

Persistent Scatterer Interferometry **uma abordagem geodésica na medição da deformação**

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Cap. 7 Interferometria SAR

Tópicos

1. Interferometria RADAR de abertura sintética (SAR)
2. *Persistent Scatterer* e análise de séries temporais
3. Fusão de dados InSAR e GPS
4. Mitigação dos efeitos atmosféricos
5. Perspetivas para a interferometria SAR

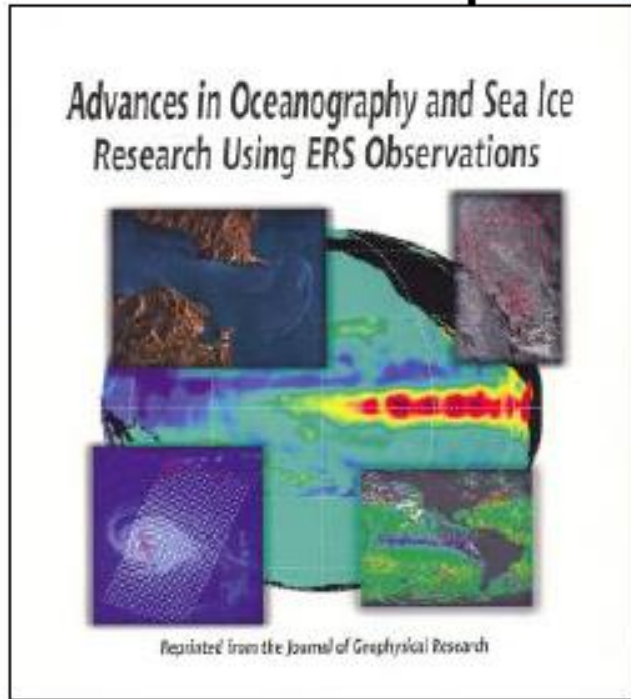
Radar de abertura Sintética



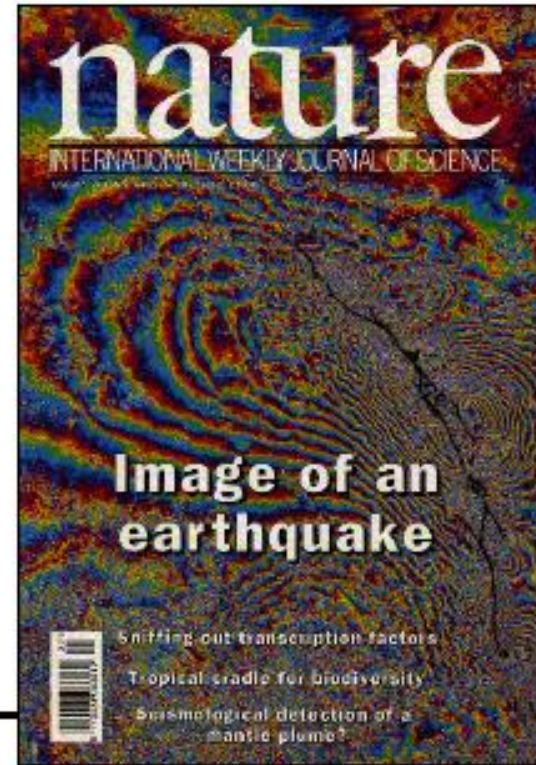
(2000)

ERS and Volcanic activities

Oceanography and sea Ice

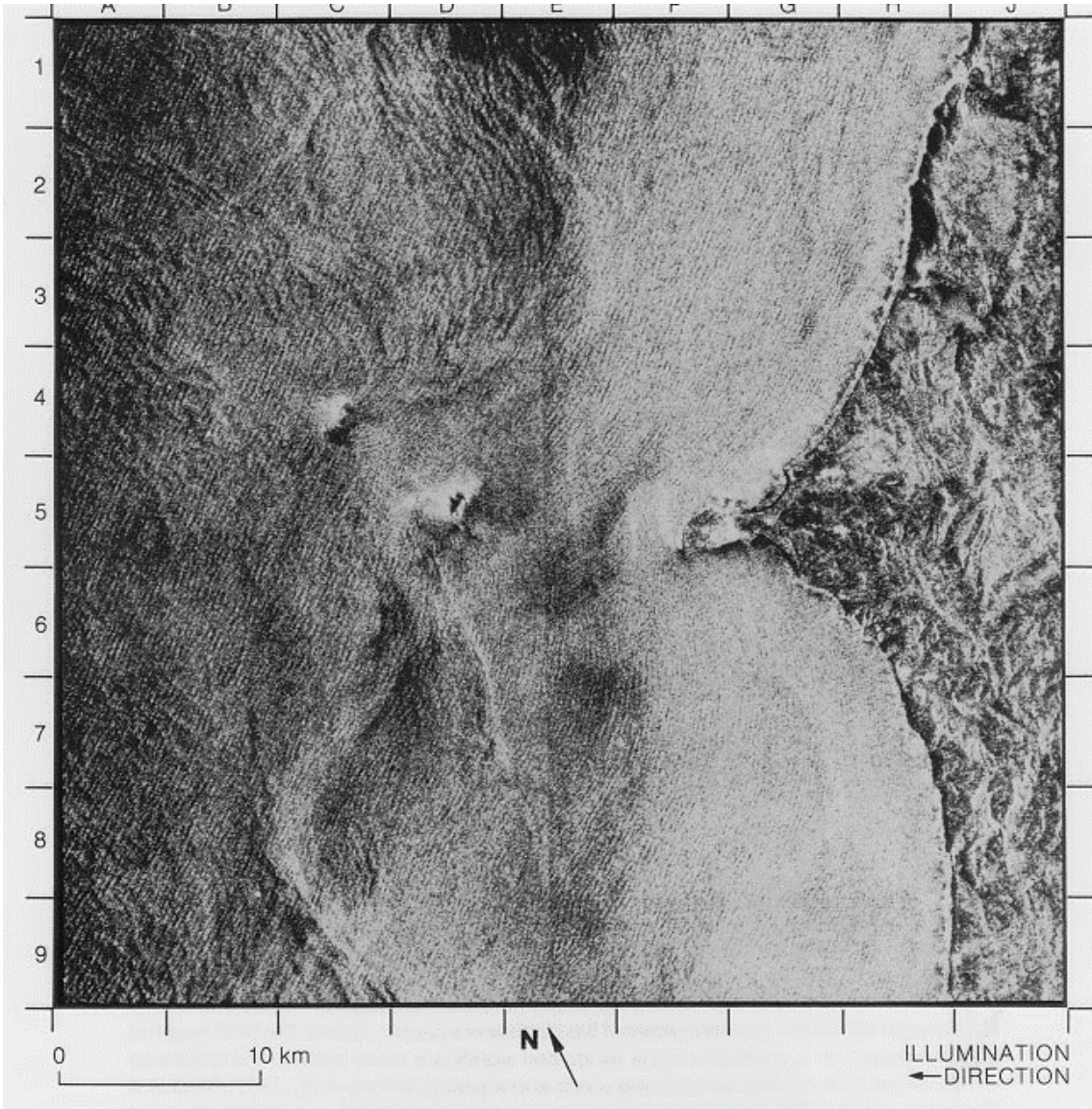


ERS and SAR Interferometry



(1993)

Introdução



Seasat SAR

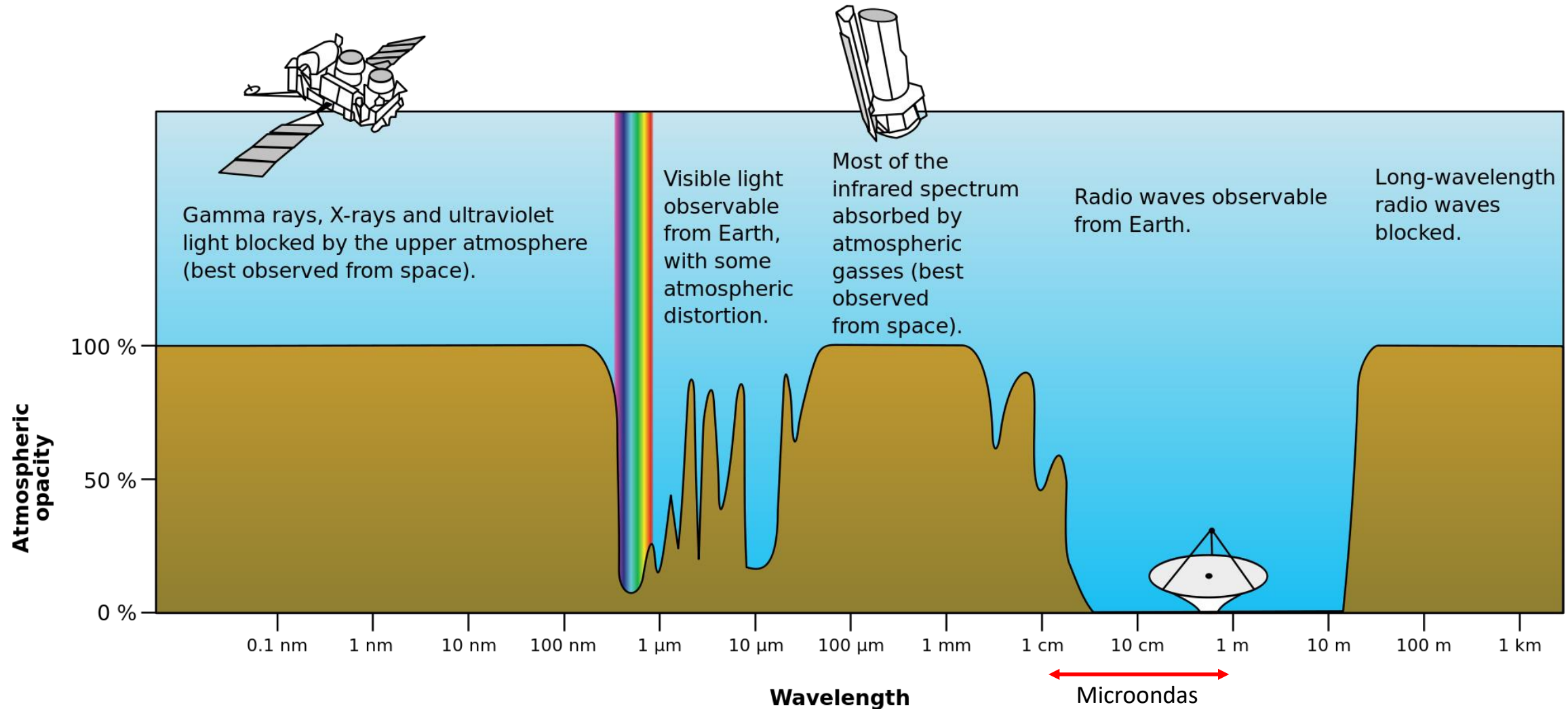
One of the microwave radars on board Seasat was a synthetic-aperture radar (SAR).

(Radar de Abertura Sintética, banda L)

The refraction of impinging deep ocean waves by varying bottom topography in near-shore areas is one of the major concerns of coastal engineers. This image shows how deep ocean waves are refracted by the bottom topography west of Portugal.

Fu, L-L, Holt, B., **1982**. Seasat Views Oceans and Sea Ice with Synthetic-Aperture Radar. JPL Publication 81-120, NASA, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, p. 200.

Deteção Remota na banda das microondas

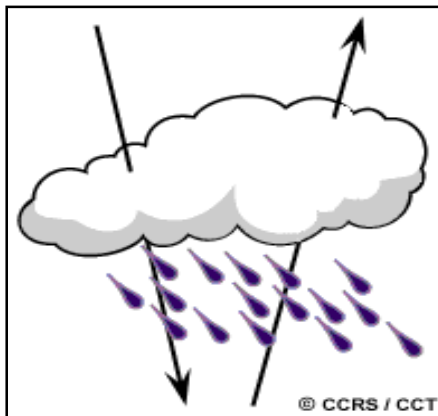


Deteção Remota na banda das microondas

As microondas têm propriedades importantes para a DR devido ao seu grande comprimento de onda (quando comparado com o visível)



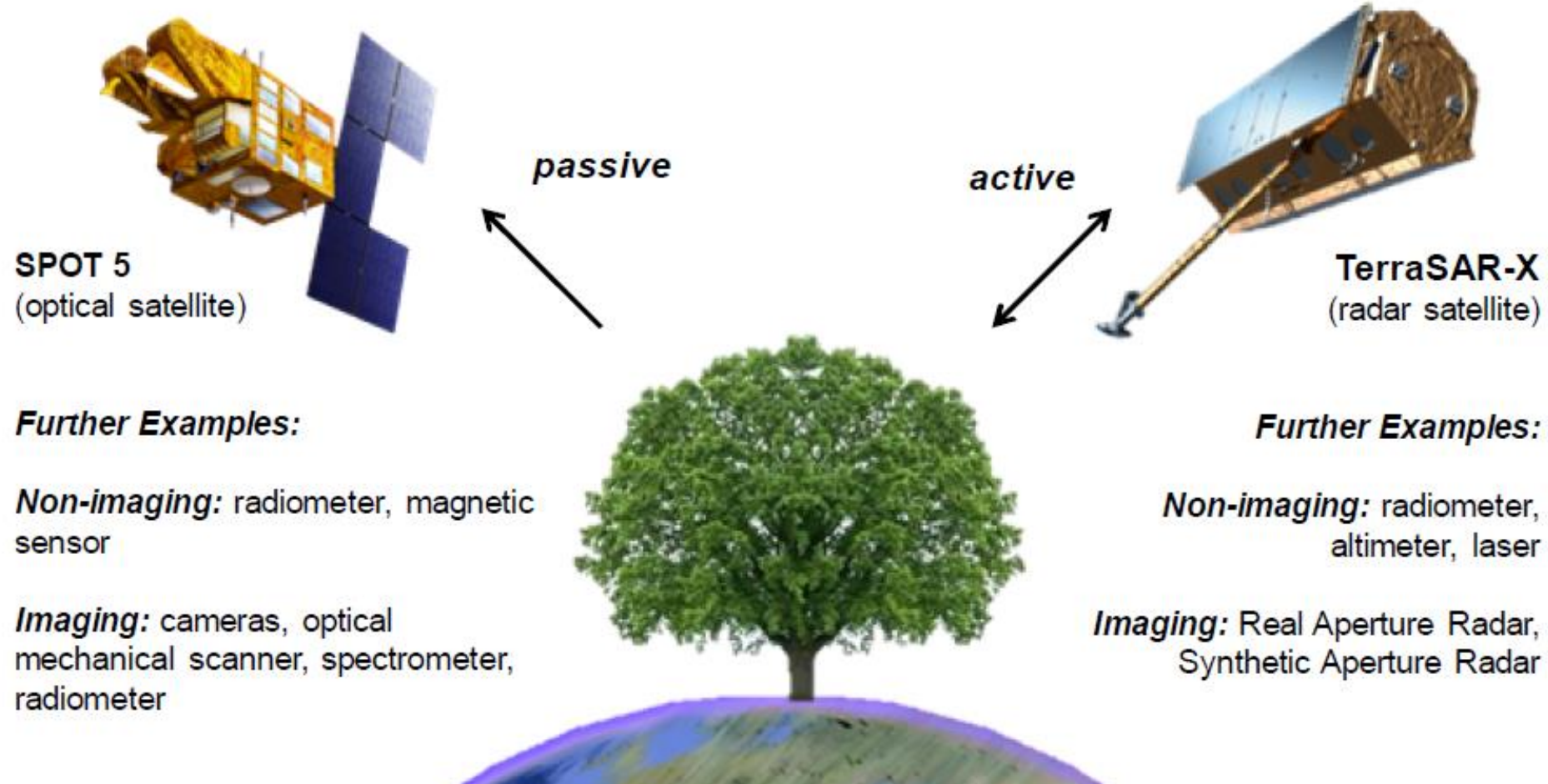
Os maiores comprimentos de onda podem atravessar nuvens, pó, "haze" ou mesmo chuva leve uma vez que os maiores c.o. não são susceptíveis à dispersão atmosférica.



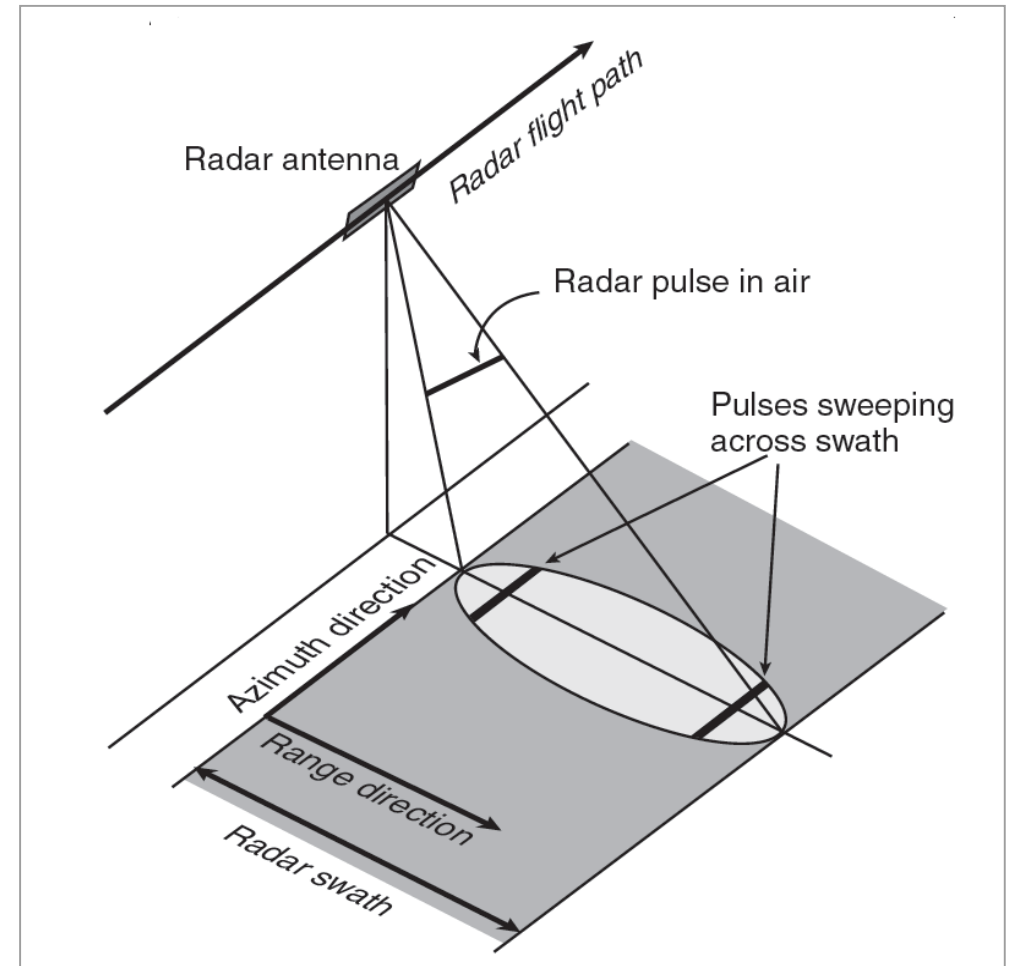
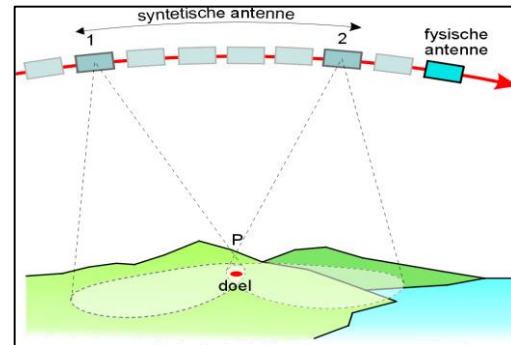
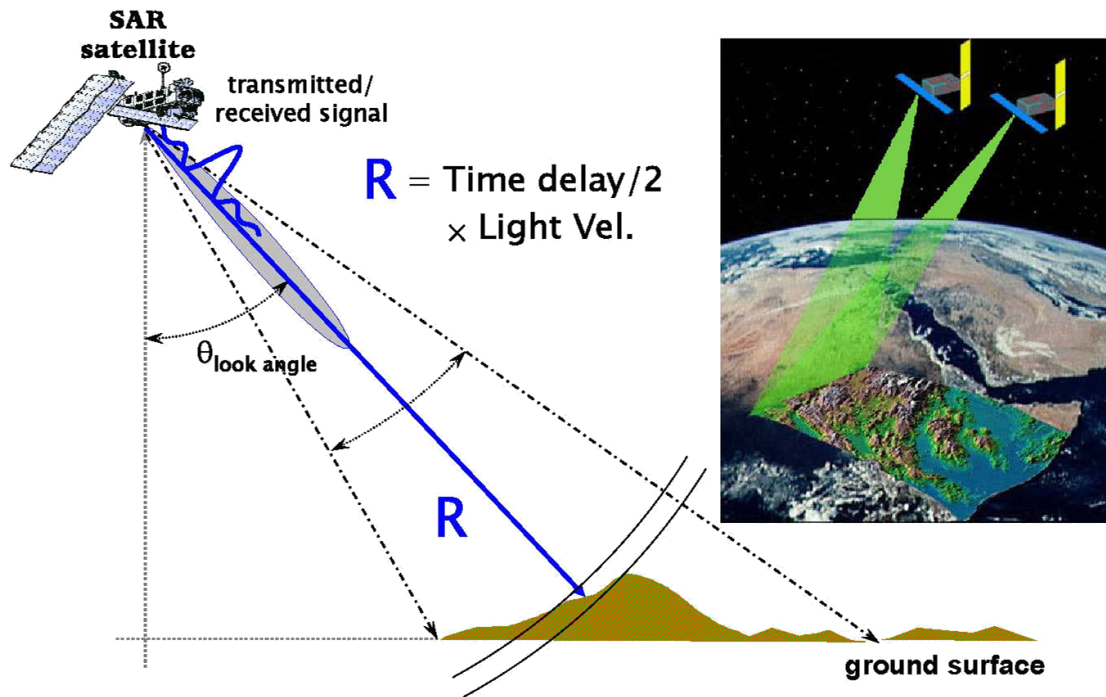
"All-weather"

