INTERFEFOMETRIC AND RADARGRAMMETRIC DEM FROM COSMO-SKYMED DATASET: RESULT AND VALIDATION

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Abstract
The COSMO-SkyMed (CSK) constellation is formed by 4 LEO (Low Earth Orbit) satellites equipped with high resolution SAR (Synthetic Aperture Radar) sensors in X-band. It has been designed and developed to maximize its flexibility and innovative data acquisition capabilities. The system ensures day/night and any weather global coverage. Currently 3 satellites are in orbit.
This paper describes how to generate Digital Elevation Model (DEM) from Cosmo-SkyMed data using interferometric (InSAR) and radargrammetric techniques. Various acquisition modes and level of processing have been tested in order to establish better processing criteria and eventually identify critical COSMO-SkyMed system characteristics.
The test-side used is San Andreas Fault, centered on Parkfield town - Southern Califorrnia (USA).
The experiment was carried out by ASI-CIDOT (Italian Space Agency - Earth's Observation Data Interpretation Centre) in collaboration with GEOTEC s.r.l., and D.I.F. University of Bari

1. Introduction: COSMO SkyMed Mission

COSMO-SkyMed is the largest Italian investment in Space Systems for Earth Observation, commissioned and funded by Italian Space Agency (ASI) and Italian Ministry of Defence (MoD). It is a Dual-Use (Civilian and Defence) End-to-End Earth Observation System providing products and data for a wide range of applications, such as Emergency and Risk Management, Scientific and Commercial Applications and Defence Applications.
The system consists of a constellation of four LEO mid-sized satellites, each equipped with a multi-mode high-resolution SAR sensor operating at X-band.
Primary Mission objective is the design development operation and maintenance of a spaceborne Earth Observation System capable to provide:

- Environmental Risk Management for both civilian Institutional and Defence needs, through monitoring and surveillance applications assessing exogenous, endogenous and anthropogenic risks.
- Commercial products and services (e.g. for agriculture, territory management) to world-wide civilian user community under economical, time and political constraints.

In order to reach these objectives the system has been conceived with the following main features:

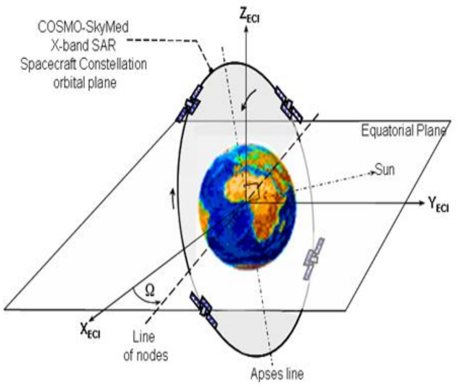
- It is able to acquire images all over the world in every atmospheric condition during night and day;
- It is able to produce a wide number of images with high resolution, accuracy (geolocation, radiometry, etc) and quality;
- It is able to produce images for polarimetric and interferometric applications.

	Resol. [m]	*Swath [km]*	*Possible Pol. [T/R]*	
SPOTLIGHT	1 x 1	10 x 10	Single	HH or VV
STRIPMAP HIMAGE	3 x 3 5 x 5	40 x 40	Single	HH or VV
PING-PONG	15 x 15	30 x 30	Alternating	HH, VV, VH and HV
SCANSAR WIDE REGION	30 x 30	100 x 100	Single	HH or HV or VH or VV
SCANSAR HUGE REGION	100 x 100	200 x 200	Single	HH or HV or VH or VV

Table 1: *characteristics of each SAR acquisition mode*

In order to supply data for a wide variety of applications the SAR payload has been designed to acquire a scene in various modes (Table 1)

It is able to acquire images with very short revisit and response times according to a specific product order.
The COSMO-SkyMed system is able to operate in different mission configurations some of this aims at the 'interferometry' mission, which allows producing three-dimensional SAR images by combining two radar measurement of the same point on the ground obtained from slightly different incidence angles.



