

Detecção Remota Microondas

Interferometria SAR

João Catalão Fernandes, FCUL

ICEYE

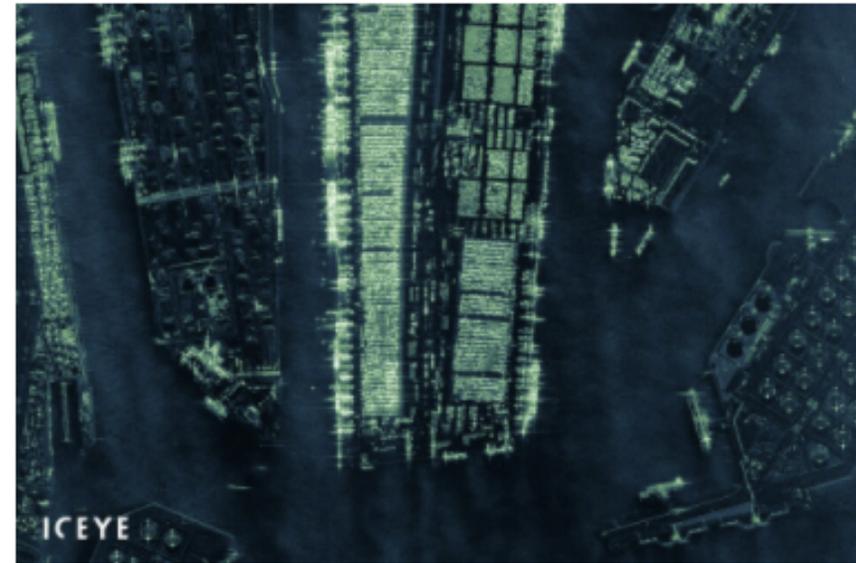


ICEYE builds and operates a commercial constellation of small synthetic aperture radar satellites. So far, 14 satellites have been launched and ICEYE plans to expand its constellation up to 18 satellites by mid-2022, with the objective of reaching an average access time of three hours anywhere on the globe.

The mission is used in many sectors, from monitoring floods and mining activities, to marine vessel detection and iceberg monitoring.

The ICEYE satellite constellation will complement existing synthetic aperture radar missions in the Copernicus programme.

Toni Tolker-Nielsen continued, “We are particularly proud to work with ICEYE, which is one the few New Space companies that we have in Europe in the field of Earth observation. In fact, this is not the first contract that ESA has signed with ICEYE. For a few years now, ESA has been buying ICEYE data and making them available to scientists and to pilot activities. I encourage scientists to use ICEYE data through the Earthnet programme.”



— Rotterdam port from ICEYE



APPLICATIONS

Copernicus Contributing Missions overview

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DETAILS

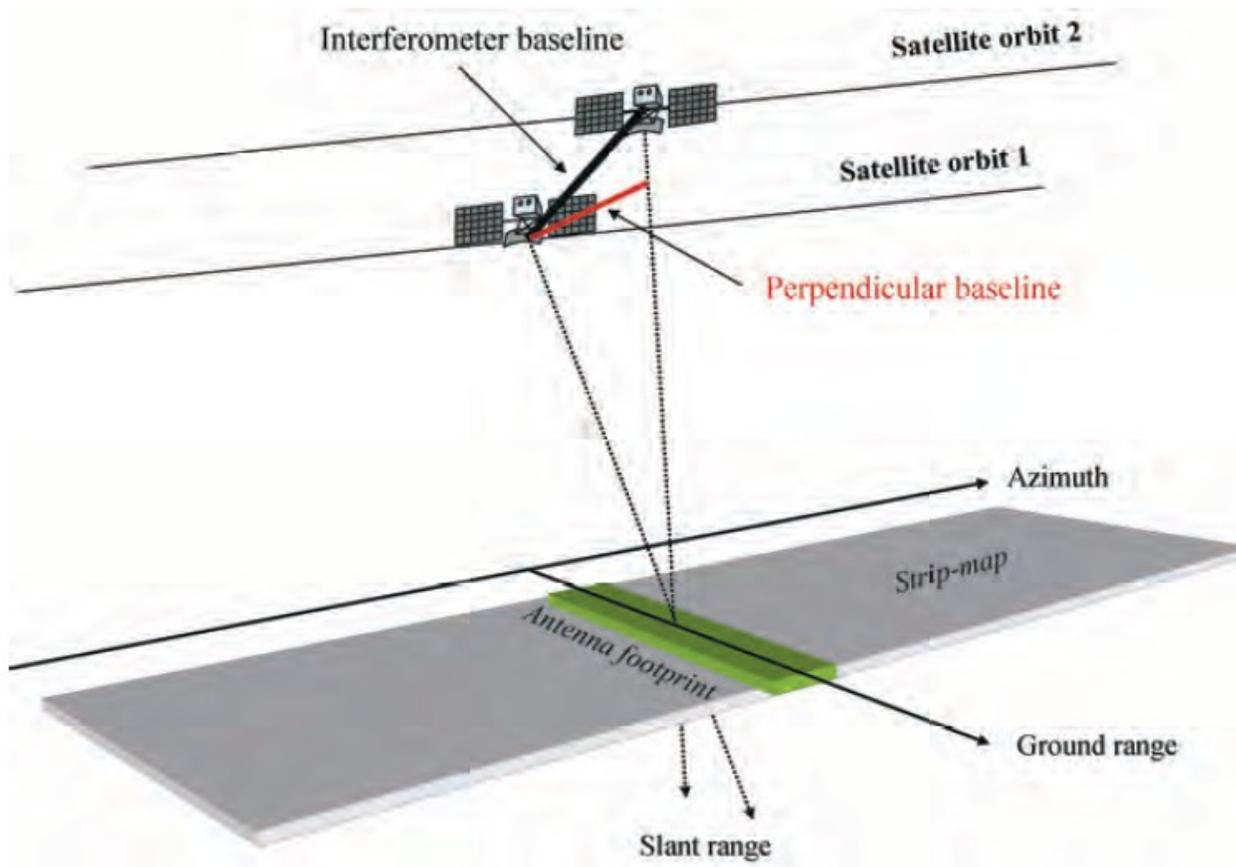
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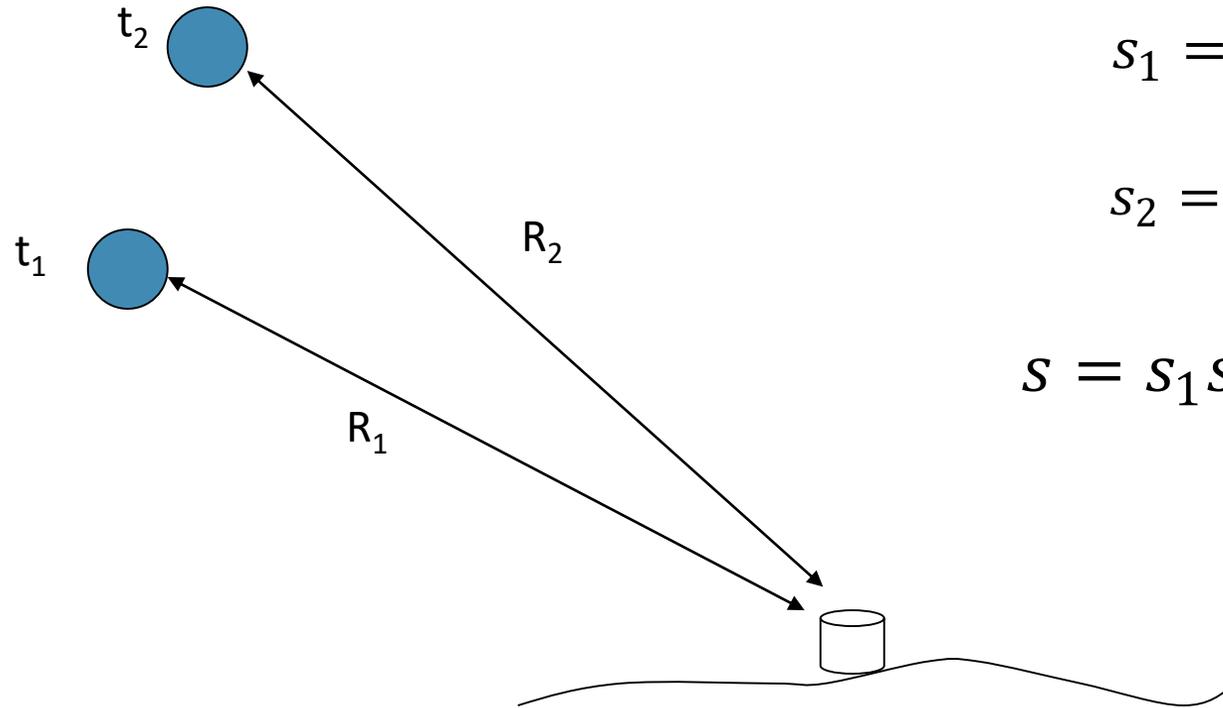
In addition to data provided by the Sentinel satellites, the Copernicus Contributing Missions play a crucial role, delivering complementary data to ensure that a whole range of observational requirements is satisfied. The existing or planned Contributing Missions include missions from ESA, their Member

Tópicos

- Interferometria RADAR de abertura sintética (SAR)
- Interferometria Diferencial
- Contribuição atmosférica
- Persistent Scatterer* e análise de séries temporais
- Aplicações PSINSAR
- STAMPS
- Fusão de dados InSAR e GPS
- Mitigação dos efeitos atmosféricos
- Perspetivas para a interferometria SAR

Geometria da interferometria SAR





$$s_1 = A \cdot e^{(j\phi_B)} \cdot e^{-j\left(\frac{4\pi}{\lambda}\right) \cdot R_1}$$

$$s_2 = A' \cdot e^{(j\phi'_B)} \cdot e^{-j\left(\frac{4\pi}{\lambda}\right) \cdot R_2}$$

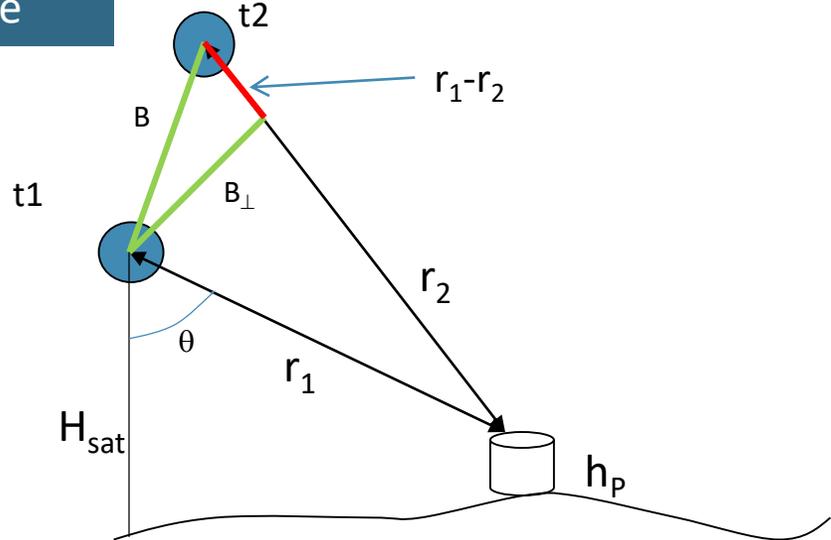
$$s = s_1 s_2^* = |s_1| |s_2| e^{-j\left(\frac{4\pi}{\lambda}\right) \cdot R_1 + j\left(\frac{4\pi}{\lambda}\right) \cdot R_2}$$

Interferograma

$$\phi_I = -\frac{4\pi}{\lambda} (R_1 - R_2)$$

Se $\phi_B = \phi'_B$, ou seja se não houver alteração do mecanismo de scattering da célula de resolução.

Sem movimento da superfície



$$h_p = H_{sat} - r_1 \cos \theta$$

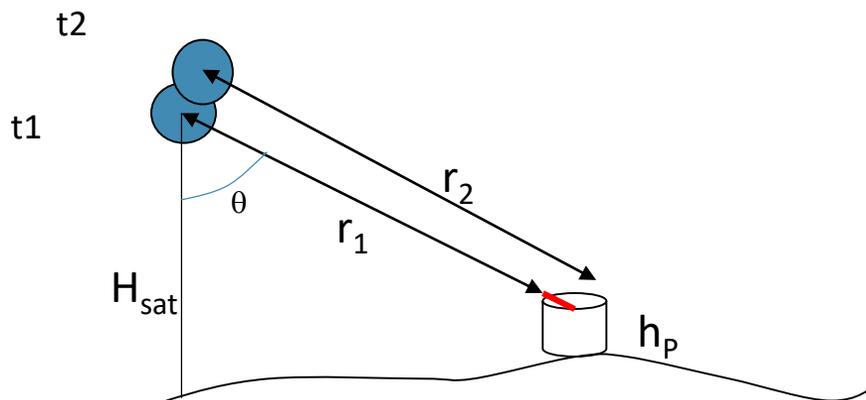
$$\phi_{top} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_1 \sin \theta} h_p$$

Se $\phi_{top} = 2\pi \rightarrow h_p = \frac{\lambda r_1 \sin \theta}{4\pi B_{\perp}} 2\pi = \frac{\lambda r_1 \sin \theta}{2B_{\perp}}$

(Ambiguidade da altitude)

$B_{\perp} = 100\text{m}$
 $h_{2\pi} = 146\text{ m}$

Com movimento da superfície

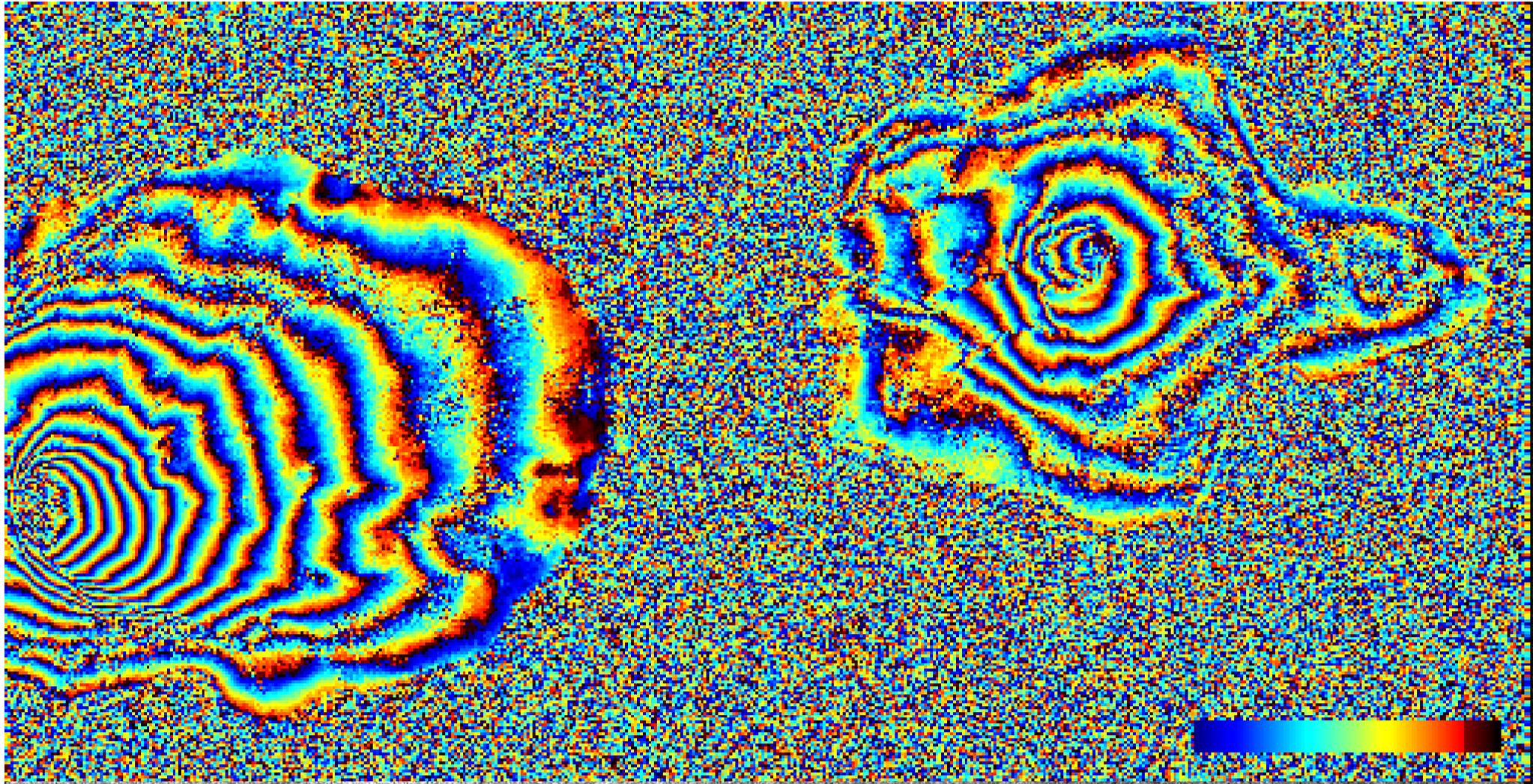


$$\phi_I = \phi_{top} - \frac{4\pi}{\lambda} (r_1 - r_2)$$

$$\phi_I = -\frac{4\pi}{\lambda} \delta r_{desloc} + \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin \theta_p} h_p$$

Sensitivity to deformation 1000x higher than for topography

$B = 100\text{m}$
 $k=0.003$

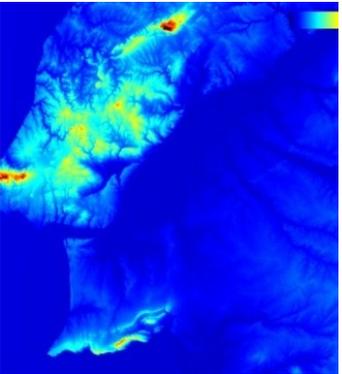
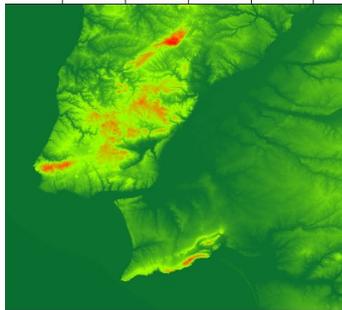


Ambiguidade da altitude= 76 m, B = 100m

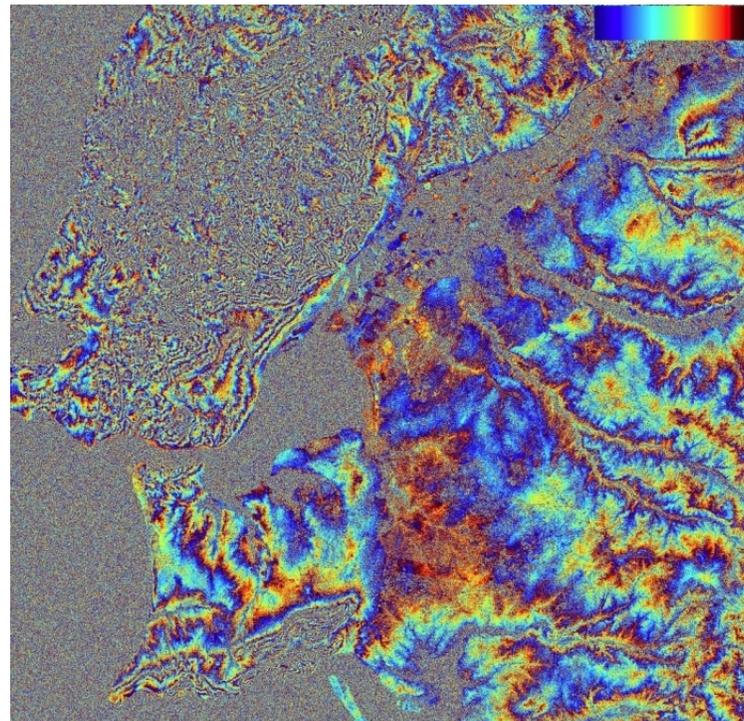
Differential interferogram

$$\phi_I = -\frac{4\pi}{\lambda} \delta r_{desloc} + \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin\theta_p} h_p \quad \rightarrow \quad \phi_{Def} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin\theta_p} h_p - \phi_I$$

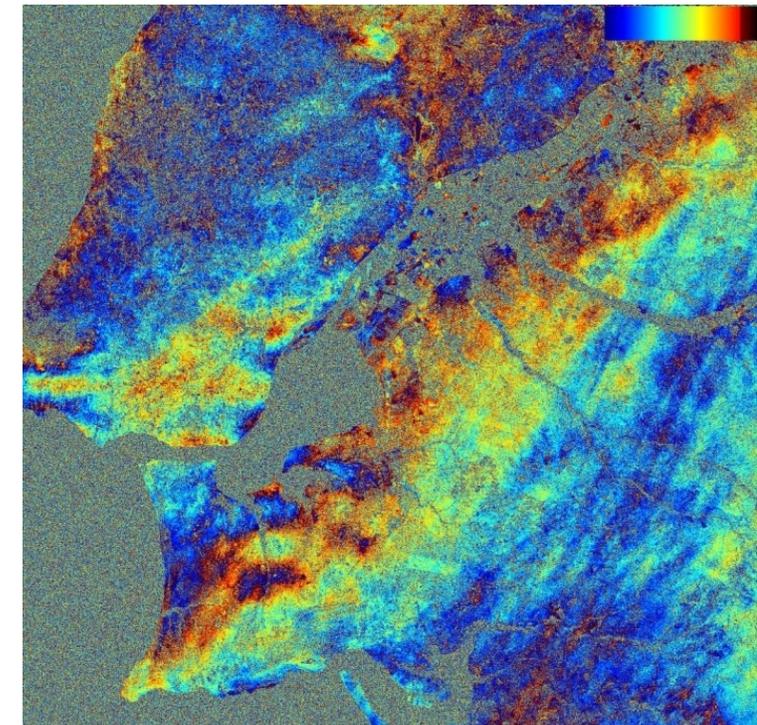
h_p



$$\frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin\theta_p} h_p$$



ϕ_I



$$\phi_{Def} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin\theta_p} h_p - \phi_I$$

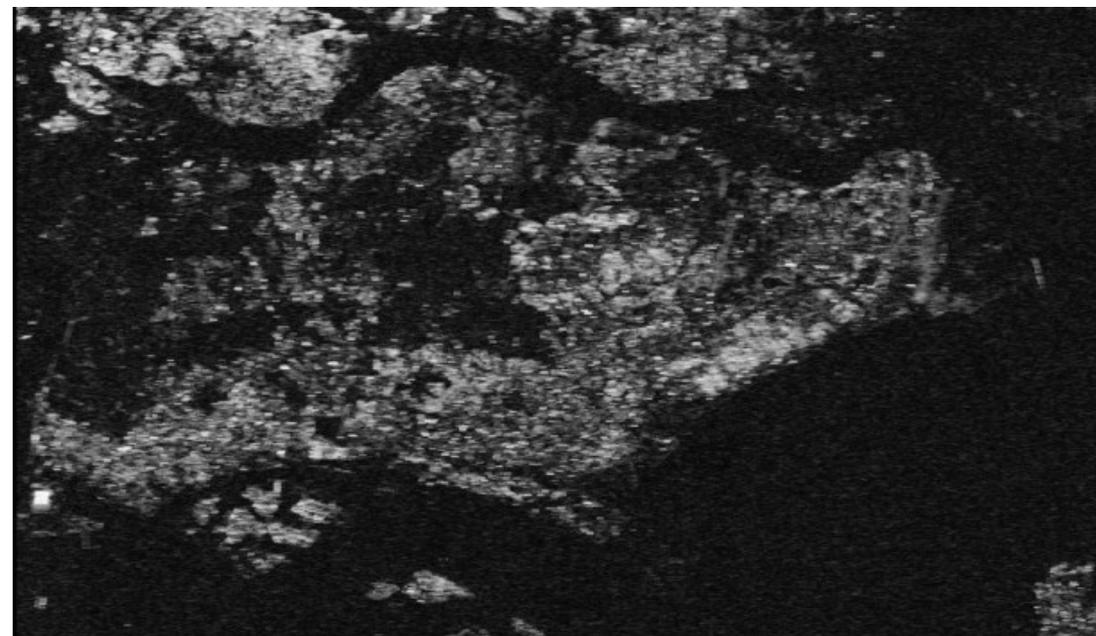
A medida da qualidade da fase de um interferograma é dada pela **coerência** γ de cada píxel do interferograma.

