OBSERVATION PERFORMANCE OF A PARIS ALTIMETER IN-ORBIT DEMONSTRATOR

Salvatore D'Addio, Manuel Martin-Neira

Acknowledgment to: Nicolas Floury, Roberto Pietro Cerdeira

TEC-ETP, Electrical Engineering Department
European Space Agency

PARIS IoD Mission Summary Table

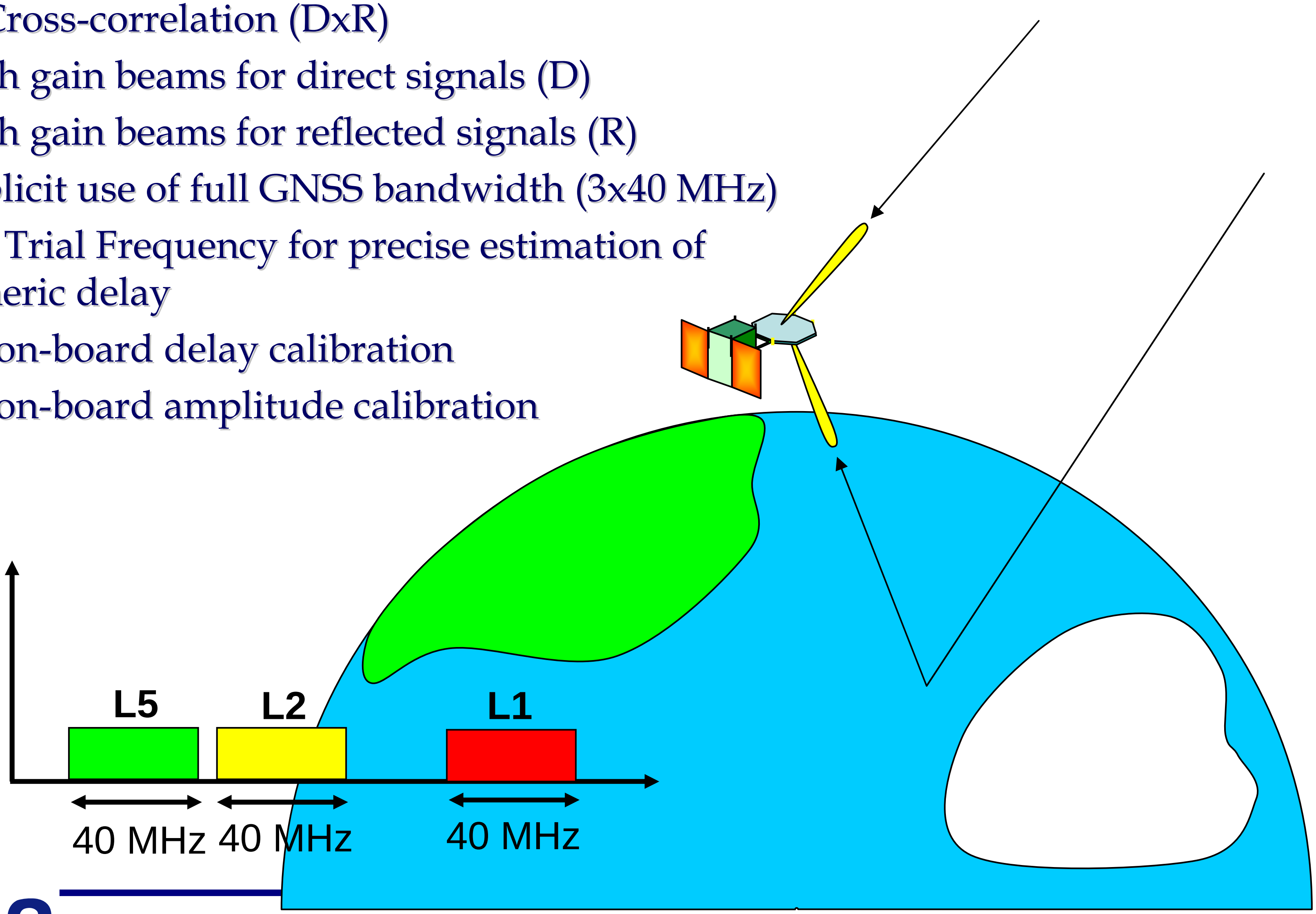
Instrument	PARIS Altimeter	
Main Scientific Product	Mesoscale Ocean Altimetry	
Secondary Scientific Product	Polar Ice Thickness	
Scientific by-products	Ionospheric total electron content Wind speed over ocean Wind direction over ocean Significant Wave Height Mean Square Slope of ocean surface Sea Ice Extent	
Particular Application	Tsunami detection	
	In-orbit Demonstrator	**Operational Mission**
Orbit	Polar Sun Synchronous	Polar Sun Synchronous
Orbital Height	800 km	1500 km
Swath	900 km	1500 km
Revisit Time	3 days	2 days
Spatial Resolution	100 km	< 100 km
Antenna Diameter / Gain	0.9 m / 19 dB	2.4 m / 30 dB
Number of Beams	4	16
Frequencies	GPS L1+L5 Galileo E1+E5	All 3 bands of GPS, GLONASS, GALILEO, BEIDOU
Total Altimetry Accuracy (1σ)	**< 17-20 cm**	**< 5-7.5 cm**
Platform	PROBA-like	PROTEUS-like
Launcher Configuration	Piggy back	Main passenger

Factors affecting altimetry accuracy

	Factors affecting altimetry accuracy	Comment
Precision	Allowed incidence angle of specular point	•Higher incidence angle reduces the height precision, but increases swath •Scanning reduce antenna gain
	Instrument Characteristics: 1. Antenna Gain, Receiver NF 2. XC Coherent integration time	1. Improve SNR 2. Fundamental for performance optimization
	Waveform Retracking Performance	Optimum retracker to be defined
Accuracy	Uncertainties on Propagation: 1. Ionosphere 2. Troposphere 3. EM Bias 4. Skewness Bias	1. Use of 2 or 3 Frequencies 2. Estimated or measured 3. Frequency Dependent 4. Fraction of EM Bias
	Uncertainties on Geometry/Orbit	
	Residual instrument errors after calibration	On-board Delay/Amplitude Calibration needed