"Day and Night"

Passive and active remote sensing

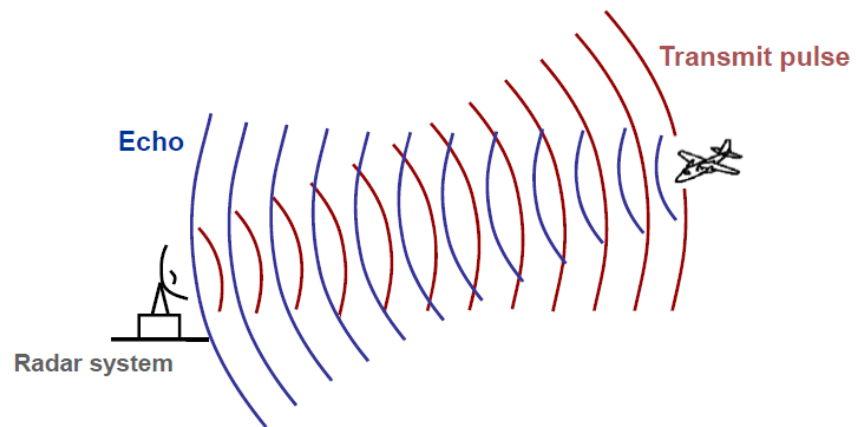


Sistema RADAR espacial

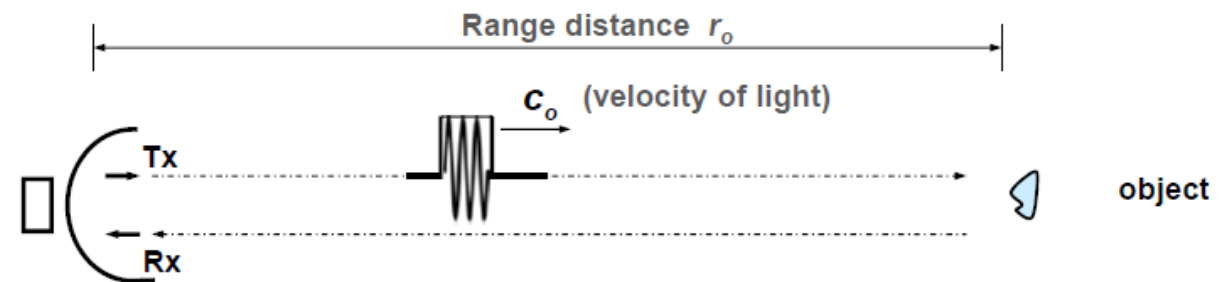


$$s_1 = A \cdot e^{(j\phi_B)} \cdot e^{(-j\left(\frac{4\pi}{\lambda}\right) \cdot r_1)}$$

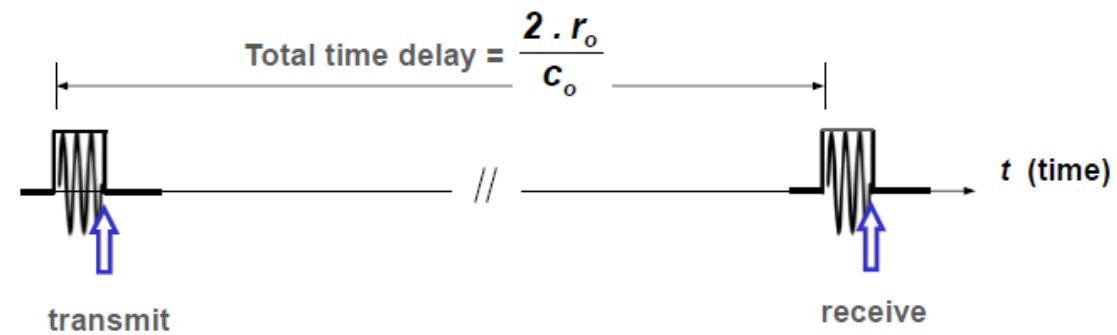
Radar Principle



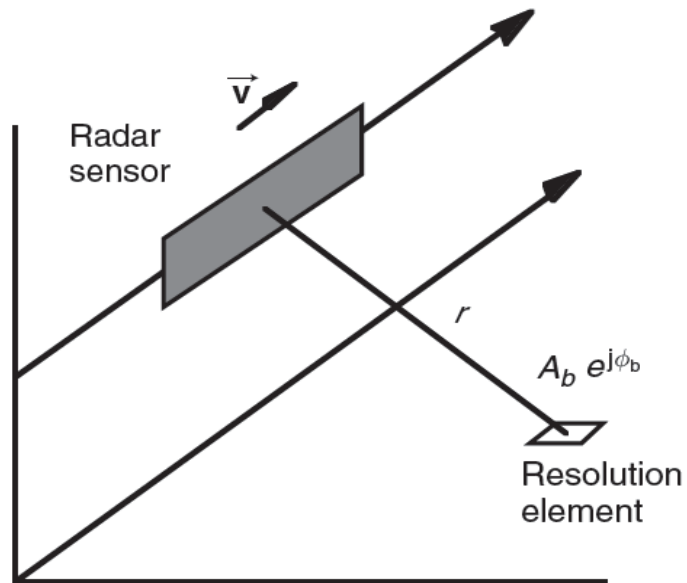
Radar Measurement Principle



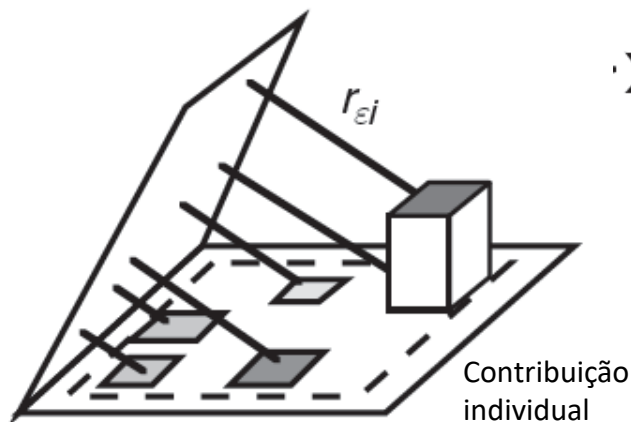
- Received echo signal (back-scattered signal of imaged object):



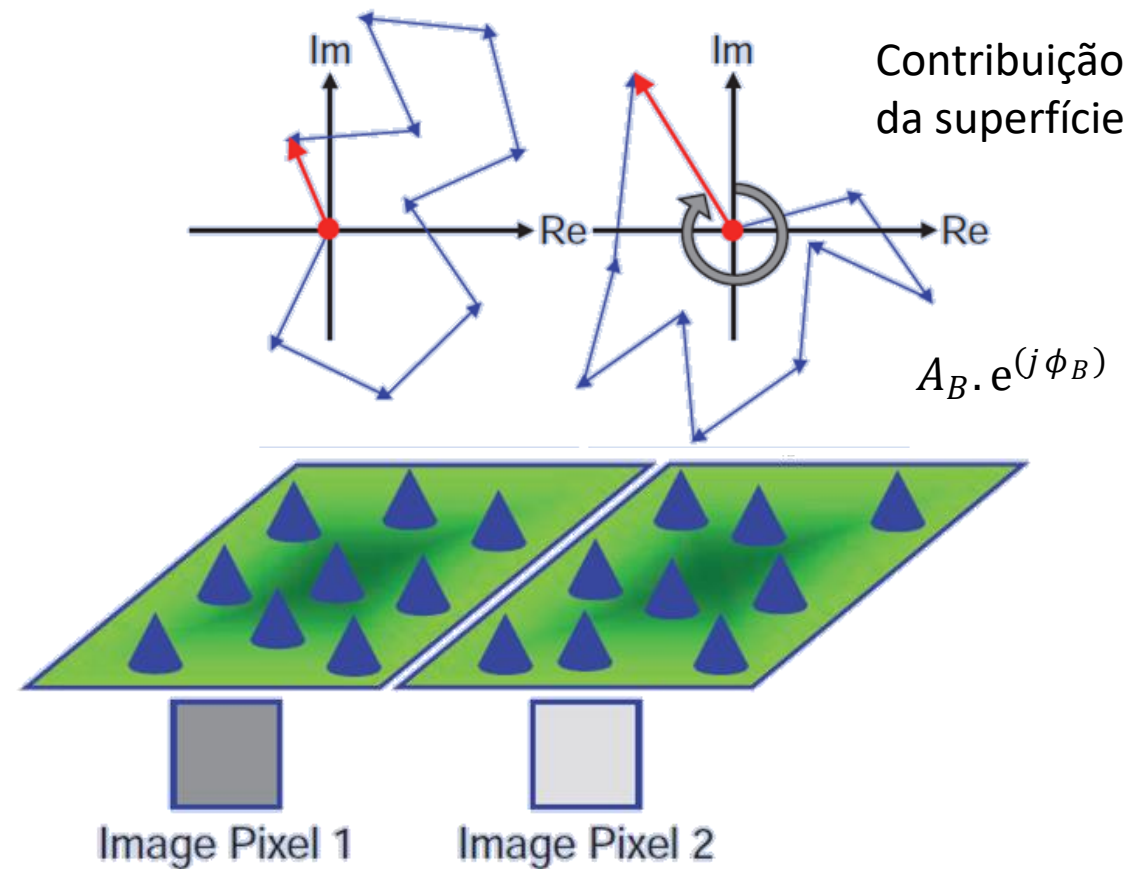
Interação com a superfície



Resolution element

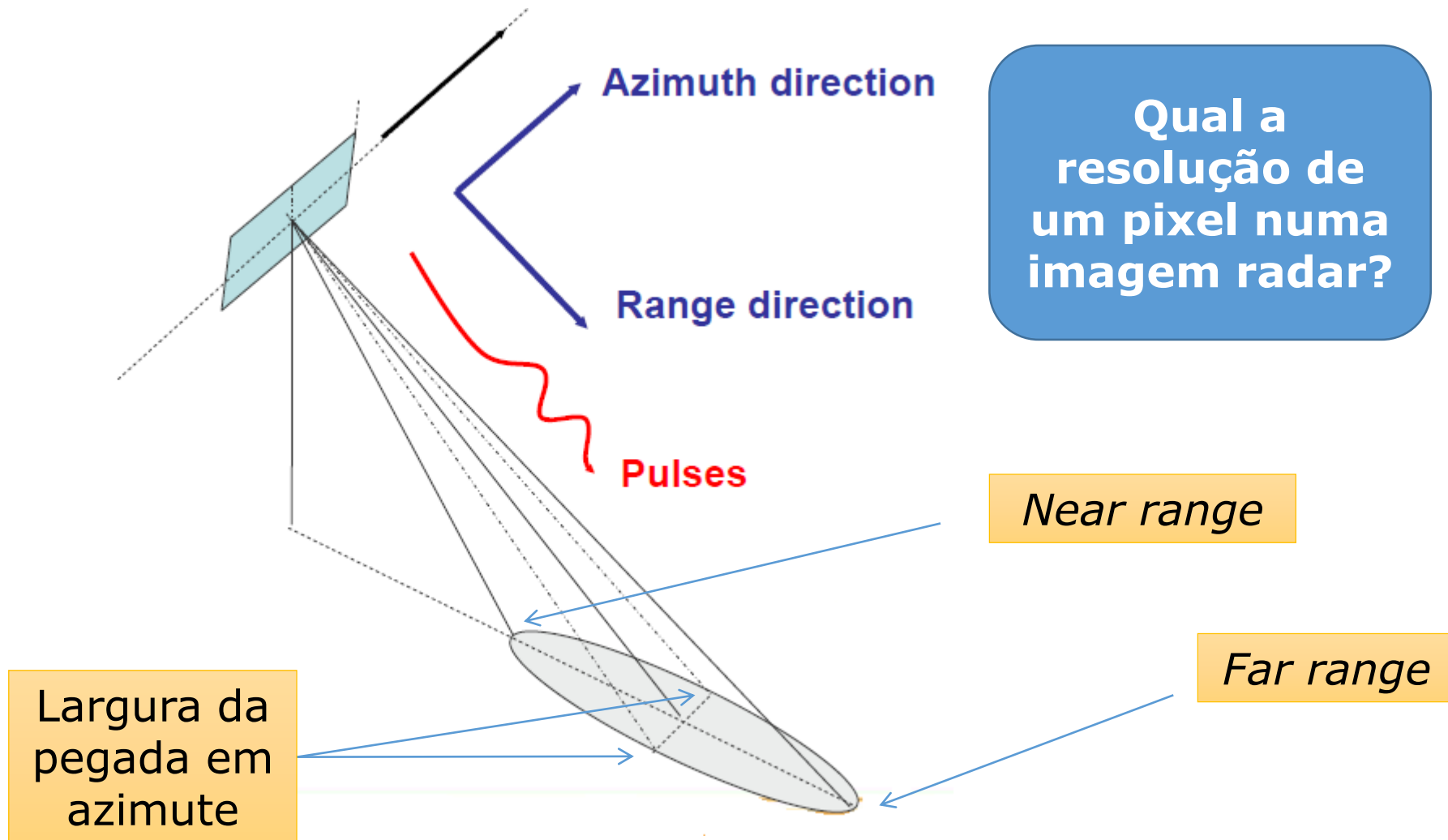


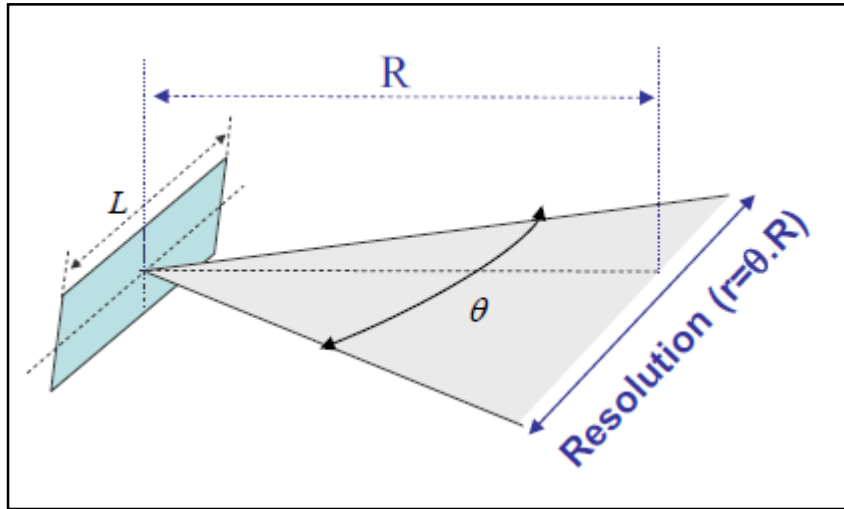
$$\sum_i A_{ei} e^{j\phi_{ei}} e^{-j(4\pi/\lambda)r_{ei}}$$



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

Fasor complexo
(complex phasor)





Para uma antena de largura L

Abertura angular

Comprimento de onda

$$\theta = \frac{\lambda}{L}$$

Largura da antena

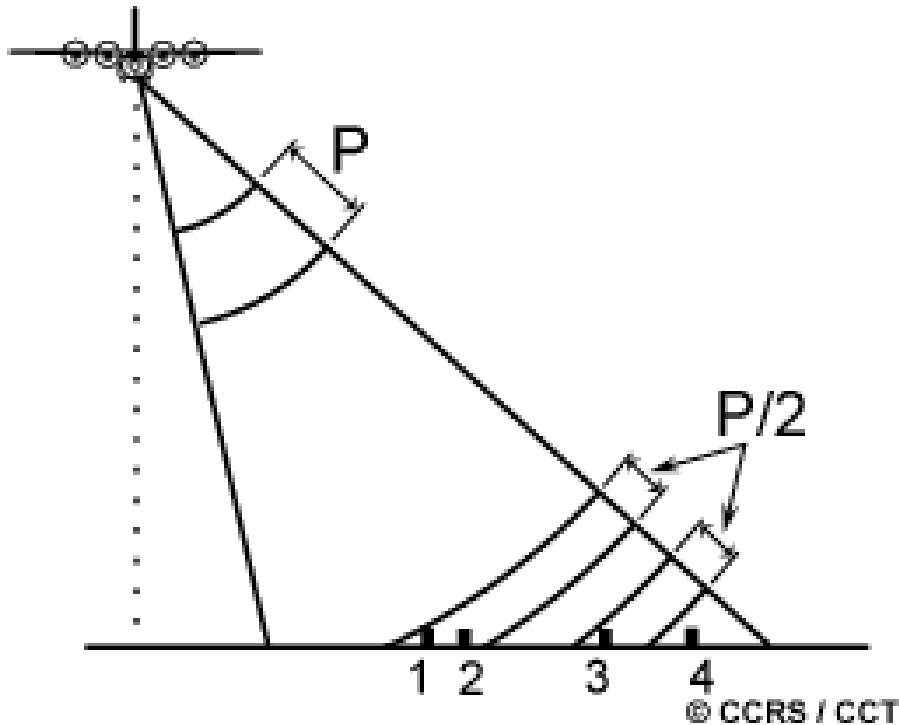
$$r = \frac{\lambda R}{L}$$



Quanto maior a antena mais fina é a resolução

Exemplo:

Para uma antena de 10m e c.o. de 5 cm (banda C) a resolução em azimute é de **5 km**

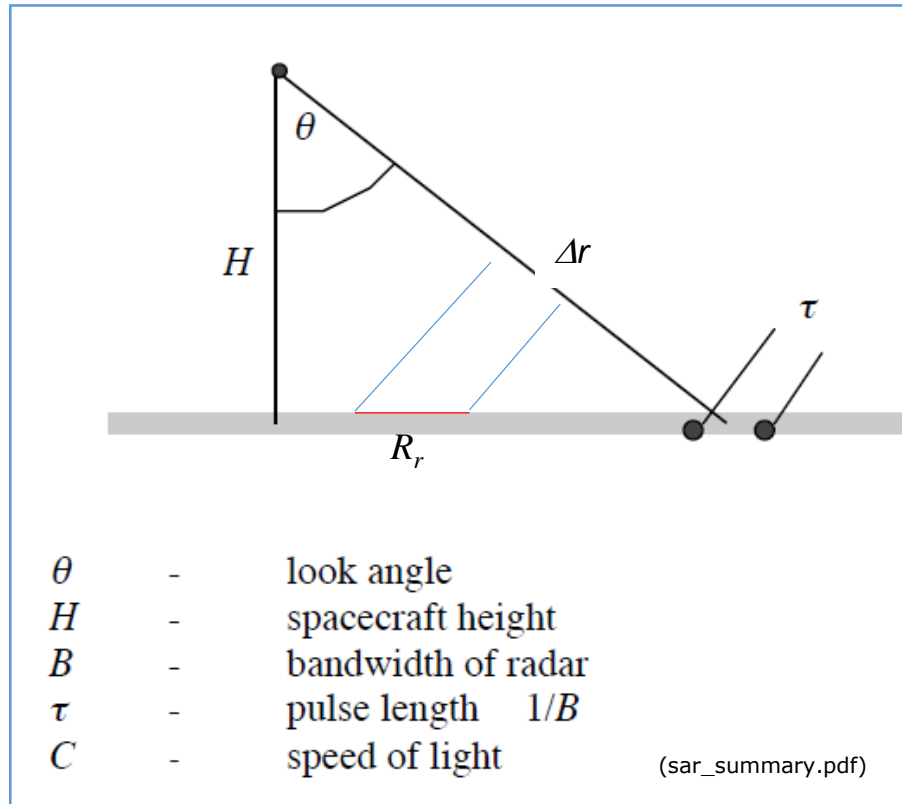


A resolução em range é dependente do comprimento do pulso (P) na direção do "slant range".