Rodriguez e Martin (1992) apresentaram uma expressão analítica para a variância da fase:

$$\sigma_{\phi}^2 = \frac{1}{2N_L} \frac{1 - \gamma^2}{\gamma^2}$$

A coerência é definida como :

$$\gamma = \frac{E(s_1 s_2^*)}{\sqrt{E\{|s_1|^2\} \cdot E\{|s_2|^2\}}} \quad 0 \leq |\gamma| \leq 1$$



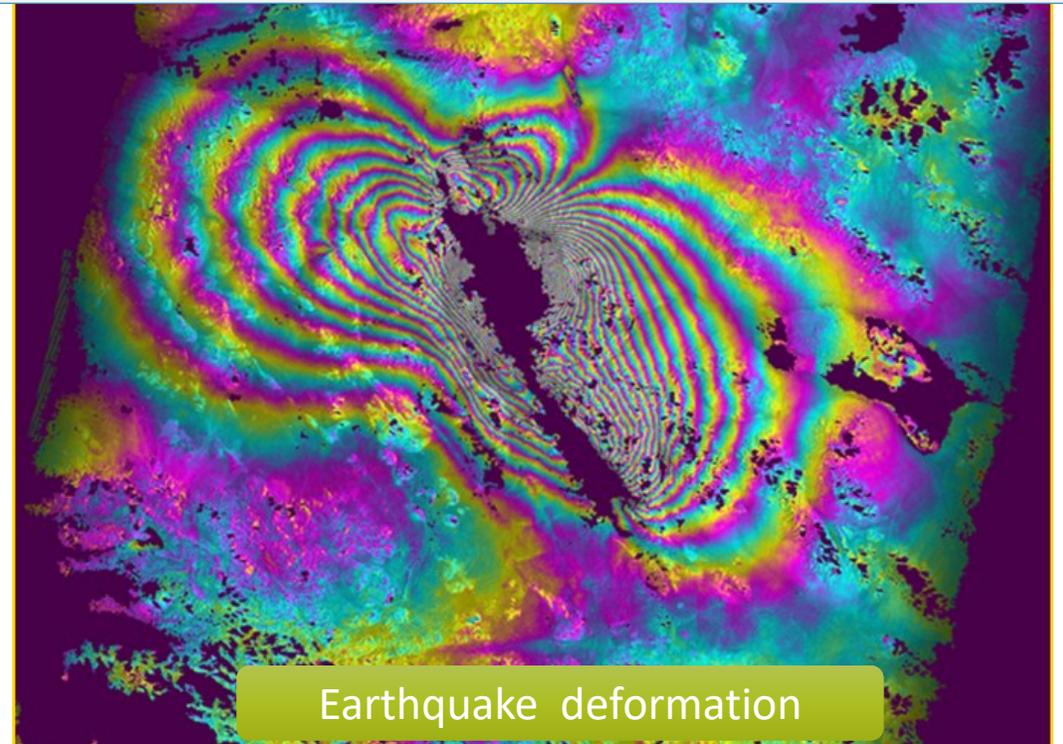
DINSAR Applications



Volcanic Hazards



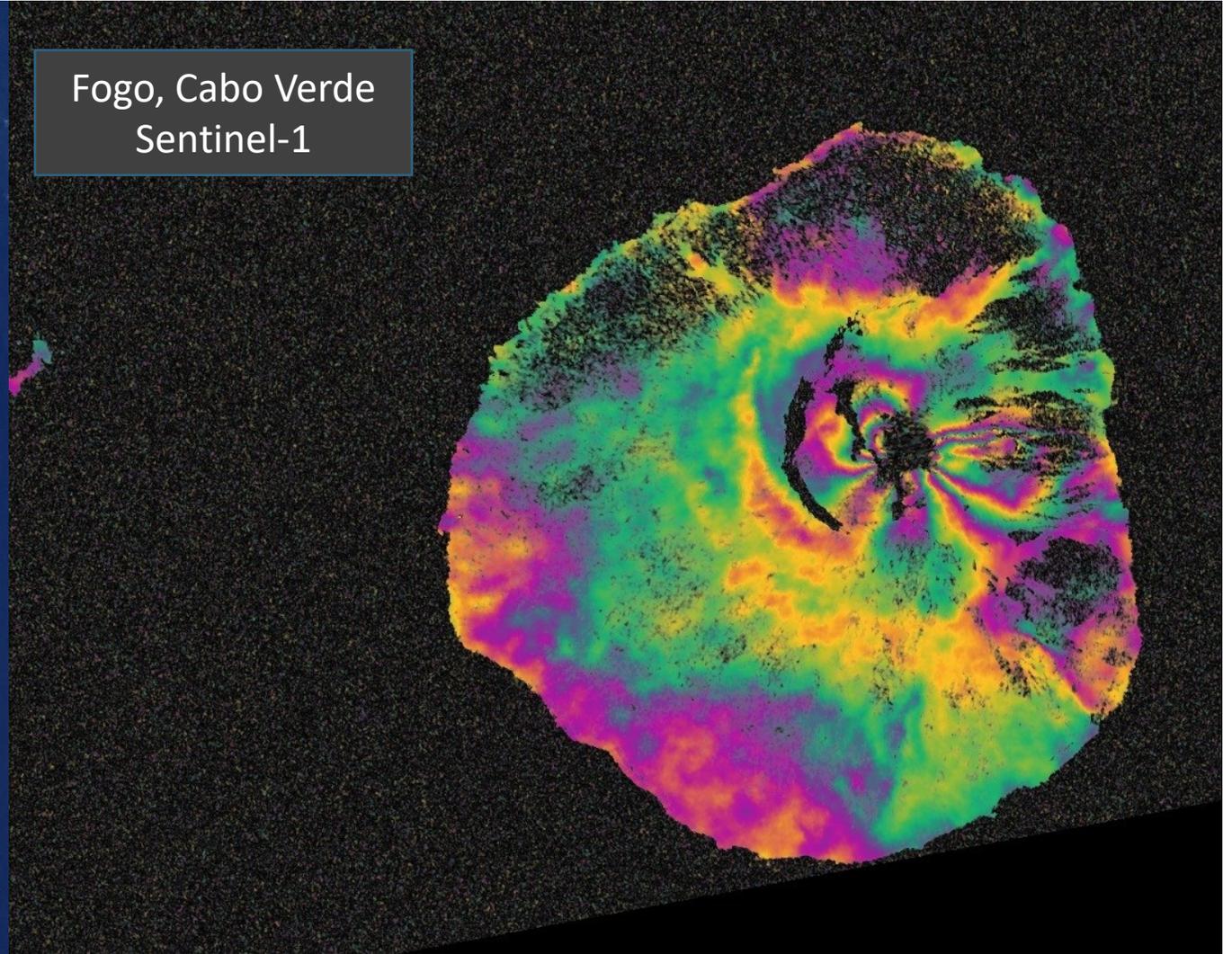
- **Volcano deformation**
- **Earthquake deformation**
- **Permafrost and Glaciar displacement**

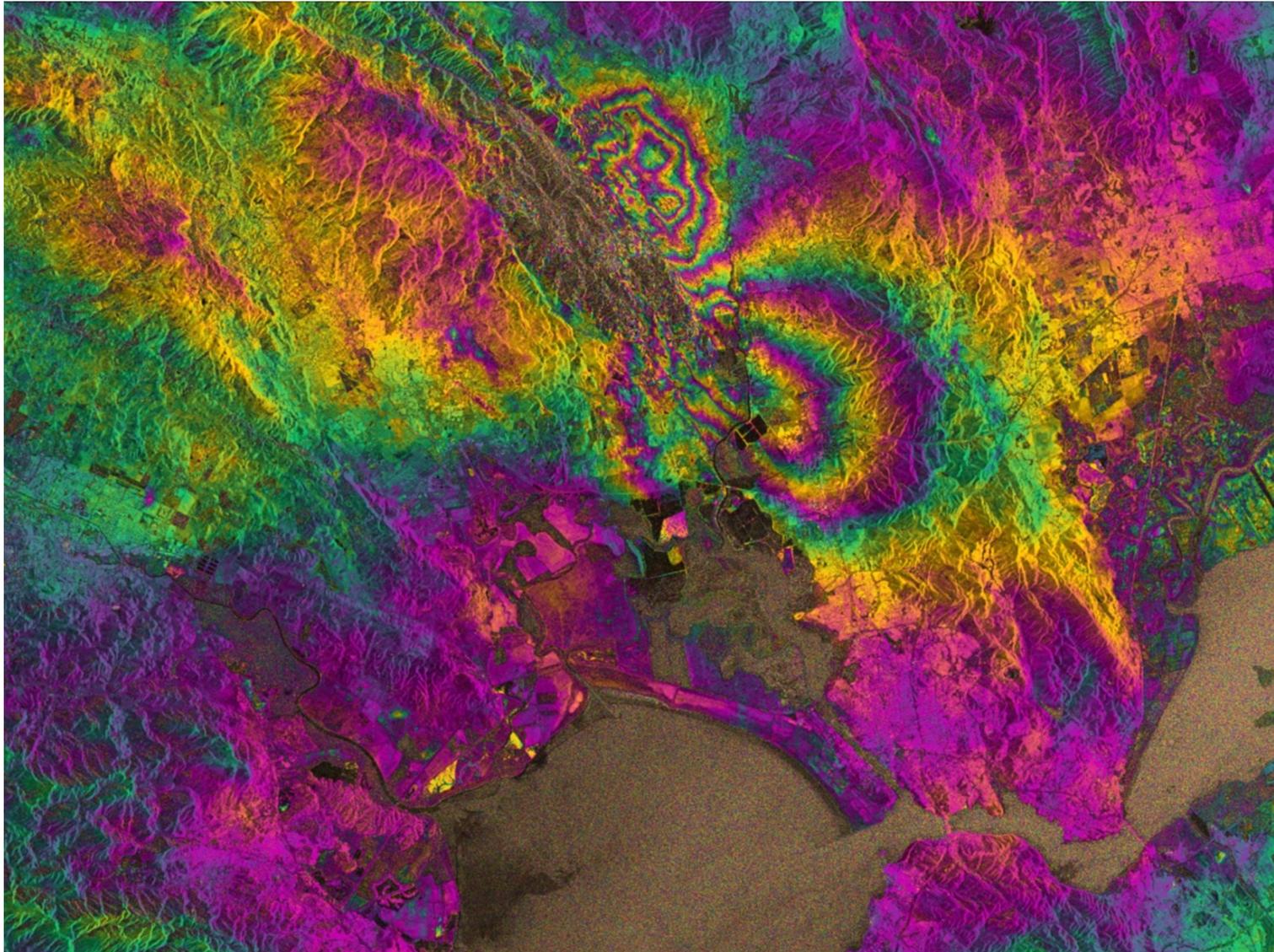


Volcano Monitoring



Fogo, Cabo Verde
Sentinel-1



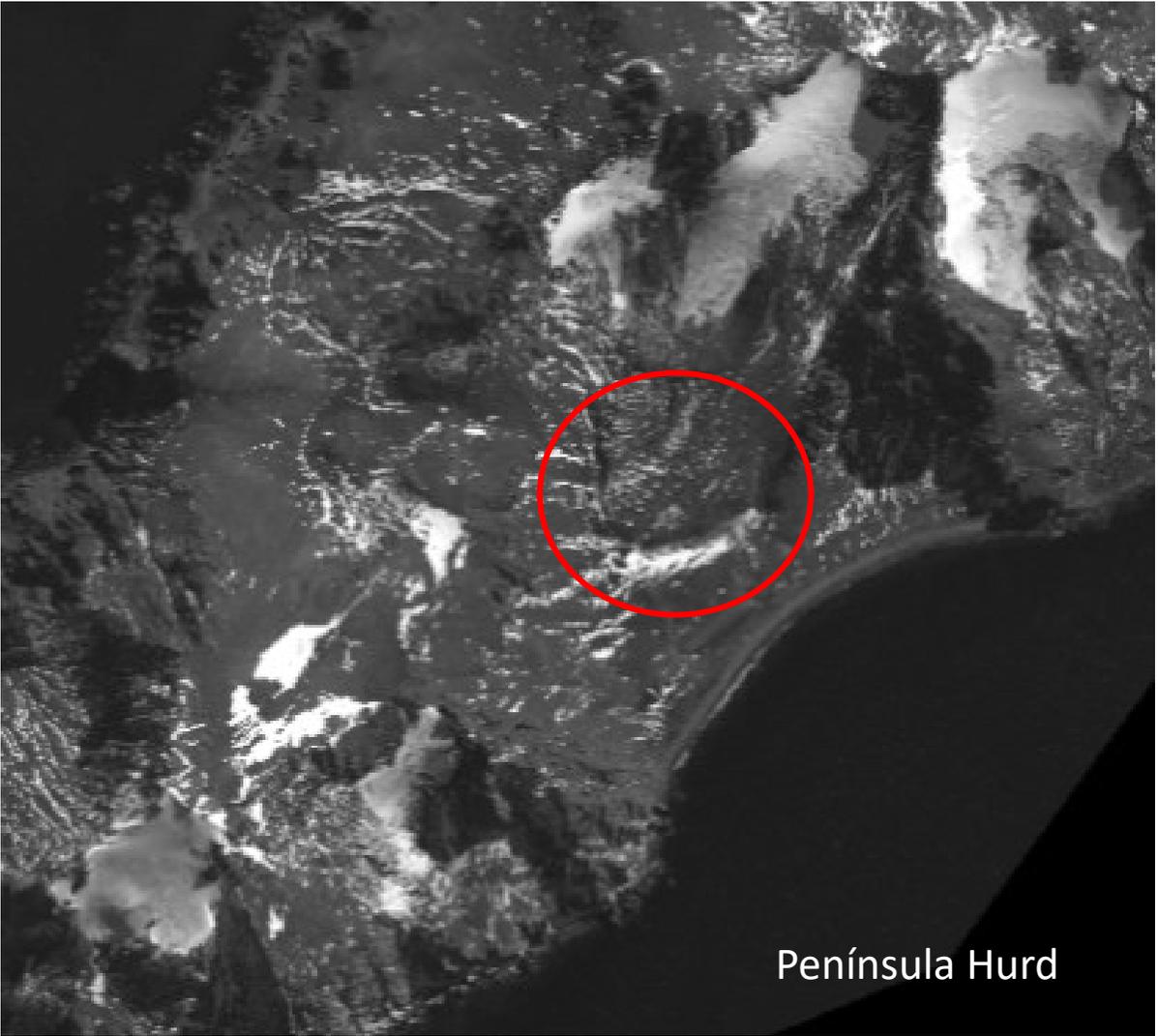


Earthquake deformation

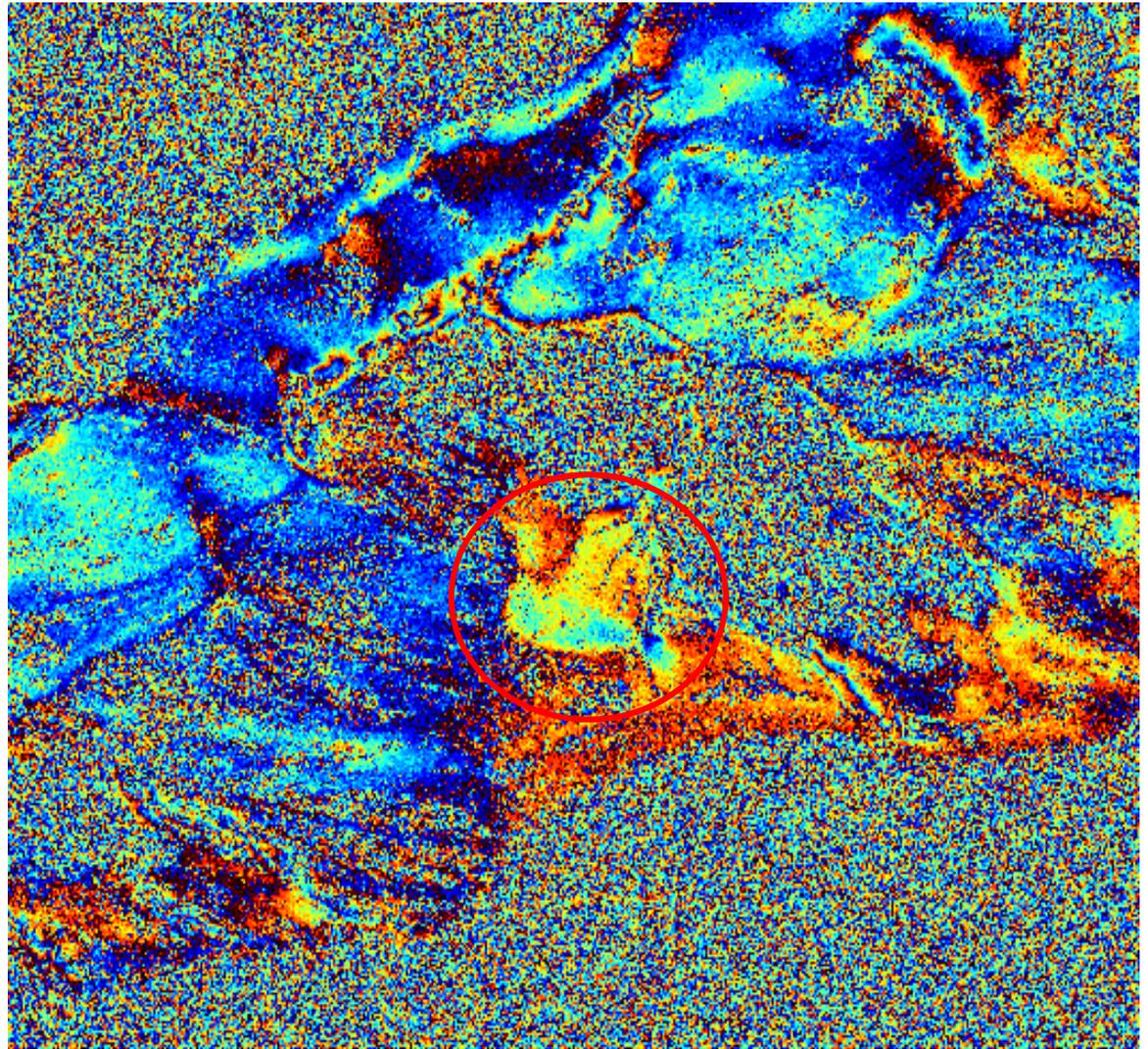
**Napa Valley earthquake,
24 Agosto 2014**