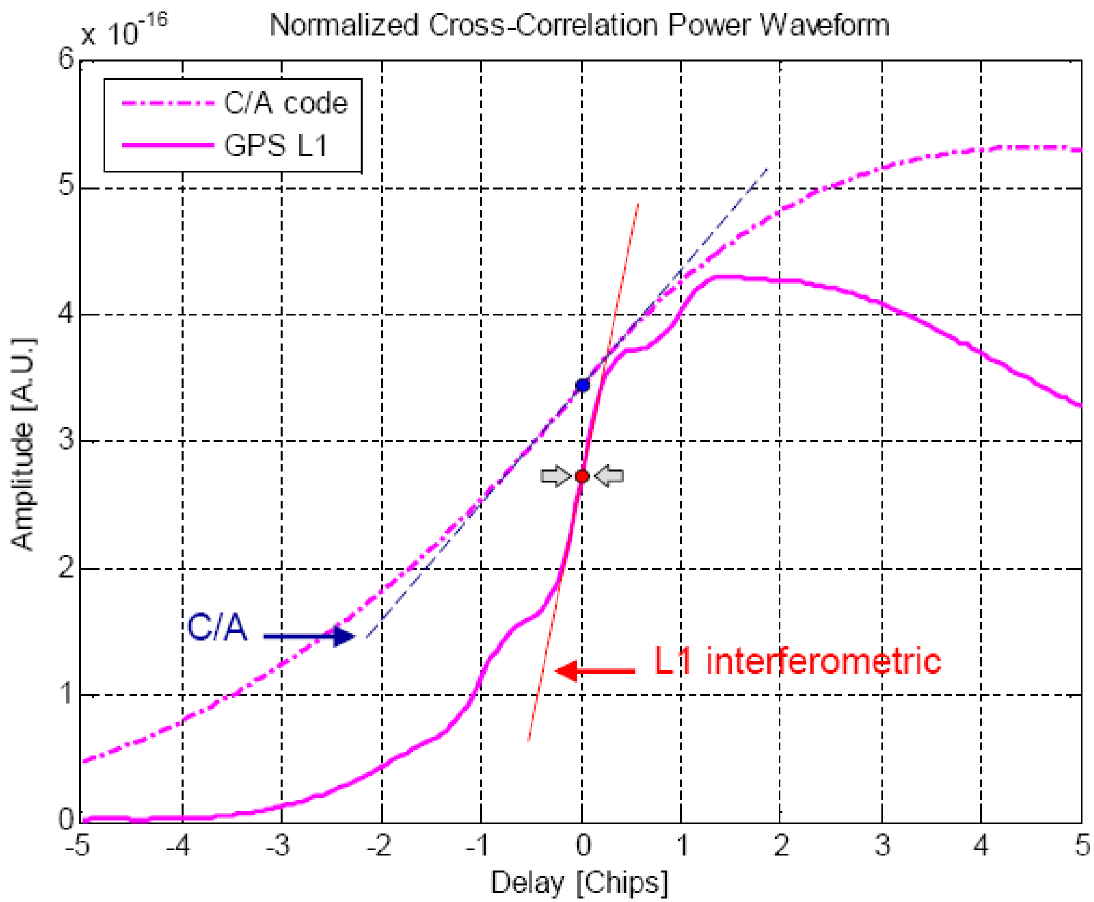
PARIS IOD System Concept

- Direct Cross-correlation (DxR)
  - High gain beams for direct signals (D)
  - High gain beams for reflected signals (R)
  - Implicit use of full GNSS bandwidth (3x40 MHz)
- Dual or Trial Frequency for precise estimation of ionospheric delay
- Precise on-board delay calibration
- Precise on-board amplitude calibration



PARIS IoD L1 Power Waveform

- GPS L1 Composite, Orbit Height: 500Km, Down-Looking Antenna Gain: 19dBi, Nadir Looking Geometry



Factors affecting altimetry accuracy

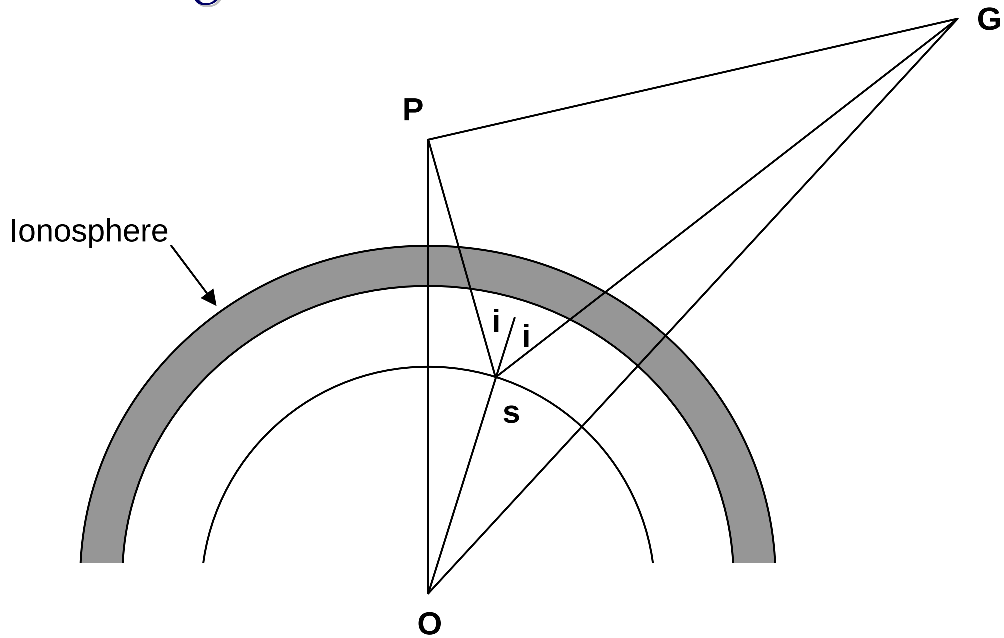
	Factors affecting altimetry accuracy	Comment
Precision	Allowed incidence angle of specular point	•Higher incidence angle reduces the height precision, but increases swath •Scanning reduce antenna gain
	Instrument Characteristics: 1. Antenna Gain, Receiver NF 2. XC Coherent integration time	1. Improve SNR 2. Fundamental for performance optimization
	Waveform Retracking Performance	Optimum retracker to be defined
Accuracy	Uncertainties on Propagation: 1. Ionosphere 2. Troposphere 3. EM Bias 4. Skewness Bias	1. Use of 2 or 3 Frequencies 2. Estimated or measured 3. Frequency Dependent 4. Fraction of EM Bias
	Uncertainties on Geometry/Orbit	
	Residual instrument errors after calibration	On-board Delay/Amplitude Calibration needed