In details the COSMO-SkyMed constellation offers several possibilities to acquire SAR image in interferometric mode:

- Tandem-like (i.e. One-day interferometry). This configuration allows the system to produce Digital Elevation Model (DEM) products, combining two radar acquisitions of the same target area.
- Tandem interferometry.

For more details about the COSMO-SkyMed mission, we might refer to COSMO-SkyMed SAR Products Handbook [1].

2. Test side description: Parkfield California USA

Parkfield is a little town located at 35°53′59″N and 120°25′58″W in Monterey County, Southern California – USA - at an elevation of 466 meter, it lies along the San Andreas Fault, one of the longest and most active faults.
The fault marks the divide between the North American Plate and the Pacific Plate. Parkfield has had an earthquake of 6 or greater magnitude on average of every 22 years. The last earthquake is happened in September 28, 2004 when a magnitude 6.0 earthquake struck at 10:15 am Pacific Daylight Time.
Parkfield is the most closely observed earthquake zone in the world. Scientists constantly measure the strain in rocks, heat flow, microseismicity, and geomagnetism around Parkfield.
Since 1985, the United States Geological Survey has been working on a project known as "The Parkfield Experiment", a long-term research project on the San Andreas Fault. In 2004, work began just north of Parkfield on the San Andreas Fault Observatory at Depth (SAFOD).
The reason of this choice are principally attributed to the presence of a permanent GPS site arrays which information can be freely provided by SOPAC website, the great number of interferometric-like acquisition available starting from the 2008 and the availability of free SRTM DEM with a ground resolution cell of 30 meters.

3. Interferometric technique: Theory and Dataset used

InSAR Interferometry is a radar technique which compares the phases of images with a difference of position or with a difference of time. After proper image registration the resulting difference of phase is a kind of image called interferogram. It is an interference pattern of fringes containing all the information on relative geometry.
The SAR images used for interferometric study have been acquired from COSMO-SkyMed system in one-day interferometric configuration. The utilized images are stripmap, in particular two in right ascending, and two in right descending configuration. The one-day offset offered by the tandem-like configuration increases the probability of having high coherence between the acquired data. This is excellent data for applications in SAR interferometry.

	Right descending pair	**Left descending pair**
Acquisition date	2010/02/15 2010/02/16	2010/02/19 2010/02/20
Polarization	Vertical – Vertical	Vertical – Vertical
Temporal baseline	1 Day	1 Day
Perpendicular baseline	-232 Meter	132,8 Meter
Parallel baseline	-261,8 Meter	111,1 Meter
Horizontal baseline	-333 Meter	171,7 Meter
Vertical baseline	107,3 Meter	22,4 Meter
Baseline	350 Meter	173,2 Meter
Baseline orientation	162,1 Degree	7,4 Degree
Look angle	30,6 Degree	47,3 Degree
Incidence angle	34 Degree	53,9 Degree
Angle between orbits	0,00163075 Degree	0,000859105 Degree
Height = h_amb*phase/2π	27,9 Meter	-93,6 Meter

***Table 2**: Some details of the two pairs of SAR images used.*

Fig. 1

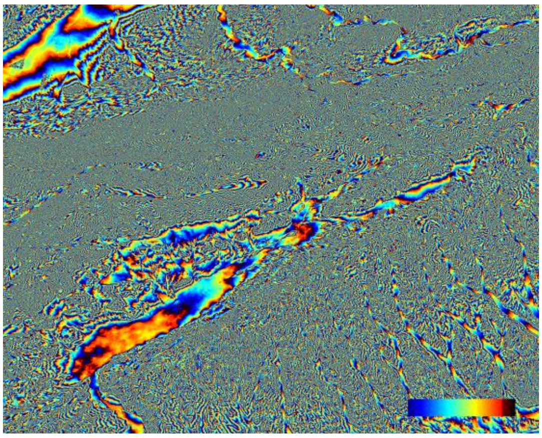
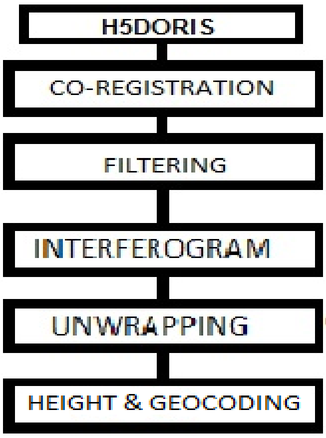