Sentinel -1

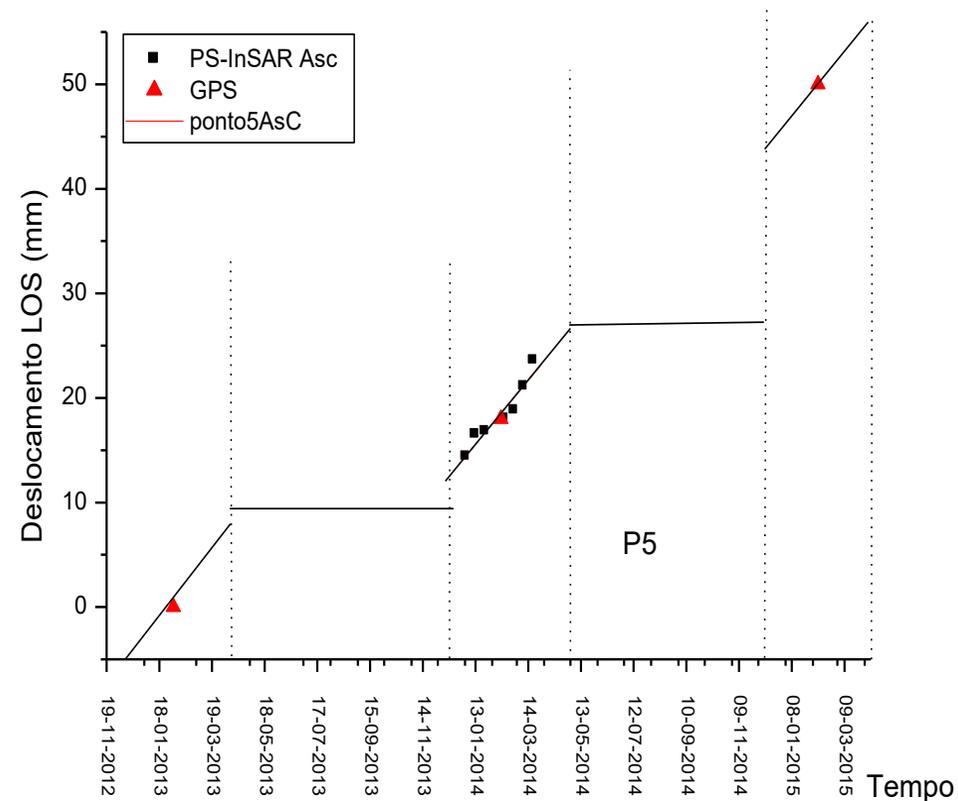
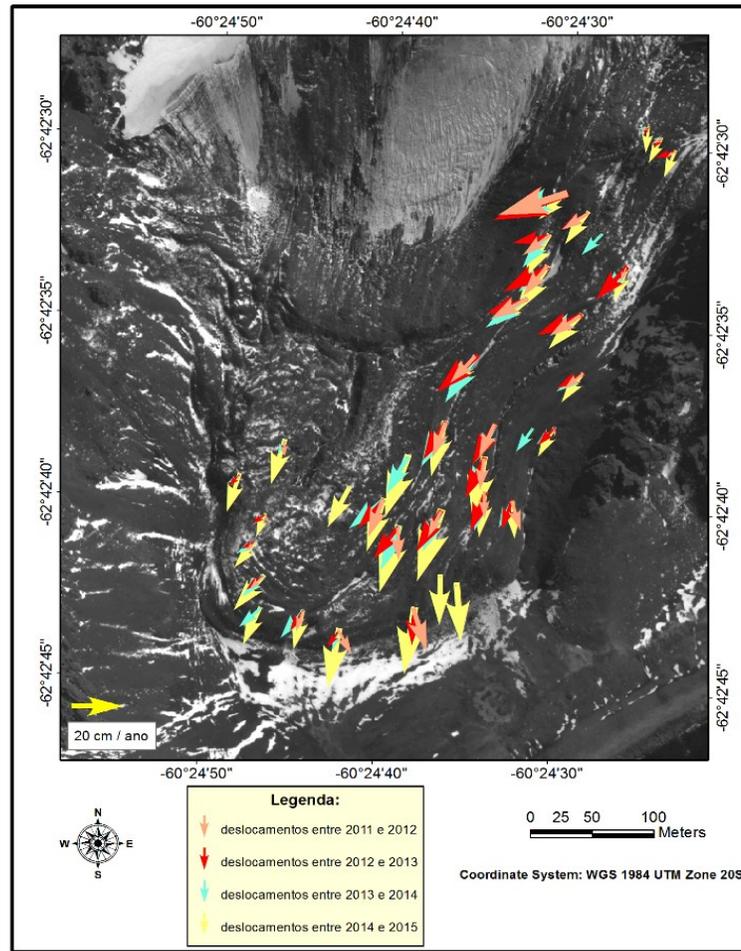
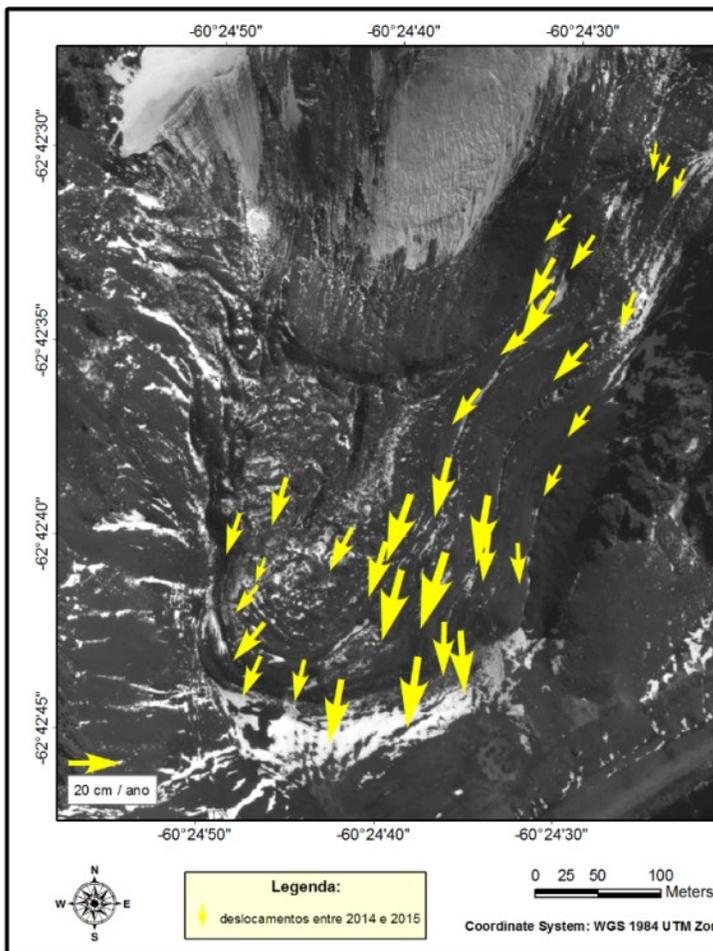
RockGlaciar movement



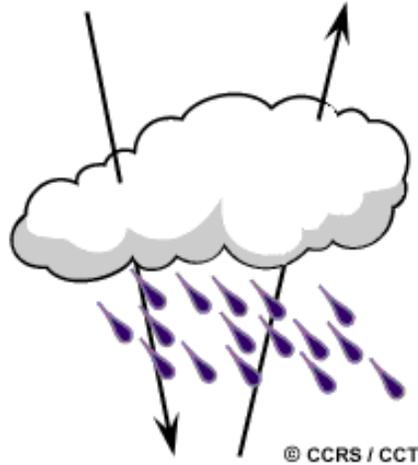
Península Hurd



RockGlaciar movement



The atmospheric contribution



Longer wavelength microwave radiation can penetrate through cloud cover, haze, dust, as the longer wavelengths are not susceptible to atmospheric scattering.

BUT

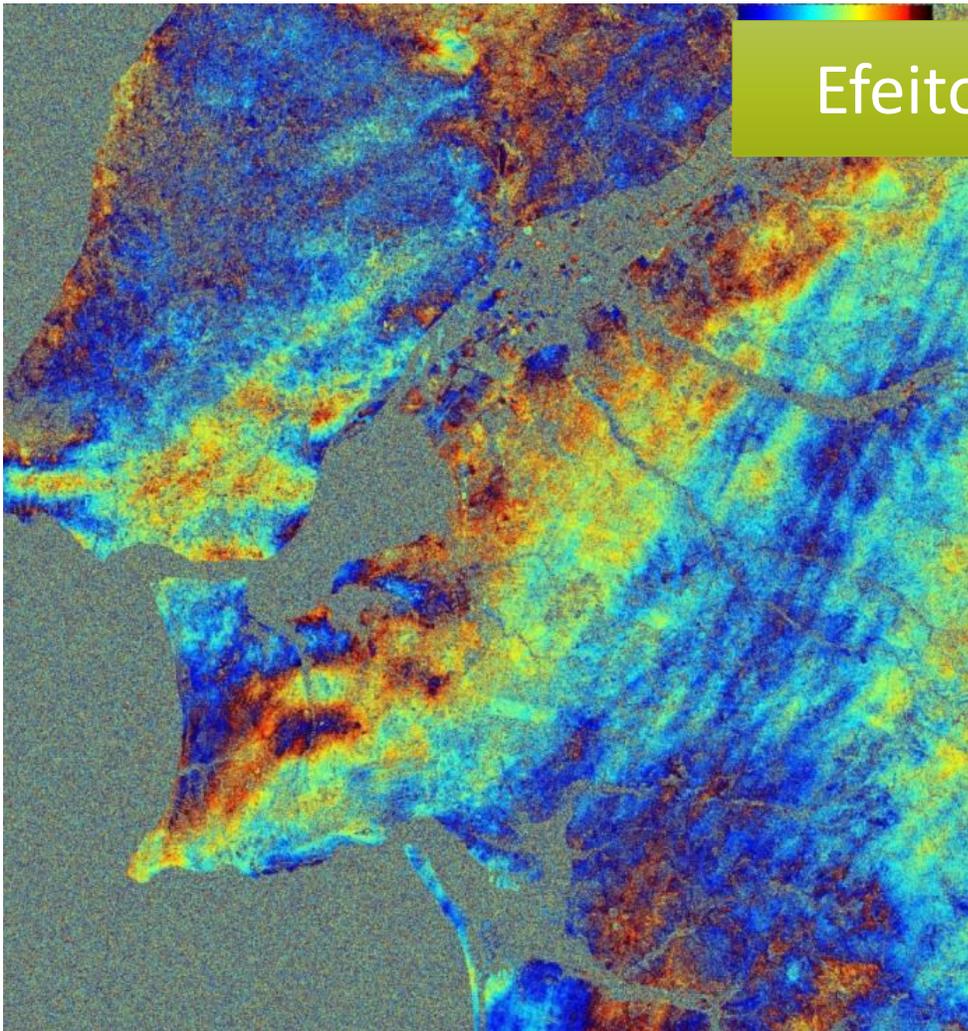


Radiation travel path can be affected by atmospheric humidity, temperature and pressure

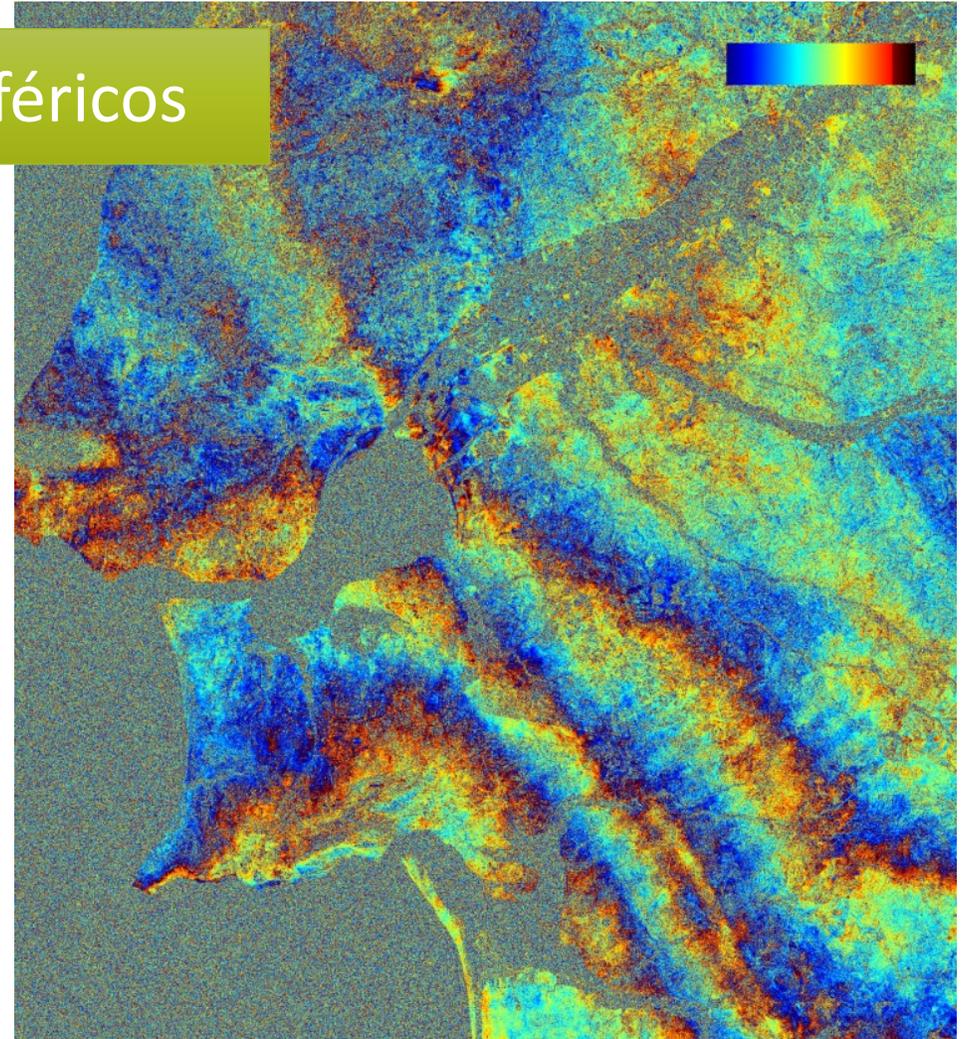


Two SAR images not simultaneous, can be affected differently by the atmosphere with consequences on the interferometric phase.

Limitações da InSAR Diferencial



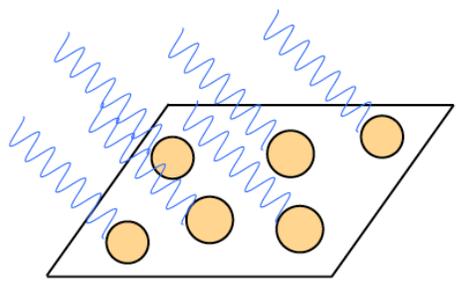
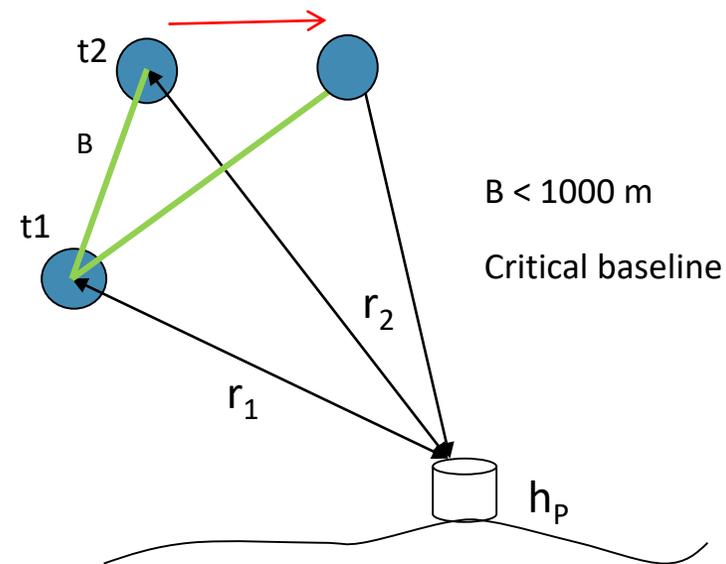
Efeitos atmosféricos



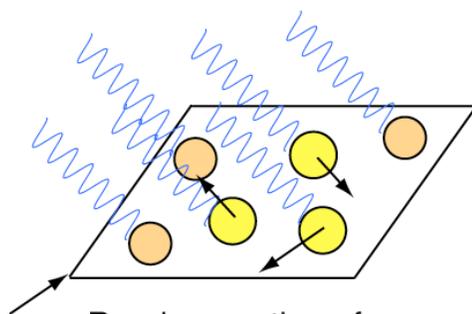
Limitações da InSAR Diferencial

Descorrelação geométrica

Descorrelação Temporal

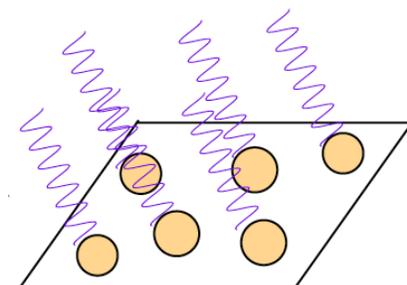


Received signal is superposition of waves from all scattering centers



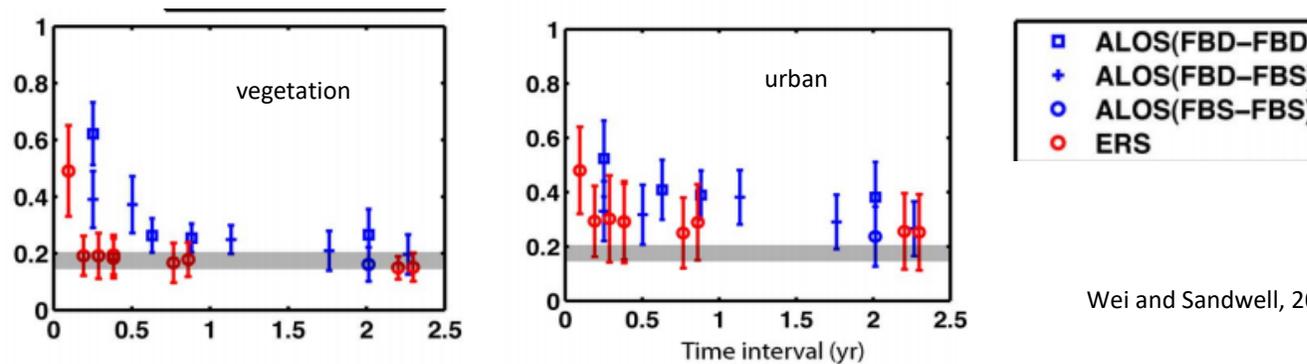
Random motion of scatterers causes wavelets to interfere- "temporal decorrelation"

$$s_2 = A \cdot e^{(\phi'_B)} \cdot e^{(-j(\frac{4\pi}{\lambda})r_2)}$$



Change in incidence angle causes wavelets to interfere- "baseline decorrelation"

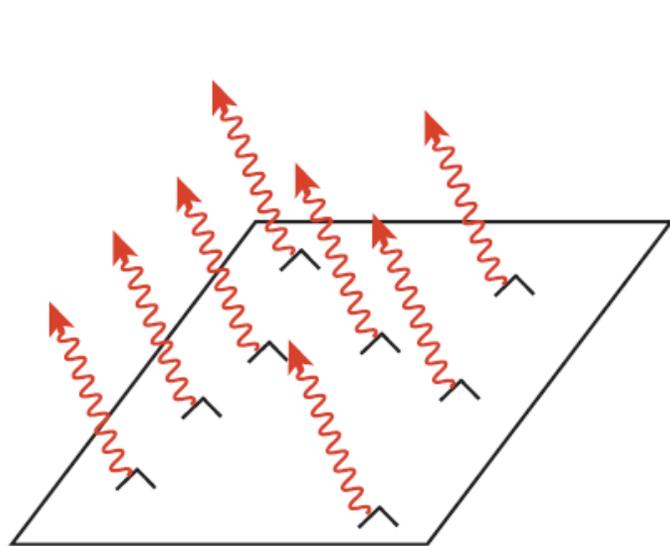
Coerencia



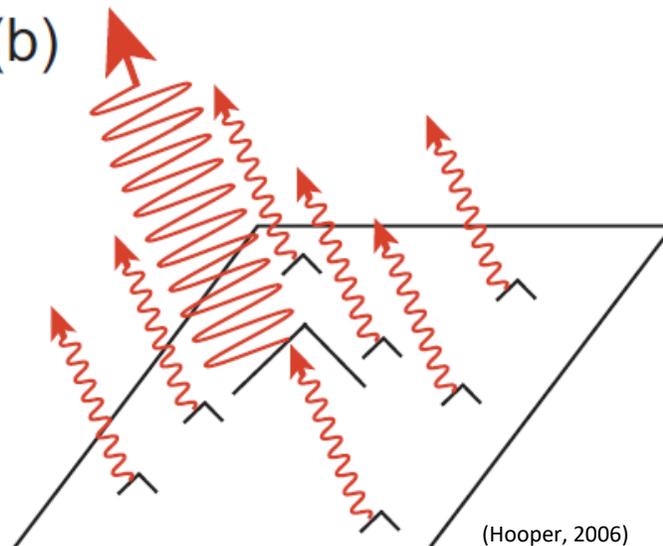
Wei and Sandwell, 2010 (IEEE TGRS)

Persistent Scatterer (PS)

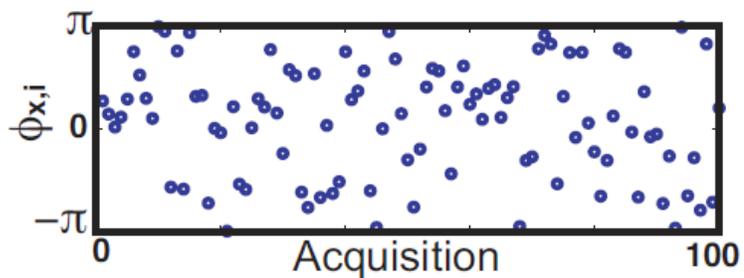
(a)