Max Incidence Angle (1/2)

The incidence angle plays an important role in the definition of critical parameters of the PARIS mission, such as:

(a) Precision

(b) Sampling and Coverage



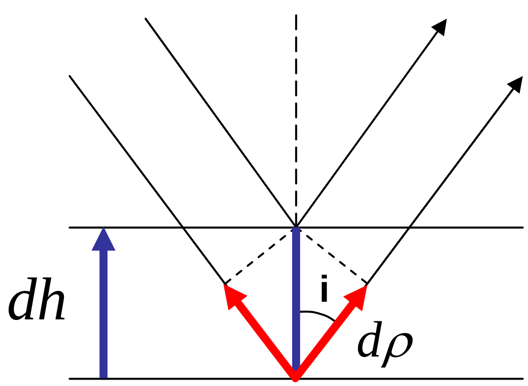
Max Incidence Angle (2/2)

a) Altimetric performance degrades with incidence angle

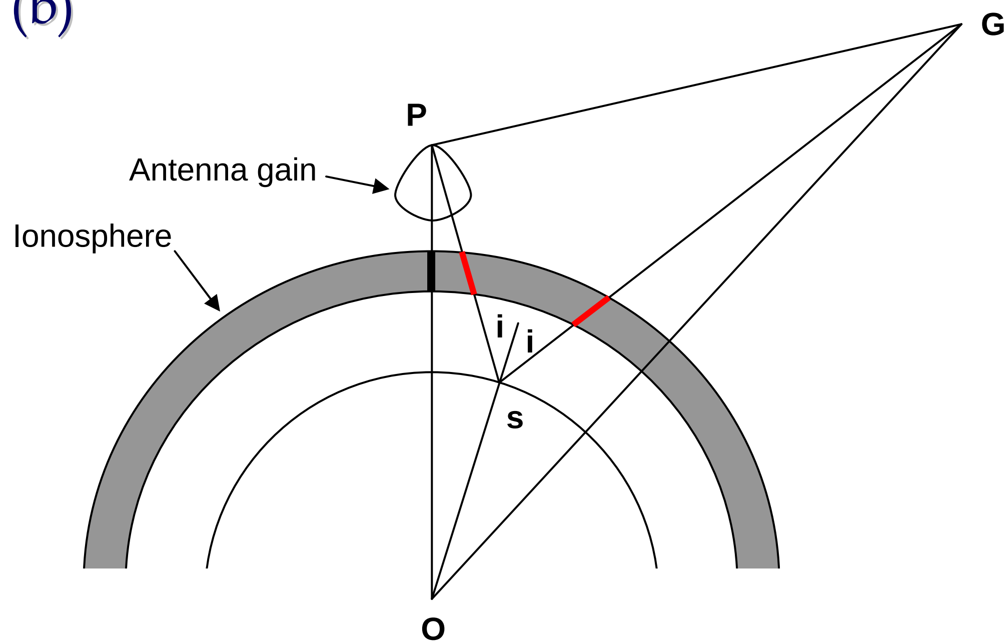
b) Ionospheric delay and antenna losses increase with incidence angle

(a)

$$dh = -\frac{d\rho}{2\cos i}$$



(b)



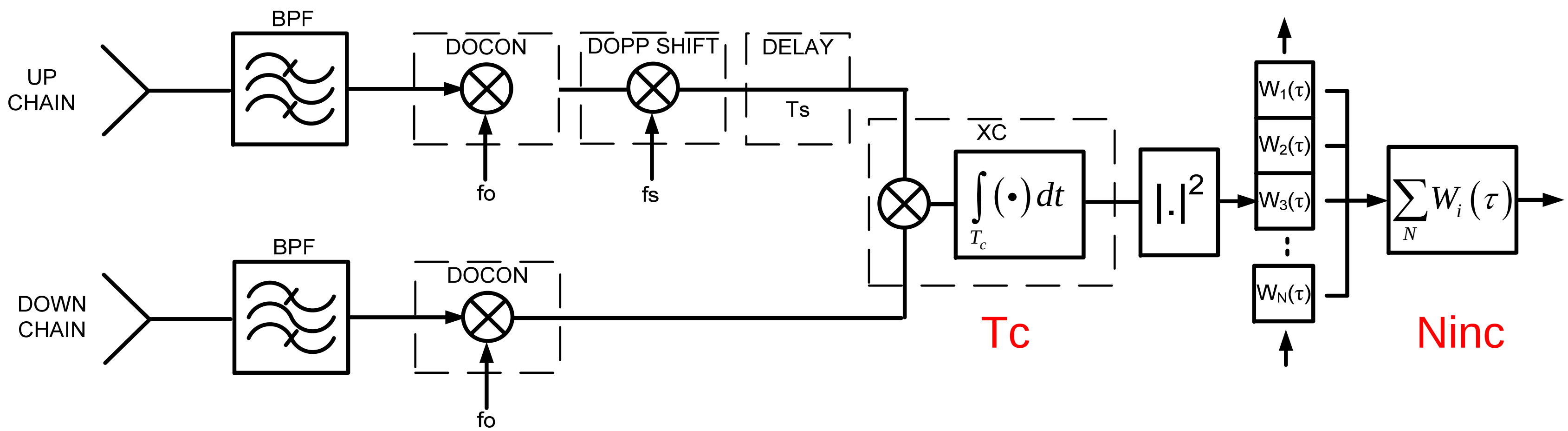
The incidence angle i should be minimised.

