & check

Word dictations, Tests, and Dialogues

Unit 1

I. Words and phrases.

a. Translate the following words and phrases into Russian

I	II	III
screen	accurate	interferometer
measuring	observation	quality control
interaction	machine-building	alter
beam	velocity	constraint
establish	acquisition	incoherent
homogeneous	inhomogeneity	prevent
arbitrary	laterally	propagation
vapour	resolvable	insensitive
fringe	baseline	absorption
sub-pixel	sparse	subsidence

b. Translate the following words and phrases into English

I	II	III
отделять	распространение	неоднозначность высоты
наблюдение	произвольный	пар
случайный	передавать	разрешимый
оценка качества	поверхность	предотвращать
подпиксельный	отделять	ложный сигнал
угол падения	слабое покрытие	оползень
латерально (в стороне от)	почва	скорость
окружающее освещение	исходящая волна	изменение фазы
разность фаз	редкий	снимок
суммированный вклад	остаточная фаза	смежные пиксели

II. Choose proper phrases to complete the sentence.

1. Interferograms ____________ to produce digital elevation maps (DEMs) using __________ caused ____________ differences in _____________between the two images.

   a. can be used **b.** by slight **c.** the stereoscopic effect **d.** observation position **e.** short baseline

2. InSAR can be used in a variety of volcanic _________, including deformation associated with _________, inter-eruption strain caused by changes in ___________ at

depth, gravitational spreading of volcanic edifices, and volcano-tectonic deformation __________.

a. eruptions **b.** effects **c.** settings **d.** magma distribution **e.** signals

3. If the wave travelled through _________ it should theoretically be possible (subject to sufficient accuracy of timing) to use the two-way _________ of the wave in combination with to calculate _________distance to the ground.

a. travel-time **b.** a vacuum **c.** reflective **d.** the phase **e.** the exact

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Unit 2

I. Words and phrases.

a. Translate the following words and phrases into Russian

I	II	III
operational capability	a number of smth	dedicate to
accurate measurements	mode of operation	enhance
operational control	primary objectives	facilitate
to be in orbit	factors affecting smth	ground range
in combination with	due to the curvature of smth	inclination
look angle	incidence angle	mitigate
to be acceptable for	to be associated with	overlap
ascending orbit	resolution cell dimension	payload
descending orbit	acceptable	point out
to be foreshortened	accuracy	slant-range

b. Translate the following words and phrases into English

I	II	III
эксплуатационные качества	точные измерения	управление полётами
находиться на орбите	в сочетании с	угол обзора
быть приемлемым для	восходящая орбита	нисходящая орбита
факторы вносящие вклад в	рабочий режим	главные цели
угол падения	ассоциироваться с	разрешение размера ячейки
точность	высота	азимутальное направление
усиливать, улучшать	проникающий сквозь облака	посвящать
стереопара	линия прямой видимости	горизонтальная дальность
запускать	разрешающая способность	околополярный
полезная нагрузка	точные измерения	двухмерный массив

II. Exercise XVI.

A.: Hello Professor! I heard that ERS-2 differs from ERS-1. It has much better resolution. It is possible to distinguish all the houses in SAR images.

P.: I can’t agree with you. ERS-2 is identical to ERS-1. It has the same resolution but there are some extra instruments not influencing the SAR images.

A.: So what ERS-2 was launched for?

P.: It was launched to get a greater interferogram coherence, because ERS-2 was linked to ERS-1. It was a so called “tandem” mission.
A.: Do you remember what orbit ERS operates in?
P.: ERS operates in the near-polar orbit.
A.: How does this orbit influence the acquisition geometry?
P.: It influences the final DEM. It strongly depends on the local terrain slope. We should combine DEM’s obtained from ascending and descending orbits.
A.: And what can you say about foreshortening in the hilly terrain for these two orbits. Which one is more preferable?
P.: If a slope is mainly oriented to the west, a descending orbit should be used. If not, then an ascending orbit should be taken into consideration.
A.: I heard these satellites finished their mission. Is it true?
P.: Yes. It’s true. ERS-1 finished its operations in 2000 and ERS-2 stopped its mission in 2011.
A.: What do you know about Envisat?
P.: Envisat is the largest Earth Observation spacecraft. It has better resolution and other parameters.
A.: How many instruments does it carry?
P.: There are 9 instruments collecting information about land, water, ice and the atmosphere using various methods of measurements.
A.: Ok. That is all I wanted to know. Thank you a lot.
P.: I am glad I could help you. Have a nice day.
A.: Good bye, professor.