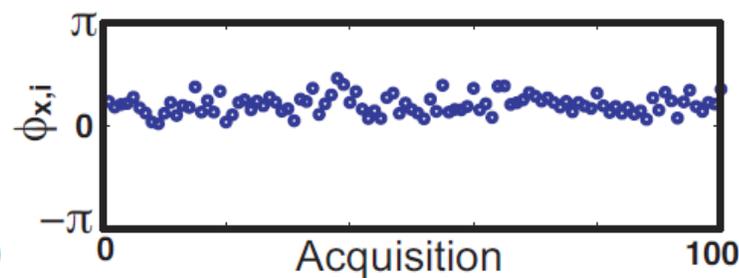
(b)



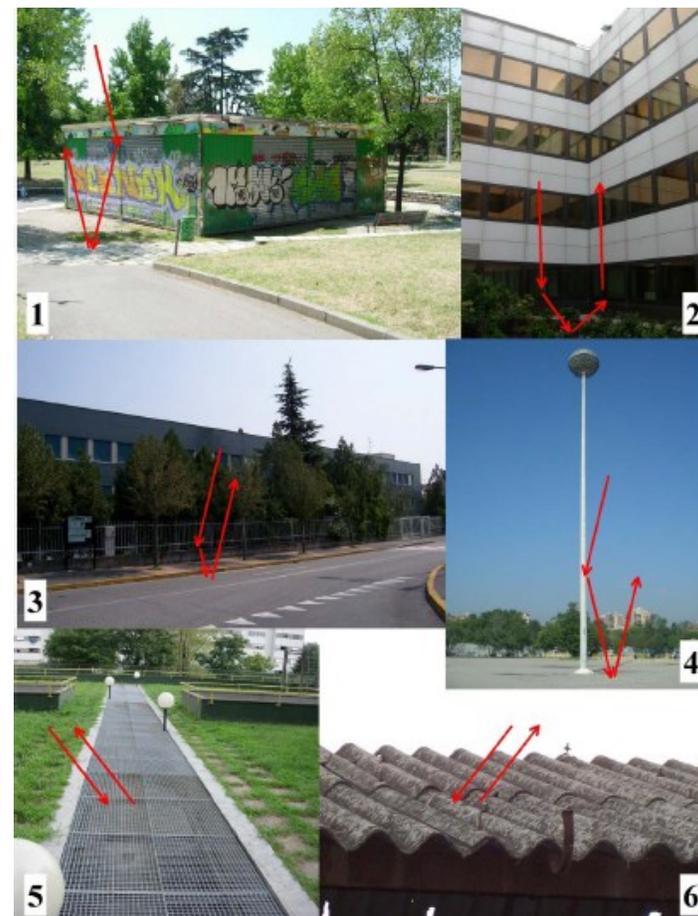
(Hooper, 2006)



Distributed Scatterer

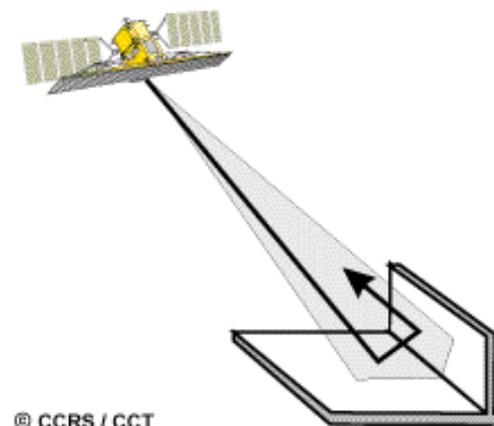


Persistent Scatterer



Corner Reflectors

Estruturas que tenham duas ou mais superfícies (geralmente suaves) com ângulos rectos podem ser “corner reflectors” se as faces estiverem viradas para o satélite.



A orientação para o satélite de superfícies com um ângulo recto entre elas faz com que a maioria da energia radar seja reflectida directamente para a antena devido à dupla reflexão.

Em ambientes urbanos são frequentes os “corner reflectors” com formas complexas. Edifícios, pontes e outras estruturas edificadas.

FCUL



Barragem do Pizão



Em 2001, Ferretti et al., propuseram uma técnica designada por “Permanent Scatterers technique” que permite a análise de longas séries temporais de interferogramas.

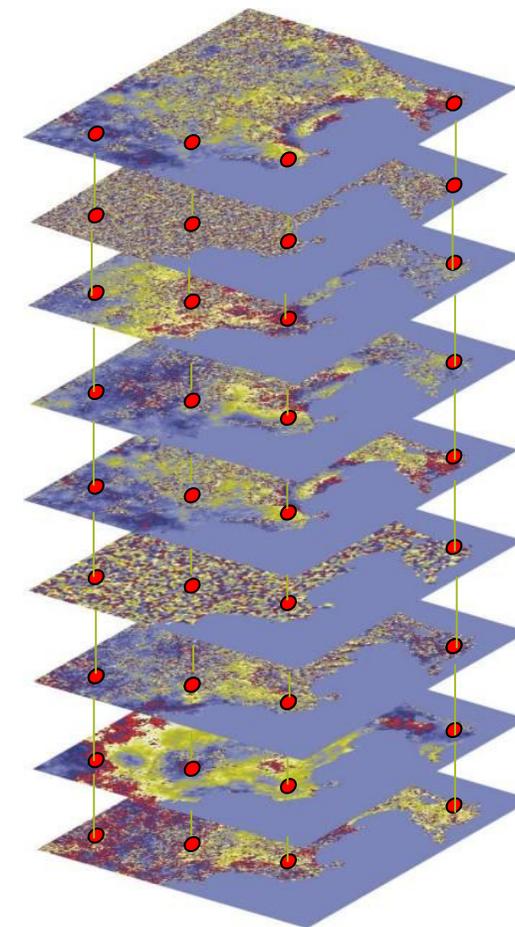
A técnica baseia-se num conjunto de píxeis coerentes ao longo do tempo e permite, dentro de certas condições:



A determinação do erro do DEM usado no interferograma diferencial



A deteção de movimentos da superfície com uma precisão milimétrica



$$D_a = \frac{\sigma_a}{\bar{a}} = \hat{\sigma}_\phi$$



To estimate/mitigate atmospheric signal

To separate topography and deformation

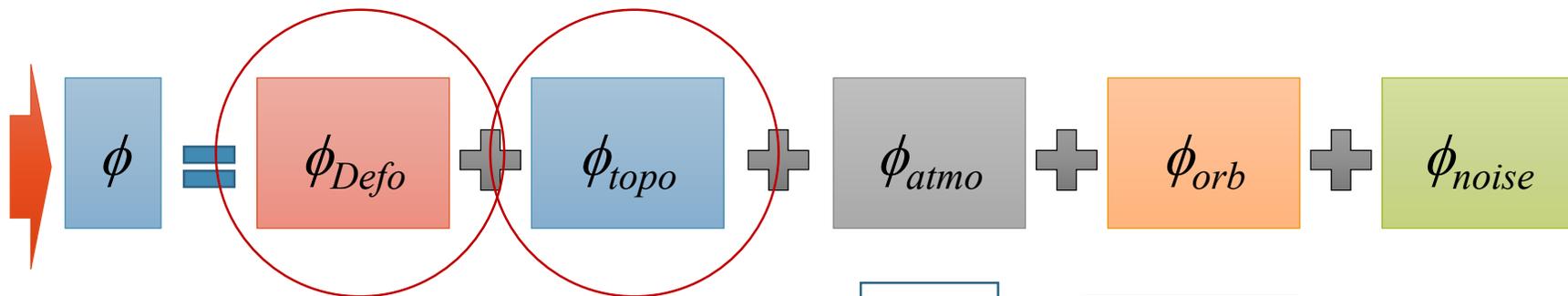
To estimate orbit errors

To resolve the ambiguities

PERSISTENT SCATTERER

Ferretti et al., 2001,

The interferometric phase of point P of interferogram k, is:

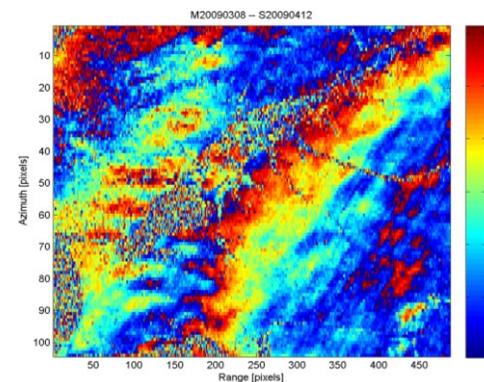
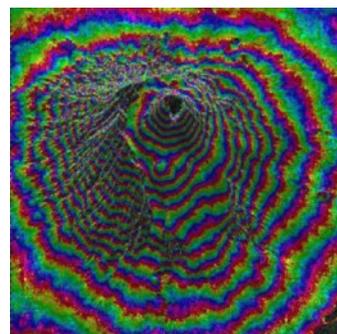


$$-\frac{4\pi}{\lambda} T^k v(x)$$

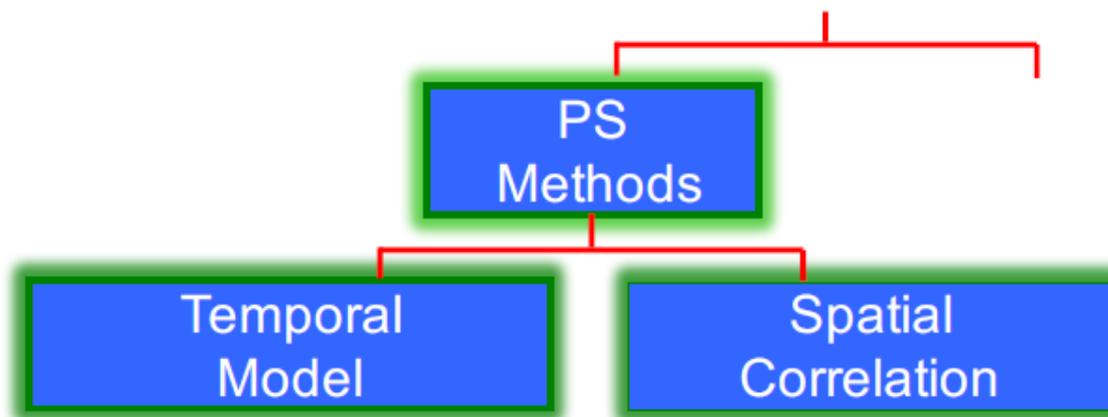
$$-\frac{4\pi}{\lambda} \frac{B_{\perp x}^k}{r_x^m \sin \theta_{x,inc}^m} \cdot h_x$$

?

$$-\frac{4\pi}{\lambda} \frac{B_n s}{R \tan \theta}$$



PS Processing Algorithms



- Relying on model of deformation in time: e.g. “Permanent Scatterers” (Ferretti et al. 2001), Delft approach (Kampes et al., 2005)
- Relying on correlation in space: StaMPS (Hooper et al. 2004)

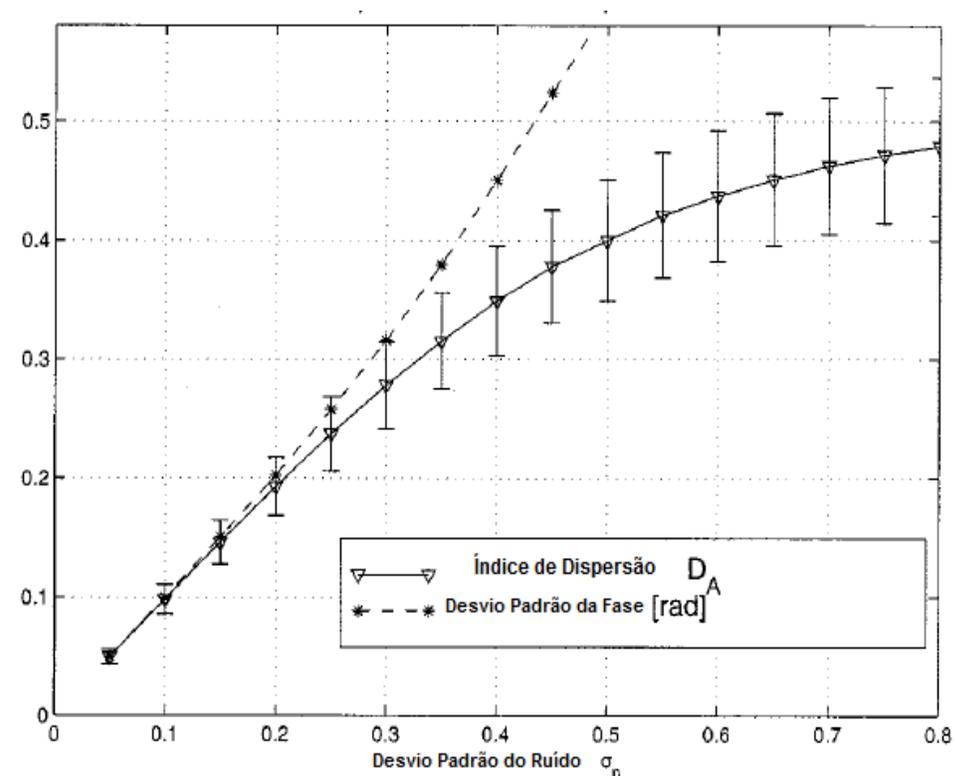
Persistent Scatter Candidates

Ferretti et al. (2001) proposed to select a PSC if the amplitude dispersion is below a threshold, typically between 0.25 (Colesanti et al., 2003).

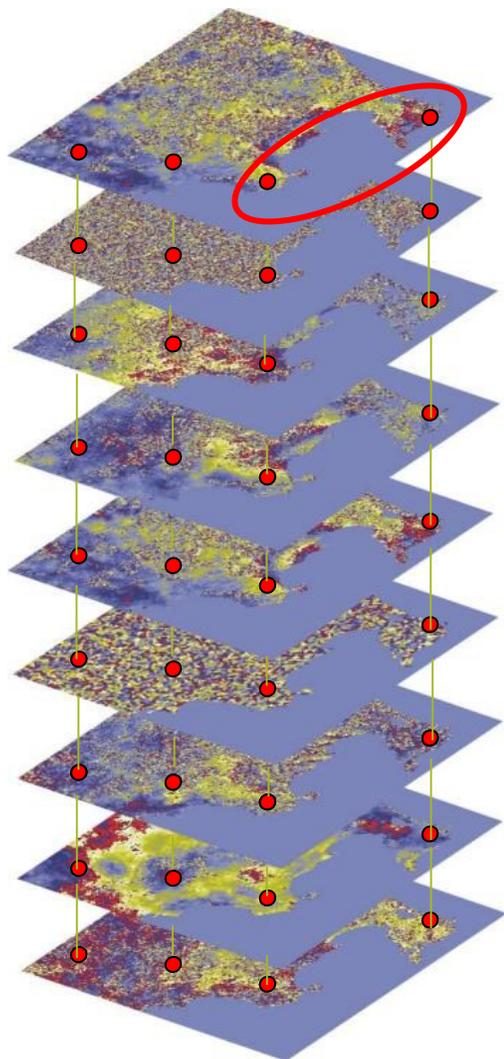
The amplitude dispersion index D_a is a proxy of the phase standard deviation and is defined as:

$$D_a = \frac{\sigma_a}{\bar{a}} = \hat{\sigma}_\phi$$

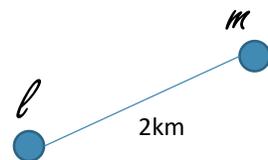
Where σ_a is the temporal standard deviation of the amplitude and \bar{a} the temporal mean of the amplitude for a certain pixel.



Persistent Scatterer functional model



$$\phi^k = -\frac{4\pi}{\lambda} T^k v(x) - \frac{4\pi}{\lambda} \frac{B_{\perp x}^k}{r_x^m \sin \theta_{x,inc}^m} \cdot h_x + \phi_{atmo}^k + \phi_{ruído}^k$$



$$\Delta\phi_{l,m}^k = -\frac{4\pi}{\lambda} T^k \Delta v(x) - \frac{4\pi}{\lambda} \frac{B_{\perp x}^k}{r_x^m \sin \theta_{x,inc}^m} \cdot \Delta h_x + \omega_{l,m,k}$$

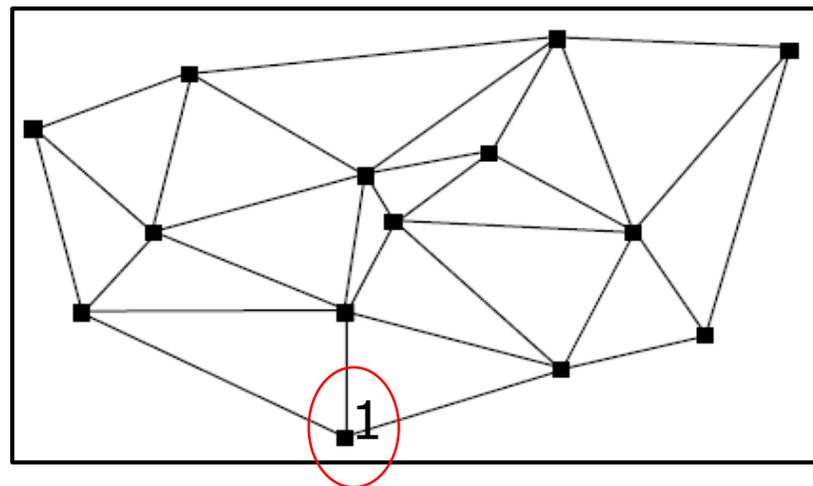
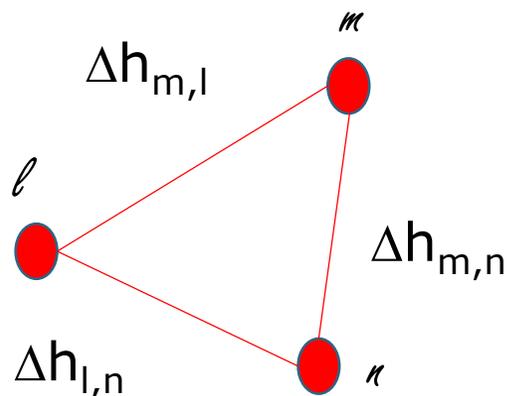
$$\Delta\phi_{l,m}^k = k_v \Delta v_{l,m} T_k + k_\varepsilon \cdot B_{n,k} \Delta h_{l,m} + \omega_{l,m,k}$$

System of k equations with 2 parameters

Busca no espaço solução dos valores que maximizam a função γ

$$\gamma_{l,m} = \frac{1}{K} \sum_{k=1}^K \exp (j \cdot (\Delta\phi_{l,m}^k - k_v \Delta v_{l,m} T_k - k_\varepsilon \cdot B_{n,k} \Delta h_{l,m} - \omega_{l,m,k}))$$

Integration relative to a reference



$$\begin{bmatrix} \Delta h_{2,1} \\ \Delta h_{3,1} \\ \Delta h_{4,1} \\ \vdots \\ \Delta h_{3,2} \\ \Delta h_{4,2} \\ \vdots \\ \Delta h_{H-1,H} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 0 & \dots & 0 \\ 0 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & -1 & 0 & \dots & 0 \\ 1 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & -1 \end{bmatrix} \begin{bmatrix} \Delta h_2 \\ \Delta h_3 \\ \Delta h_4 \\ \vdots \\ \Delta h_{H-1} \\ \Delta h_H \end{bmatrix}$$



$$\widehat{\Phi}_x^k = -\frac{4\pi}{\lambda} T^k v(x) - \frac{4\pi}{\lambda} \frac{B_{\perp x}^k}{r_x^m \sin \theta_{x,inc}^m} \cdot h_x$$

$$e_x^k = \Phi_x^k - \frac{4\pi}{\lambda} T^k v(x) - \frac{4\pi}{\lambda} \frac{B_{\perp x}^k}{r_x^m \sin \theta_{x,inc}^m} \cdot h_x$$

Fase residual devida aos efeitos atmosféricos e deformação não uniforme.