Factors affecting altimetry accuracy

	Factors affecting altimetry accuracy	Comment
Precision	Allowed incidence angle of specular point	•Higher incidence angle reduces the height precision, but increases swath •Scanning reduce antenna gain
	Instrument Characteristics: 1. Antenna Gain, Receiver NF 2. XC Coherent integration time	1. Improve SNR 2. To be optimized for maximum precision
	Waveform Retracking Performance	Optimum retracker to be defined
Accuracy	Uncertainties on Propagation: 1. Ionosphere 2. Troposphere 3. EM Bias 4. Skewness Bias	1. Use of 2 or 3 Frequencies 2. Estimated or measured 3. Frequency Dependent 4. Fraction of EM Bias
	Uncertainties on Geometry/Orbit	
	Residual instrument errors after calibration	On-board Delay/Amplitude Calibration needed

Cross-Correlation Integration Time

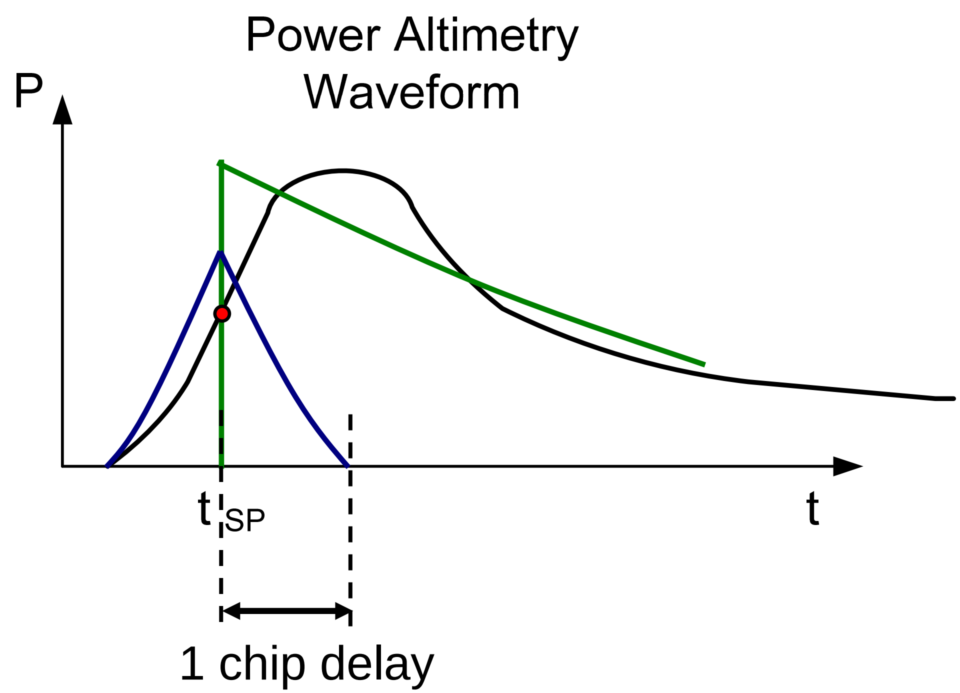
Interferometric Processing Schematic

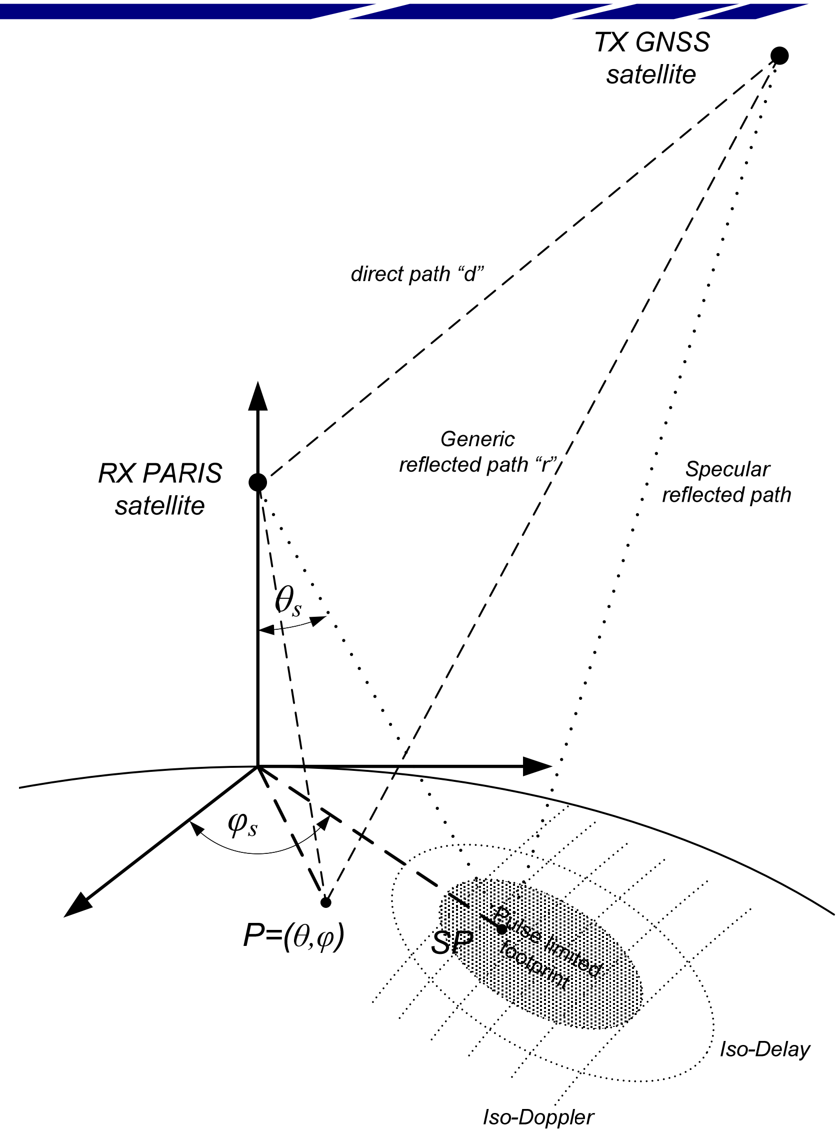


For a given target along track spatial resolution, e.g. **100Km**, the coherent integration time and the incoherent averaging are **inversely proportional**:

$$T_{100Km} = T_c N_{inc}$$

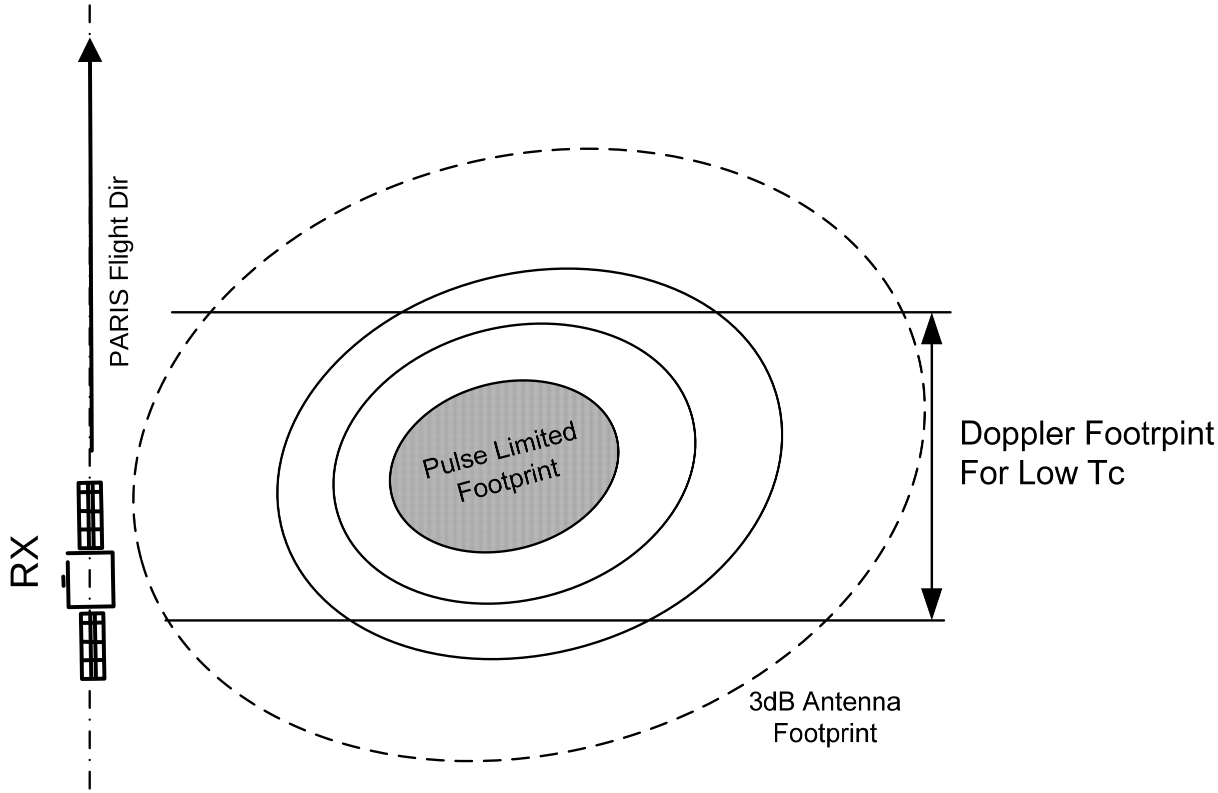
Power Altiemtry Waveform





$$\left\langle \left| Z_S(\tau) \right|^2 \right\rangle = \int_{\theta,\phi} P_{R,\theta,\varphi} \left| ACF(\Delta\tau) \frac{\sin(\pi \Delta f T_c)}{\pi \Delta f T_c} \right|^2$$

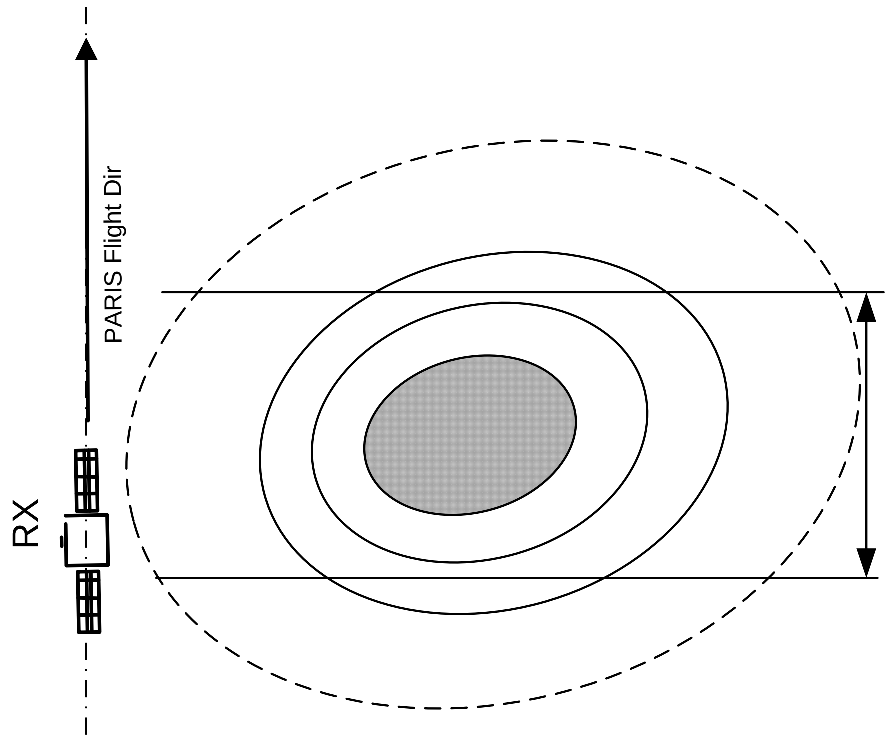
The role of Tc

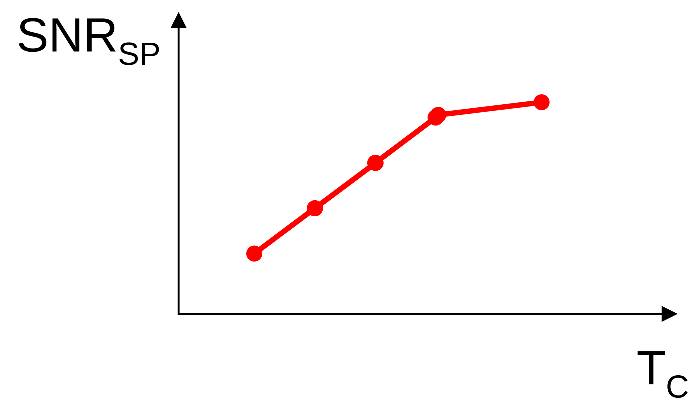


High Tc

$$\langle |Z_S(\tau)|^2 \rangle = \int_{\theta,\phi} P_{R,\theta,\varphi} \left| ACF(\Delta\tau) \frac{\sin(\pi \Delta f T_c)}{\pi \Delta f T_c} \right|^2$$