Unit 3

I. Words and phrases.

a. Translate the following words and phrases into Russian

I	II	III
slightly different	cross-multiplying	dominant point scatterer
adjacent discontinuities	temporal change	take into consideration
ambiguous	draw attention	cancel out
complex conjugate	confine	contour line
eliminate	flatten	phase unwrapping
pre-processing step	reference plane	far apart
phase discontinuity	simultaneously	relative position
hypothesize	multiple	slant range
speckle	split into	wavelength
inversely proportional	spectral shift	cross-correlation coefficient

b. Translate the following words and phrases into English

I	II	III
поперечное перемножение	взаимно уничтожаться	смежные неоднородности
усреднённый	принимать во внимание	черно-белый переход
ограничивать	соединенный, связанный	комплексно-сопряжённый
общая полоса частот	слегка отличающийся	горизонталь
рассматривать	общепринятый эллипсоид	двусмысленный
искажать	обращать внимание	коэф. взаимной корреляции
устранять, исключать	результат, последствие	сглаживать; выравнивать

обратно пропорциональный	кратный	длина волны
развёртывание фазы	элемент разрешения РЛС	одновременно, синхронно
спектральный сдвиг	скачок фазы	разбивать на

Vocabulary

Vocabulary of the course

absorption (n) – поглощение
acceptable (adj) – приемлемый, допустимый
accuracy (n) – точность
accurate (adj) – точный
acquisition (n) – сбор (данных)
advantage (n) – преимущество
aforementioned (adj) – вышеупомянутый
aliasing (n) – наложение спектров
alter (v) – изменять, менять
altitude (n) – высота
altitude of ambiguity – неопределенность высот
ambient illumination – окружающее освещение, внешняя засветка
ambiguous (adj) – двусмысленный
amplify (v) – расширять, увеличивать
antenna footprint – контур диаграммы направленности антенны
anticipate (v) – ожидать
apart from (adv) – помимо, за исключением
apply (v) – применять
aquifer (n) – водоносный слой
arbitrary (adj) – произвольный
arbitrary (adj) – произвольный, случайный
arrangement (n) – классификация, систематизация
aseismic (adj) – не поддающийся разрушениям
assume (v) – принимать, допускать
augment (v) – дополнять, усиливать
availability (n) – доступность
averaged (adj) – усреднённый
avoid (v) – избегать, уклоняться
azimuth direction (n) – азимутальное направление
backscattered (adj) – рассеянный в обратном направлении
bandwidth (n) – ширина полосы (зоны)
baseline (n) – базис
beam (n) – луч
black/white transition (n) – черно-белый переход
cancel out (v) – уравновешивать, взаимно уничтожаться
casualty (n) – человек, пострадавший от несчастного случая
C-band (n) – диапазон частот, выделенный для частной и служебной связи
circular (adj) – круглый, округлый
cloud-penetrating (adj) – проникающий сквозь облака
collapse (n, v) – обрушение, рушиться
commensurate (adj) – соизмеримый, соразмерный
common band (n) – общая полоса частот
complex conjugate (adj) – комплексно-сопряжённый
comprehensive (adj) – всесторонний, полный
comprise (v) – содержать, заключать в себе
confine (v) – ограничивать
conjugate (adj) – соединенный, связанный