Final estimation

A média temporal da fase residual é uma estimativa da fase atmosférica na data da master. Pode ser removida de todos os PSC.

$$e'_x{}^k = e_x^k - \bar{e}_x$$

O restante resíduo é sucessivamente filtrado no tempo e no espaço para se obter a componente atmosférica de cada interferograma.

$$\phi_{x,atmo}^k = [[e'_x{}^k]_{HP_time}]_{LP_space} + [\bar{e}_x]_{LP_space}$$

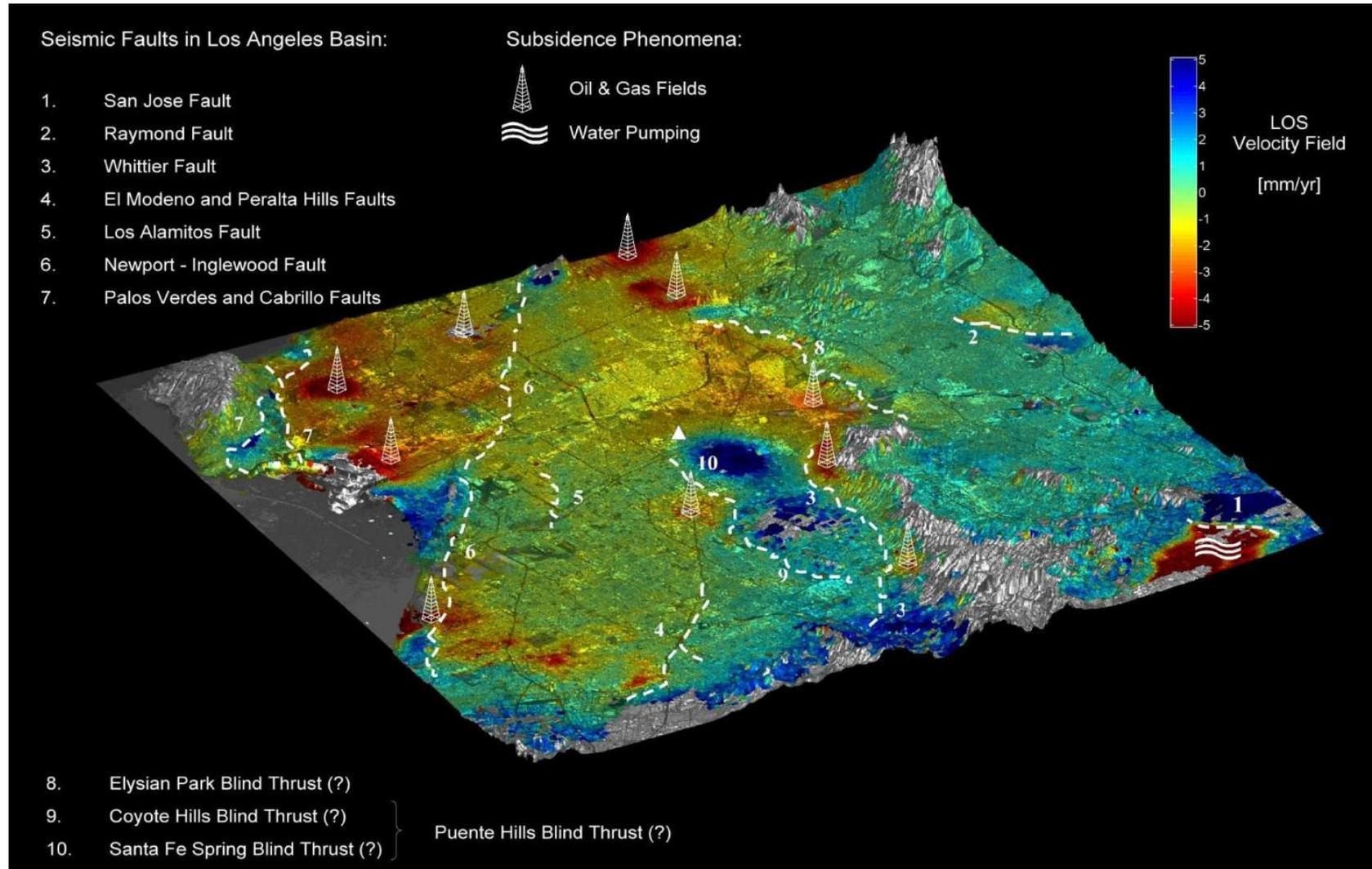
A APS é removida de todos os interferogramas e o processo reiniciado para todos os píxeis.

Requisitos

3 a 4 PS /km²: para interpolação da APS (Colesanti et al., 2003)

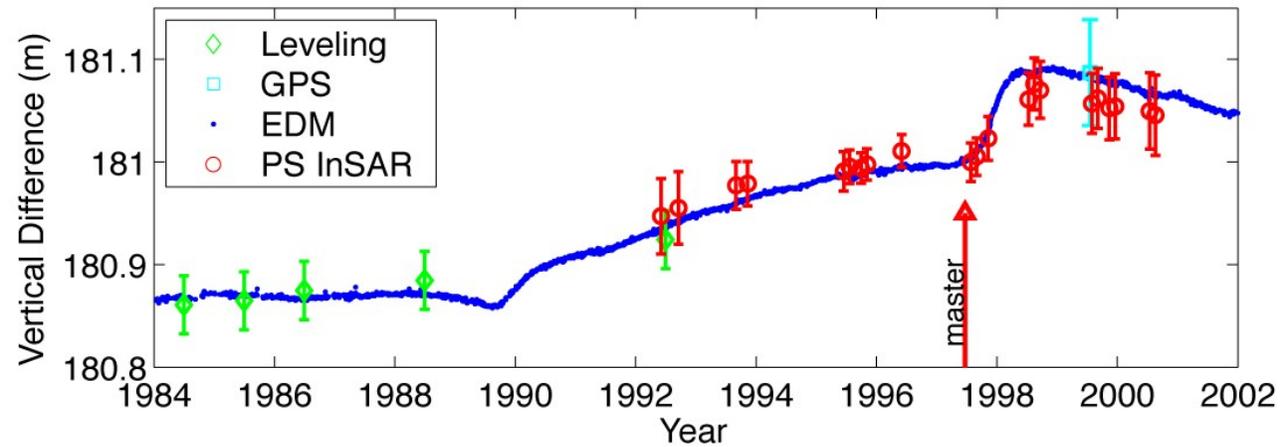
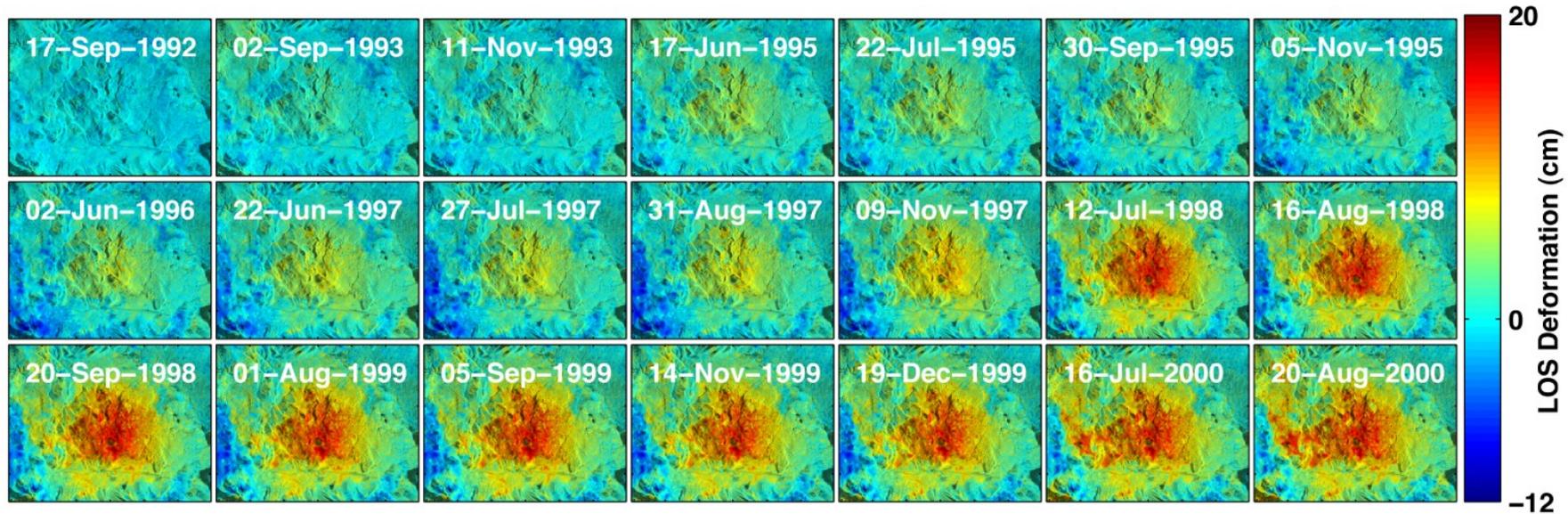
20 a 25 interferogramas para identificação dos PSC com significância estatística

Aplicações PSINSAR: Tectónica e Subsidência

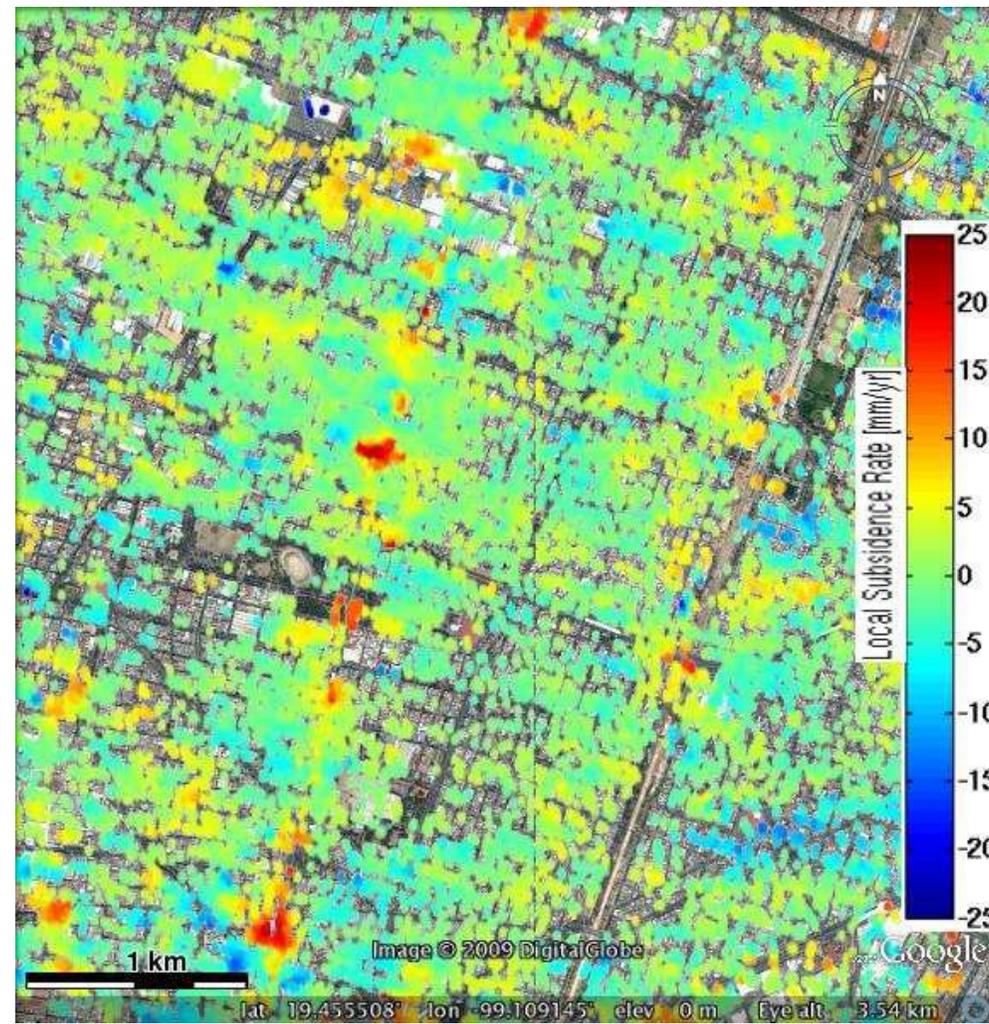
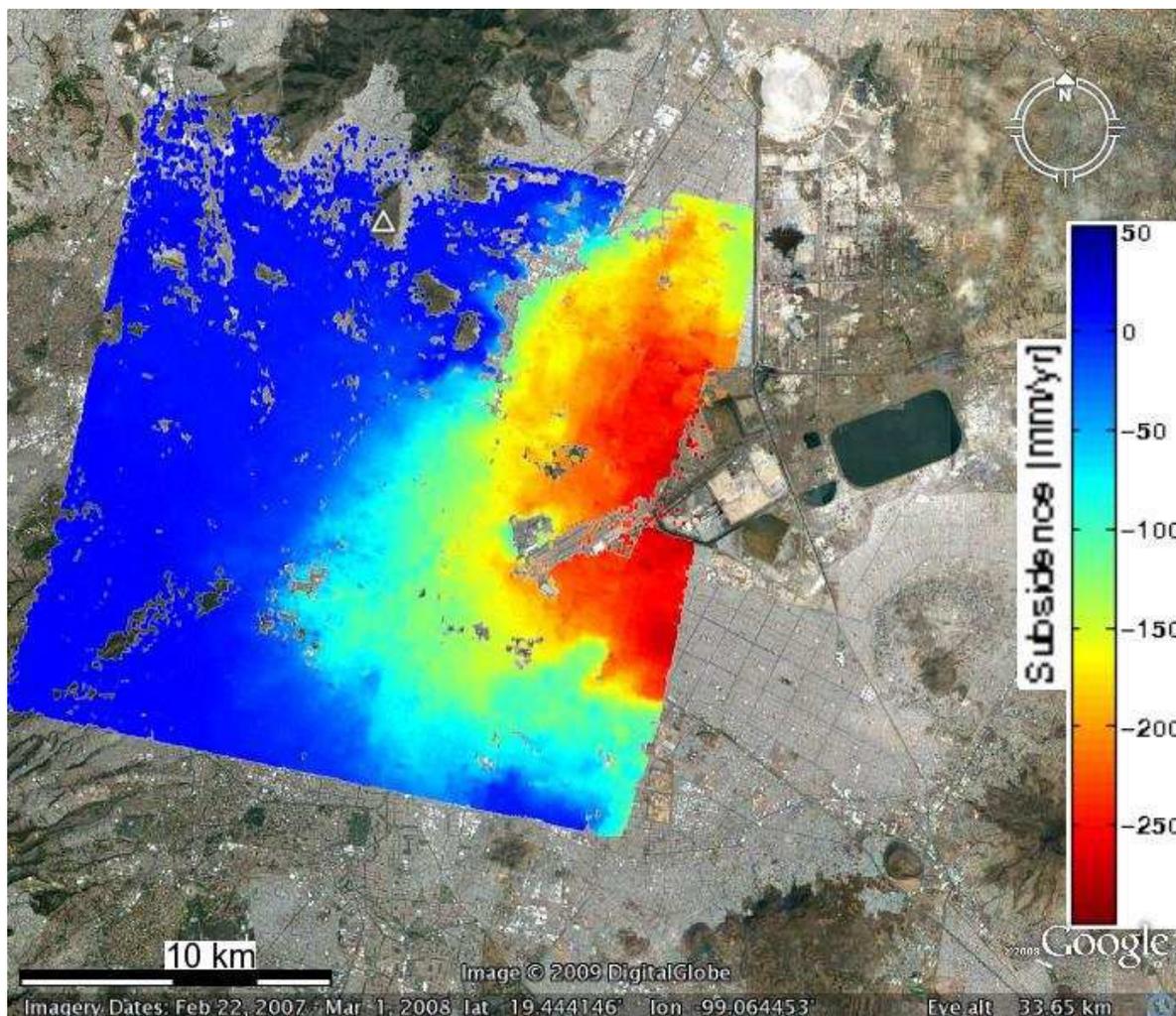


TRE, SA

Long Valley Caldera – PS InSAR



Aplicações PSINSAR: Subsidiência (extração de água)



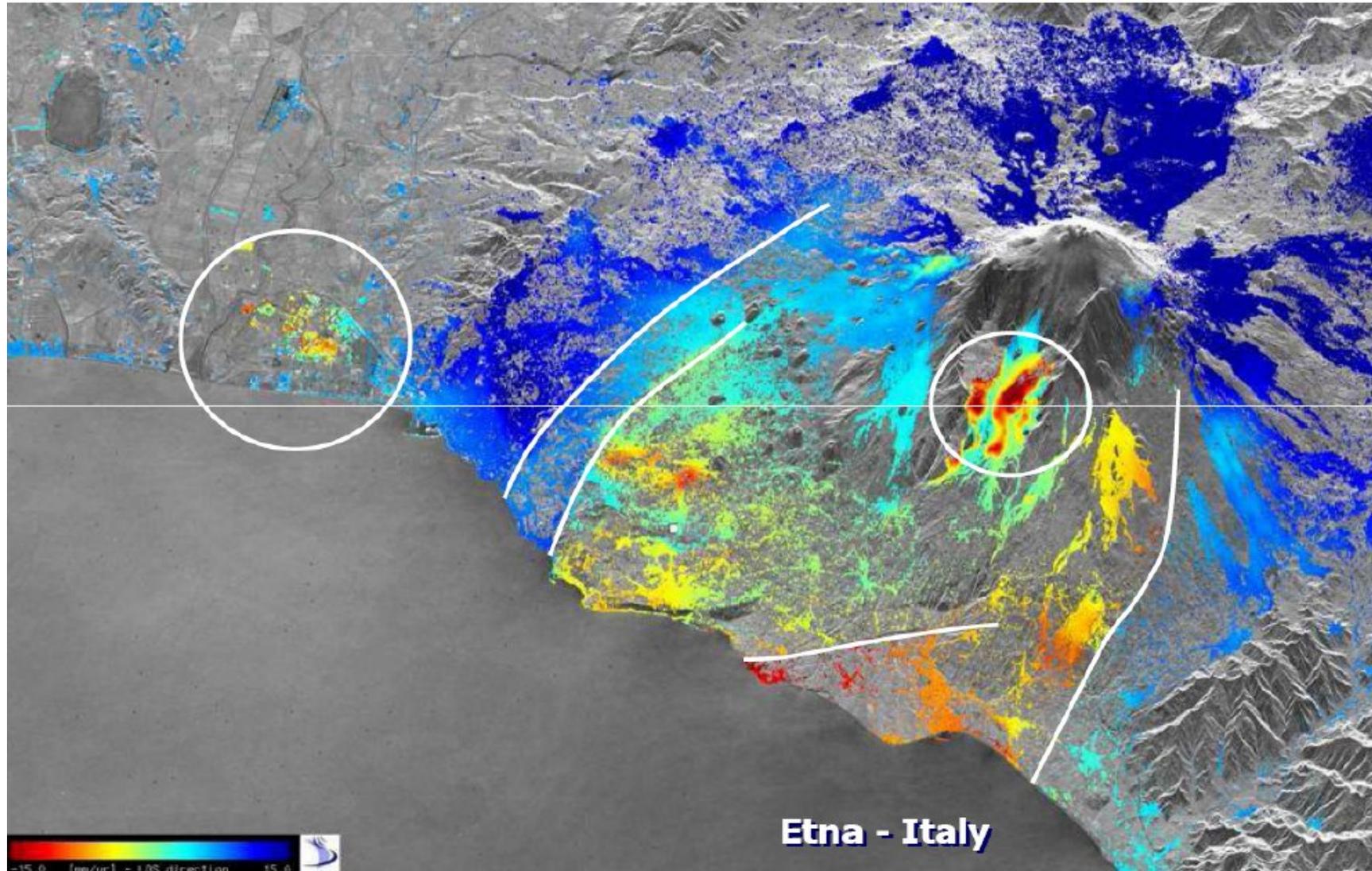
Cidade do México

Osmanoglu et al., 2011

João Catalão Fernandes (jcf Fernandes@fc.ul.pt)

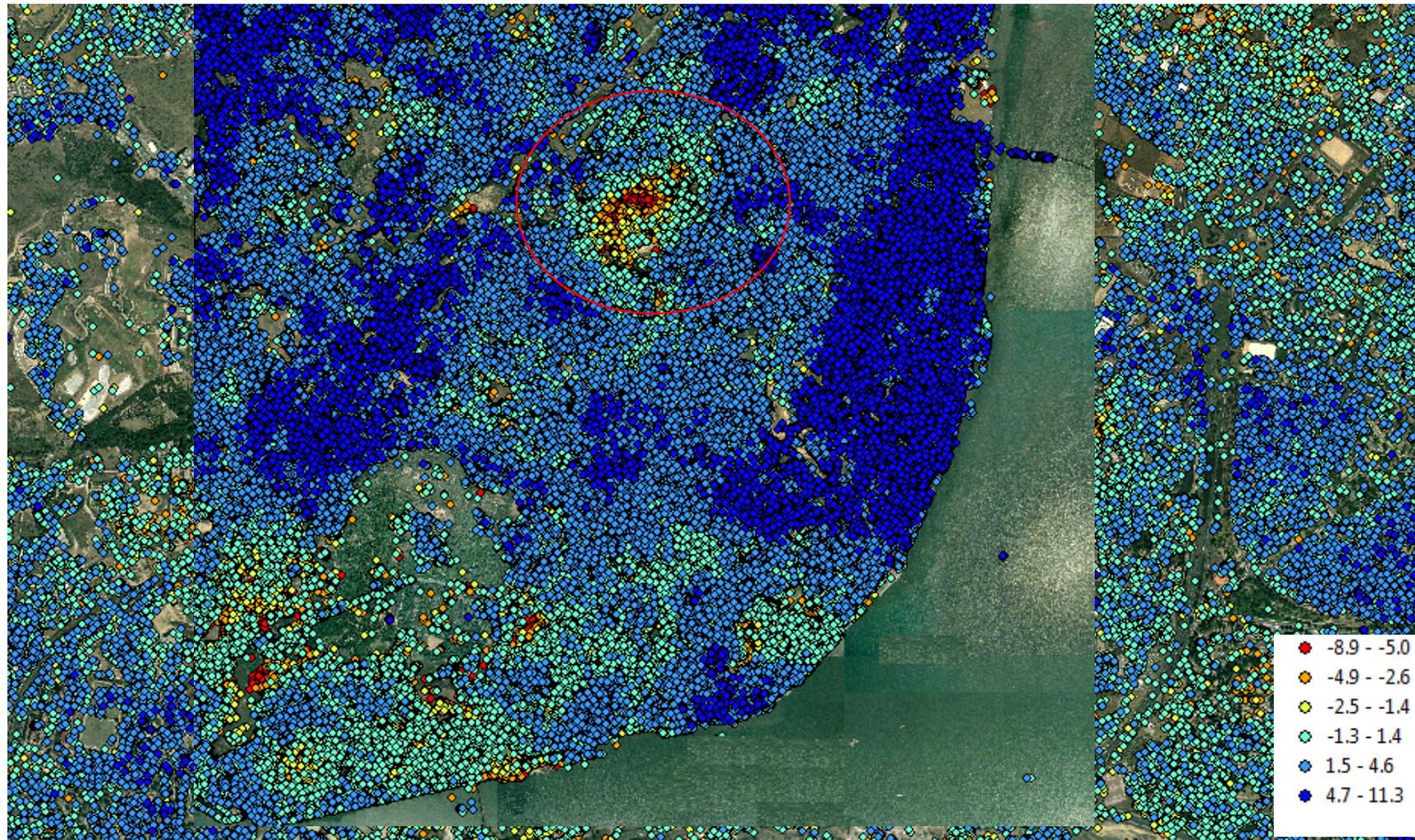
Subsidence rates for the period 16 January 2004 to 14 July 2006 using Envisat ASAR

Aplicações PSINSAR: Deslizamentos



TRE, ESA

Subsidencia em Lisboa (2010 – 2011), TSX



Catalão, J, et al.2011, 2015. Detection of ground subsidence in the city of Lisbon: comparison of InSAR and topographic measurements.