Tc vs SNR





$$SNR_{SP} \propto \int_{\theta,\phi} P_{R,\theta,\varphi} \left| ACF\left(\Delta\tau\right) \frac{\sin\left(\pi \Delta f T_c\right)}{\pi \Delta f T_c} \right|^2 \bullet T_c$$

Cross-Correlation Integration Time (Tc)

- Analytical model for altimetry precision:

$$\sigma_h = \frac{c\,\overline{P_{Z,S}}}{2\cos\theta_{inc,SP}\,\overline{P_{Z,S}}'}\frac{1}{\sqrt{N_{inc}}}\sqrt{\left(1+\frac{1}{SNR}\right)^2+\left(\frac{1}{SNR}\right)^2}$$

$$N_{inc} = \frac{T_{100Km}}{T_c}$$

$$SNR \propto T_c$$

$$\sigma_h = const_1\sqrt{T_c}\sqrt{\left(1+\frac{1}{const_2 T_c}\right)^2+\left(\frac{1}{const_2 T_c}\right)^2}$$

- Tc shall be chosen such to have a sufficient SNR (e.g. 6dB) but cannot be increased further otherwise the altimetric precision is degraded because speckle is not averaged enough
- However, Tc cannot be too low otherwise consecutive XC samples may be correlated and speckle would anyway not be averaged

Interferometric Processing SNR

- Up / Down-looking Antenna Gain and Up/Down RX NF shall be such to have sufficient SNR
- In PARIS IoD with interferometric processing, the final power waveform SNR is given as:

$$SNR_{\text{int}}(\tau) = \frac{SNR_{cr}(\tau)}{\left[1 + \frac{1 + SNR_R}{SNR_D}\right]}$$

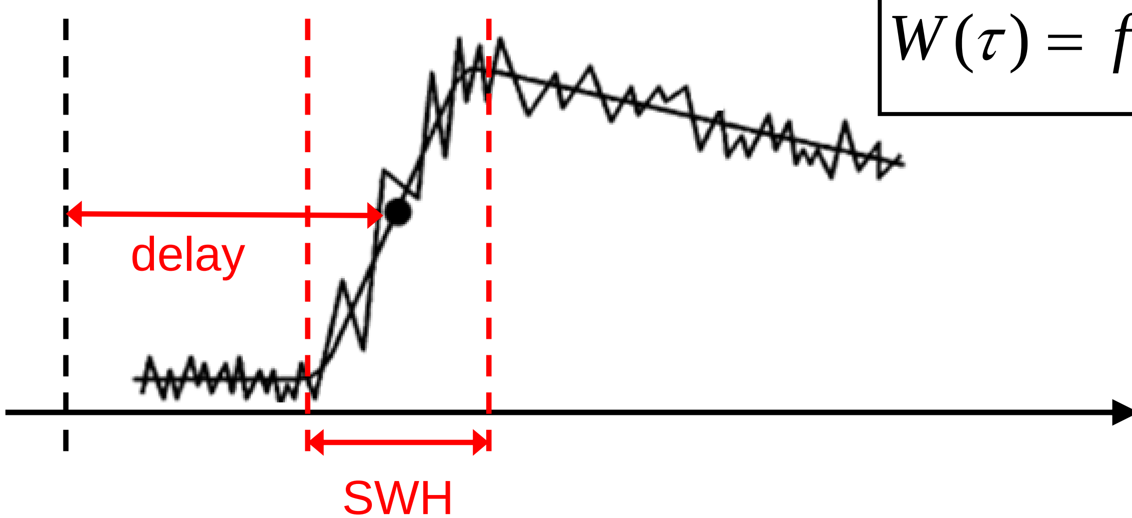
Factors affecting altimetry accuracy

	Factors affecting altimetry accuracy	Comment
Precision	Allowed incidence angle of specular point	• Higher incidence angle reduces the height precision, but increases swath • Scanning reduce antenna gain
	Instrument Characteristics: 1. Antenna Gain, Receiver NF 2. XC Coherent integration time	1. Improve SNR 2. Fundamental for performance optimization
	Waveform Retracking Performance	Optimum retracker to be defined
Accuracy	Uncertainties on Propagation: 1. Ionosphere 2. Troposphere 3. EM Bias 4. Skewness Bias	1. Use of 2 or 3 Frequencies 2. Estimated or measured 3. Frequency Dependent 4. Fraction of EM Bias
	Uncertainties on Geometry/Orbit	
	Residual instrument errors after calibration	On-board Delay/Amplitude Calibration needed

Waveform Retracking

- The retracking has the objective of estimating the sea state parameters and the sea mean surface height by fitting a theoretical model to measured waveforms
- Maximum likelihood estimation (MLE) or on weighted least squares estimation has been extensively used in Conventional Radar Altimetry.
- The MLE method estimates the parameters by determining which values maximize the probability of obtaining the recorded waveform shape in the presence of noise of a given statistical distribution.