conjunction (n) – связывание, сцепление, соединение
consecutive (adj) – последовательный
consequence (n) – результат, последствие
consider (v) – рассматривать
constraint (n) – ограничение
contour line (n) – контурная линия; горизонталь
contribution (n) – вклад
conventional ellipsoid (n) – общепринятый эллипсоид
conversely (adv) – обратно, наоборот
corrupt (v) – искажать
creep (v) – медленно двигаться, красться,
cross-correlation coefficient (n) – коэффициент взаимной корреляции
cross-multiplication (n) – перемножение
crust (n) – кора (земная)
curvature (n) – выгиб, изгиб, искривление, кривизна
dedicate to (v) – посвящать
degrade (v) – ухудшать
densely (adv) – густо, плотно
drawback (n) – помеха, препятствие
dub (v) – дублировать
duration (n) – длительность, продолжительность
dwell period (n) – время (выполнения ч.-л.)
eager (adj) – страстно желающий
edifice (n) – сооружение, строение
efficiently (adv) – эффективно
elapsed (p.p.) – пройденное (время)
elevation angle (n) – угол возвышения
eliminate (v) – устранять, исключать
embed (v) – внедрять, вставлять
embrace (v) – воспользоваться
enhance (v) – усиливать, улучшать
ensure (v) – обезопасить себя от
environment (n) – окружающая среда
equator (n) – экватор
ERS – European Resource Sensor
eruption (n) – извержение
essentially (adv) – 1) по существу; по существу дела 2) существенно, существенным образом
establish (v) – устанавливать
ever-growing (adj) – неуклонно растущий
exceed (v) – превышать, выходить за пределы
expand (v) – распространять
exploit (v) – пользоваться, использовать
exquisitely (adv) – совершенно
extract (v) – извлекать
facilitate (v) – способствовать
far apart – на большом расстоянии друг от друга
flatten (v) – сглаживать; выравнивать
flaw (n) – брак, порок
flood (n) – наводнение
flood plain – пойма, заливной луг
fraction (n) – доля, порция, часть
fringe (n) – цветовая линия, полоса
gap (n) – брешь
generation (n) – генерирование, создание
govern (v) – определять, обуславливать
ground range (n) – горизонтальная дальность
ground subsidence (n) – оседание поверхности земли
gyro failure – ошибка гироскопа
hazard (n) – риск, опасность
hence (adv) – поэтому, следовательно
herald (v) – извещать, уведомлять
homogeneous (adj) – однородный
hypothesize (v) – строить гипотезу
ice flow (n) – поток плавучего льда
image pair (n) – стереопара
immobile (adj) – недвижимый; неподвижный, стабильный, стационарный
implementation (n) – осуществление, реализация
implications (n, pl)– последствия ненадёжности
impose (v) – налагать (обязательства)

improvement (n) – улучшение
in essence (adv) – в сущности
in situ – на месте проведения работ
inclination (n) – наклон
incoherent (adj) – несогласованный
induce (v) – вызывать, приводить к ч.-л.
infer (v) – делать, заключение, выводить
inhomogeneity (n) – неоднородность
initially – в начале
insensitive (adj) – нечувствительный
insight (into) (n) – представление (о чем-либо)
integer (adj) – целый
interact (v) – взаимодействовать
interaction (n) – взаимодействие
interferometer (n) – интерферометр
interferometric synthetic aperture radar (InSAR, IfSAR) – интерферометрический радар с синтезированной апертурой.
interleaved (adj) – перемежающийся
intrinsic (adj) – присущий, свойственный
intrinsically (adv) – в действительности
inversely proportional (adj) – обратно пропорциональный
isolate (v) – отделять
landslide (n) – оползень
laterally (adv) – латерально (в стороне от)
launch (v) – запускать (в космос)
L-band (n) – диапазон сверхвысоких частот (от 300 до 1550 мегагерц)
line of sight (LOS) – линия прямой видимости
machine-building (n) – машиностроение
machine-tool building (n) – станкостроение
maintain (v) – поддерживать (в состоянии)
manageable (adj) – поддающийся управлению
matched-filter (n) – согласованный фильтр
measuring (adj) – измерительный
mention in passing – упомянывать вскользь
microwave (adj) – микроволновый
mining (n) – горное дело; горная промышленность
misleading (adj) – вводящий в заблуждение
mitigate (v) – уменьшать, смягчать
monsoon (n) – муссон
mosaic (n) – мозаика
multimode (adj) – многорежимный
multiple (adj) – кратный, неоднократный, повторяющийся
multiple (n) – кратное число
narrow (adj) – узкий
near-polar (adj) – околополярный
nemesis (n) – беда, возмездие
obliquely (adv) – наискось
observation (n) – наблюдение
occur (v) – происходить, случаться
ongoing (adj) – непрерывный, постоянный
optical (adj) – оптический
overlap (v) – перекрывать
path (n) – путь
payload (n) – полезная нагрузка
permanent (adj) – постоянный, неизменный; долговременный;
persistent (adj) – длительный, продолжительный
phase (v) – поэтапно осуществлять (что-л.)
phase discontinuity (n) – скачок фазы
phase unwrapping (n) – развёртывание фазы
plane (n) – плоскость
plethora (n) – изобилие, избыток
point out (v) – отмечать
predict (v) – предсказывать, прогнозировать
preliminary (adj) – предварительный
pre-processing step (n) – этап предварительной обработки
prevent (v) – предотвращать
primarily (adv) – первоначально
prior (adj) – прежний, бывший; предшествующий
propagation (n) – распространение
quality control (n) – оценка качества
quantification (n) – подсчёт
quasi-polar (adj) – околополярный