Aplicações PSINSAR: Modelo Digital de Elevação

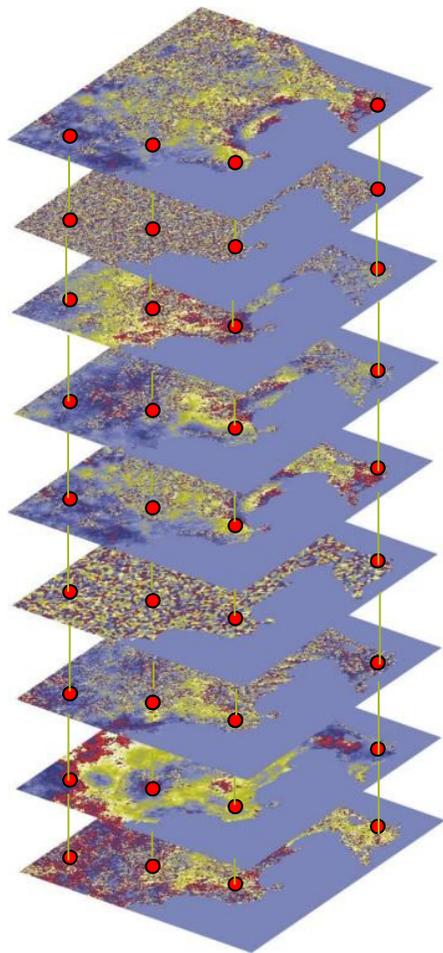


Crosetto, M., Monserrat, O., Iglesias, R.
and Crippa, B., 2010.

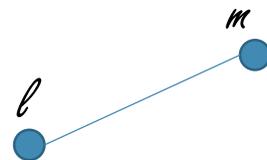


Zhu and Bamler, 2010

Limitações da técnica



1



Distância entre PSC < 2 km



Em ambientes naturais esta condição não é verificada.

2

Os PS devem obedecer a uma modelo predefinido de deformação, linear no tempo.



Muitos dos processos de deformação seguem processos não lineares no tempo (deslizamentos, vulcanismo)

Hooper et al. (2004) propõe um método baseado na análise da fase e na correlação espacial das fases, em alternativa a um modelo pré-definido de deformação.

Explora a correlação espacial do sinal de deformação.

O método Ferretti assume um modelo linear de deformação

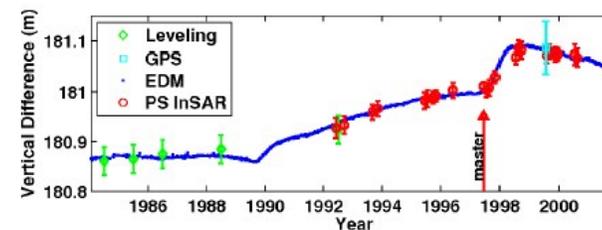
StaMPS PS Approach

Developed for more general applications, to work:

a) in rural areas without buildings (low amplitude)



b) when the deformation rate is very irregular



Análise da Fase

A fase de um pixel x no interferograma k é dado por:

$$\psi_x^k = W\{\phi_{x,def.}^k + \phi_{x,atmo}^k + \phi_{x,orb}^k + \phi_{x,\theta}^k + \phi_{x,noise}^k\}$$

A parte correlacionada do sinal é estimada usando um filtro da **média** no domínio das frequências e removido do sinal original:

$$\psi_x^k - \tilde{\psi}_x^k = W\left\{\frac{4\pi}{\lambda} B_{\perp,x}^k \Delta\theta_x^u + \phi_{x,noise}^{k,u} + \Delta_x\right\}$$

Equação não linear
devido à fase enrolada

u designa a parte espacialmente não correlacionada.

Hooper definiu a norma para a variação da fase residual de um píxel como:

$$\gamma_x = \frac{1}{K} \left| \sum_{k=1}^K \exp\left[i\psi(\psi_x^k - \tilde{\psi}_x^k - \Delta\tilde{\phi}_{x,\theta}^{k,u})\right] \right|$$

O valor de da fase topográfica é seleccionada por maximização desta norma.

γ_x é uma medida do nível de ruído da fase e uma indicação da estabilidade da fase de píxel e usada para decidir se um píxel é ou não um PS.

Seleção dos PS

Sabendo o valor de γ_x para cada pixel



Determinar valor γ^* que maximize a probabilidade do pixel x ser PS

$$q = \frac{(1 - \alpha) \int_{\gamma^*}^1 p_R(\gamma_x) d\gamma_x}{\int_{\gamma^*}^1 p(\gamma_x) d\gamma_x}$$

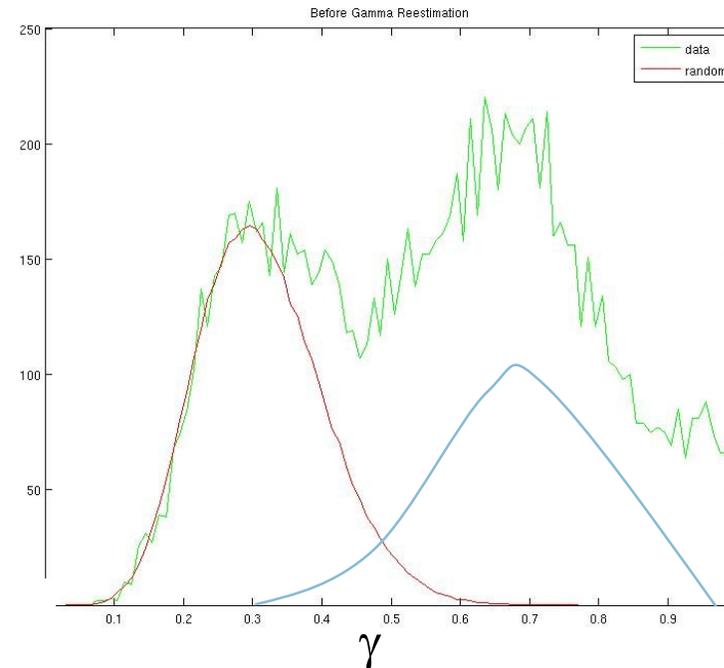
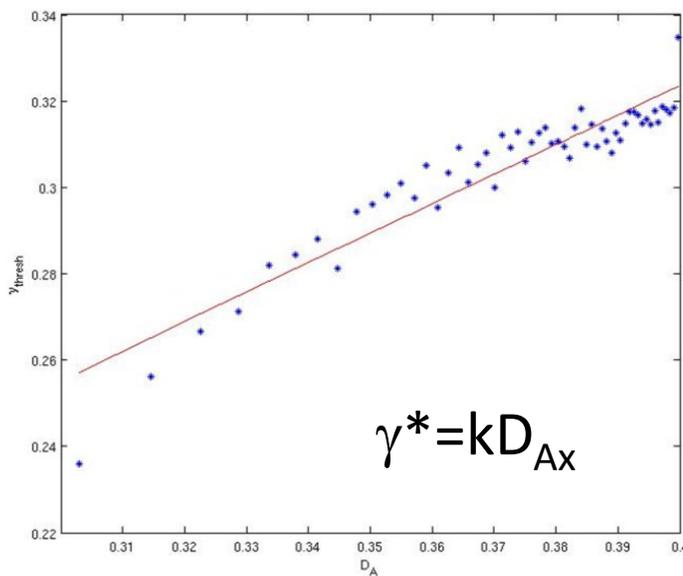


γ^*

q: é a probabilidade de seleccionar falsos PS

$(D_{A,x}, \gamma_x^*)$ →

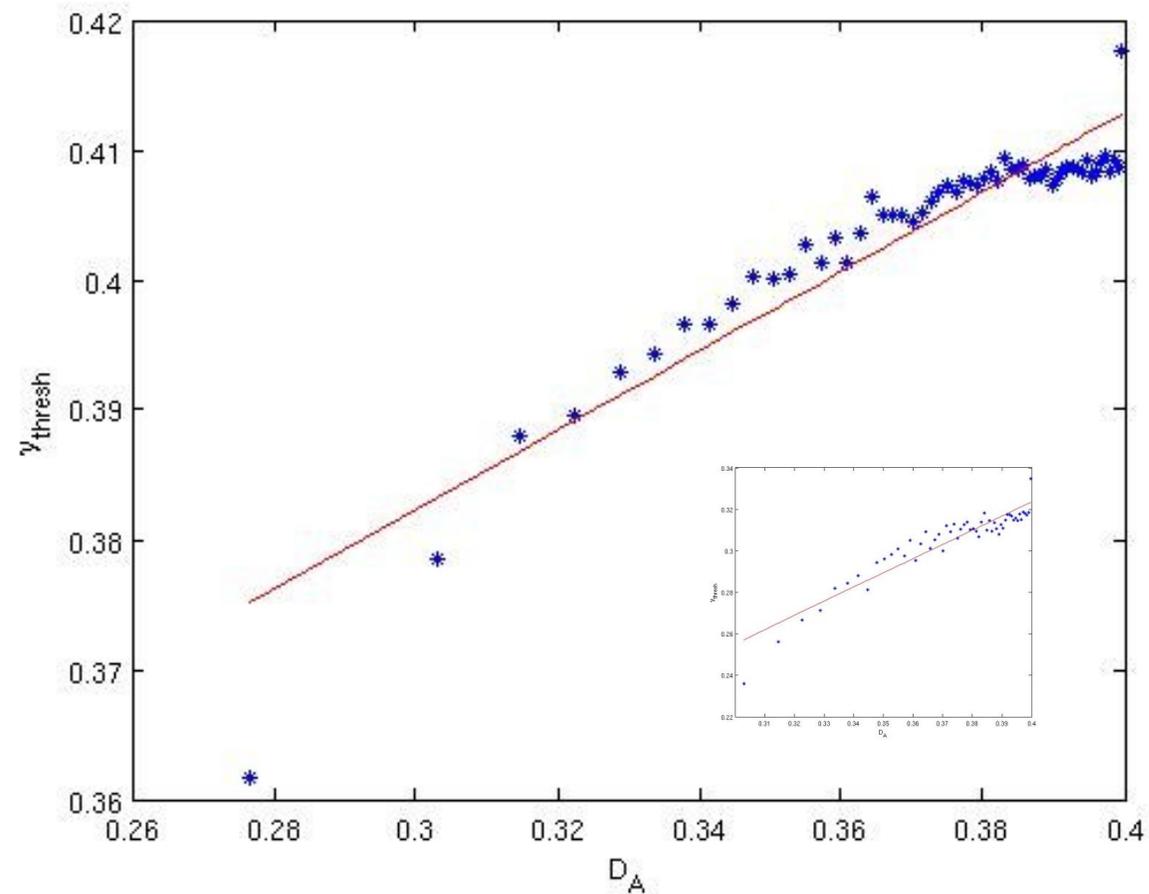
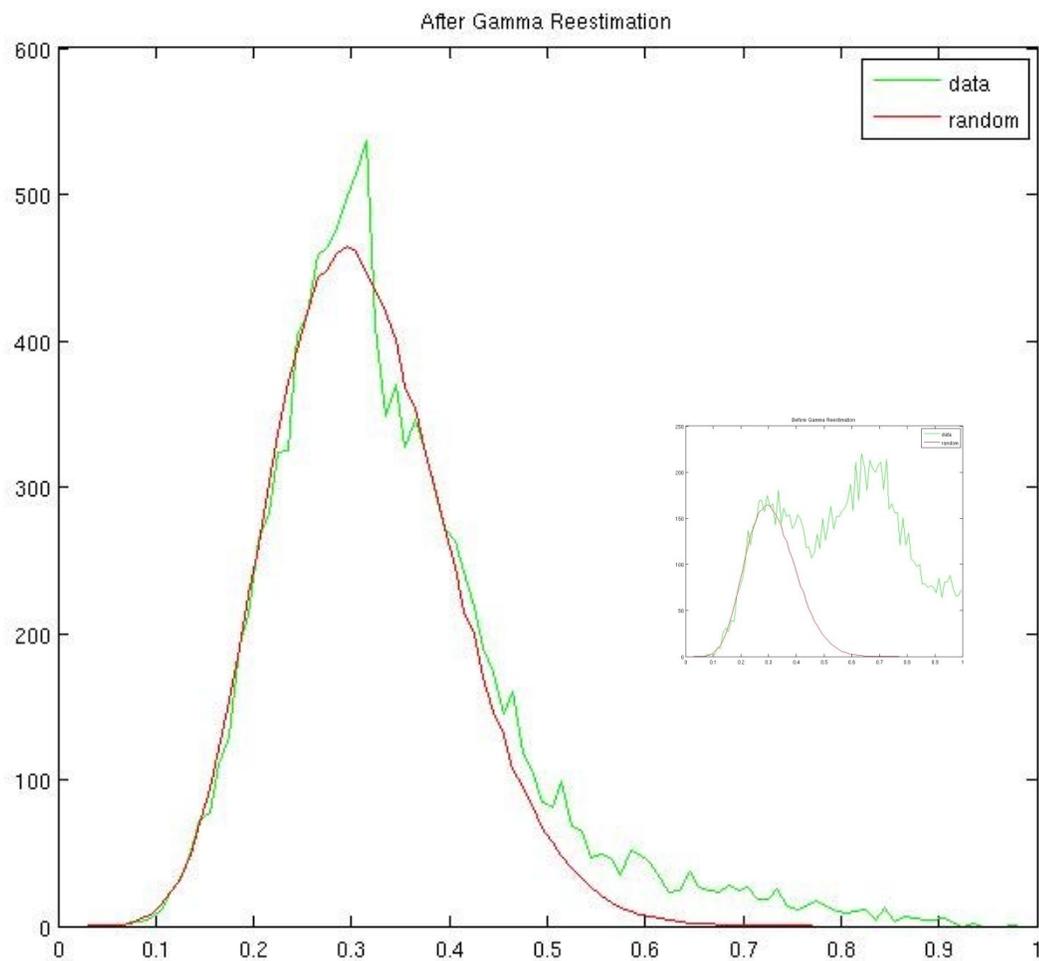
Determinar a constante de proporcionalidade k



Será PS todo o pixel que verifique a relação:

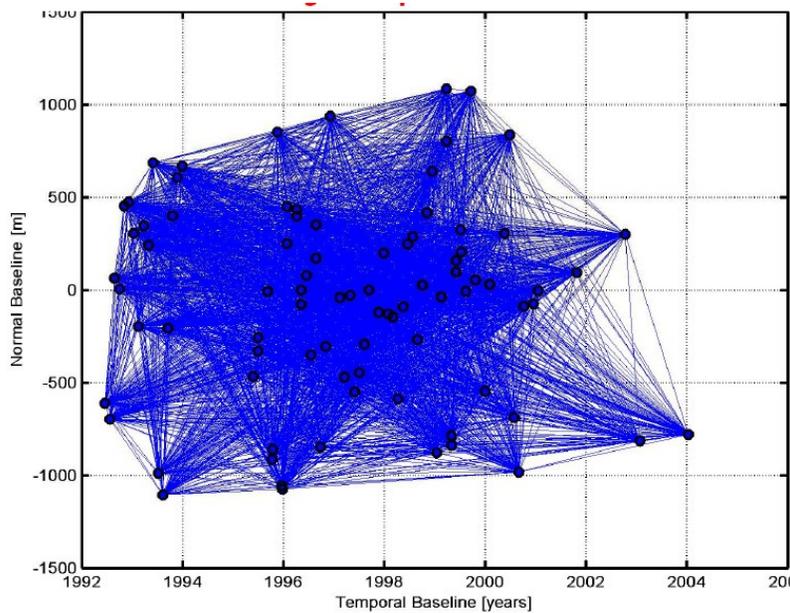
$$\gamma_x > k D_{A,x}$$

PS Selection (after)

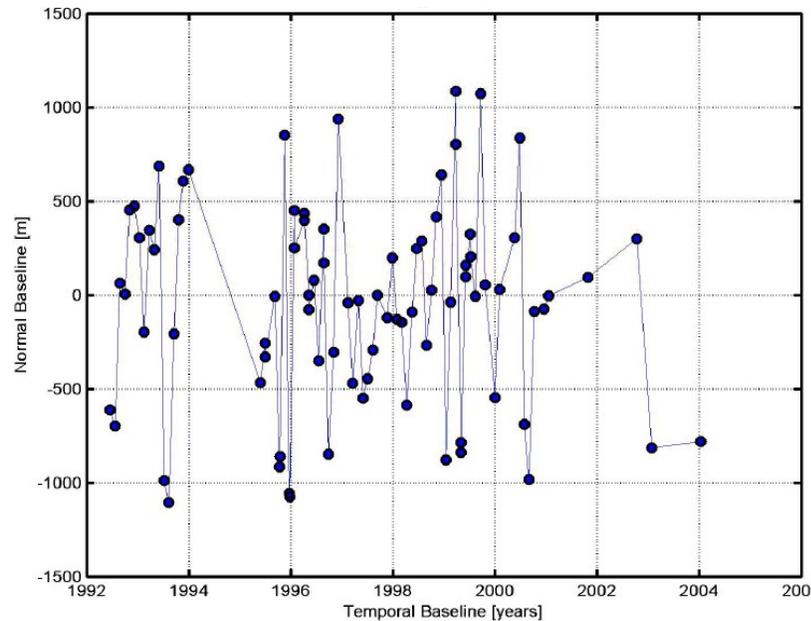


Estratégias para a combinação das imagens SAR

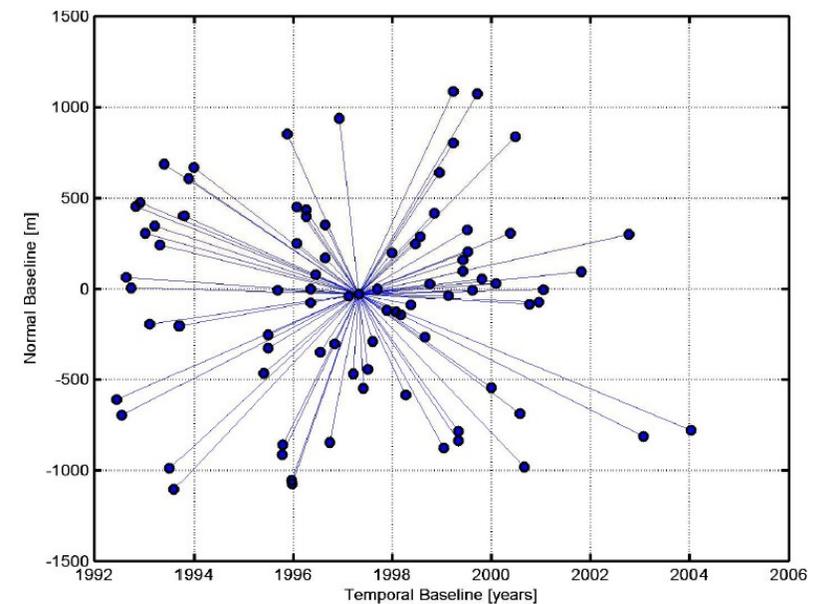
Todos com Todos



Temporal baseline minimization



PS analysis



Persistent Scatterers (Hooper)



Marques, F.O., Catalão, J., Hildenbrand, A.,
Madureira, P., 2015. Tectonophysics

Copyright: ©2014 Esri, DeLorme, HERE, Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Limitações da técnica PSInSAR

... numa perspectiva geodésica

(medição da forma e campo gravítico da Terra e suas variações temporais)

Série temporal limitada ao tempo de vida do satélite.