$$W(\tau) = f\left(\tau_{sp}, \sigma_0, SWH\right)$$



Factors affecting altimetry accuracy

	Factors affecting altimetry accuracy	Comment
Precision	Allowed incidence angle of specular point	•Higher incidence angle reduces the height precision, but increases swath •Scanning reduce antenna gain
	Instrument Characteristics: 1. Antenna Gain, Receiver NF 2. XC Coherent integration time	1. Improve SNR 2. Fundamental for performance optimization
	Waveform Retracking Performance	Optimum retracker to be defined
Accuracy	Uncertainties on Propagation: 1. Ionosphere 2. Troposphere 3. EM Bias 4. Skewness Bias	1. Use of 2 or 3 Frequencies 2. Estimated or measured 3. Frequency Dependent 4. Fraction of EM Bias
	Uncertainties on Geometry/Orbit	
	Residual instrument errors after calibration	On-board Delay/Amplitude Calibration needed

The impact of Ionosphere

- At L-band, the ionosphere is a major contributor to the propagation delay

$$\rho = -2h\cos i + I$$

with

$$I = \frac{40.3}{f^2} TEC$$

- Multi-frequency observations allow to remove the ionospheric effect

$$\rho_1 = -2h\cos i + \frac{I'}{f_1^2}$$

$$\rho_5 = -2h\cos i + \frac{I'}{f_5^2}$$

$$\Rightarrow \quad h_{15} = 1.26\frac{\rho_5}{2\cos i} - 2.26\frac{\rho_1}{2\cos i}$$

- However this is at the expense of a severe error amplification factor

$$\sigma_{h_{15}} = \underline{2.59}\ \sigma_\rho$$

Possible Ionospheric Correction Method

- Starting from range equation: $y = -h + \frac{x}{f^2}$
- Multi-frequency observations are taken:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} -1 & f_1^{-2} \\ -1 & f_5^{-2} \end{bmatrix} \begin{bmatrix} h \\ x \end{bmatrix}$$

- The ionospheric delays are retrieved with the following uncertainties:

$$\frac{x}{f_1^2} = -1.26 \frac{\rho_1}{2\cos i} + 2.26 \frac{\rho_5}{2\cos i}$$

$$\frac{1}{f_1^2}\sigma_x = 1.78\sigma_y \qquad \frac{1}{f_5^2}\sigma_x = 3.2\sigma_y$$

$$\downarrow \qquad \downarrow$$

- A regression is performed over N samples of ionospheric delay

$$\frac{1}{f_1^2}\sigma'_x = \frac{1.78}{\sqrt{N}}\sigma_y \qquad \frac{1}{f_5^2}\sigma'_x = \frac{3.2}{\sqrt{N}}\sigma_y$$

- The smoothed ionospheric delay is used in the range equations, resulting in an improved error amplification factor

$$y = -h + \frac{\langle x \rangle_N}{2\cos i\, f^2}$$

$$h_{15} = -\frac{1}{2}\frac{\rho_1 + \rho_5}{2\cos i} + \frac{1}{2}\left(f_1^{-2} + f_5^{-2}\right)\frac{\langle I' \rangle_N}{2\cos i}$$

$$\sigma_h = \sqrt{\frac{1}{2} + \frac{1.78^2}{4N} + \frac{3.2^2}{4N}}\,\sigma_y$$

$$\sigma_{h_{125}} = 1.08\,\sigma_y \quad \text{for } N = 5 \text{ (4th order regression)}$$

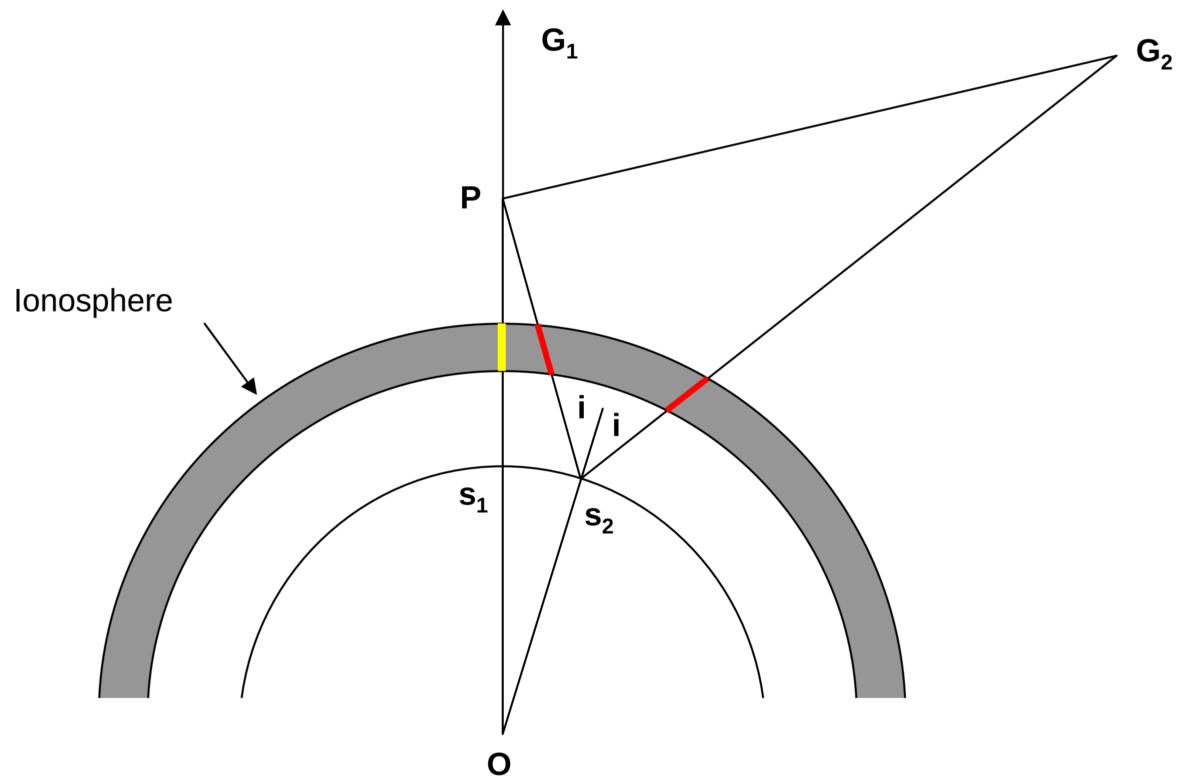
$$\sigma_{h_{15}} = 1.27\,\sigma_y \quad \text{for } N = 3 \text{ (linear regression)}$$