Dois alvos são separáveis se a sua separação é superior metade do comprimento do pulso

$$\Delta r = \frac{c P}{2} \quad \text{Resolução slant range}$$

A resolução em "slant range" é constante (e independente da altitude do voo) enquanto que a resolução na "ground range" é variável e dependente do ângulo de incidência.



$$\Delta r = \frac{C\tau}{2} \quad - \text{ slant range resolution}$$

$$R_r = \frac{C\tau}{2} \frac{1}{\sin\theta} \quad - \text{ ground range resolution}$$

ERS: Band width 15.5 MHz
 Slant Range resolution = 9.6 m
 Ground range resolution = 24.7 m

TRX: Band width 150 MHz
 Slant Range resolution = 1.0 m
 Ground range resolution = 2.9m



ERS
 Azimuth = 5 km
 Range = 25 m

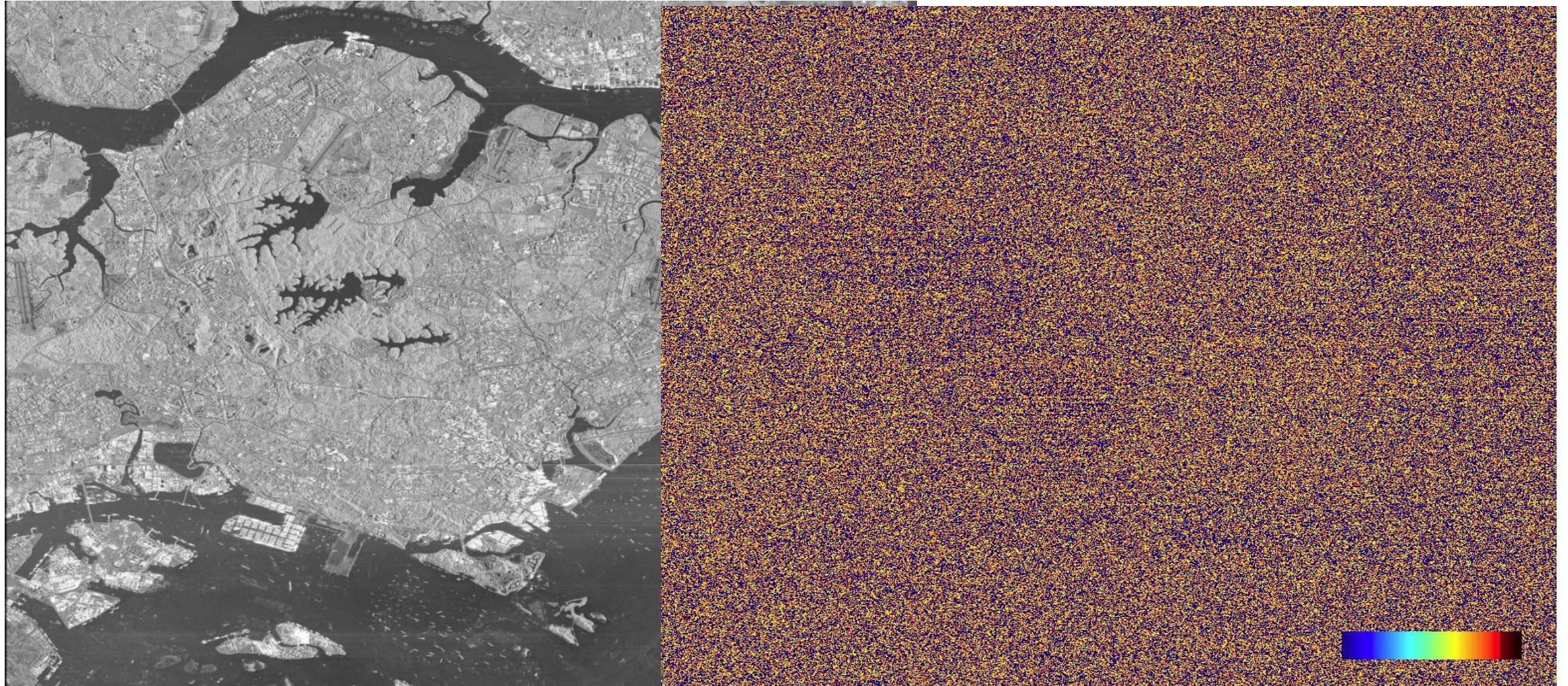
PRF = 1.640 - 1.720 kHz



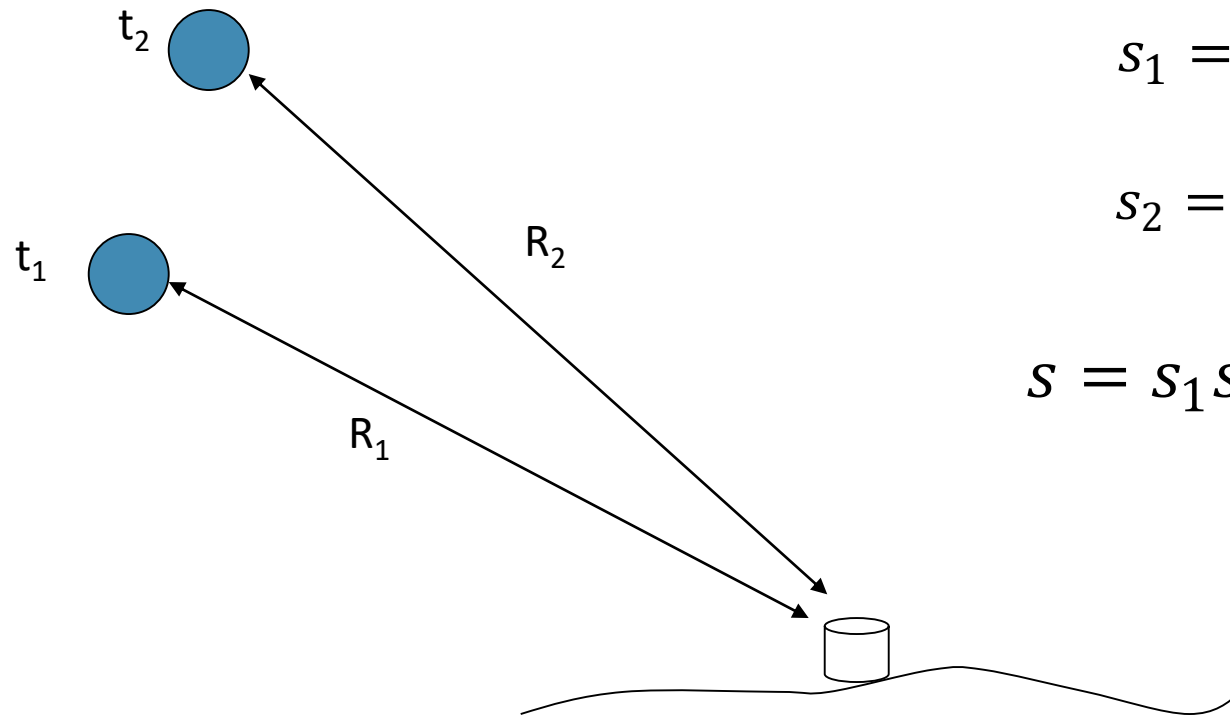
TRX
 Azimuth = 4.4 km
 Range = 3 m

PRF = 2.0 - 6.5 kHz

Imagem SAR SLC



Geometria e fase InSAR



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

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

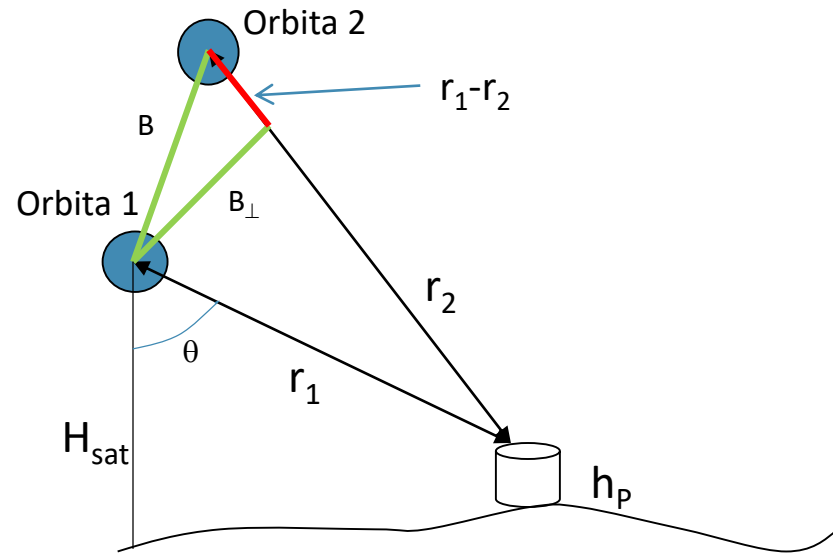
$$s = s_1 s_2^* = |s_1| |s_2| e^{-j\left(\frac{4\pi}{\lambda}\right) \cdot R_1 + j\left(\frac{4\pi}{\lambda}\right) \cdot R_2}$$

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.

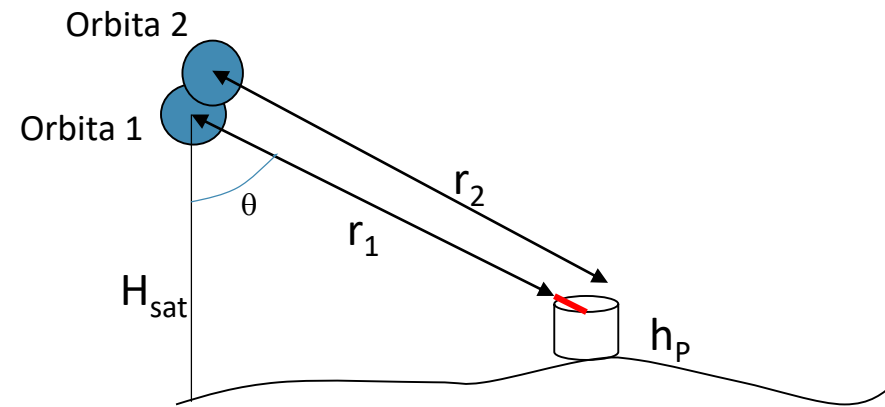
Geometria e fase InSAR



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

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

$$H_{2\pi} = \frac{-\lambda R_1 \sin \theta^{\circ}}{4\pi B_{\perp}} 2\pi = \frac{-\lambda R_1 \sin \theta^{\circ}}{2B_{\perp}}$$



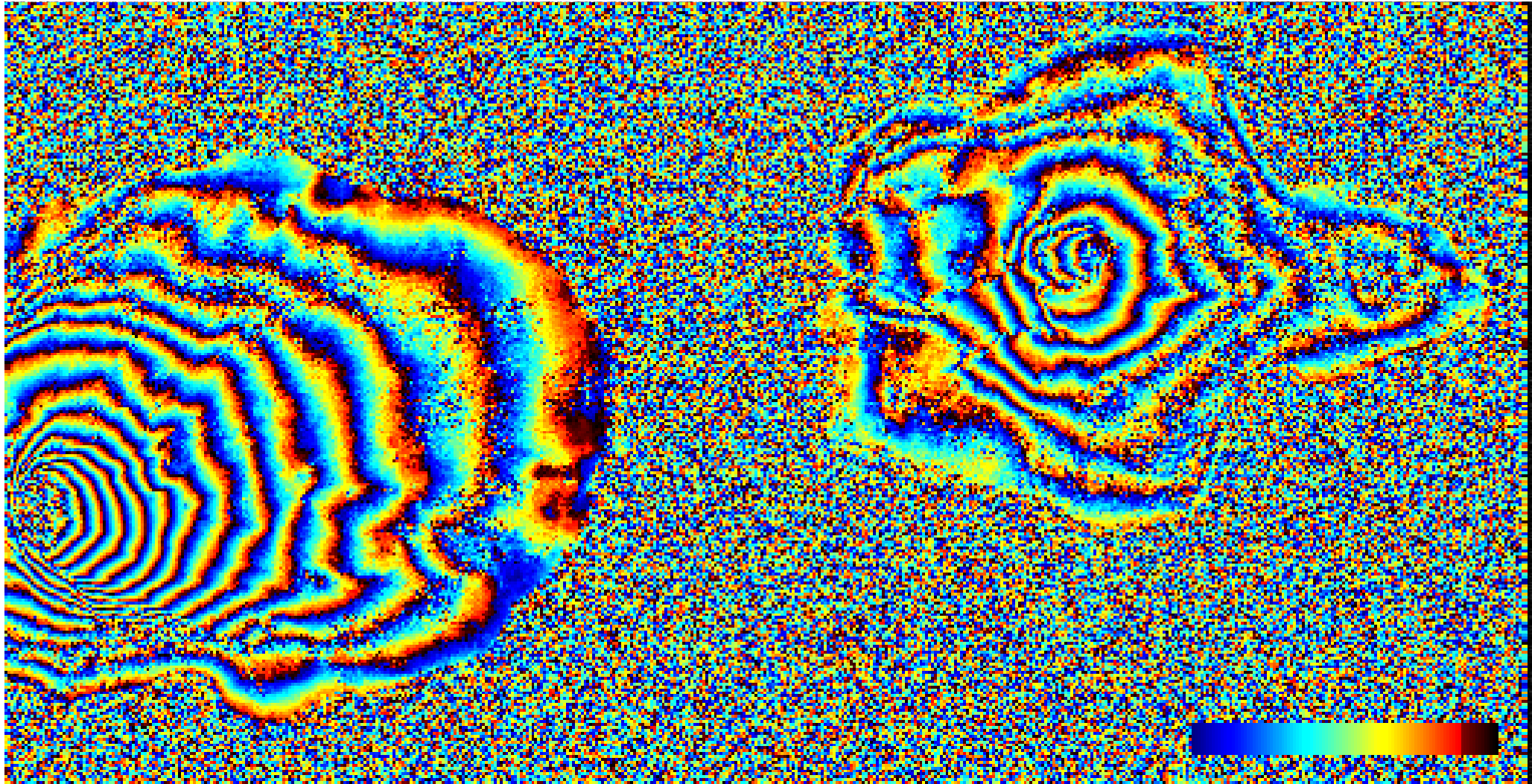
$$\phi_I = \phi_{top} - \frac{4\pi}{\lambda} (r_1 - r_2)$$

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

Sensitivity to deformation 1000x higher than for topography

B = 100m
k=0.003

Topographic phase



$$H_{2\pi} = \frac{-\lambda R_1 \sin \theta^\circ}{4\pi B_\perp} 2\pi = \frac{-\lambda R_1 \sin \theta^\circ}{2B_\perp}$$

Ambiguidade da altitude= 76 m, B = 100m

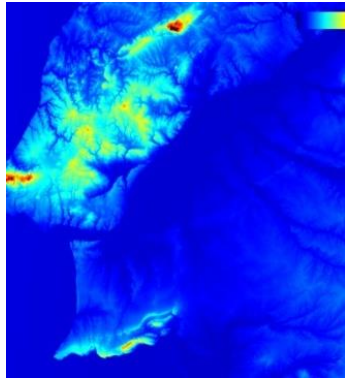
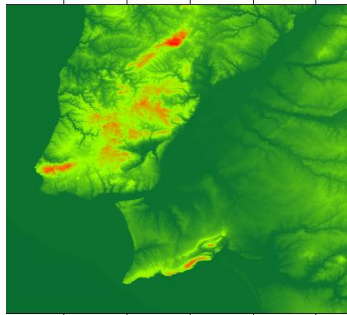
Interferometria Diferencial

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

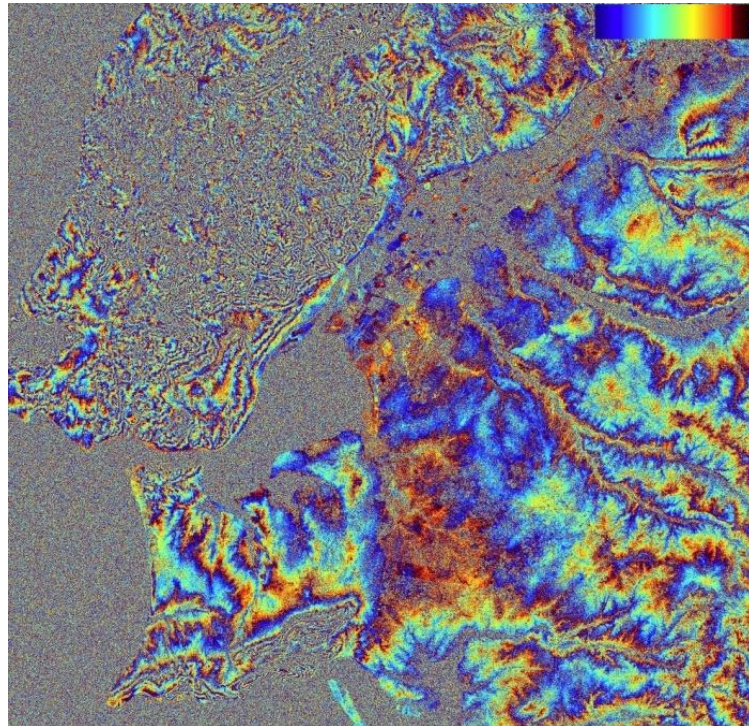


$$\phi_{Def} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{r_p \sin\theta_p} h_p - \phi_I$$