Fig. 2

4. Software utilized for DEM generation & Experiment results & Validation



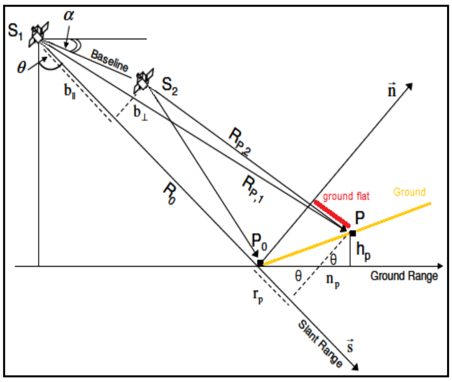


Fig. 3

The software used for DEM generation is DORIS (Delft Object-oriented Radar Interferometric Software) by Delft University of Technology. Only particular steps have been executed starting from two SAR images in complex form

- **Co-registration**: Interferometric processing of a complex SAR data which combine two complex images (SCS) referring slave image to the geometry of the master image. Precise co-registration of coherence interferometric SAR image pairs is essential for the generation of SAR interferogram.
- **Interferogram generation**: Inteferogram generation concern the computation of the third dimension of object and the measurement of small displacements of objects between two image acquisitions. In an interferogram, after subtracting flat-earth contribution, phase of two SAR images of the same terrain is a function of radar wavelength, perpendicular baseline, look angle and distance target-sensor (figure 3).

$$\phi_P = -\frac{4\pi b_\perp}{\lambda R_0} \cdot \frac{h_P}{\sin\theta}$$

- **Phase unwrapping**: Phase unwrapping is a technique that permits retrieving the unwrapped phase from the wrapped phase in an interferogram, which for the InSAR, is a necessary step for the generation of DEM.
- **Height map & Geocoding**: This step compute the heights in the radar coded system, and the radar coded heights are converted to geocoded coordinates (WGS84).