Aleatoriedade na localização dos PSs

Indefinição do sistema de referência coordenado

Necessidade de um elevado número e aquisições (superior a 20)

Medição na linha de vista do satélite (LOS)

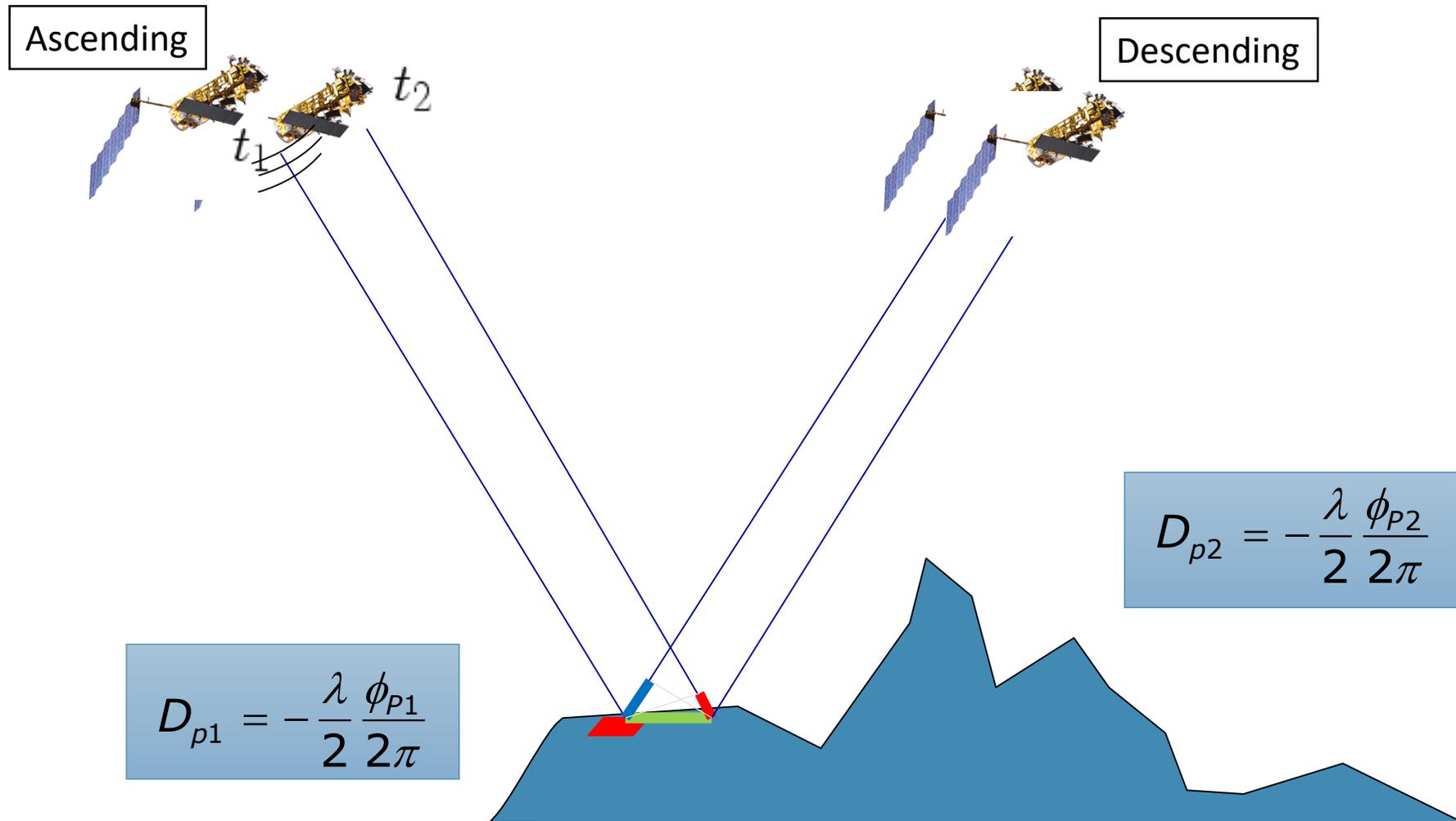
Insuficiente modelação dos efeitos atmosféricos

Modelo Funcional + Modelo estocástico

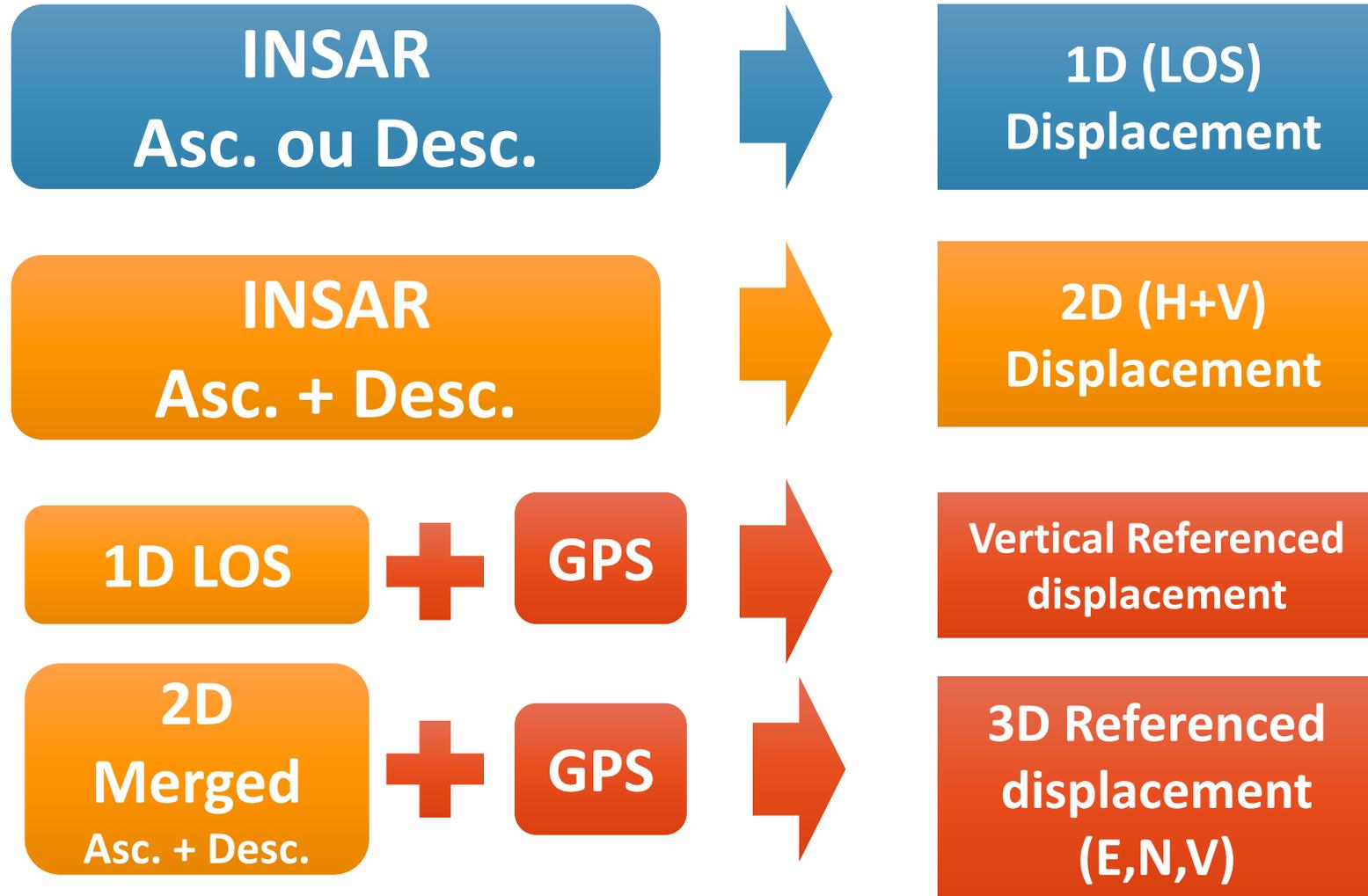


STUN, Bert Kampes, 2006

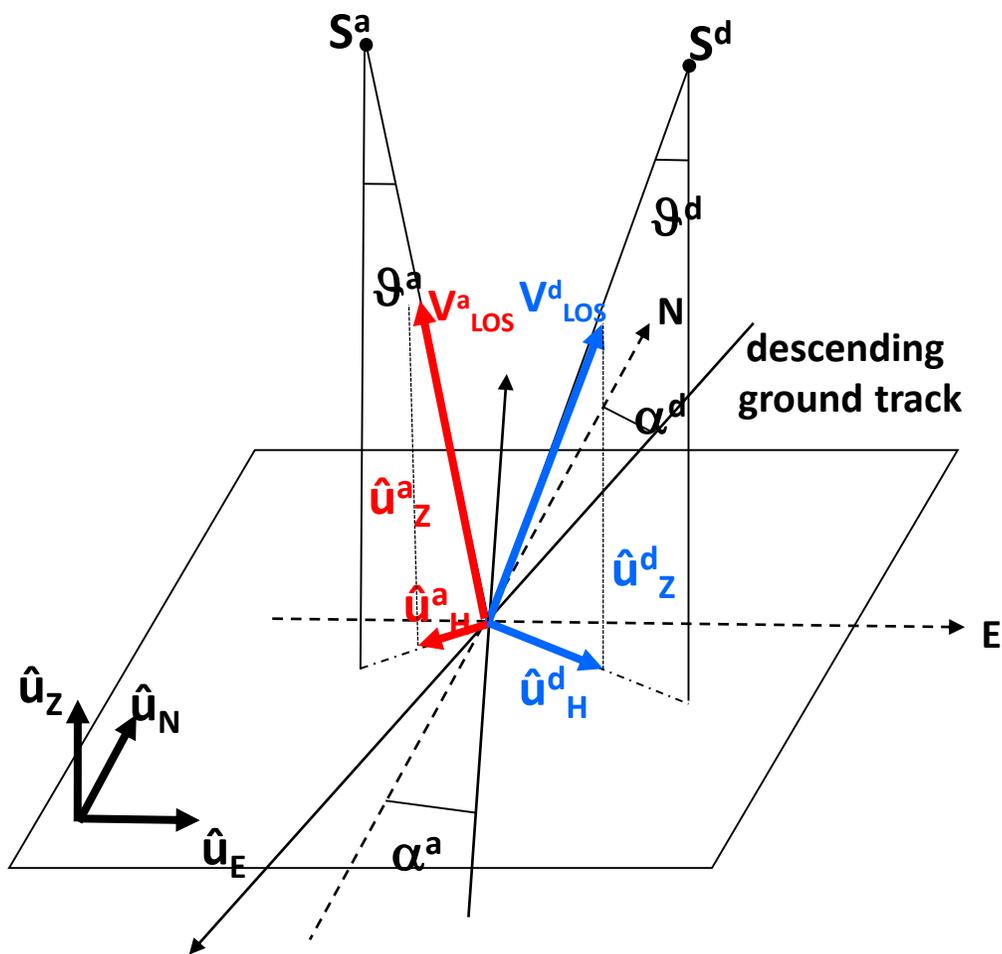
Deformation and Phase



InSAR displacement decomposition



Deslocamento 2D (horizontal + vertical)



$$V_{LOS} = (V_E, V_N, V_Z) \cdot (u_E, u_N, u_Z)$$

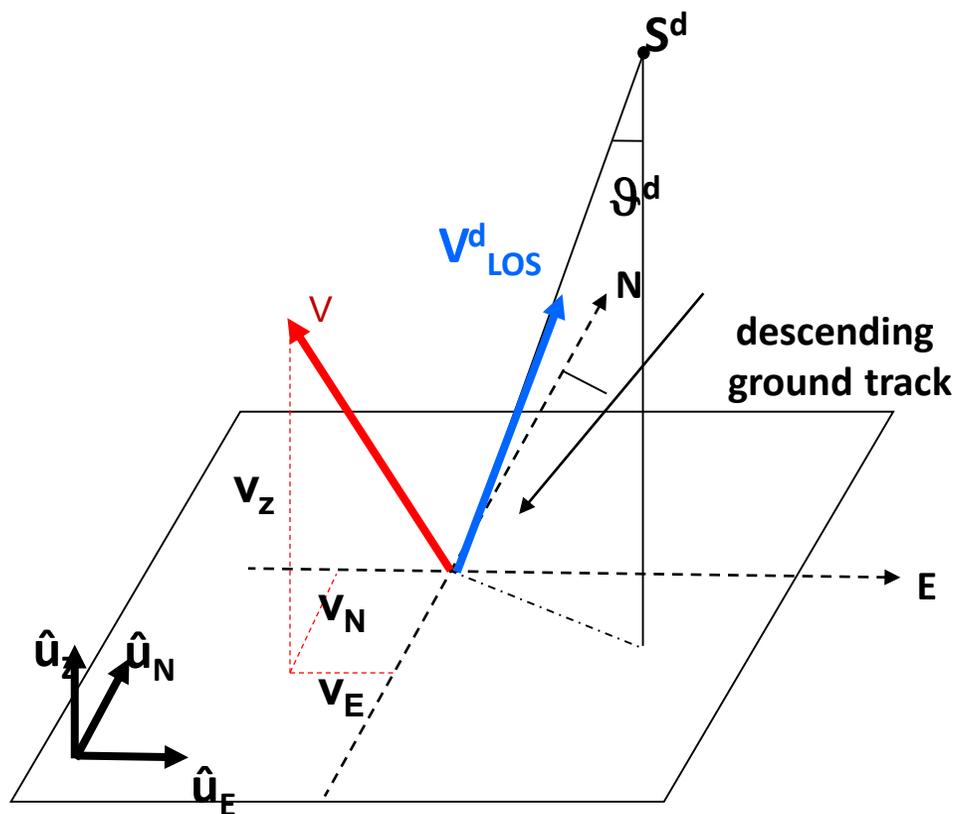
$$\begin{cases} V_{LOS}^a = (V_E, V_N, V_Z) \cdot (u_E^a, u_N^a, u_Z^a) \\ V_{LOS}^d = (V_E, V_N, V_Z) \cdot (u_E^d, u_N^d, u_Z^d) \end{cases}$$

$$\begin{cases} V_{LOS}^d = V_H u_H^d + V_Z u_Z^d \\ V_{LOS}^a = V_H u_H^a + V_Z u_Z^a \end{cases}$$



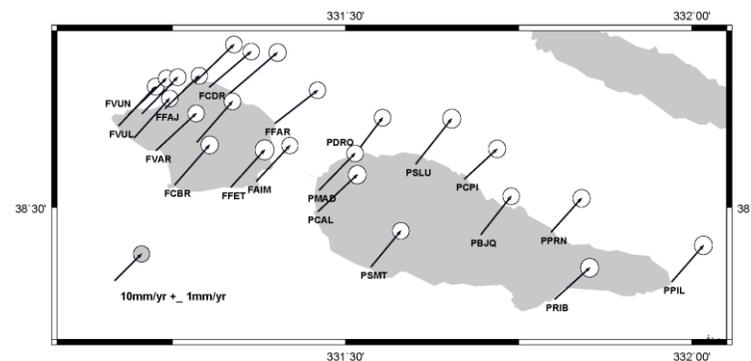
$$(V_H, V_Z)$$

Integração com GPS



$$V_{LOS} = (V_E, V_N, V_Z) \cdot (u_E, u_N, u_Z)$$

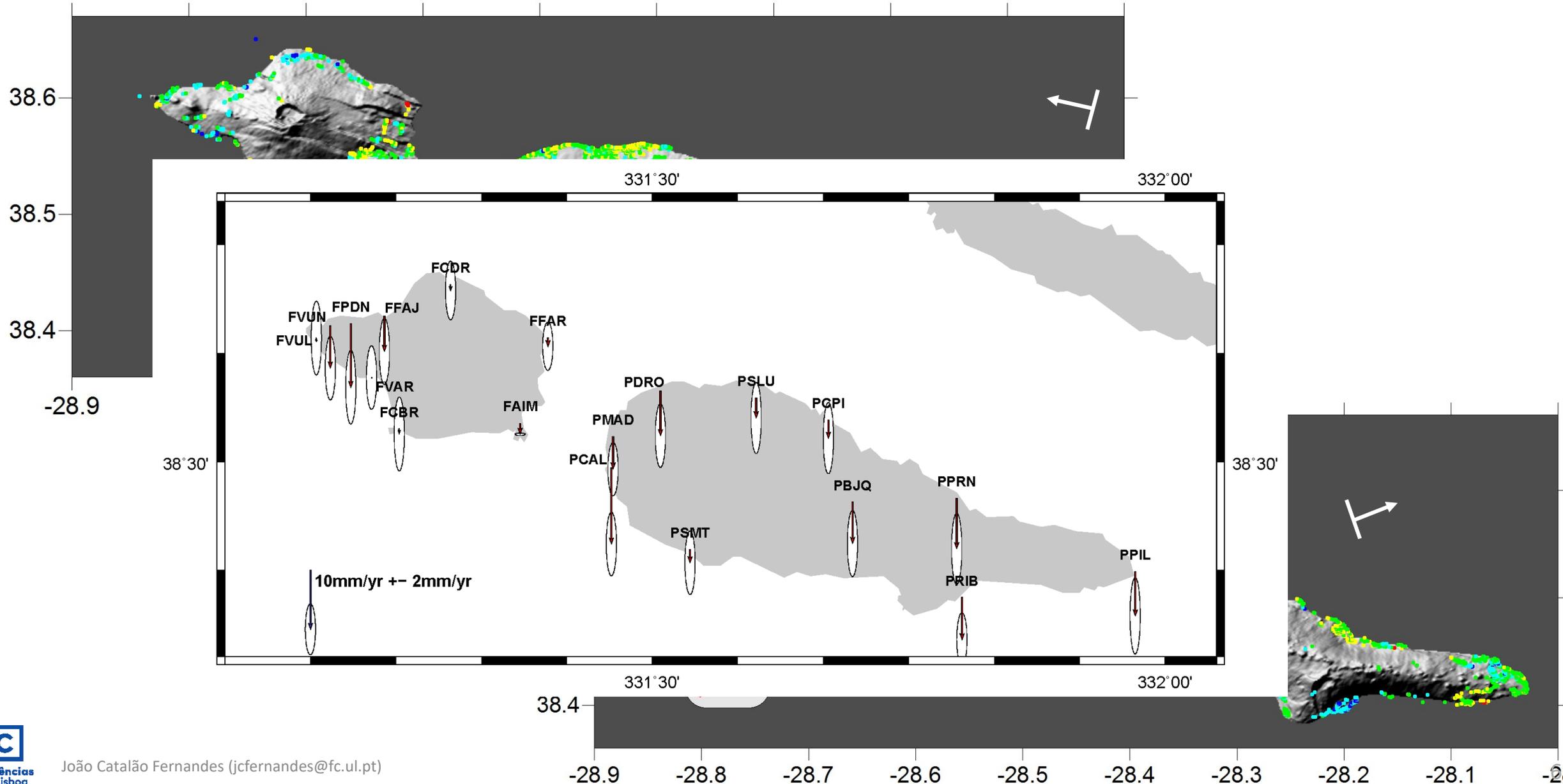
$$V_{LOS} = v_E u_e + v_N u_n + v_Z u_z$$



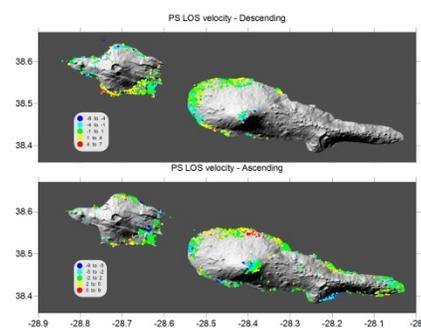
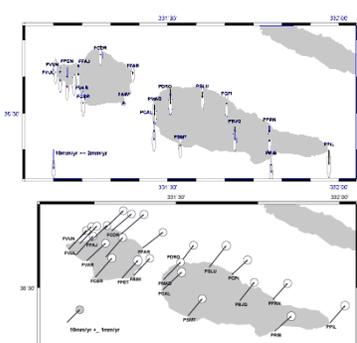
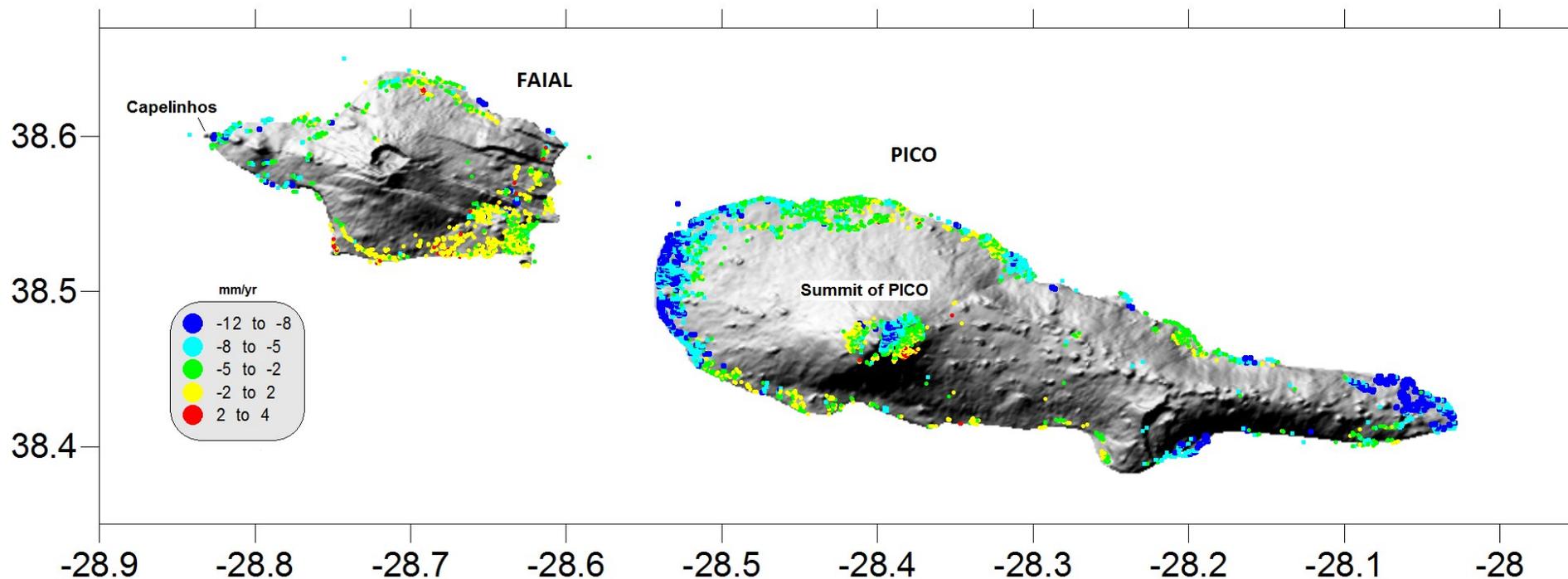
$$v_Z = \frac{1}{u_z} (V_{LOS} - \hat{v}_{GPS}^e u_e - \hat{v}_{GPS}^n u_n) \quad (V_{LOS}^e, V_{LOS}^n)$$

$$E = \sum_{i=1}^{N_{GPS}} \left\{ \mu(v_{LOS}^z)(i) + D - v_{GPS}^z(i) \right\}^2$$