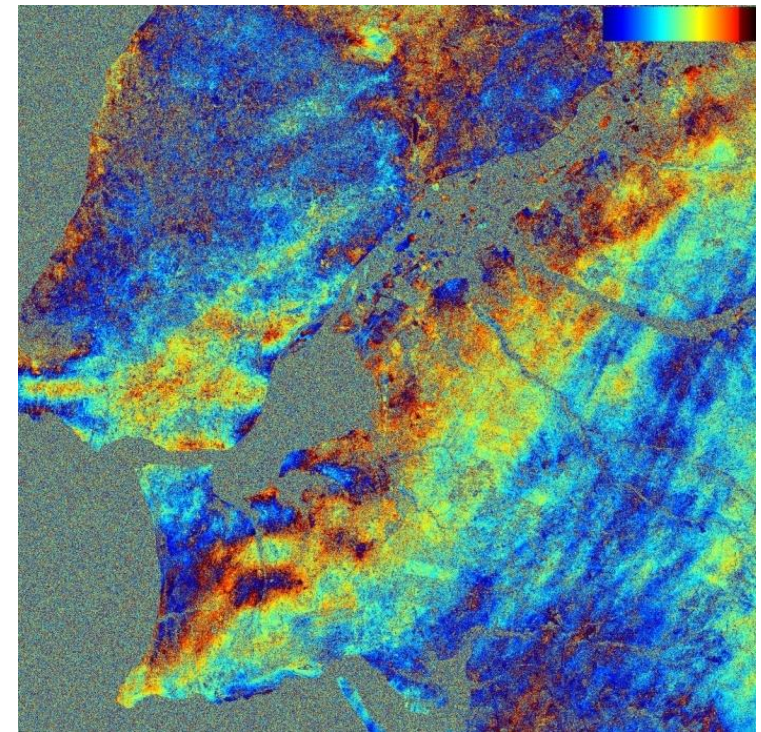
h_p



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



ϕ_I



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

DINSAR Applications

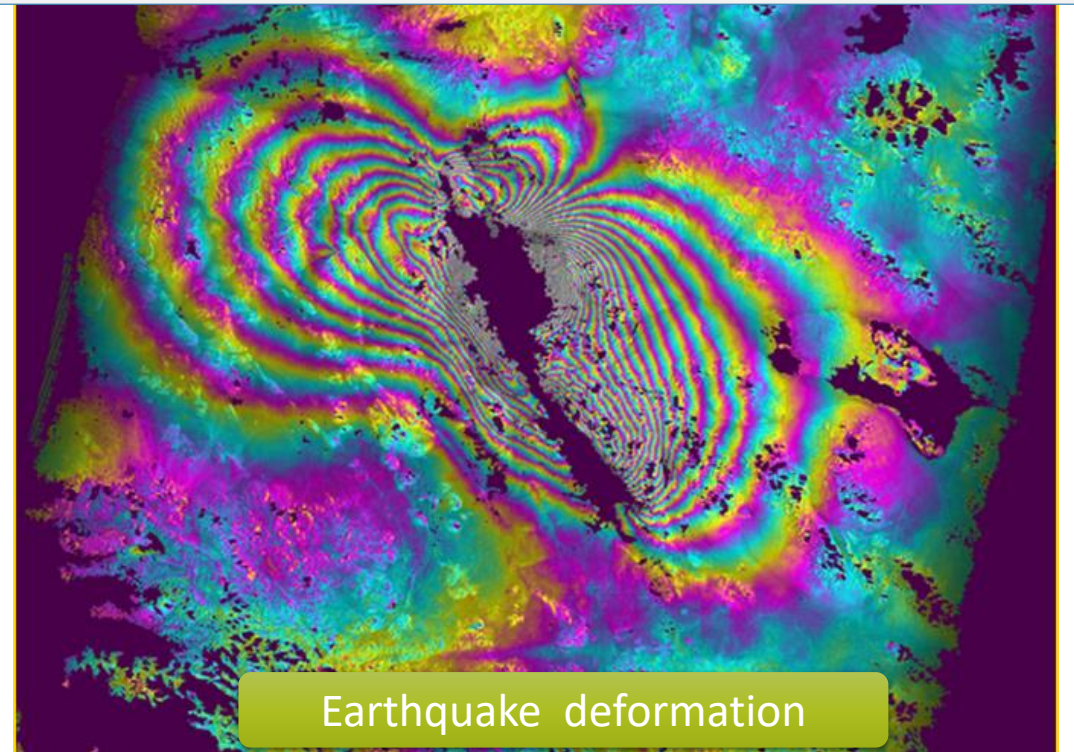


Volcanic Hazards



Volcano Monitoring

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

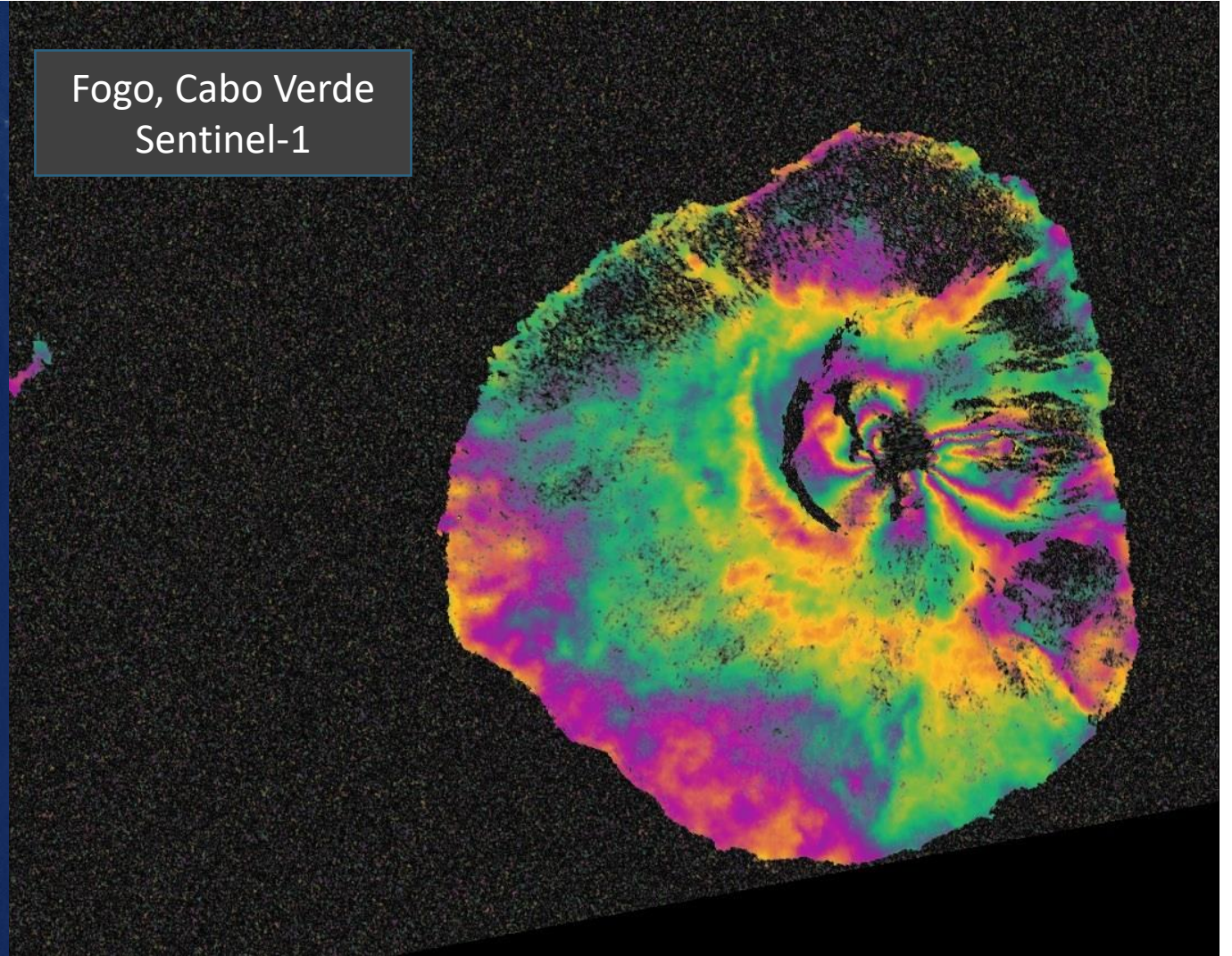


Earthquake deformation

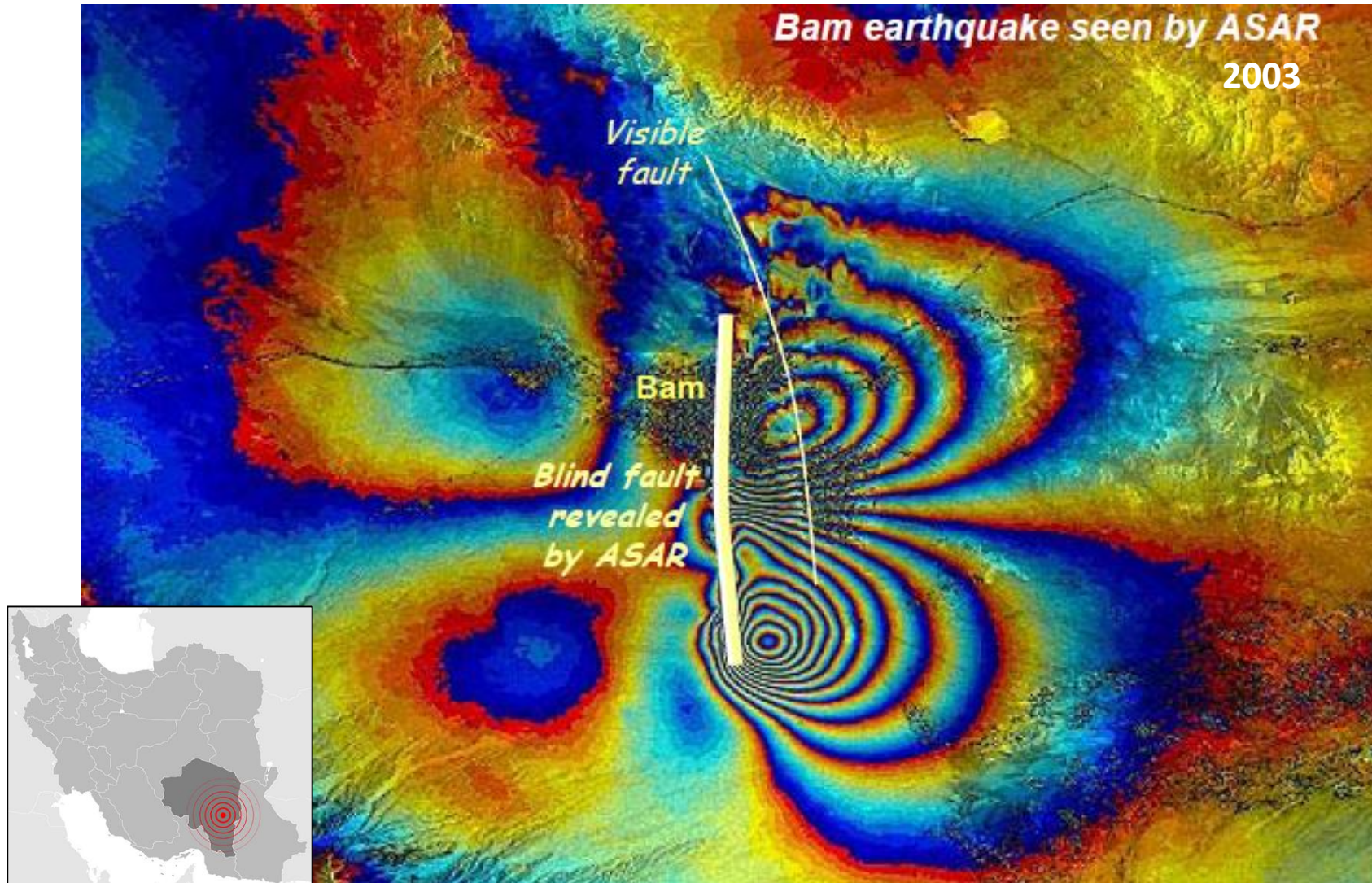
Volcano Monitoring



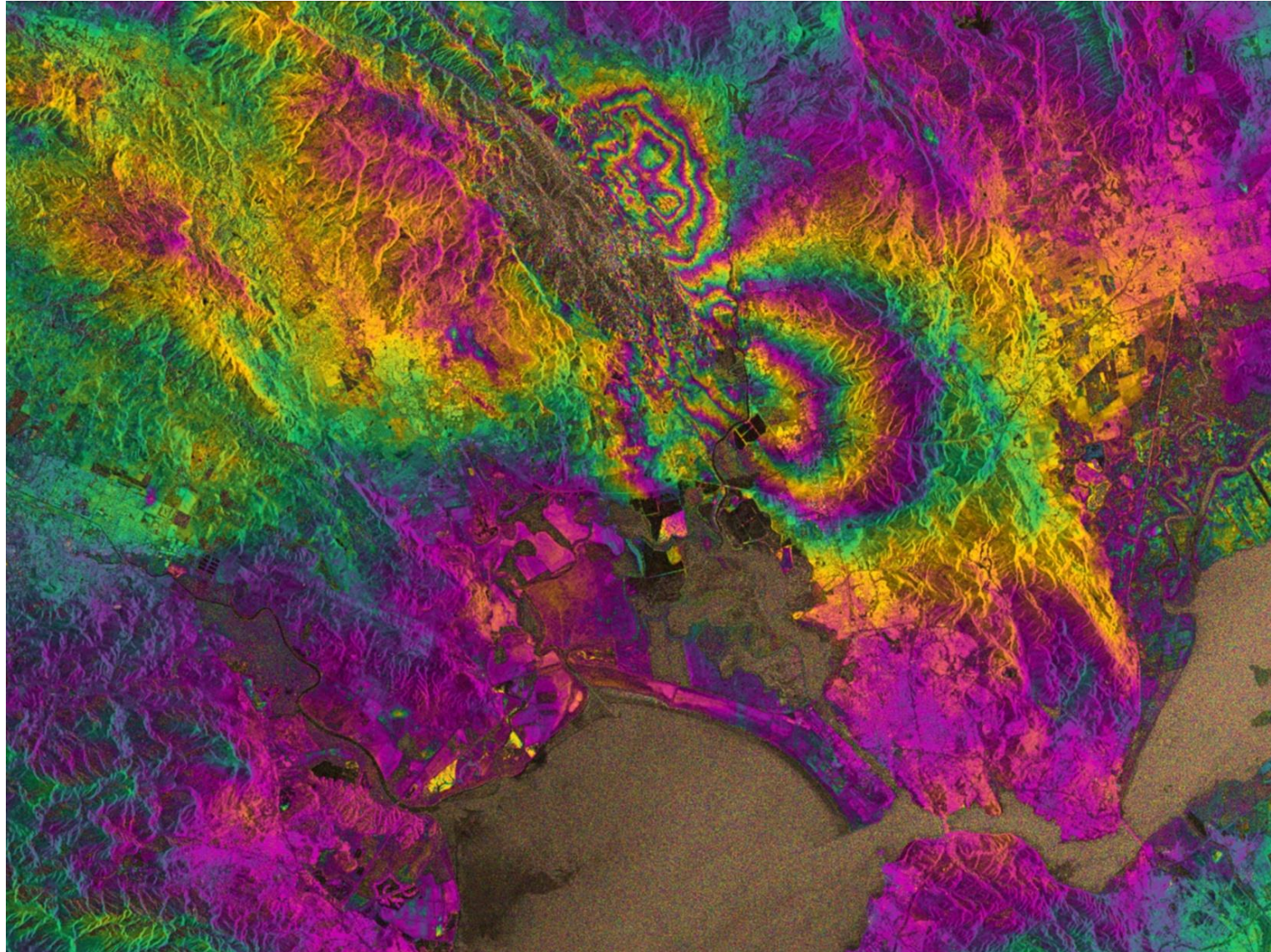
Fogo, Cabo Verde
Sentinel-1



Earthquake deformation



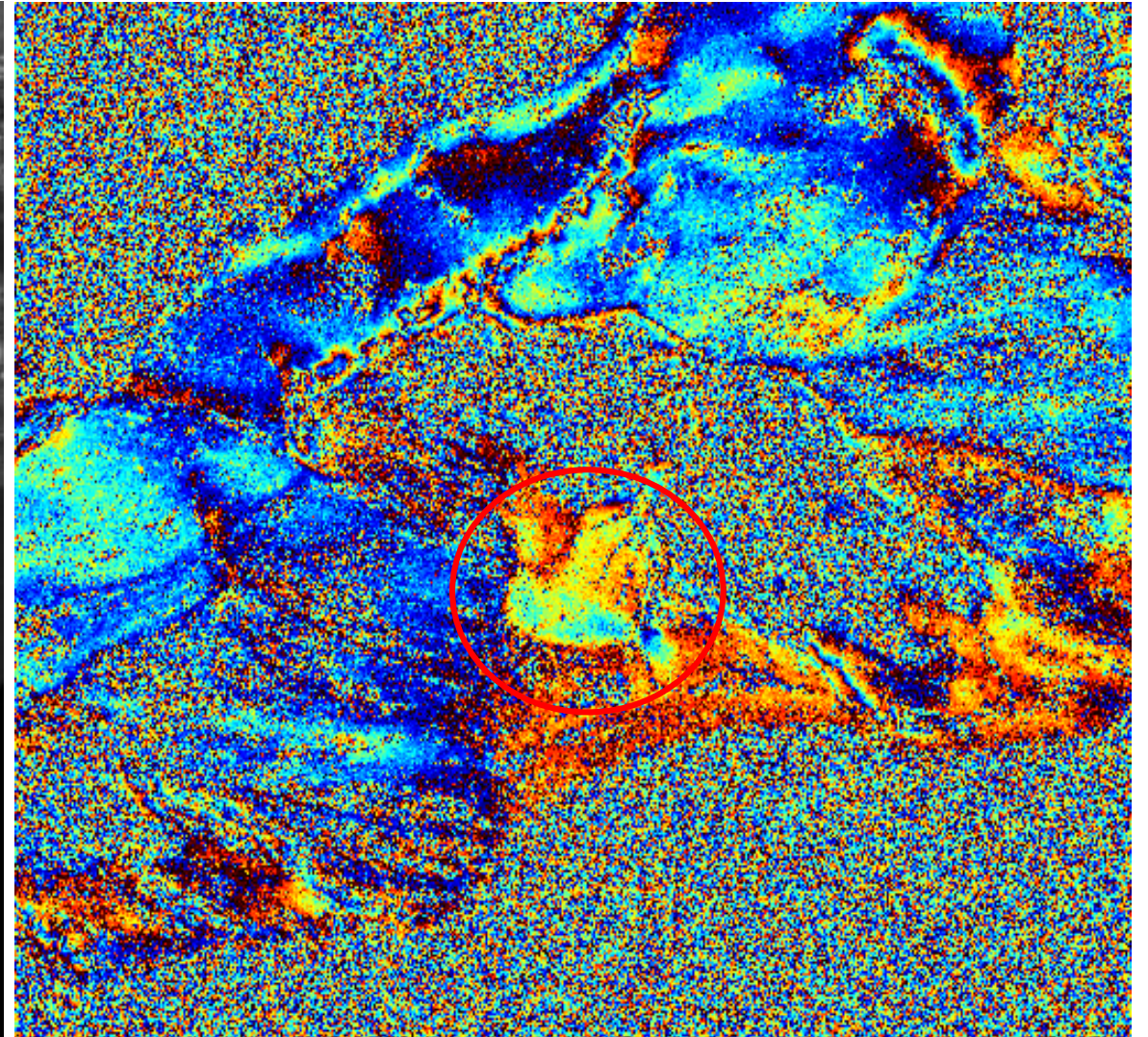
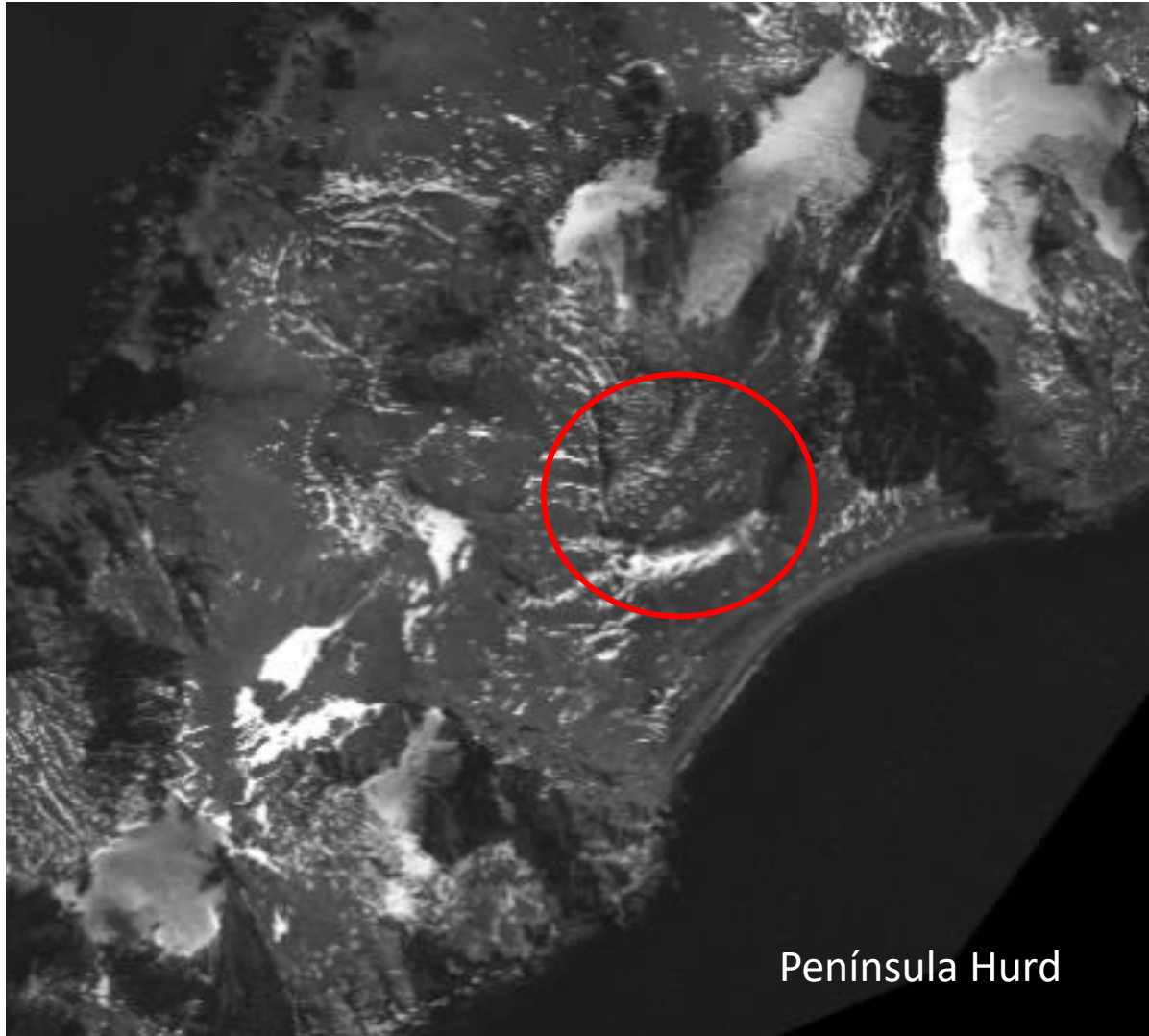
Earthquake deformation