radar(-resolution) cell (n) – элемент разрешения РЛС
random (adj) – случайный
rapid (adj) – быстрый, скоротечный
reference plane (n) – базовая плоскость; опорная плоскость; плоскость отсчёта
regardless of – невзирая на
relative position (n) – взаимное положение, относительное положение, взаимное расположение
reliable (adj) – надежный, достоверный
residual (adj) – остаточный
resolution (n) – разрешающая способность
resolvable (adj) – разрешимый
resolve (v) – разделять, разлагать (на составные части)
retain (v) – держать, удерживать
revisit time (n) – период повторной съемки
rift (n) – трещина; расселина; разлом; щель; разрыв
rifting (n) – раскалывание, рифтообразовывание
rupture (n) – разрыв
salient (adj) – бросающийся в глаза
sampling (of) (n) – образец, выборка
scarp (n) – откос, уступ
scatterer (n) – рассеиватель, отражатель
screen (n) – экран
sensitivity (n) – чувствительность
set of (n) – набор чего-либо
simultaneously (adv) – одновременно, синхронно
slant range(n) – наклонная дальность
slope (n) – уклон, наклон
snapshot (n) – снимок
soil (n) – грунт, почва
sophisticate (v) – усложнять; лишать простоты;
sparse (adj) – редкий
speckle (v) – спекл (дифракционное пятно изображения)
spectral shift (n) – спектральный сдвиг
spectrum (n) – спектр
split into (v) – разбивать на
spread (v) – распространяться (по) поверхности
spurious signal – ложный сигнал
steeply (adv) – круто
steerage (n) – управление
strain (n) – деформация
stream (n) – поток
striking (adj) – поразительный, изумительный
stringent (adj) – строгий, точный
strip (n) – полоса
strip-map (n) – карта маршрута
sub-pixel (adj) – подпиксельный
subsidence (n) – понижение
substantially (adv) – по существу, в основном
subtract (v) – вычитать
suffice (v) – удовлетворять
suite (of) (n) – комплект, набор (чего-либо)
sun-synchronous orbit – орбита солнечно-синхронного спутника
surface (n) – поверхность
surge (n) – большая волна
swath (n) – полоса обзора
terrain (n) – местность, территория
throughout – на всем протяжении
time-lapse (n) – промежуток времени
toward (prep) – к, по направлению к
transmit (v) – передавать
two-dimensional array (n) – двухмерный массив
unambiguously (adv) – однозначно
unwrapped (p.p) – развернутый
uplift (n) – подъем
validation (n) – проверка достоверности
vapour (n) – пар
variability (n) – изменчивость
velocity (n) – скорость
viable (adj) – жизнеспособный
wavelength (n) – длина волны
X-band (n) – (частотный) диапазон X (от 5,2 до 11 ГГц)

Appendix 1

Основные арифметические выражения, формулы, уравнения и правила их чтения на английском языке.