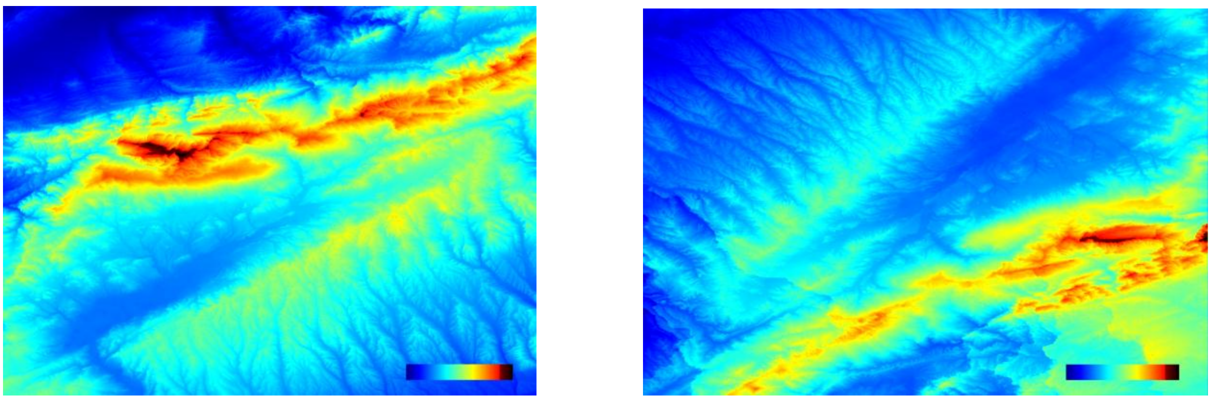


Fig. 4.a *Heights in radar coordinates obtained by DORIS step unwrap*

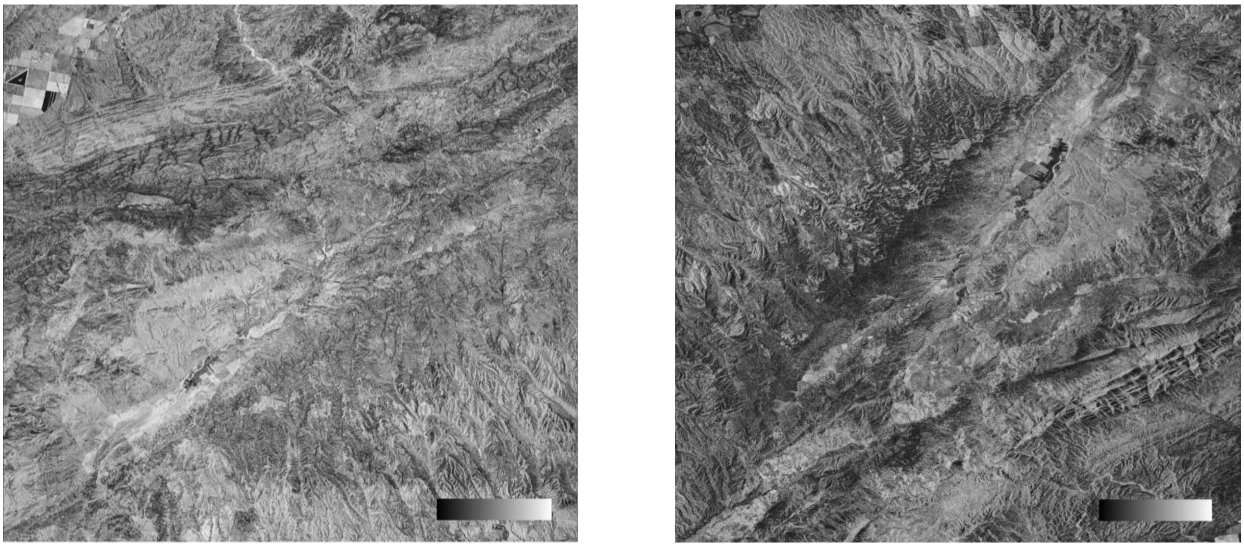


Fig. 4.b *Coherence maps obtained by DORIS step coherence, RD data has the best coherence map*.