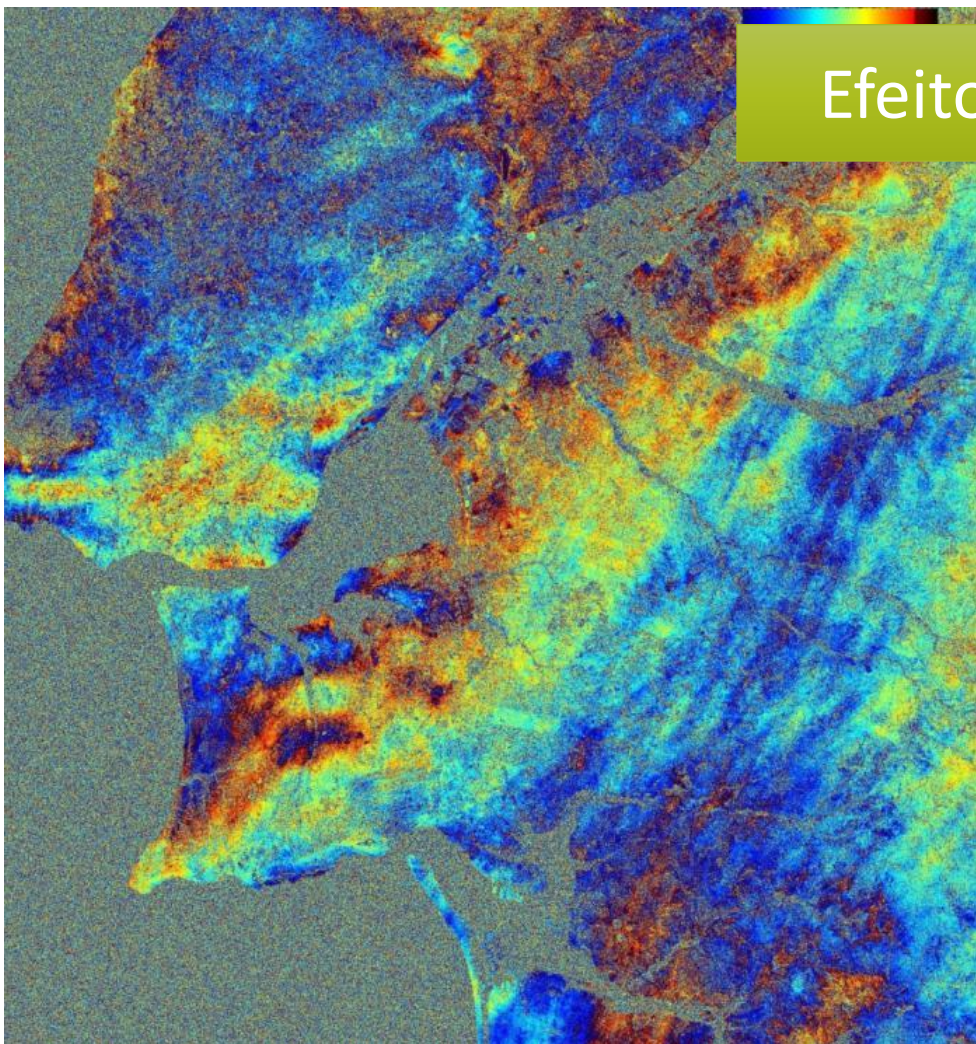
Sentinel -1

**Napa Valley
earthquake,
24 Agosto 2014**

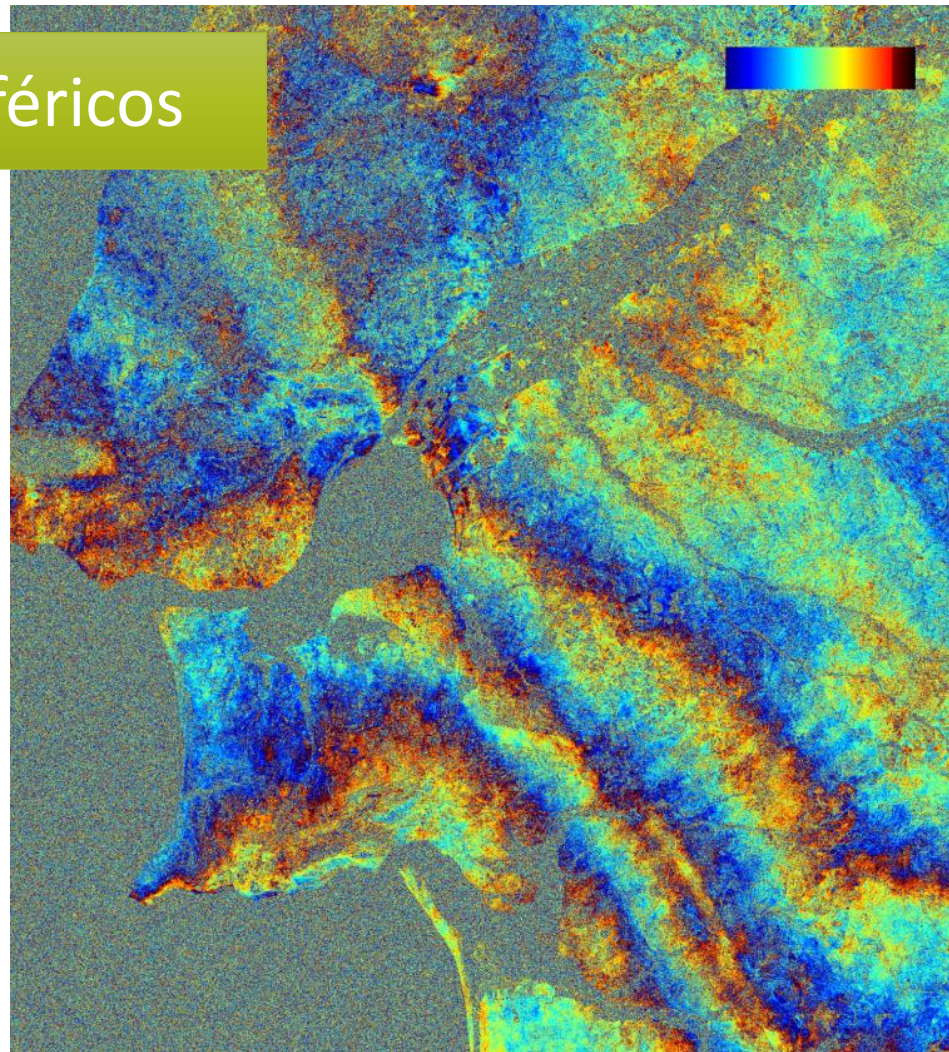
RockGlaciar movement



Limitações da InSAR Diferencial



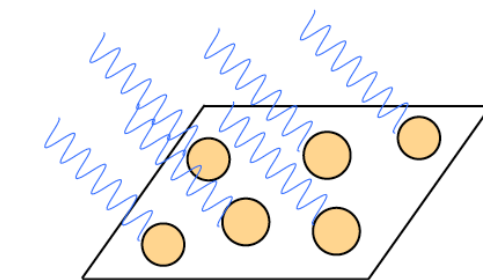
Efeitos atmosféricos



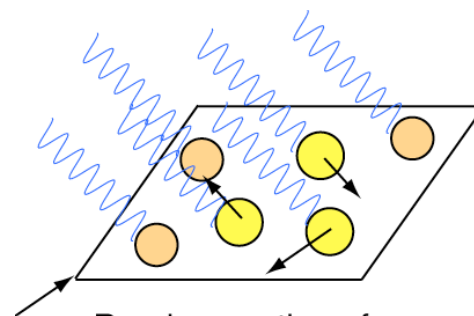
Limitações da InSAR Diferencial

Descorrelação geométrica

Descorrelação Temporal

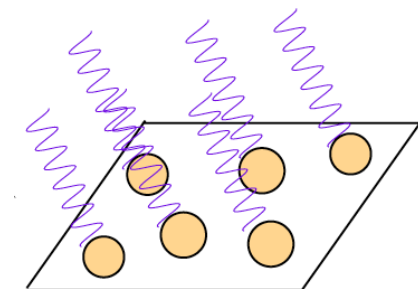


Received signal is superposition of waves from all scattering centers

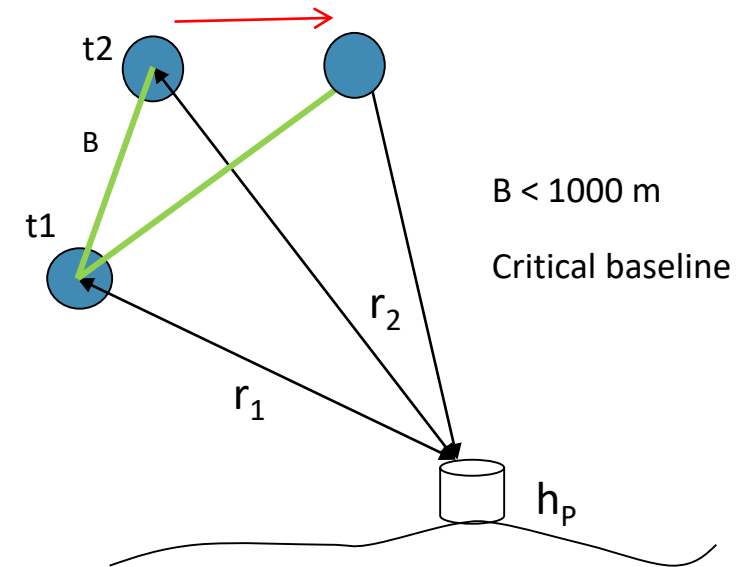


Random motion of scatterers causes wavelets to interfere- "temporal decorrelation"

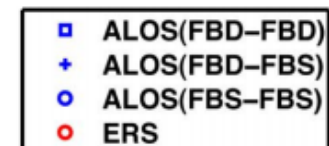
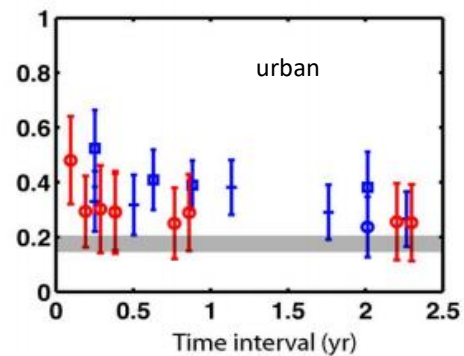
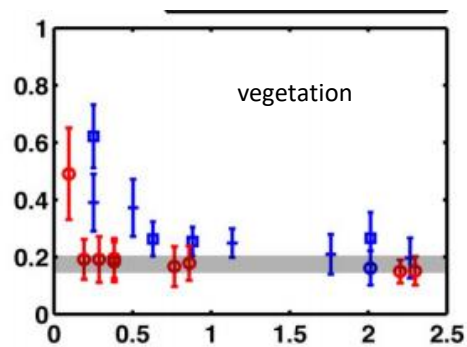
$$s_2 = A \cdot e^{(\phi'_B)} \cdot e^{(-j(\frac{4\pi}{\lambda})r_2)}$$



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

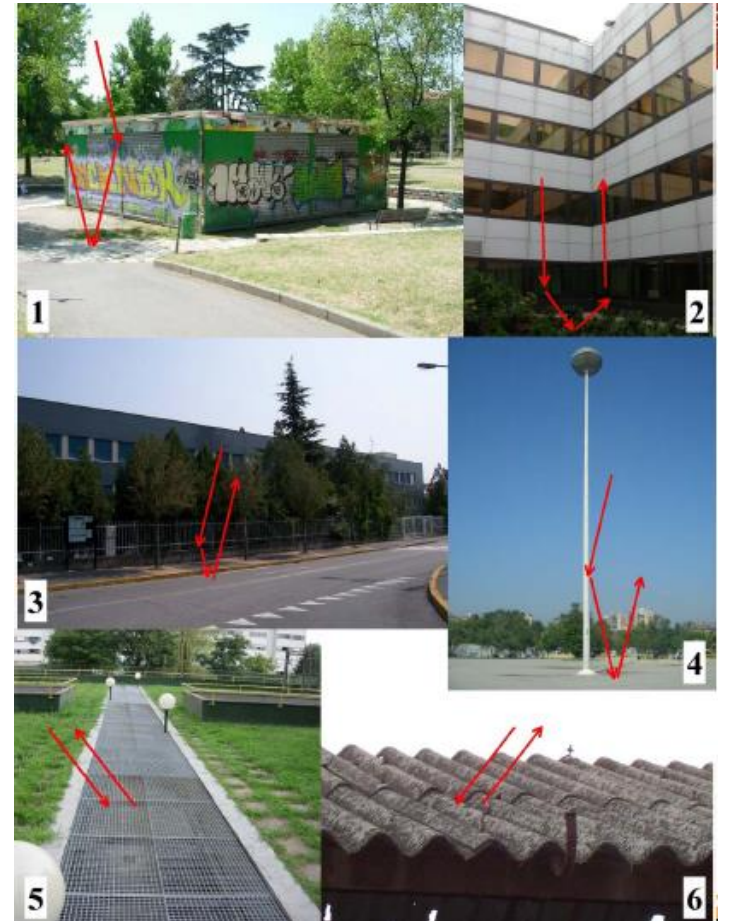
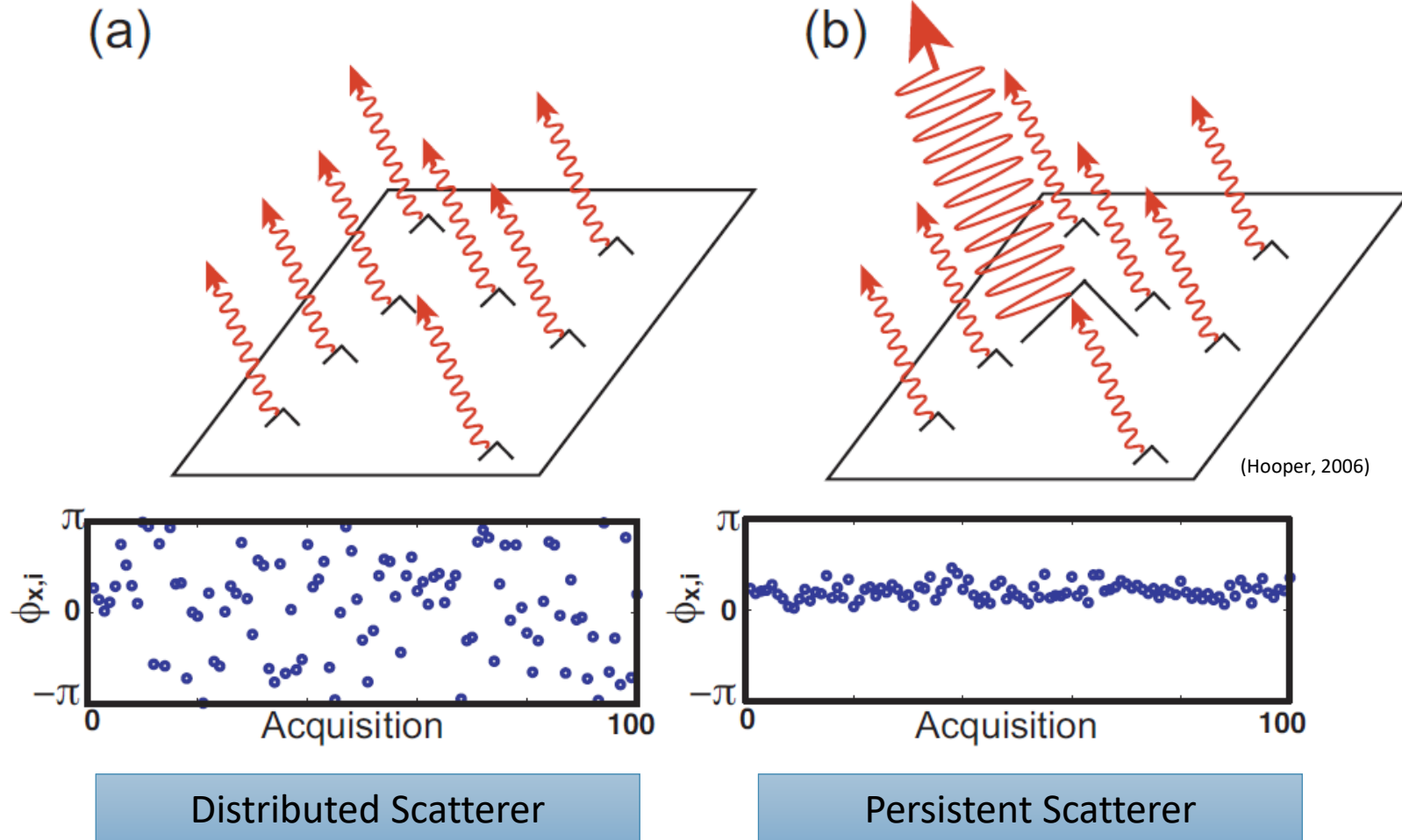


Descorrelação Temporal



Wei and Sandwell, 2010 (IEEE TGRS)

Persistent Scatterer (PS)



Persistent Scatterers (PS)

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

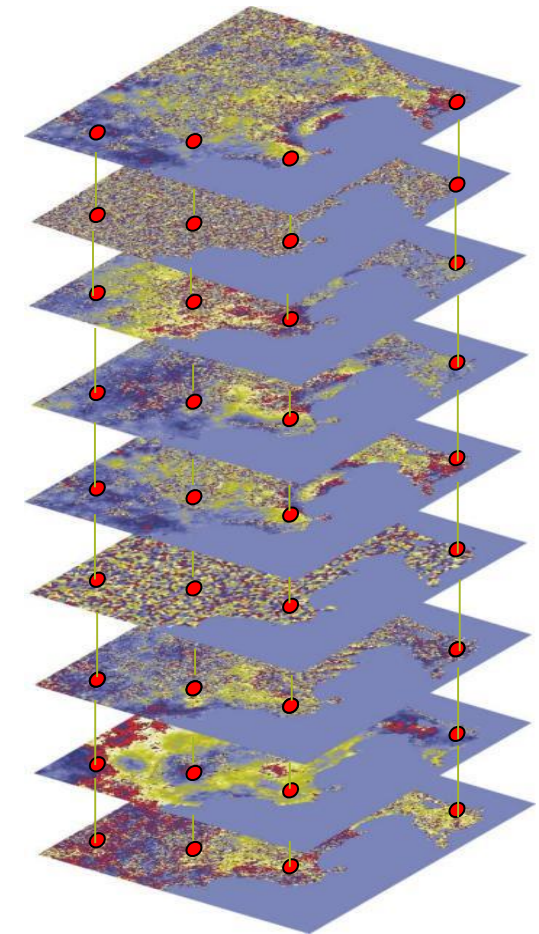
A técnica baseia-se num conjunto de pixéis coerentes ao longo do tempo e permite, dentro de certas condições:



A determinação do erro do DEM usado no interferograma diferencial

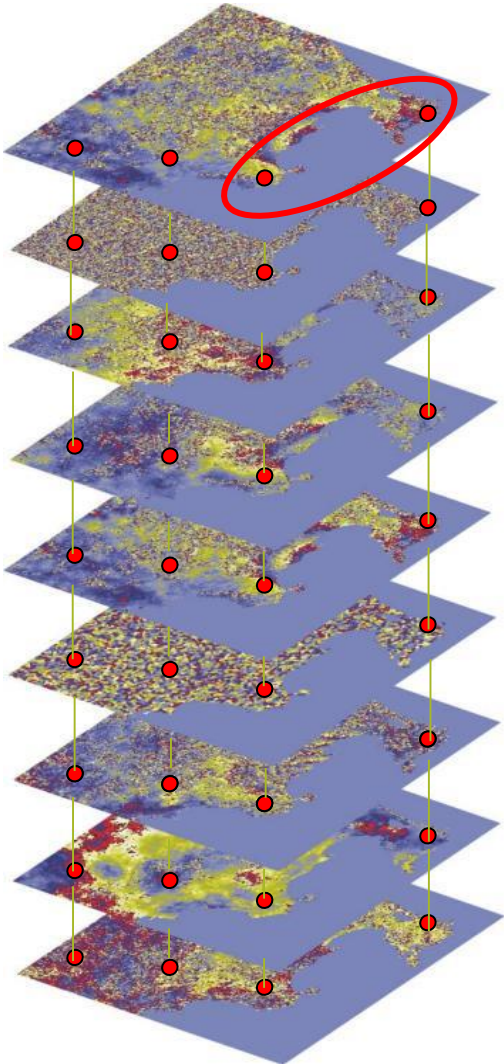


A deteção de movimentos da superfície com uma precisão milimétrica

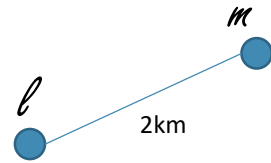


$$D_a = \frac{\sigma_a}{\bar{a}} = \hat{\sigma}_\phi$$

Persistent Scatter functional model



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



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

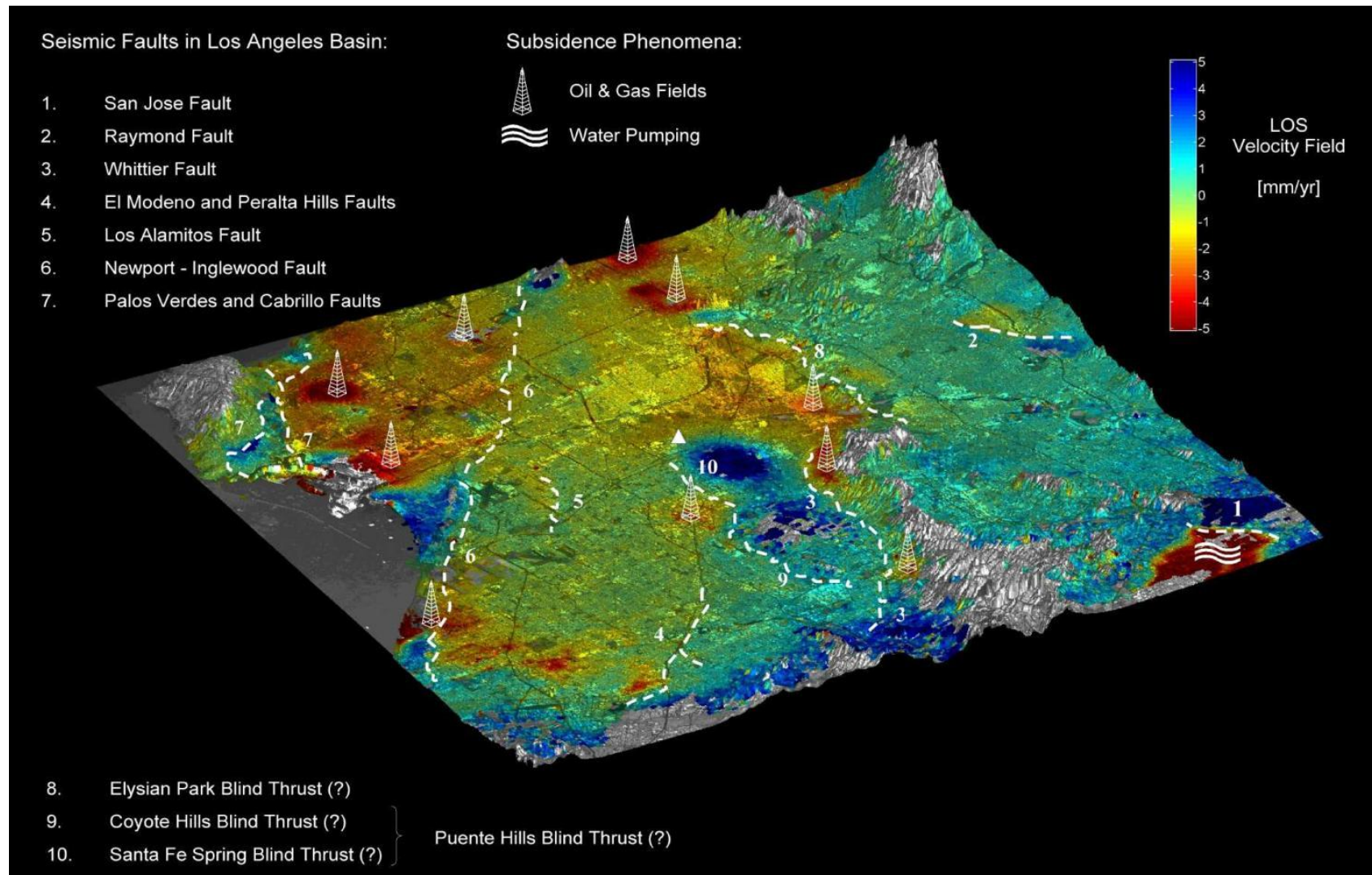
$$\Delta\phi_{l,m}^k = k_v \Delta v_{l,m} T_k + k_\varepsilon \cdot B_{n,k} \Delta h_{l,m} + \omega_{l,m,k}$$

System of k equations with 2 parameters

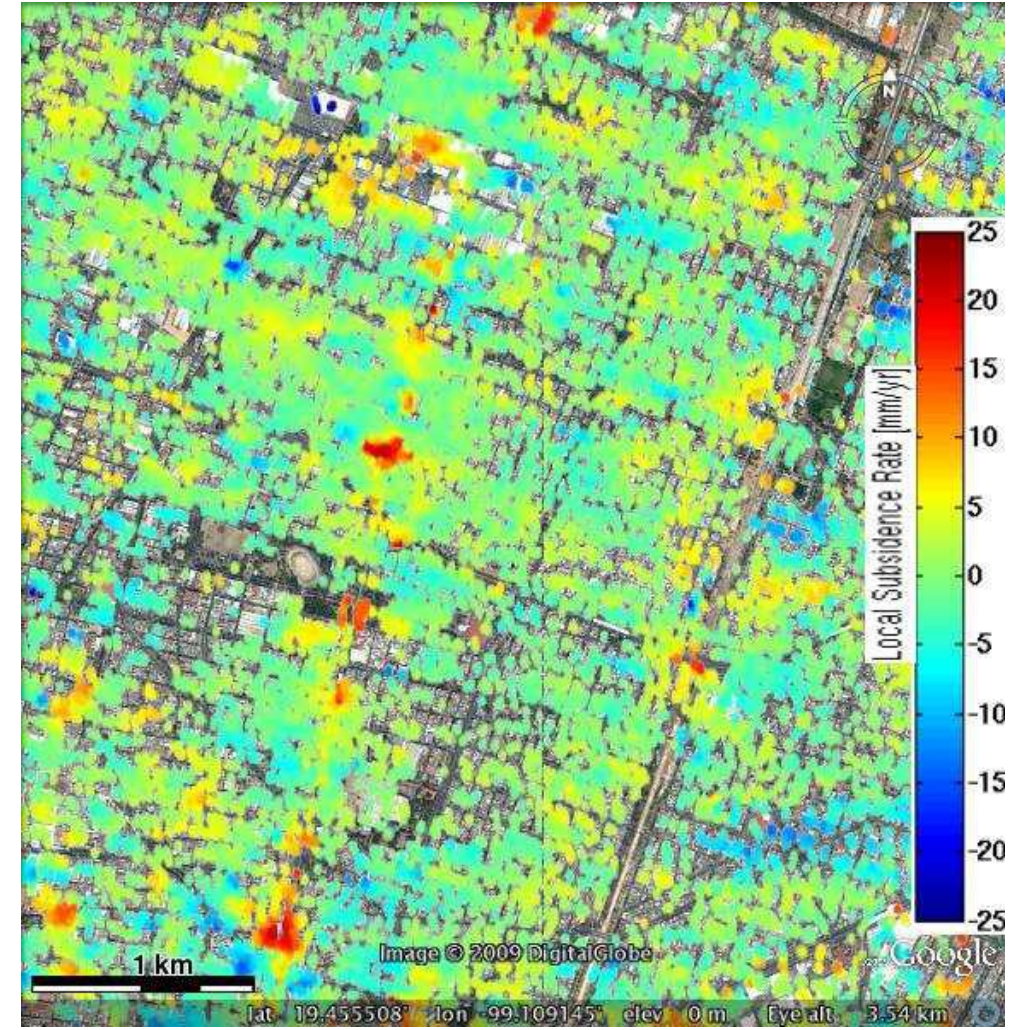
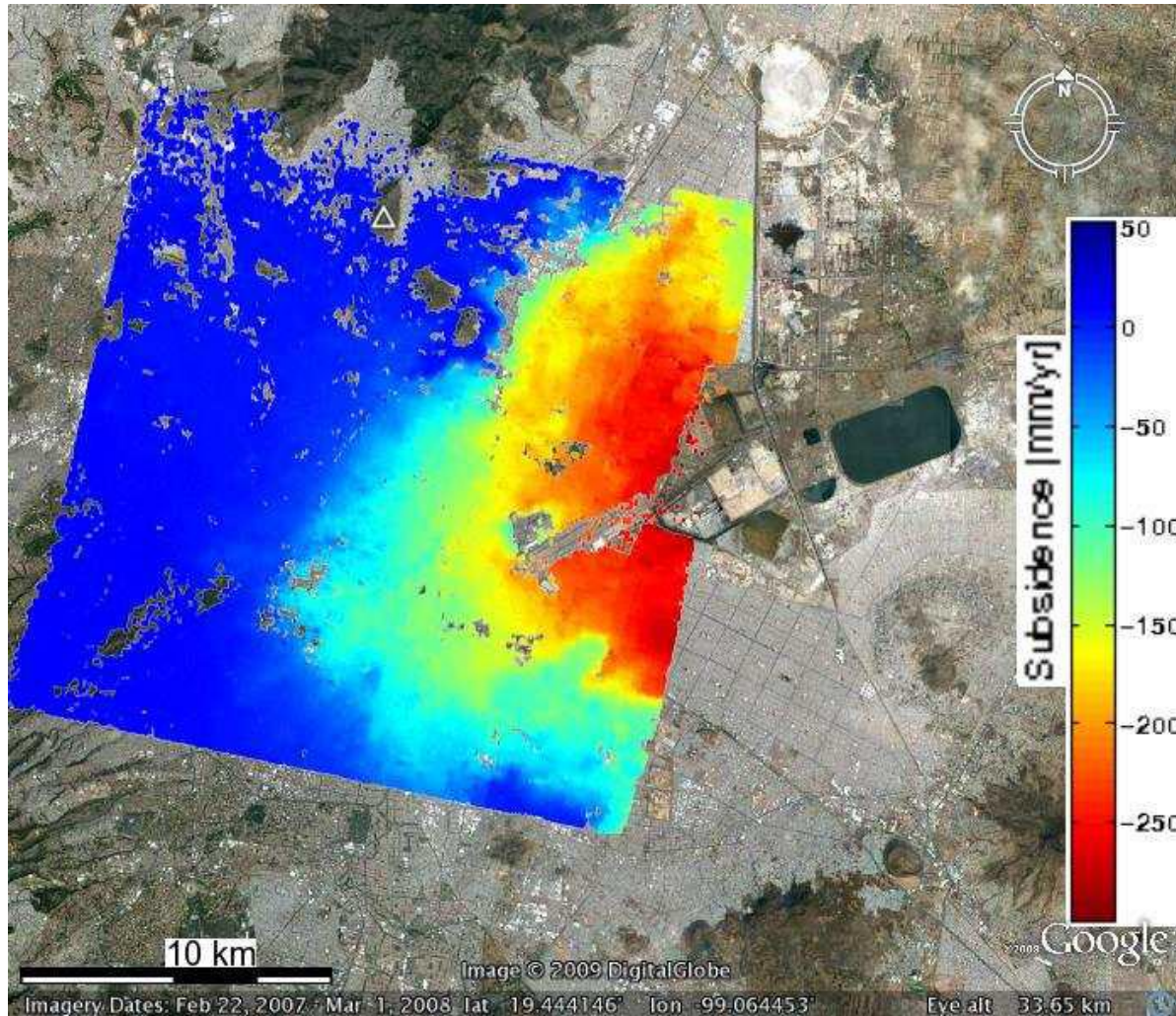
Busca no espaço solução dos valores que maximizam a função γ

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

Aplicações PSINSAR: Tectónica e Subsidiência



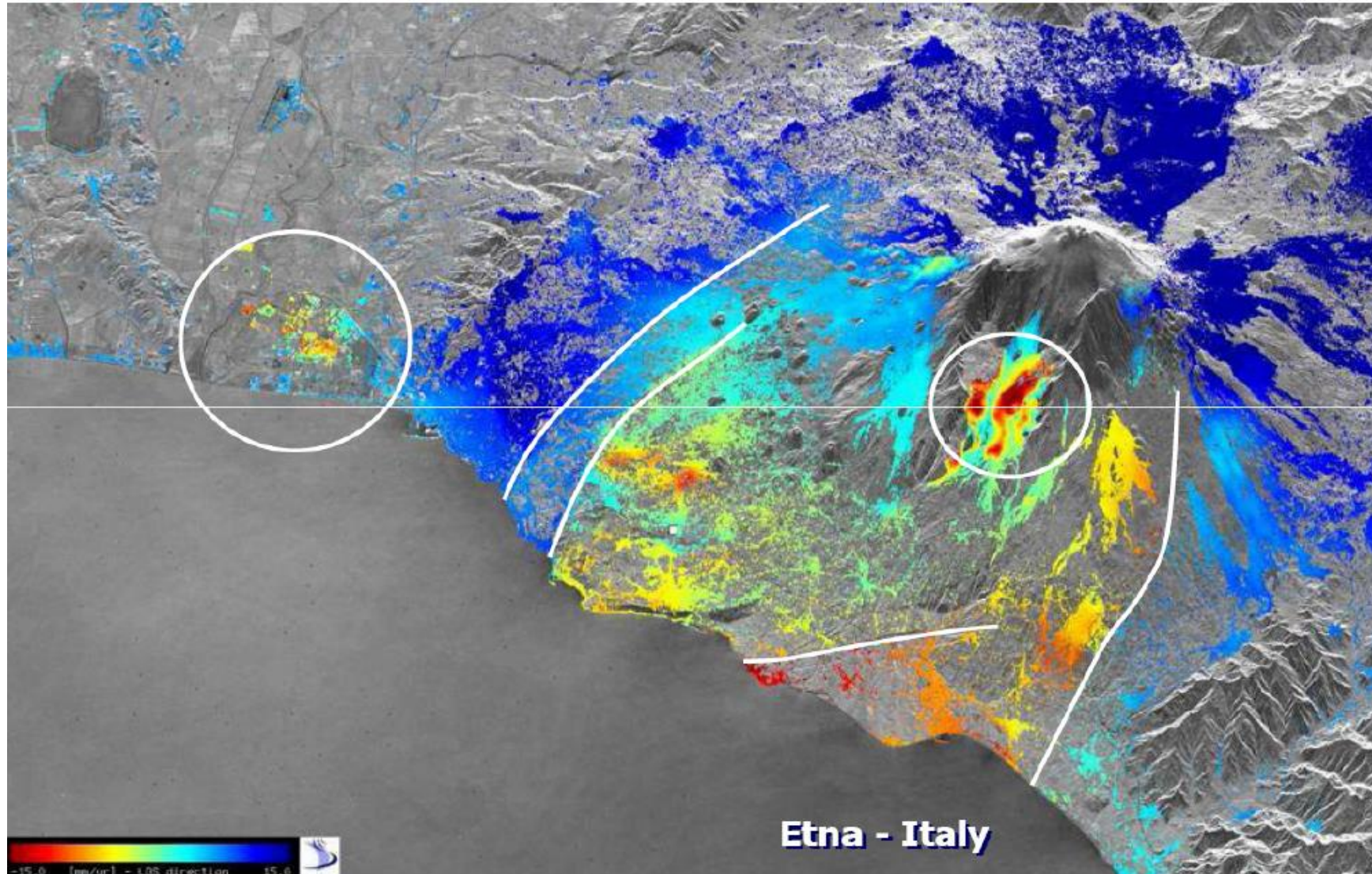
Aplicações PSINSAR: Subsidência (extração de água)



Cidade do México
Osmanoglu et al., 2011

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

Aplicações PSINSAR: Deslizamentos

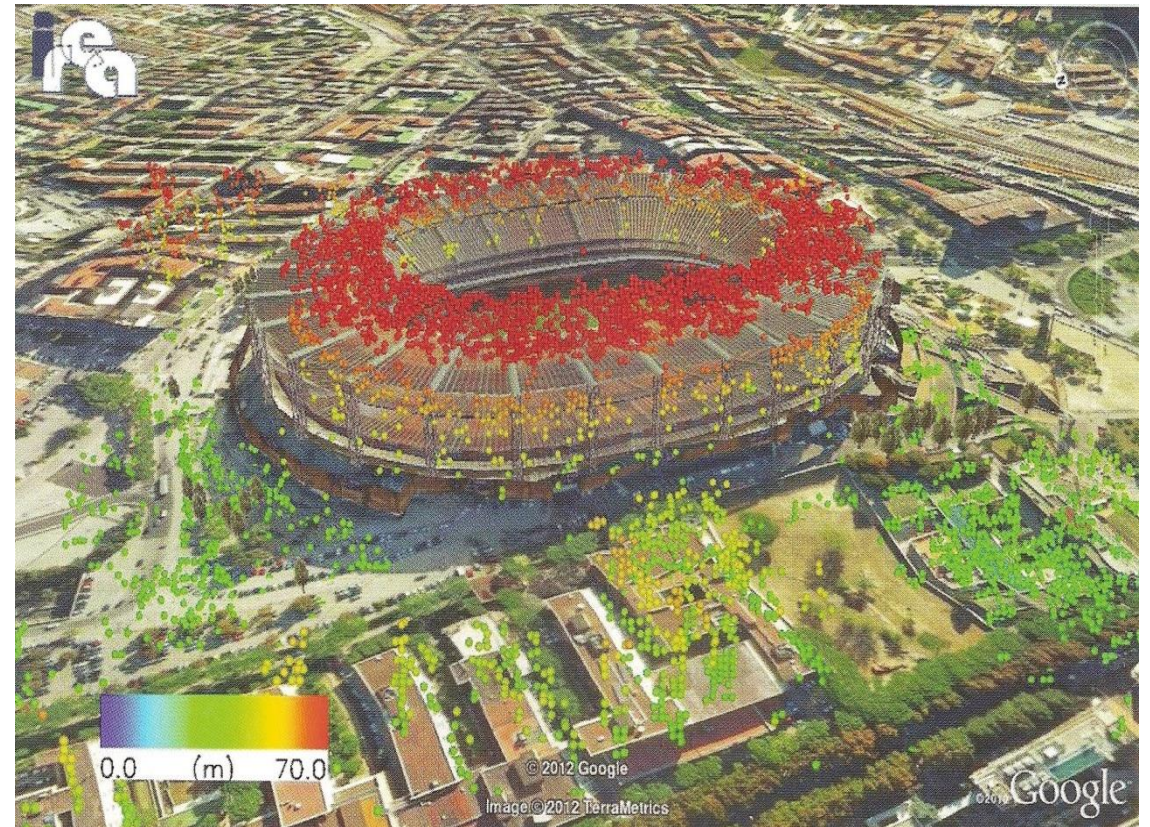


TRE, ESA

Aplicações PSINSAR: Modelo Digital de Elevação



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



Zhu and Bamler, 2010

Persistent Scatterers (Hooper)



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)

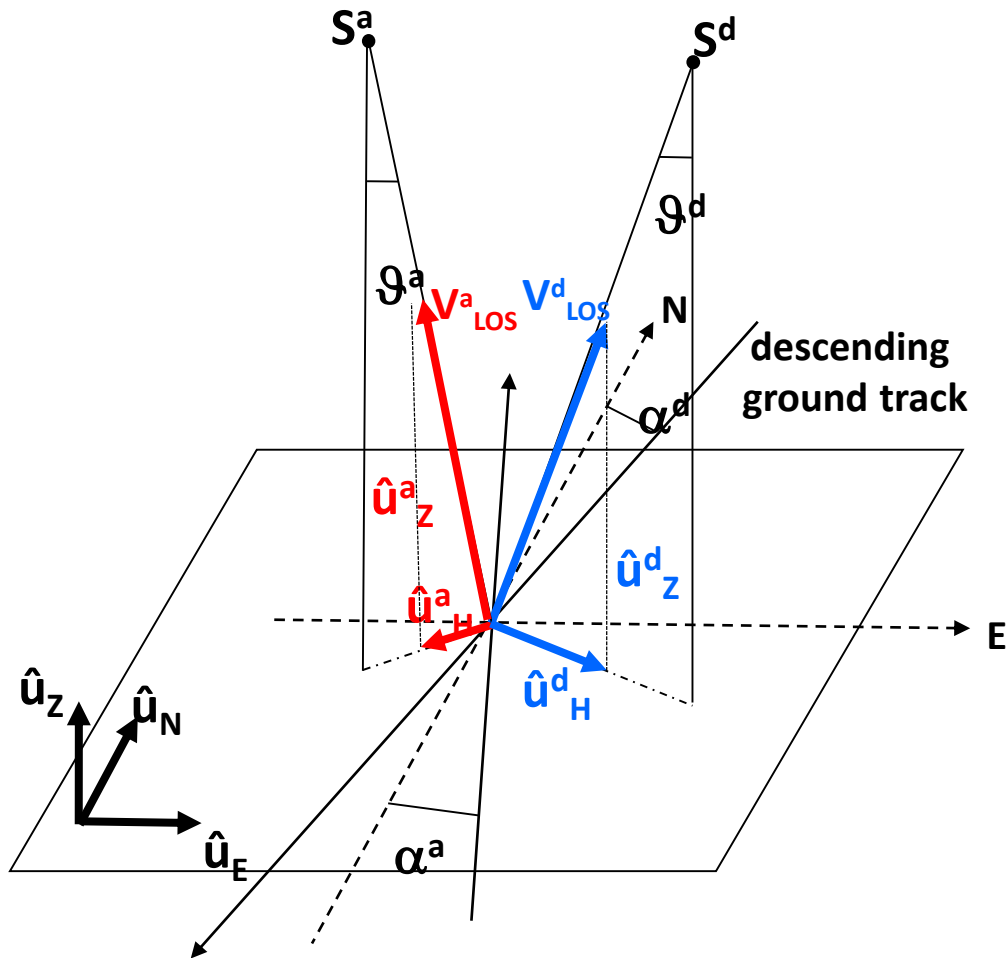
Insuficiente modelação dos efeitos atmosféricos

Modelo Funcional + Modelo estocástico



STUN, Bert Kampes, 2006

Deslocamento 2D (horizontal + vertical)