( )	round brackets; parentheses
{ }	curly brackets; braces
[ ]	square brackets; brackets
$a = b$	*a* equals *b;* or *a* is equal to *b*
$a \neq b$	*a* is not equal to *b*
$a > b$	*a* is greater than *b*
$a_2 > a_d$	*a second* is greater than *a dth*
$b < a$	*b* is less than *a*
$a >> b$	*a* is substantially greater than *b*
$a \geq b$	*a* is greater than or equal to *b*
$x \to \infty$	*x* trends to infinity
x'', x'''	*x* double prime, triple prime
ln *x*, log *x*	logarithm **of** *x*
µ	is proportional to
x^2, x^3	*x* squared, *x* cube
x^n	*x* **to the** power *n*
x_o	*x* nought
x_i	*x i*th, *x* sub *i*
$1/x$	one over *x*
x'	*x* prime
$f(x)$	*f* **of** *x*
$\lim_{(x \to 0)} f(x)$	the limit of *f* of *x* as *x* approaches 0
dy/dx	*dy* by *dx (derivative)*
sin *x*	sine of *x*
cos *x*	cosine of *x*
tan *x* (tg *x*)	tangent of *x* (сокращение - tan *x*)
cot *x* (ctg *x*)	cotangent of *x* (сокращение - cot *x*)

9.510	nine thousand five hundred and ten
32 + 8 = 40	thirty-two plus eight is (are) forty; or, thirty-two plus eight equals forty; or, thirty-two plus eight is equal to forty; or, eight added to thirty-two makes forty
20 - 5 = 15	twenty minus five is fifteen; or, twenty minus five is equal to (equals) fifteen; or, twenty minus five leaves fifteen; or, five from twenty is (leaves) fifteen
$a \pm b$	*a* plus or minus *b*
1 × 1 = 1	once one is one
2 × 2 = 4	twice two is (equals) four; or, twice two makes four
6 × 10 = 60	six multiplied by ten equals sixty; or, six multiplied by ten is (equal to) sixty; or, six times ten is sixty
work = force × distance	work is (equal' to) the product of the force multiplied by the distance; or, work is (equal to) the product of force times the distance
12 : 3 = 4	twelve divided by three equals (is) four
$\frac{1}{2}$	a (one) half
$\frac{1}{3}$	a (one) third
$\frac{2}{3}$	two-thirds
$\frac{5}{9}$	five-ninths
$4\frac{1}{2}$	four and a half
$8\frac{3}{4}$	eight and three-quarters
0.6 or .6	point six
5.34	five point thirty-four; or, five point three four
2.01	two point nought one; or two point o [ou] one
0.007	point nought nought seven; or, point two oes [ouz] seven

8 : 4 = 2	the ratio of eight to four is two.
$\frac{20}{5}=\frac{16}{4}$	the ratio of twenty to five equals (is equal to) the ratio of sixteen to four; or, twenty is to five as sixteen is to four
20°	twenty degrees
π	pi (пай)
6´	six minutes; also, six feet
10´´	ten seconds; also, ten inches
a´	*a* prime
a´´	*a* second prime; or *a* double prime; or *a* twice dashed
a´´´	*a* triple prime
9^2	nine square, or, the square of nine or, nine to the second power
6^3	six cubed; or, six to the third (power)
c^{18}	*c* [si:] to the eighteenth (power)
$3 \cdot 10^{15}$	three by ten to the fifteen
a^{-10}	*a* [ei] to the minus tenth (power)
$\sqrt{4}=2$	the square root (out) of four is (equals) two
$\sqrt{a}$	the square root of *a*
$\sqrt[3]{a}$	the cube root of *a*
$\sqrt[5]{a^2}$	the fifth root of *a* square
$(a+b)^2$	*a* plus *b* all squared
$L=\sqrt{R^2+x^2}$	*L* equals the square root (out) of *R* square plus *x* square
$\frac{x+\sqrt{x^2-y^2}}{y}$	*x* plus square root of *x* square minus *y* square all over *y*
$\sqrt[10]{a^2+b^2}$	the tenth root (out) of *a* square plus *b* square
$\sqrt{\frac{F_1+A}{2xd''}}$	square root out of *F* first plus *A* divided by two *xd th* twice dashed (or double prime)
$a^{\frac{m}{n}}=\sqrt[n]{a^m}$	a to the *m/n th* power equals the n^{th} root out of a to the m^{th} (power)