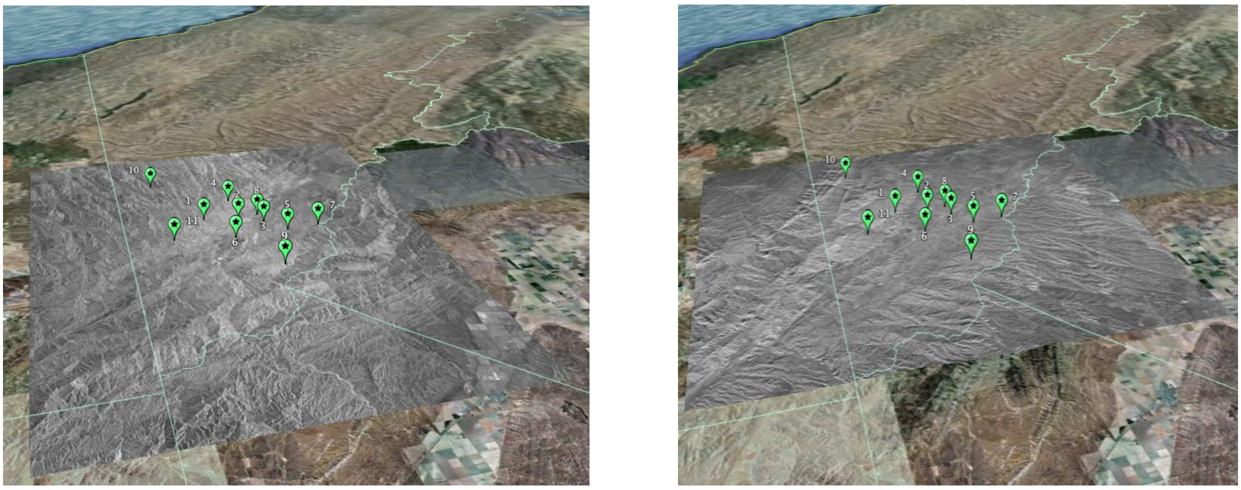


Fig. 4.c *Complex image's overlapped on Google Earth optical images.*

SRTM comparison consists of subtracting COSMO-SkyMed DEM to the reference SRTM DEM. Matrix obtained is affected by atmospherical effects which can not be estimated exactly. In order to minimize the atmospheric effect the obtained matrix has been divided in 100 sub-matrix 100x100 points and standard deviation (STDV) has been computed.

Figure 5 shows the histogram of the STDV. According to the heights accuracy of SRTM DEM 77% of the sub-matrix has a STDV less than 15 meters. The highest STDV values, corresponding to mountainous area, can be explained with geometrical deformation which afflicts SAR data due to the acquisition geometry.

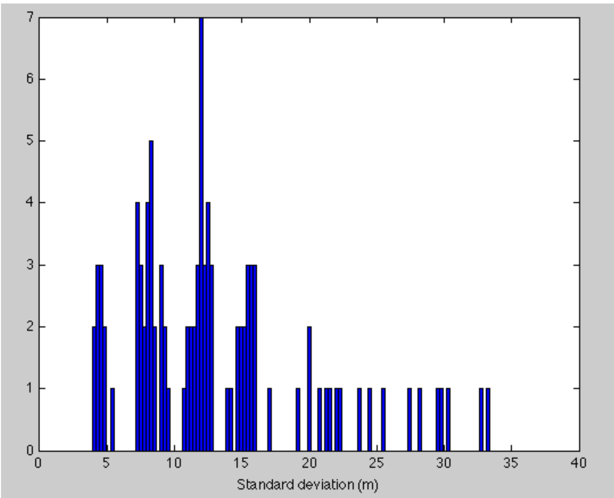


Fig. 5*. STDV Histogram (RD).*

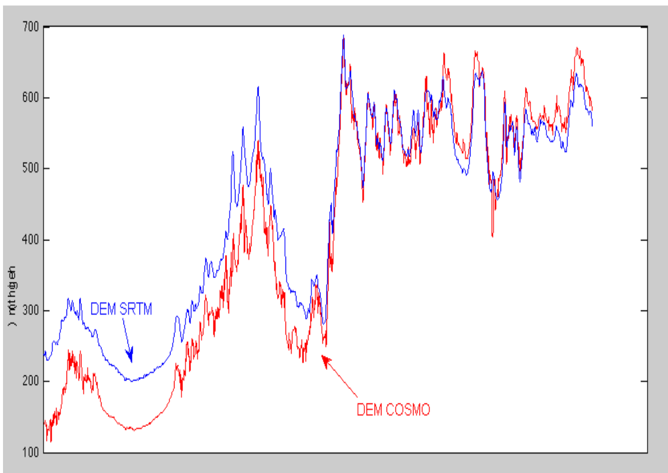
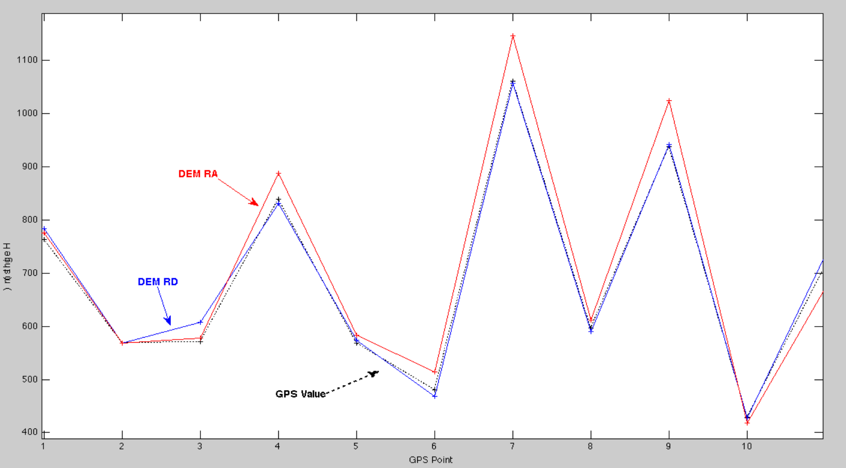