esa

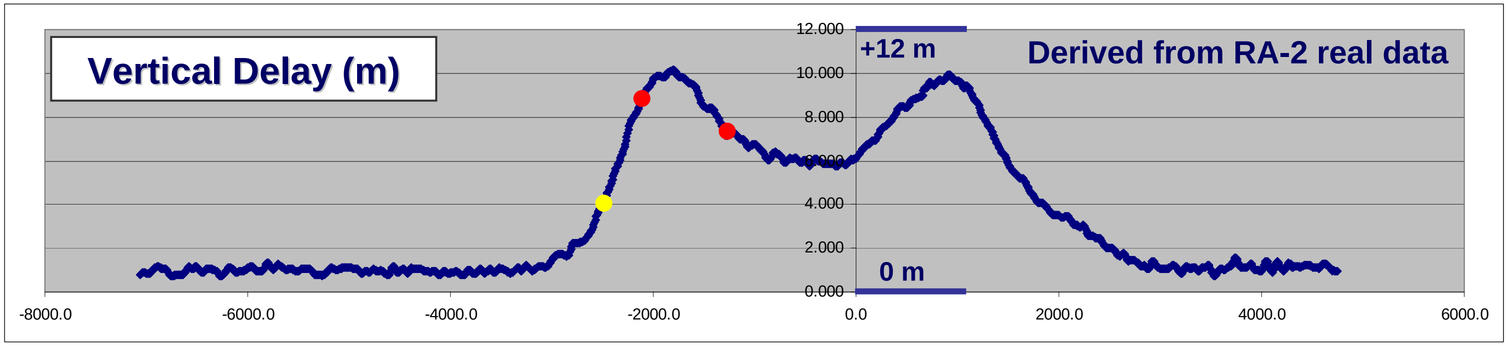
Ionospheric Correction: Example 1/2

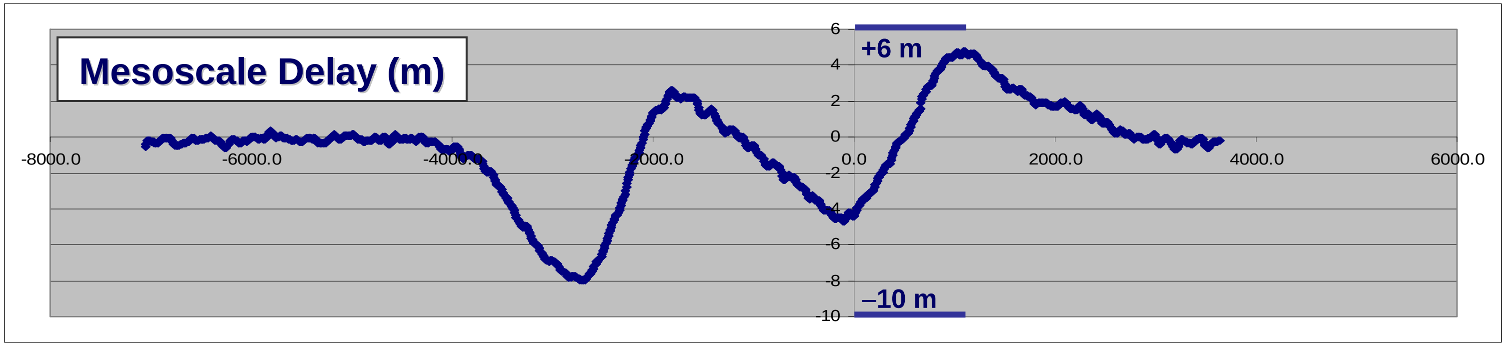
- What matters in mesoscale ocean altimetry is the difference between the ionospheric delay at two specular points

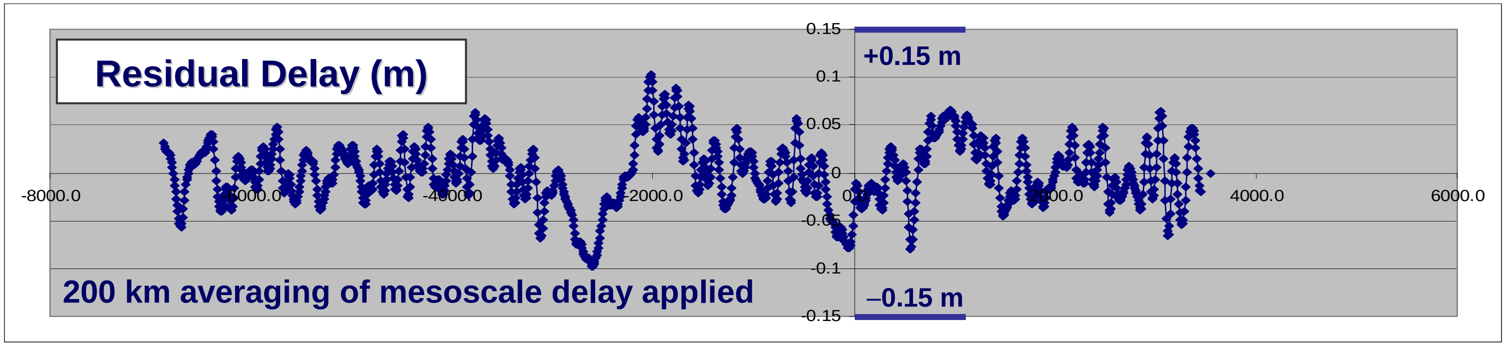
  Worst case is between nadir (i=0°) and edge of swath (i=30°)



Ionospheric Correction: Example 2/2







PARIS IoD Error Budget

Parameter	IOD L1 Height Accuracy on 100Km, G=20dBi, H=800Km
Instrument Noise and Speckle	12.5 cm
Ionosphere Averaging Noise	9.5 cm (2 frequencies, N=3)
Ionosphere Residual	5 cm
Troposphere (Wet and Dry)	5 cm
EM Bias	2 cm
Skewness Bias	1 cm
Orbit / Geometry	5 cm
Instrument error residuals	2 cm
Total RMS Height Accuracy	18 cm at Edge of Swath