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

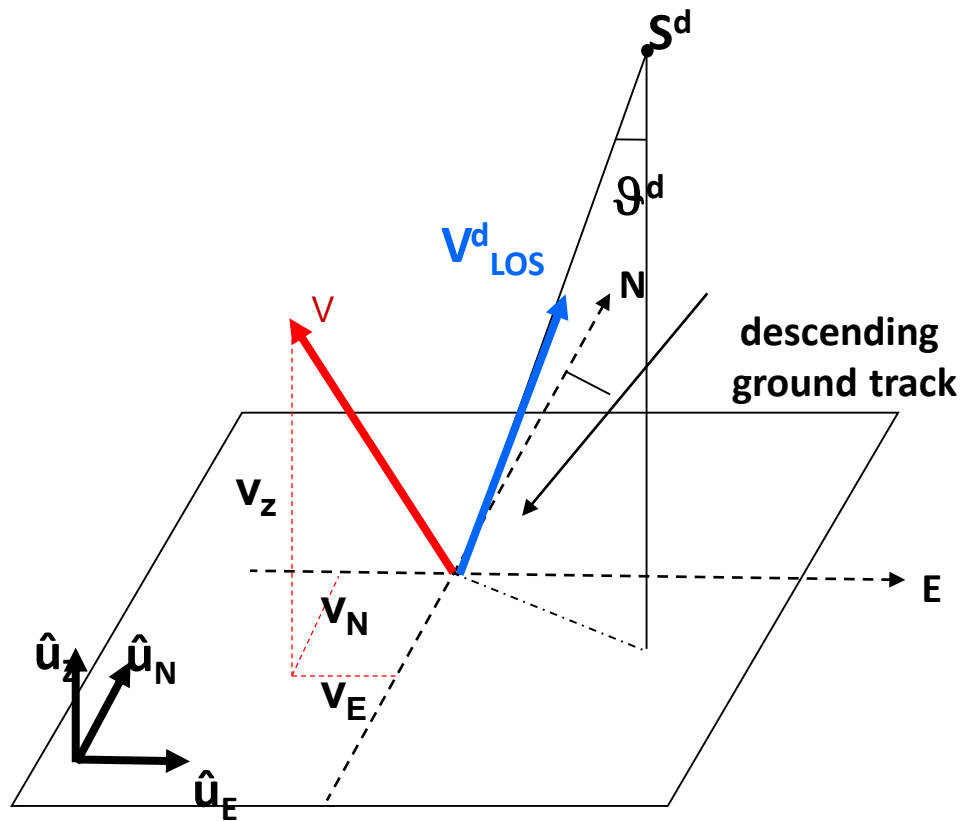
$$\begin{cases} V^a_{LOS} = (V_E, V_N, V_Z) \cdot (u^a_E, u^a_N, u^a_Z) \\ V^d_{LOS} = (V_E, V_N, V_Z) \cdot (u^d_E, u^d_N, u^d_Z) \end{cases}$$

$$\begin{cases} V^d_{LOS} = V_H u^d_H + V_Z u^d_Z \\ V^a_{LOS} = V_H u^a_H + V_Z u^a_Z \end{cases}$$



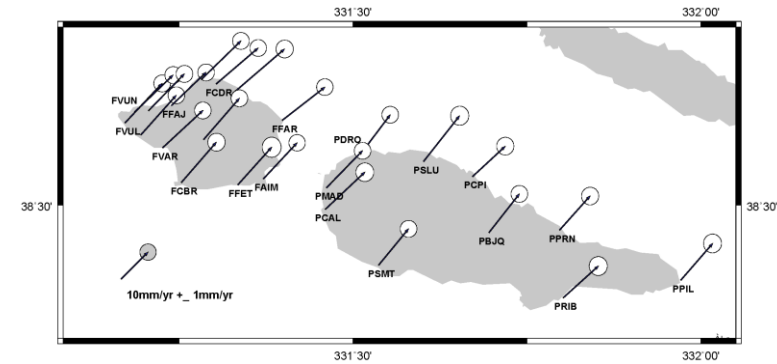
$$(V_H, V_Z)$$

Integração com GPS



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

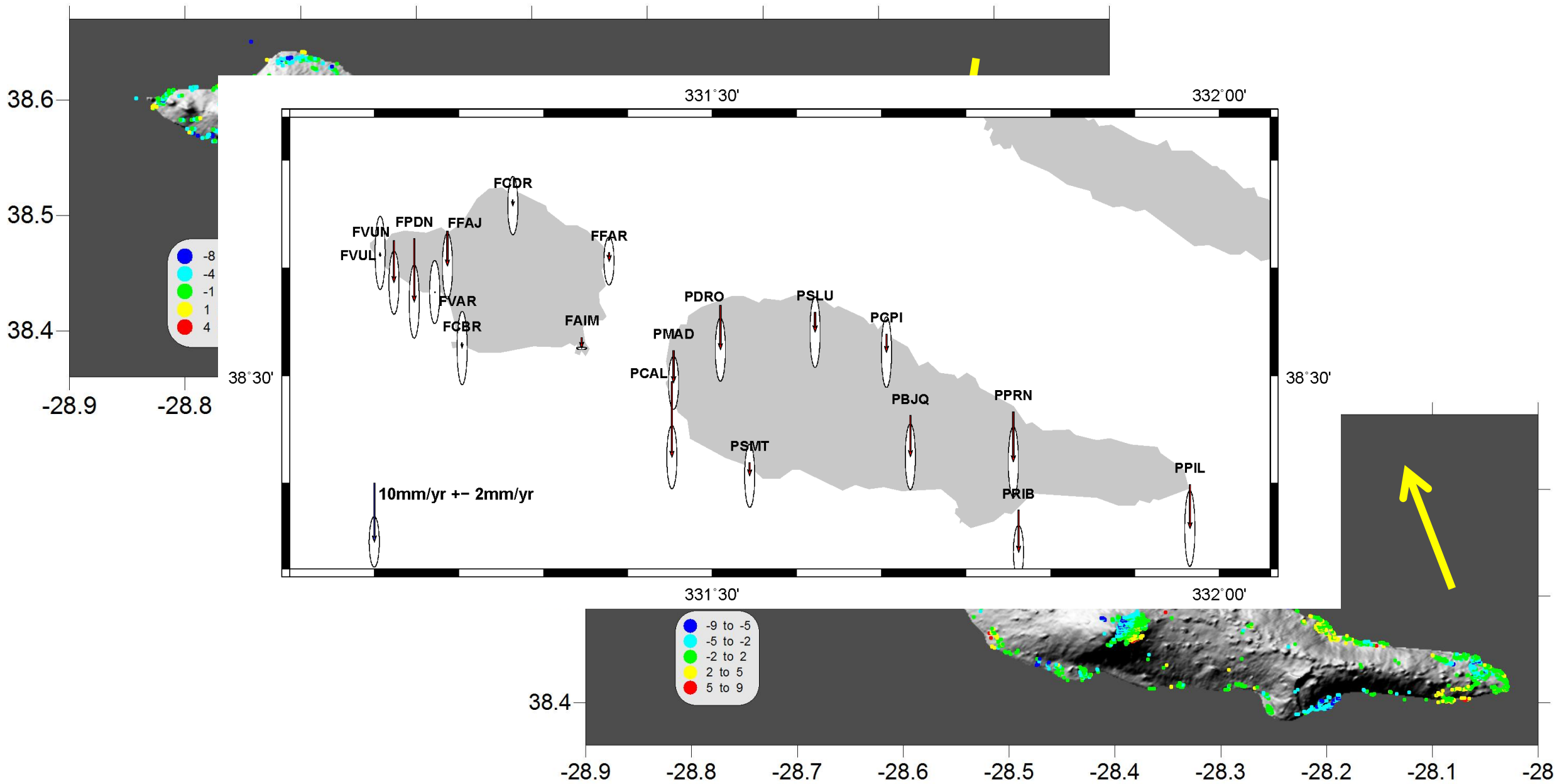
$$V_{LOS} = v_E u_e + v_N u_n + v_Z u_z$$



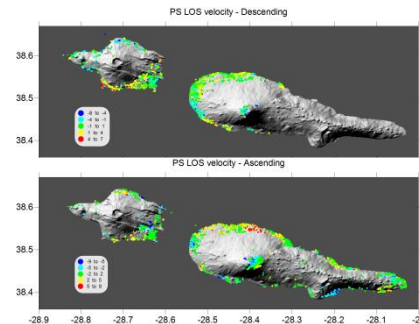
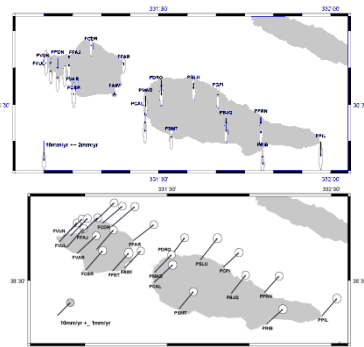
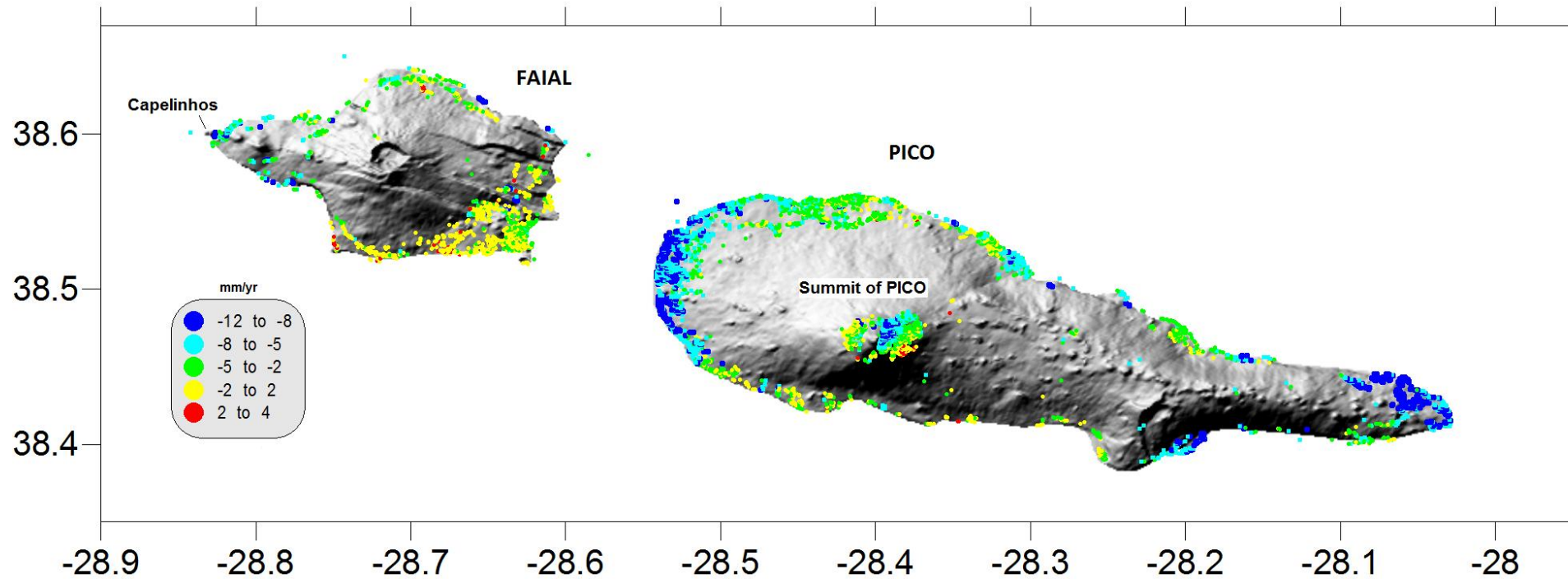
$$v_Z = \frac{1}{u_z} (V_{LOS} - \hat{v}_{GPS}^e u_e - \hat{v}_{GPS}^n u_n) (V_H u_H^d)$$

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

PS LOS velocity - Descending

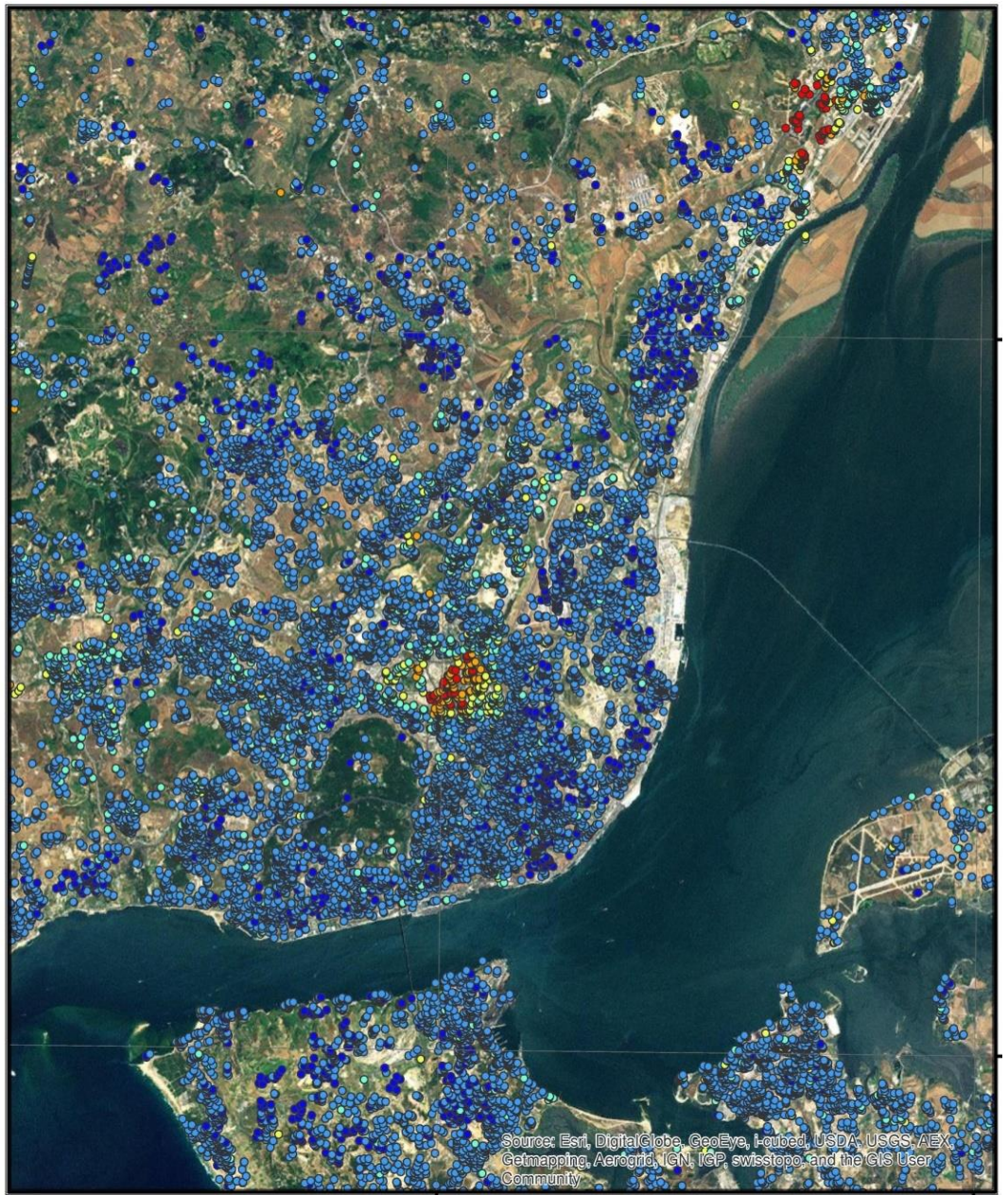


Velocidade Vertical ITRF2008 (2007-2009)



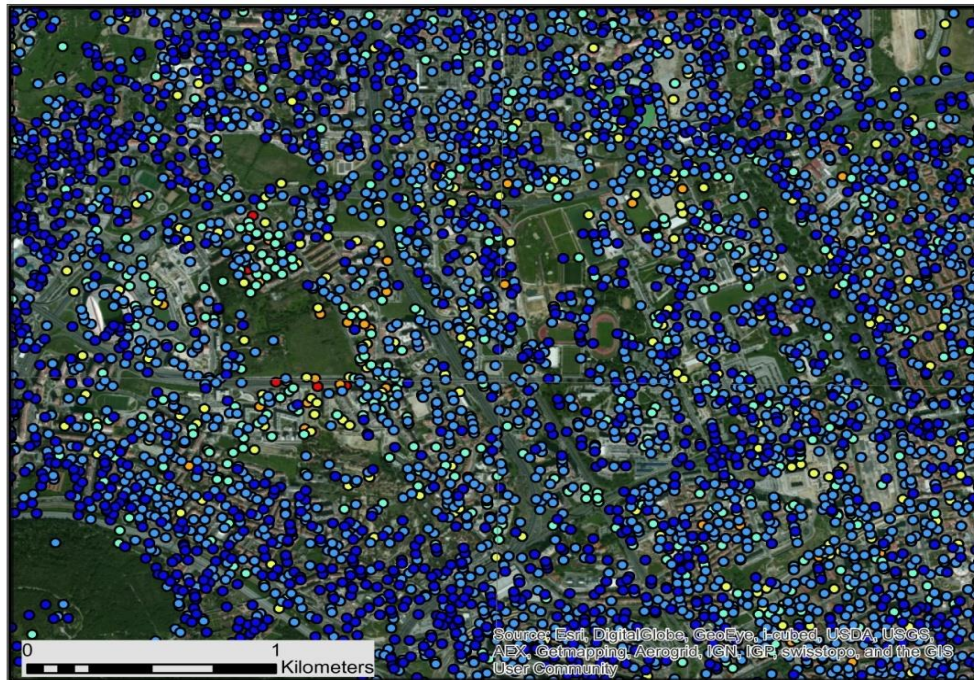
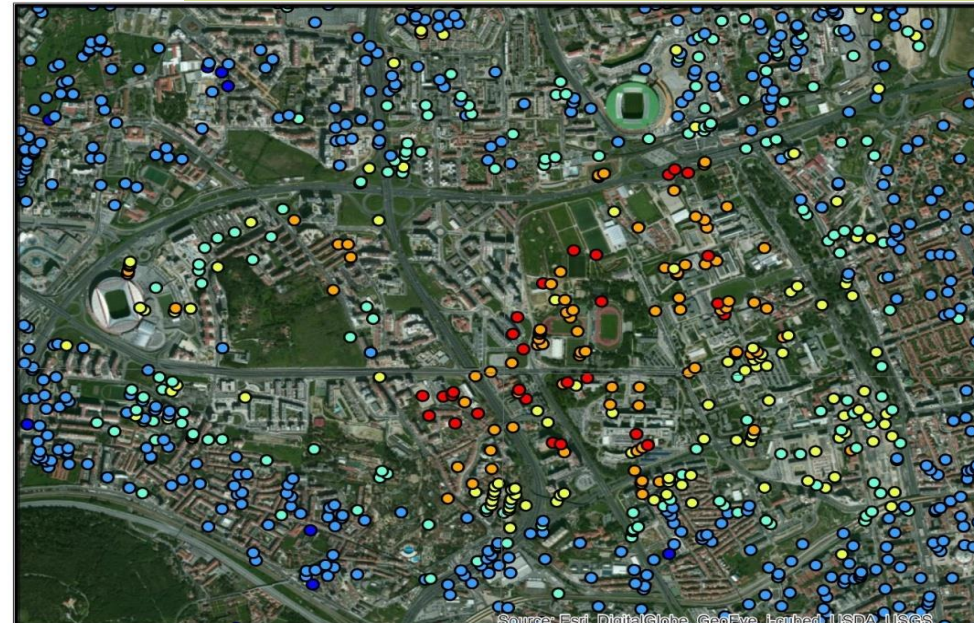
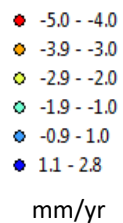
$$E = \sum_{i=1}^{N_{GPS}} \left\{ \mu(v_{PS}^v)(i) + D(\varphi, \lambda) - v_{GPS}^v(i) \right\}^2$$