$\frac{dz}{dx}$	*dz* over *dx*
$y = f(x)$	*y* is a function of *x*
$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} = 0$	partial *d* two *z* over partial *dx* plus partial *d* two *z* over partial *dy* equals zero
$\int \frac{dx}{\sqrt{a^2 - x^2}}$	indefinite integral of *dx* (divided) by the square root out of a^2 minus x^2
$\int_0^\mu$	integral from *zero* to *μ (mu)*
$\frac{d}{dx}\int_{x_0}^{x} X dx$	*d* (divided) by *dx* (or *d* over *dx*) of the integral from *x nought* to *x* of *X* large *dx*
$4c + W_2 + 2m_1 a' + R_a = 33\frac{1}{3}$	*4c* plus *W second* plus *2 m first a prime* plus *R* a^{th} equals thirty-three and one-third
$V = u\sqrt{\sin^2 i - \cos^2 i} = u$	*V* equals *u* square root of sine square *i* minus cosine square *i* equals *u*
$\tan r = \frac{\tan i}{l}$	tangent *r* equals tangent *i* divided by *l*
$\log 2 = 0.301$	the logarithm of two equals zero point three o[ou] one
$a = \log_c d$	*a* is equal to the logarithm of *d* to the base *c*
$u = \int f_1(x)dx + \int f_2(y)dy$	*u* is equal to the integral of *f* sub one of *x* multiplied by *dx* plus the integral of *f* sub two of *y* multiplied by *dy*
$K = \max_j \sum_{i=1}^{n} \lvert a_{ij}(t) \rvert, (t \in [a,b]; j = 1,2 \dots n)$	*K* is equal to the maximum over *j* of the sum from *i* equals *one* to *i* equals *n* of the modulus of a_{ij} of *t* , where *t* lies in the closed interval *ab* and where *j* runs from *one* to *n*
$A_{v_{max}} = \frac{1}{2} \cdot \frac{\mu}{r_p} \frac{\omega L_2 \omega L_1}{\sqrt{R_2\left(R_1 + \frac{\omega^2 L_1^2}{r_p}\right)}}$	A_{Vmax} is equal to one half *mu* by r *pth* omega L second omega L first (divided) by square root out of R second round brackets opened R first plus omega square L first square by r *pth* round brackets closed
$A_v = \frac{\mu\omega m \omega^2 L^2}{r_p\left[\omega^2 m^2 + R_2\left(R_1 + \frac{\omega^2 L^2}{r_p}\right)\right]}$	*Av* is equal to *mu omega m omega* square *L* square (divided) by r *pth* square brackets opened *omega* square *m* square plus *R* second round brackets opened *R* first plus *omega* square *L* square (divided) by r *pth* round and square brackets closed

Appendix 2

Произношение греческого алфавита в английской транскрипции

Capital	**Low-case**	**Greek Name**
Α	α	Alpha [ˈælfə]
Β	β	Beta [ˈbi:tə]
Γ	γ	Gamma [ˈgæmə]
Δ	δ	Delta [ˈdeltə]
Ε	ε	Epsilon [ˈepsə̥lɔn], *Brit:* [epˈsailən]
Ζ	ζ	Zeta [ˈzeitə], [ˈzi:tə]
Η	η	Eta [ˈeitə],[ˈi:tə]
Θ	θ	Theta [ˈθeitə],[ˈθi:tə]
Ι	ι	Iota [aiˈoutə]
Κ	κ	Kappa [ˈkæpə]
Λ	λ	Lambda [ˈlæmdə]
Μ	μ	Mu [mju:], [mu:]
Ν	ν	Nu [nju:], [nu:]
Ξ	ξ	Xi [zai], [sai], [ksi:]
Ο	ο	Omicron [ˈɔmə̥krɔn]
Π	π	Pi [pai]
Ρ	ρ	Rho [rou]
Σ	ς	Sigma [ˈsigmə]
Τ	τ	Tau [tɔ:], [tou]
Υ	υ	Upsilon [ˈju:psə̥lɔn],[ˈʌpsə̥lɔn], *Brit :* [jupˈsailən]
Φ	φ	Phi [fai], [fi:]
Χ	χ	Chi [kai]
Ψ	ψ	Psi [sai], [psi:]
Ω	ω	Omega [ouˈmi:gə],[ouˈmeigə],[ouˈmegə], [ˈoumegə]

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