PS LOS velocity - Descending



Velocidade Vertical ITRF2008 (2007-2009)



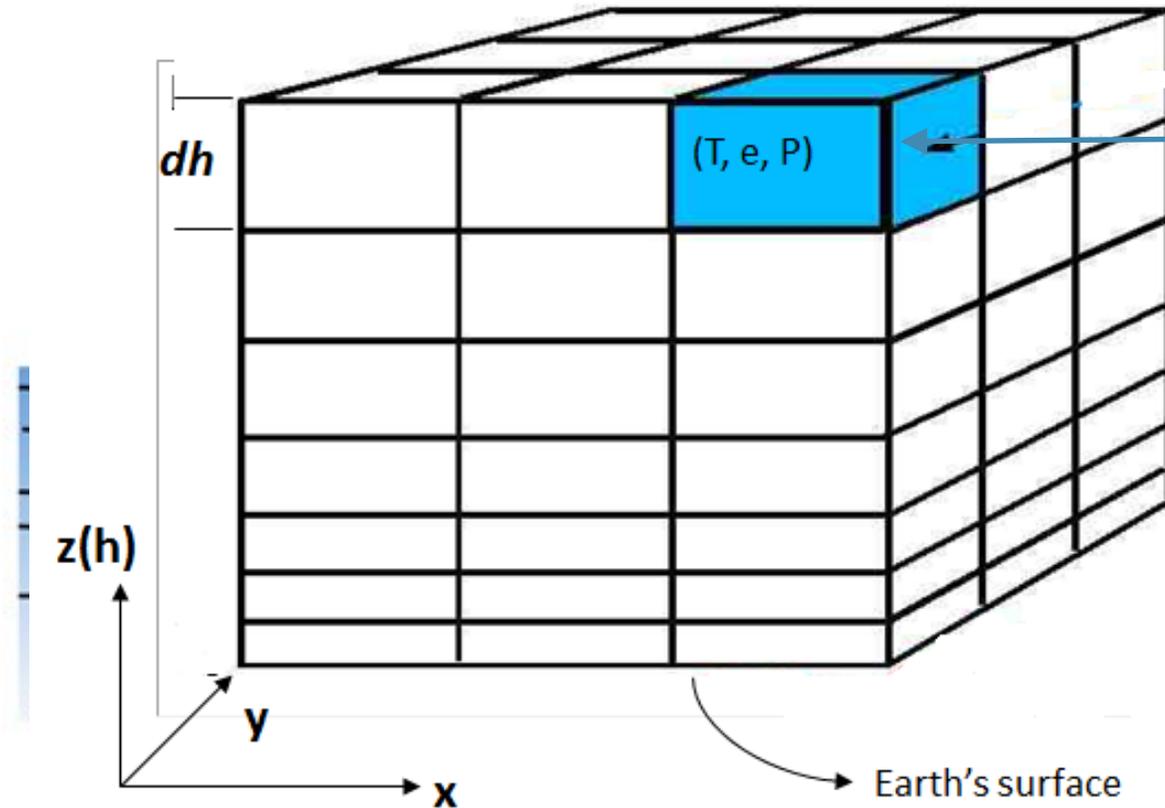
$$E = \sum_{i=1}^{N_{GPS}} \left\{ \mu(v_{PS}^v)(i) + D(\varphi, \lambda) - v_{GPS}^v(i) \right\}^2$$

$$D(\varphi, \lambda) = \alpha \cos\varphi \cos\lambda + \beta \cos\varphi \sin\lambda + \gamma \sin\varphi + \delta$$

Catalão et al., 2011

Efeitos atmosféricos

- Weather Research and Forecast (WRF)
- ERA5



$$T + e + P$$

$$N = \underbrace{k_1 \frac{P}{T}}_{N_{hydrostatic}} + \underbrace{k_2 \frac{e}{T} + k_3 \frac{e}{T^2}}_{N_{wet}}$$

$$\Delta L = ZTD = \sum_{i=1}^{i=L} N_i \cdot dh_i$$

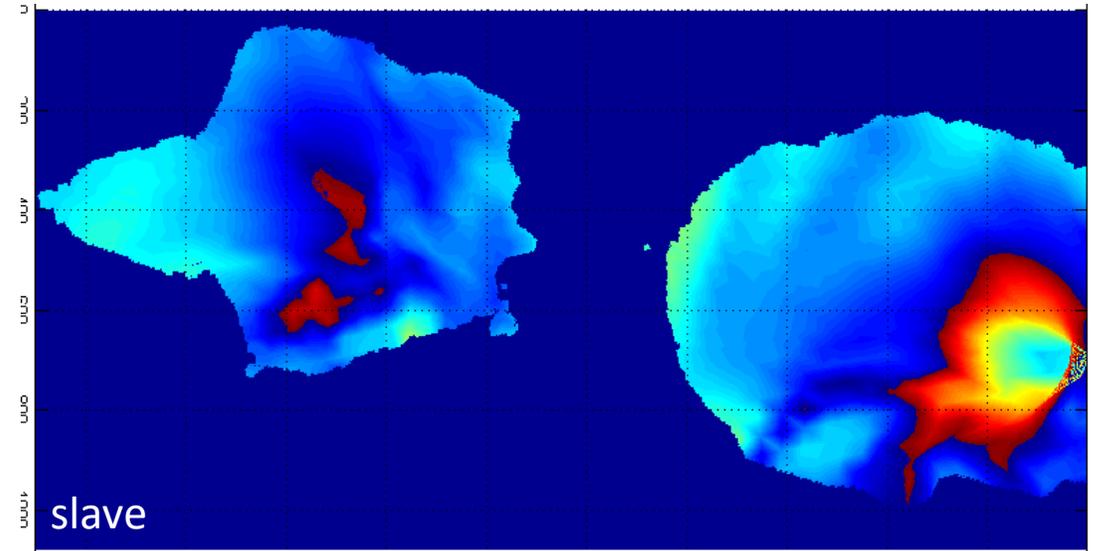
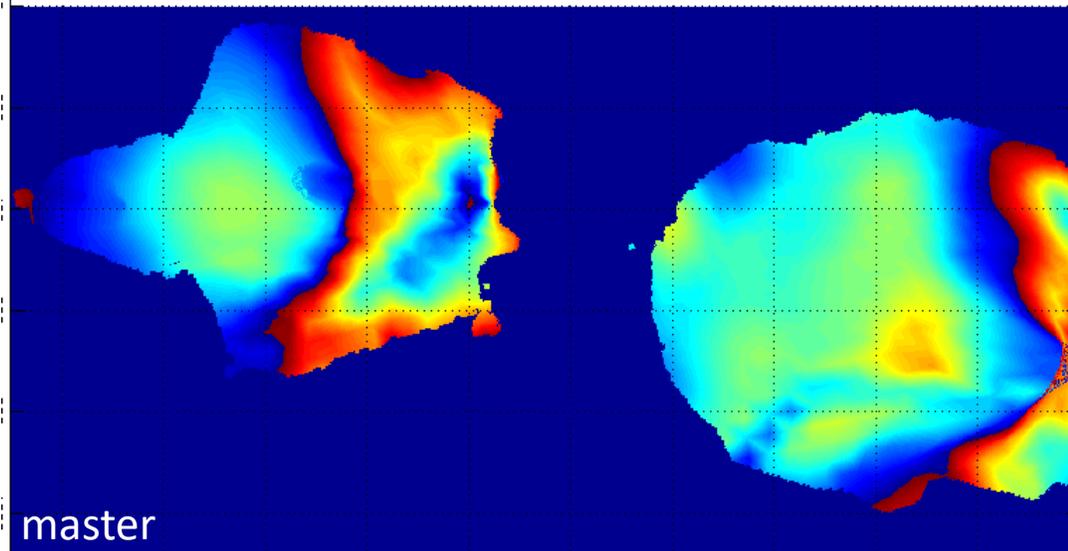
dh : thickness; L : total number of layers

$$\Delta L(\text{zenital}) = \int_0^h N(h) dh$$

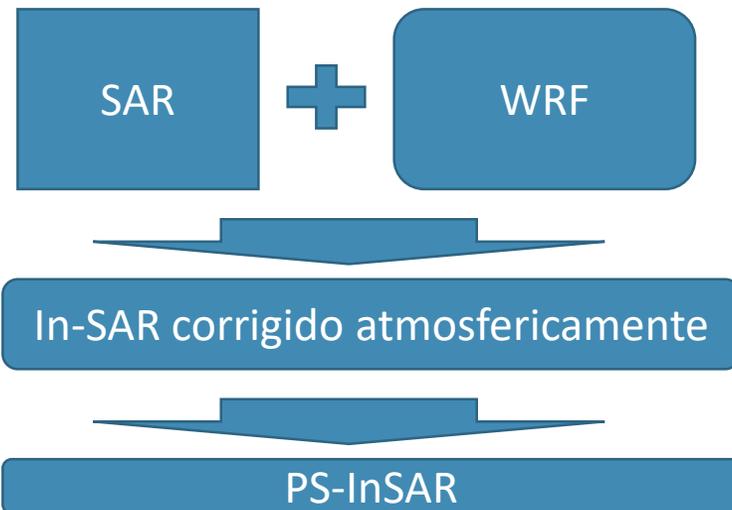
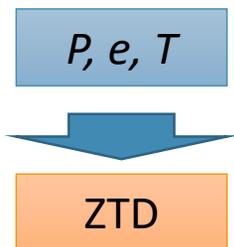
$$DZD = ZTD^{t_m} - ZTD^{t_s}$$

Atraso Diferencial

Mitigação dos efeitos atmosféricos



Modelo WRF
Resolução 1km²



Processing	PICO	FAIAL
PS	4.6	7.2
PS+WRF	3.7	5.7
PS+GPS	1.9	2.1
PS+WRF+GPS	1.6	1.5

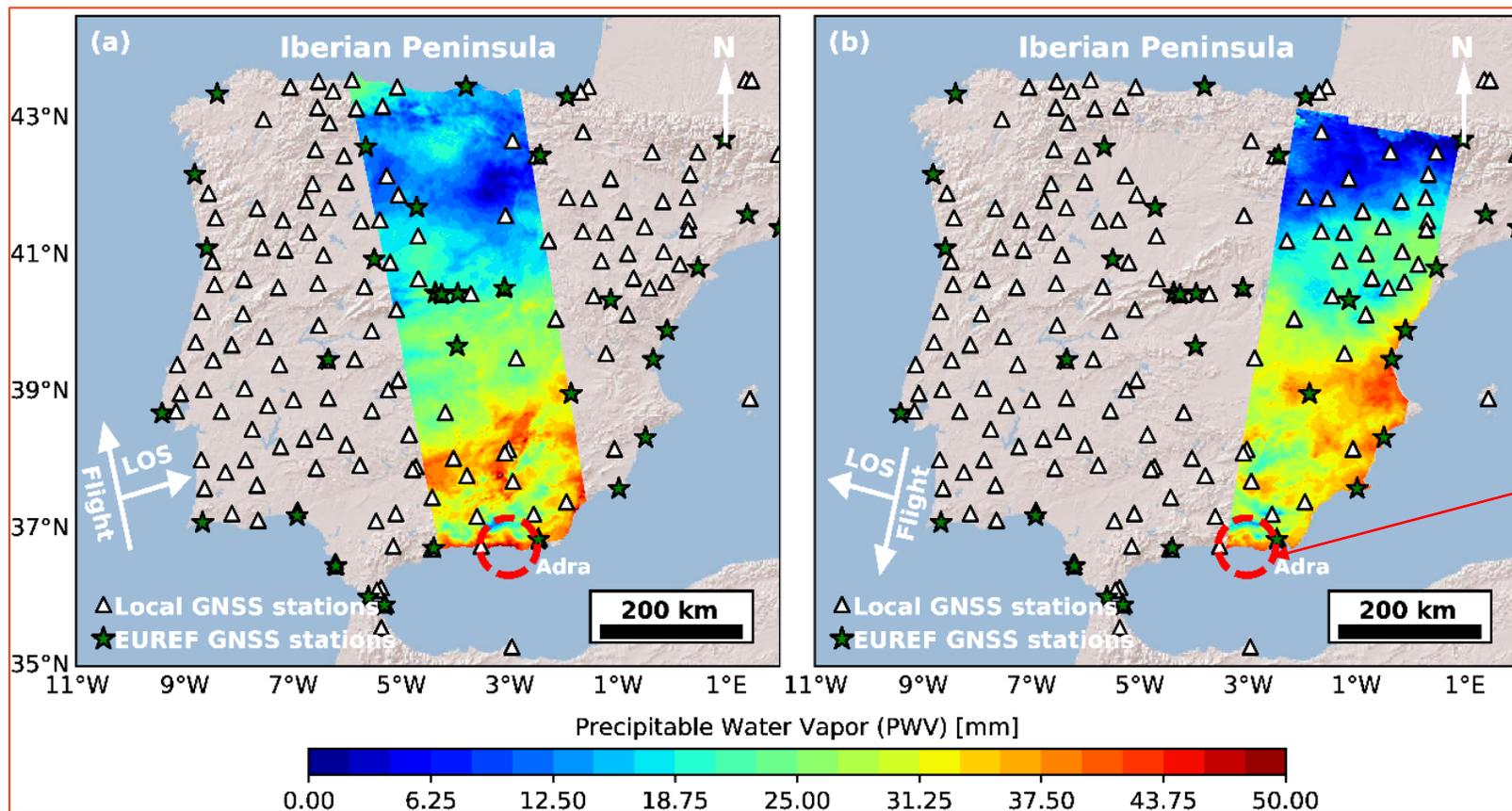
mm/yr

rms da diferença de velocidades GPS e PSInSAR

Catalão, et al., 2011.

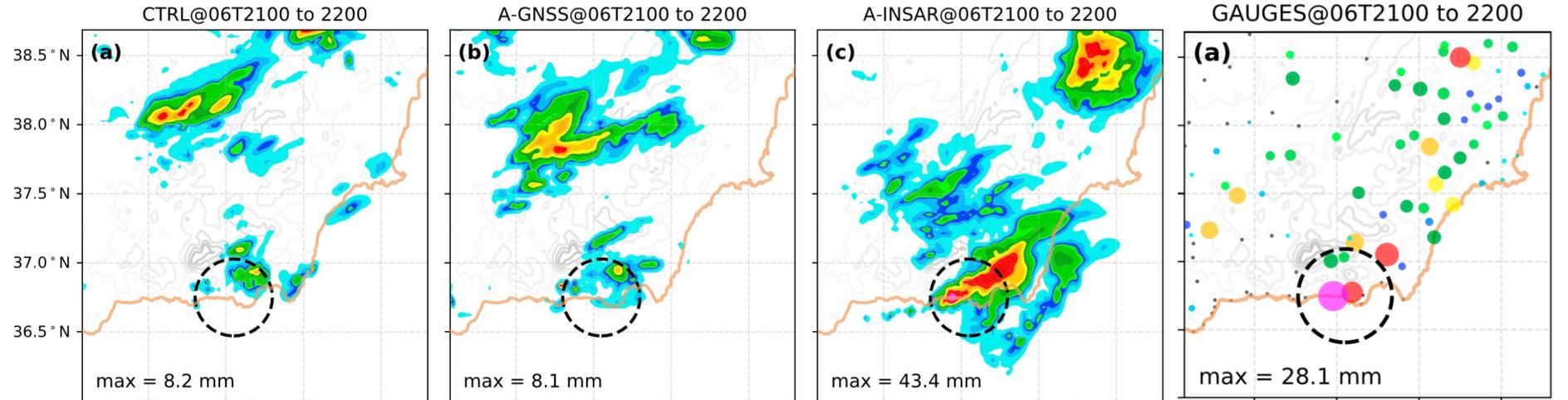
2015/9/6 18:10

2015/9/7 6:10

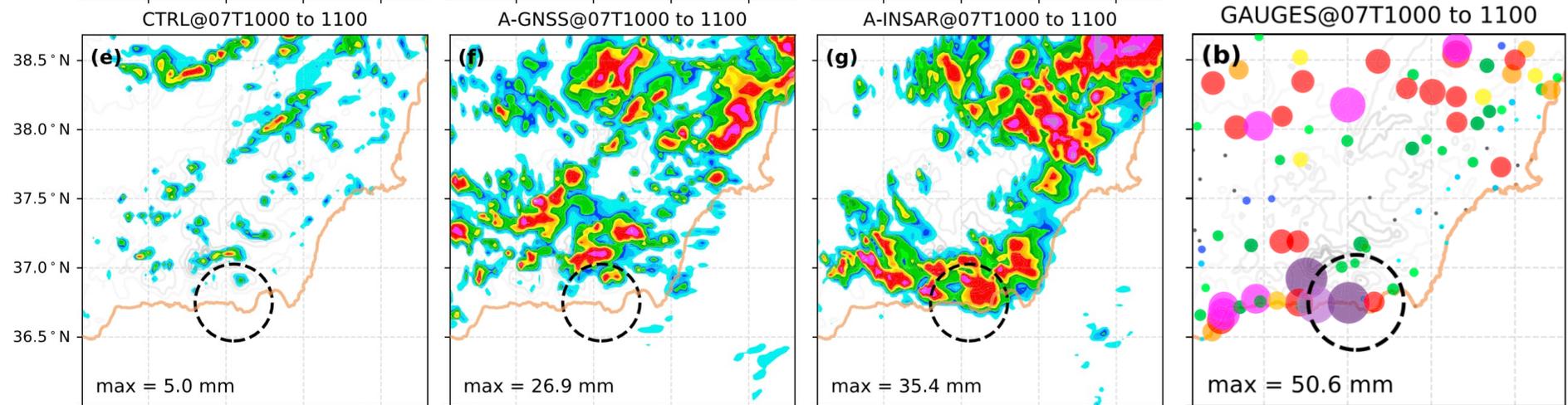


Rain

First storm

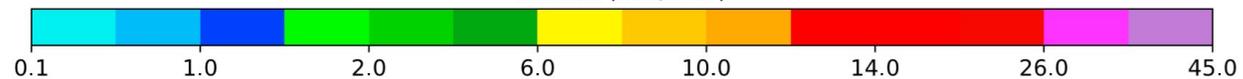


Second storm



Height (m): 50 to 2950 by 500

Rainfall (mm/hour)



Perspetivas para o radar de abertura sintética

SAR

SAR Polarimetry

InSAR

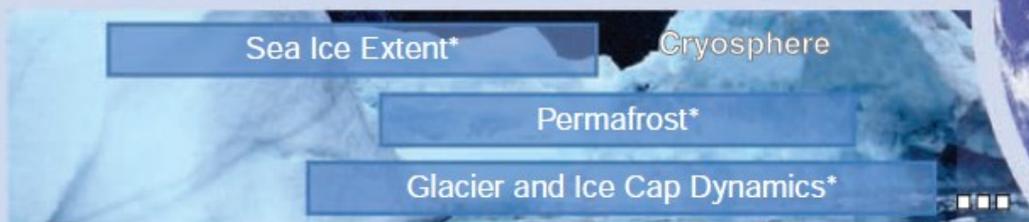
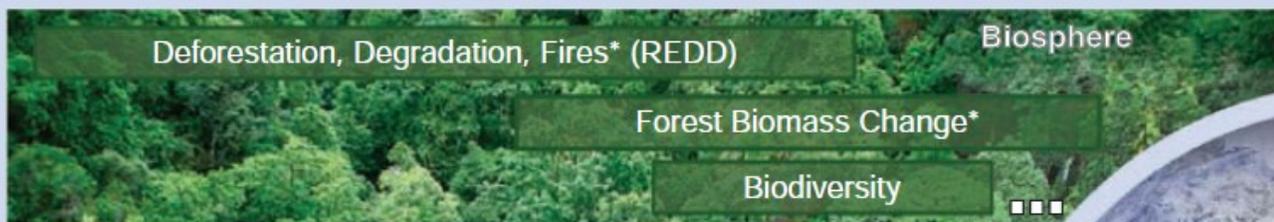
SAR

InSAR

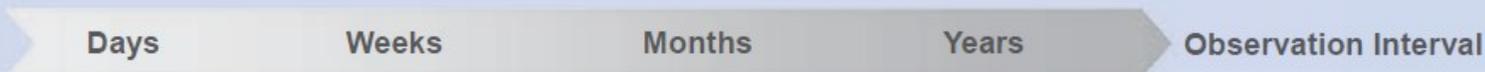
SAR

InSAR

SAR Polarimetry



*) Essential Climate Variables



(Moreira et al, 2013)

Síntese

> Interferometria Radar de Abertura Sintética Diferencial
Potencialidades e Limitações

> Persistent Scatterer vs Distributed Scatterer

> Técnica dos Persistent Scatterer,
abordagem Ferretti et al. e Hooper et al., 2004
análise da amplitude vs análise da fase

> Integração INSAR com GPS

> Mitigação dos efeitos atmosférico

Melhoria na estimativa da
deformação

> ESA / COPERNICUS, Global Monitoring for Environment and Security