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



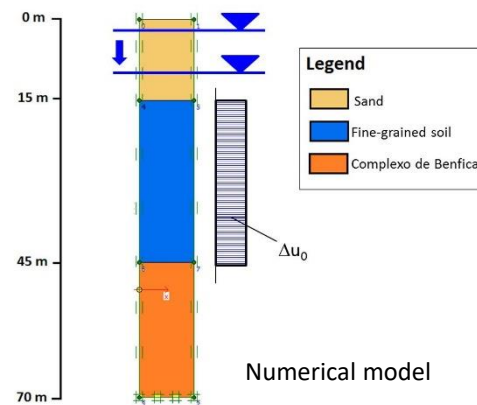
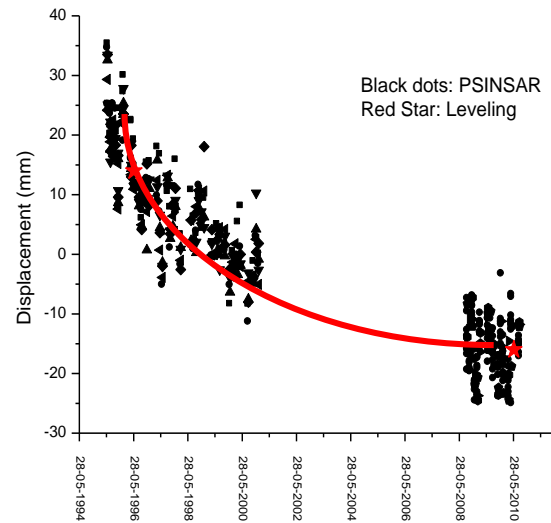
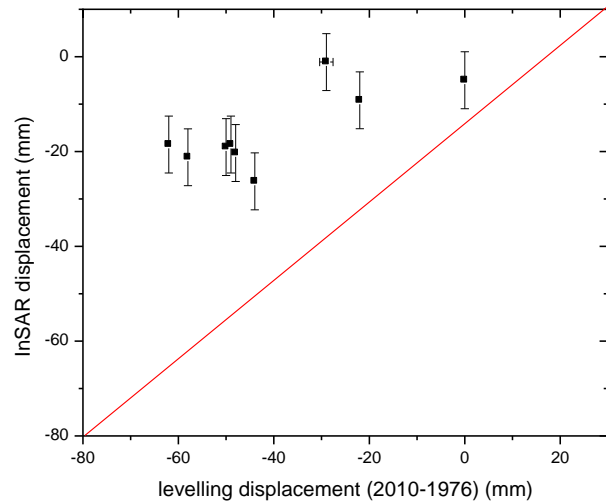
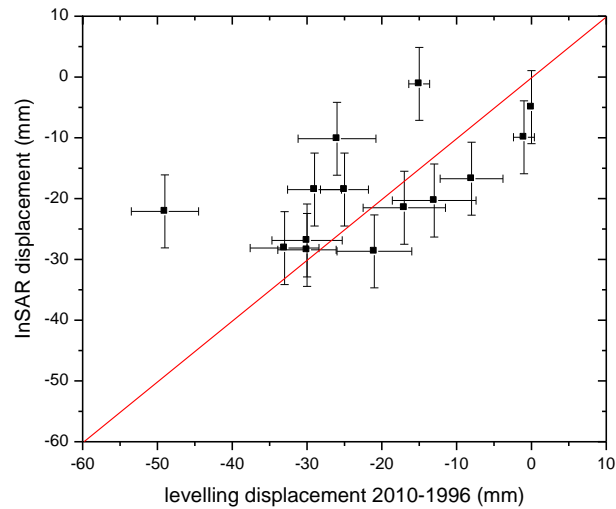
9° 10' 0" W

9° 0' 0" W

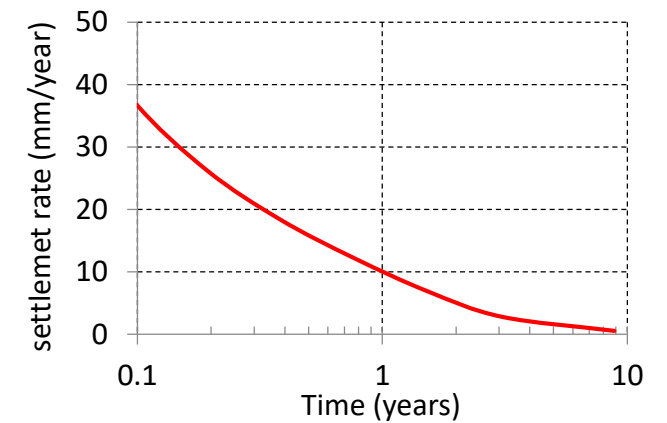
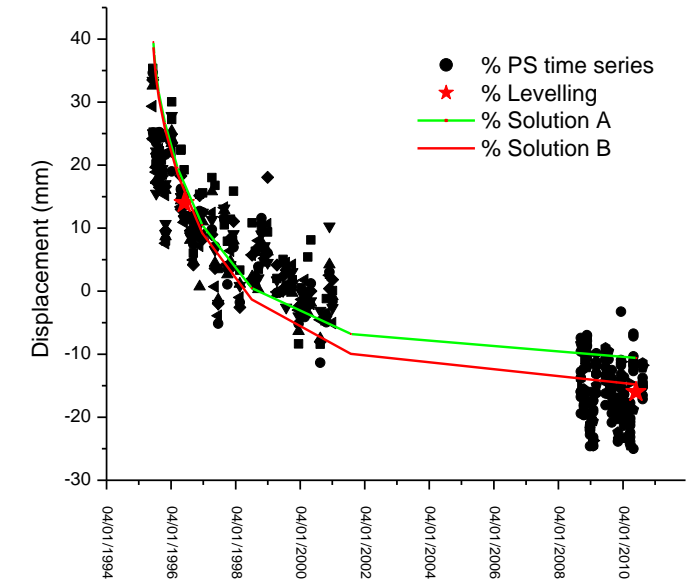


9° 10' 0" W

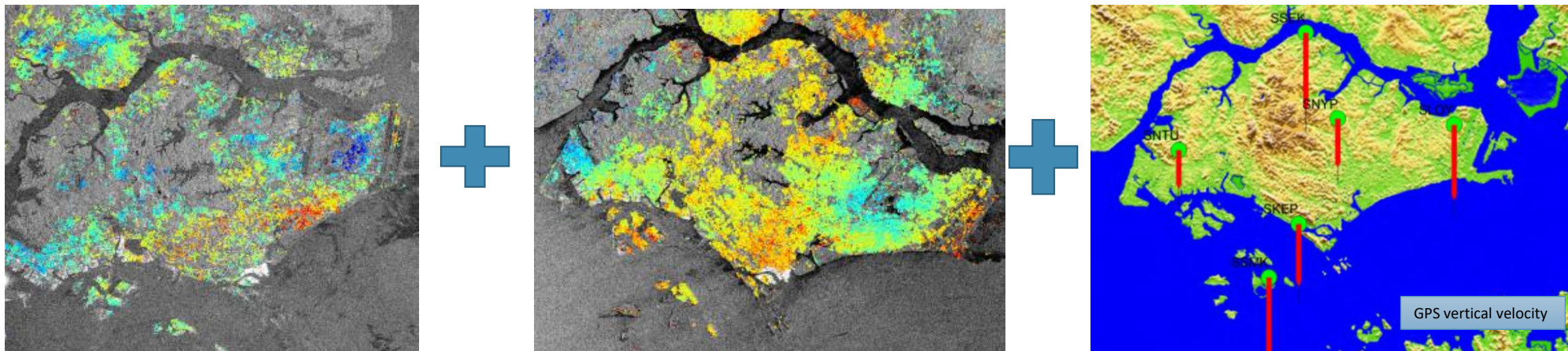
Série temporal do deslocamento vertical



Modelação numérica



Singapura : Deformação 1995 -2000



Fernandes et al., 2011

GPS station	GPS vertical velocity	Residuals descending		Residuals ascending		Residuals Merged	
		mean	std	mean	std	mean	std
SSEK	-2.0 +- 1.3	-0.18	1.2	-1.9	1.2	-0.03	0.70
NTUS	-1.0 +- 1.1	1.35	0.8	-2.1	1.0	0.01	0.90
SLOY	-1.9 +- 0.9	-2.0	1.3	-1.9	1.2	0.00	0.87
SNYP	-1.3 +- 0.9	0.43	0.8	-1.2	1.2	0.00	0.66
SKEP	-1.6 +-1.0	0.28	0.7	-3.1	1.2	--	--

(mm/yr)

Catalão et al., 2013

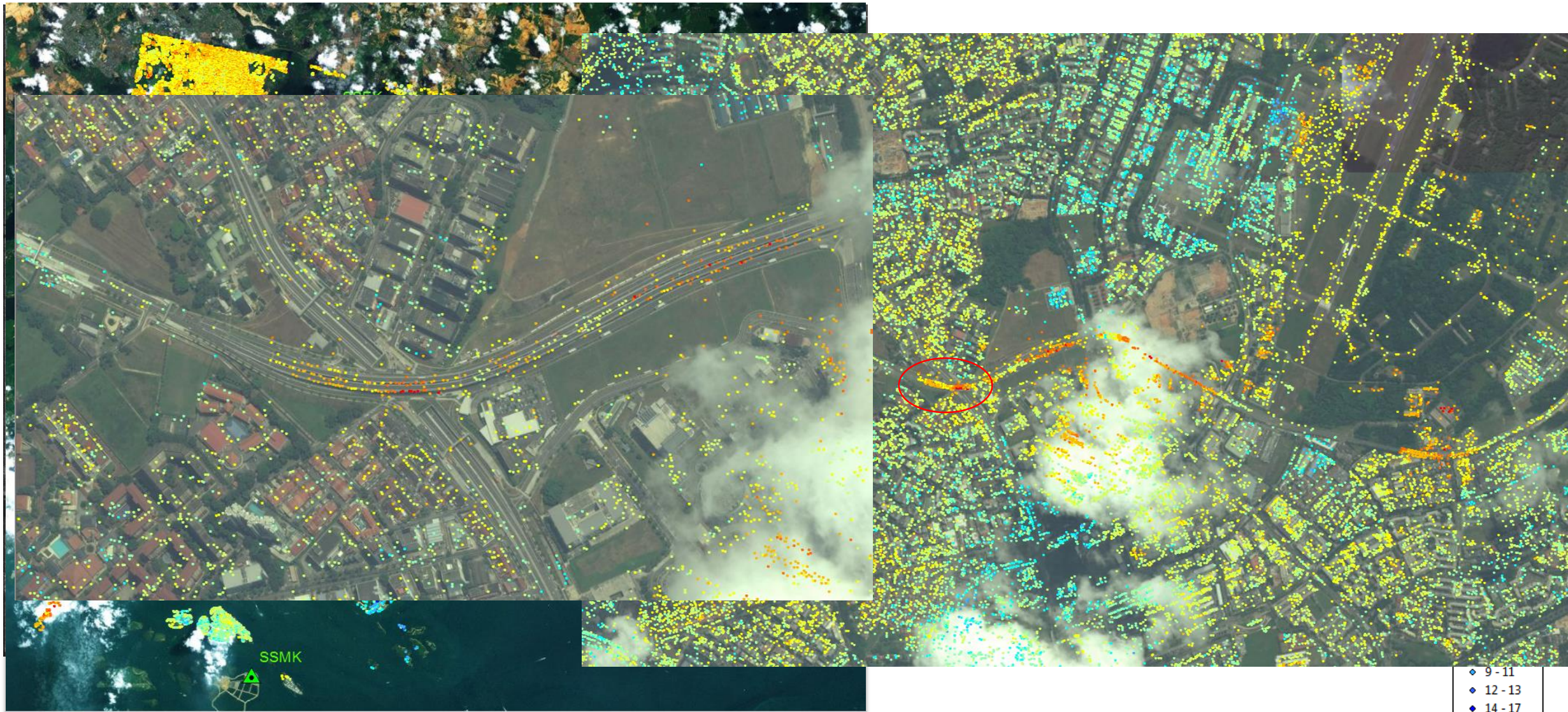
Singapura : Deformação 1995 -2000



- -9 - -5
- -4 - -3
- -2 - -1
- 2 - 3
- 4 - 7

Boat Quay

Novos sensores: banda X (TRX)

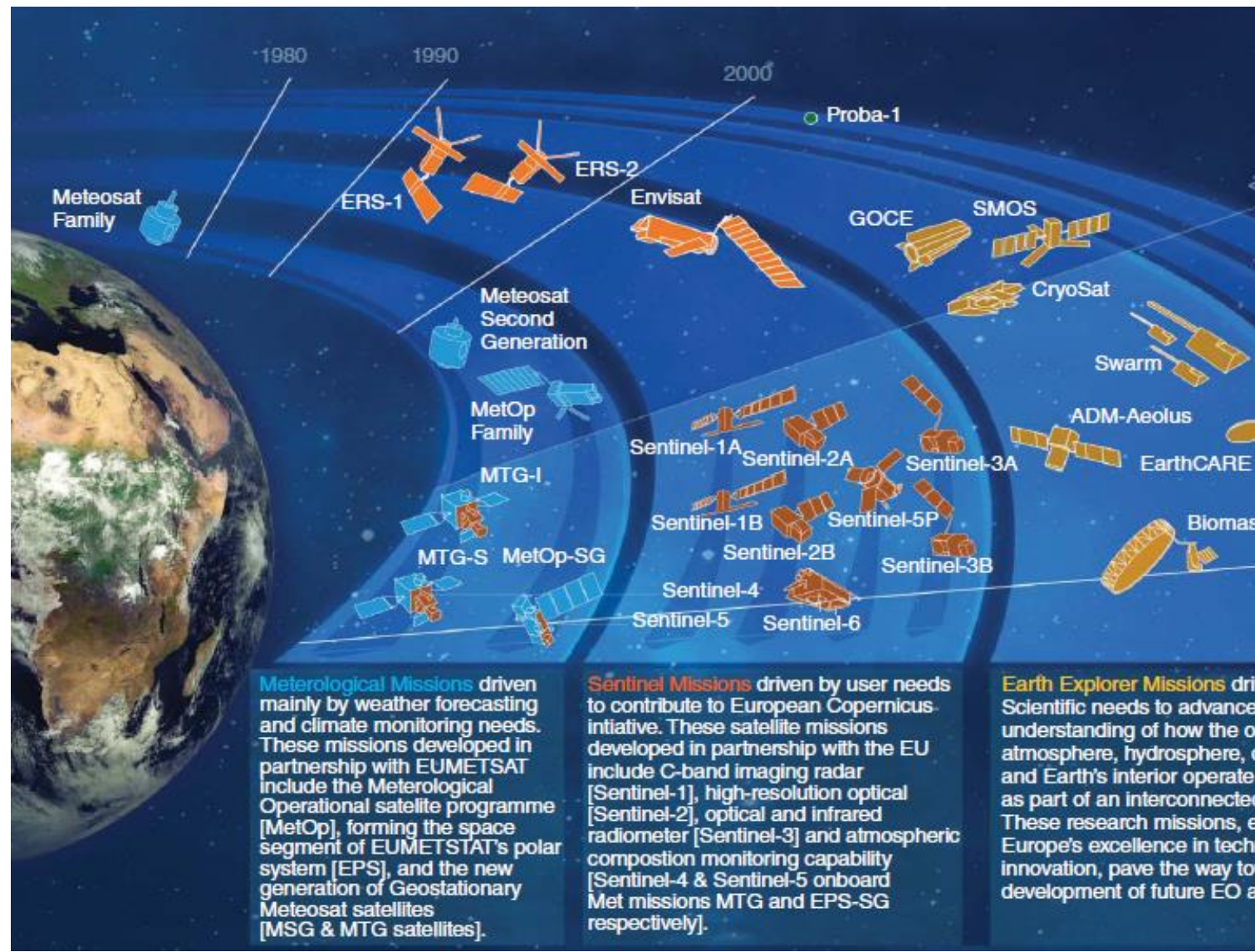


- ◆ 9 - 11
- ◆ 12 - 13
- ◆ 14 - 17

mm/yr

Perspetivas para o radar de abertura sintética

Missões ESA



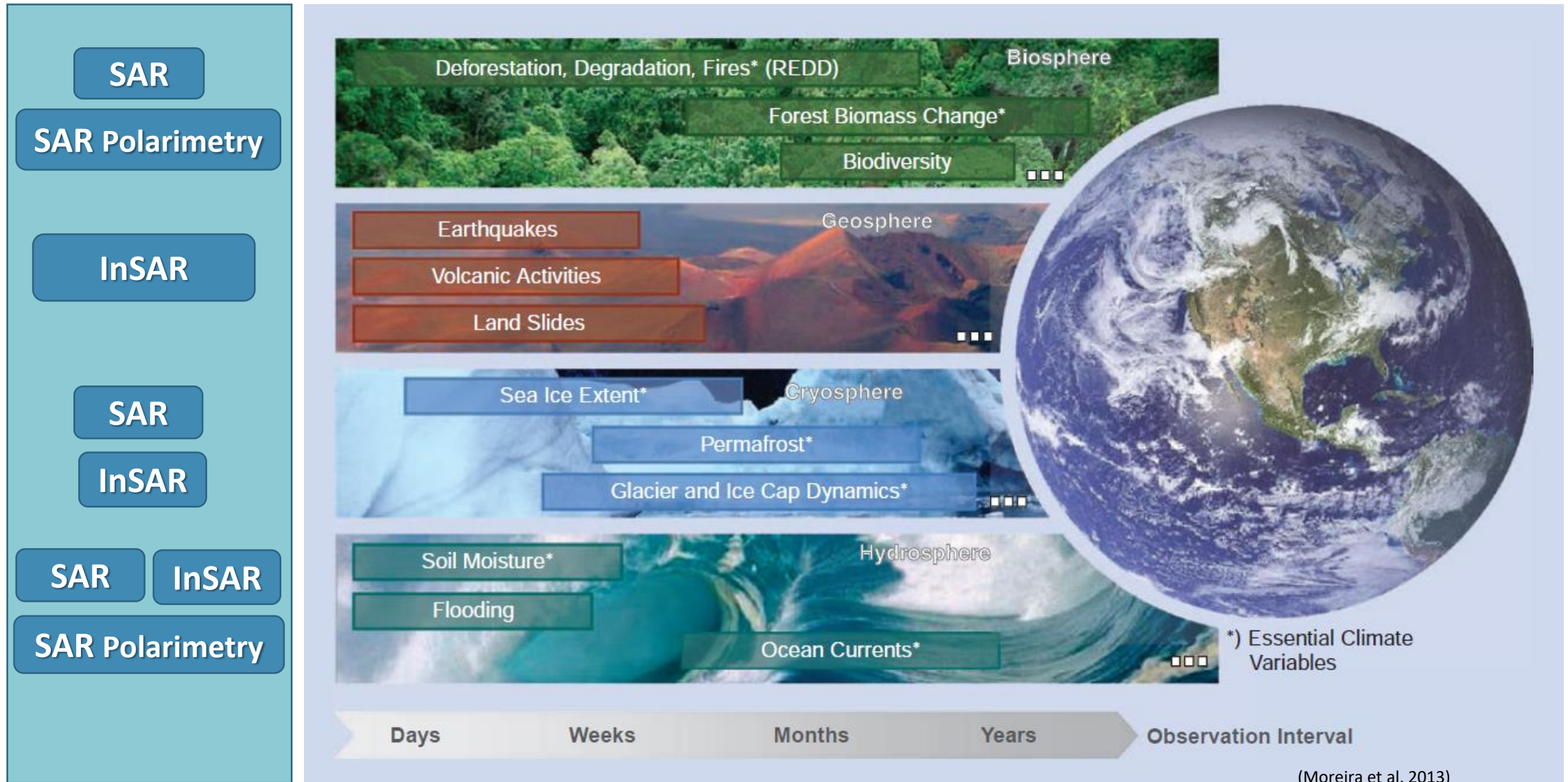
Meteorological Missions driven mainly by weather forecasting and climate monitoring needs. These missions developed in partnership with EUMETSAT include the Meteorological Operational satellite programme [MetOp], forming the space segment of EUMETSAT's polar system [EPS], and the new generation of Geostationary Meteorological satellites [MSG & MTG satellites].

Sentinel Missions driven by user needs to contribute to European Copernicus initiative. These satellite missions developed in partnership with the EU include C-band imaging radar [Sentinel-1], high-resolution optical [Sentinel-2], optical and infrared radiometer [Sentinel-3] and atmospheric composition monitoring capability [Sentinel-4 & Sentinel-5 onboard Met missions MTG and EPS-SG respectively].

Earth Explorer Missions driven by scientific needs to advance understanding of how the ocean, atmosphere, hydrosphere, and Earth's interior operate as part of an interconnected system. These research missions, exemplifying Europe's excellence in technological innovation, pave the way towards development of future EO applications.

ENVISAT/ ASAR	2002–2012	C (dual)
ALOS/PalsAR	2006–2011	L (quad)
TerraSAR-X/ TanDEM-X	2007–today 2010–today	X (quad)
Radarsat-2	2007–today	C (quad)
COSMO-SkyMed-1/4	2007 ... 2010–today	X (dual)
RISAT-1	2012–today	C (quad)
HJ-1C	2012–today	S (VV)
Kompsat-5	Launch scheduled in 2013	X (dual)
PAZ	Launch scheduled in 2013	X (quad)
ALOS-2	Launch scheduled in 2013	L (quad)
Sentinel-1a/1b	Launch scheduled in 2013/2015	C (dual)
Radarsat Constellation-1/2/3	Launch scheduled in 2017	C (quad)
SAOCOM-1/2	Launch scheduled in 2014/2015	L (quad)

Perspetivas para o radar de abertura sintética



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