Fig. 6*. Heights profile of COSMO-SkyMed & SRTM DEM*

In GPS analysis one permanent GPS has been chosen for being the reference point in which the difference DEM height-GPS height is zero. In this analysis all DEMs have been referenced to the Second GPS point.



Next, after finding on each DEM all the GPS points, the heights of the DEM referenced have been subtracted to the GPS heights value.

Table 3 shows the result of the comparison between GPS and COSMO-SkyMed (RA and RD).

RD and RA data show different STDV due to the fact that geometrical SAR distortion afflicts RA and RD images in different way**.**

Fig. 7*:* Reference point heights. COSMO-SkyMed DEM vs. GPS array

SOPAC GPS STATION				**SAN ANDREAS_RD**	**SAN ANDREAS_RA**
	Lon	Lat	h(m)	hCosmoRD hGPS (m)	hCosmoRA hGPS (m)
1	-120.47949748	35.86671531	762.8483	-20.6213	-12.4513
2	-120.47328513	35.89979122	568.5515	0	0
3	-120.45883045	35.92191212	570.6789	-37.1042	-7.2037
4	-120.52482729	35.89999480	838.8102	8.0367	-49.4857
5	-120.43369697	35.93935210	568.3932	-5.0210	-15.2043
6	-120.43082236	35.88838466	480.2552	11.4024	-34.0964
7	-120.43405235	35.96947125	1061.9098	4.3028	-84.5811
8	-120.47843700	35.91991131	597.1216	7.1641	-15.3486
9	-120.36033680	35.91741068	937.5114	-4.6830	-86.5579
10	-120.59428565	35.82870982	428.6558	0.5340	10.9989
11	-120.44306060	35.8325975	713.7298	-20.2304	42.0015
				devst 14.9524	devst 38.7899

Table 3: *Comparation result*

5. Radargrammetry: Theory and Algorithm

Radargrammetric techniques derives from photogrammetric ones, adopted for optical images but with some differences due to different acquisition modes, type of sensor (active vs passive), different Electromagnetic wavelength, phase information and different way to forms amplitude images.

In general images level processing improved for processing is Complex (SCS) and represented in Slant Range–Azimuth projection (Fig 8a): this is the start point of Radargrammetric processing.

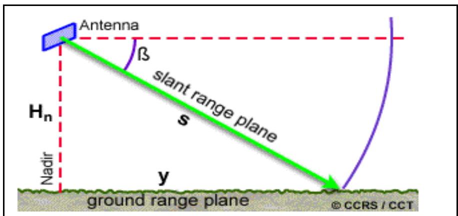


Fig. 8a

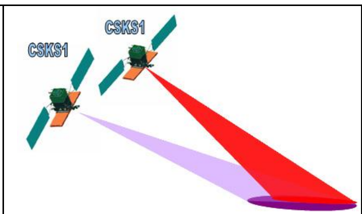


Fig. 8b

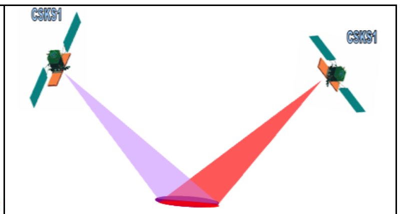


Fig. 8c

Configuration acquisition of stereo-pair can be *same-side* (fig 8b) or *opposite-side* (fig 8c); fig. 8d represents the acquisition geometry of same-side configuration that we have chosen to get radargrammetric DEM. Knowing slant range distance between satellite and *target* and satellite position, it's possible to compute target height respect a reference surface by means of parallax difference induced by two different view point (see fig 8d). So view angle (and Doppler centroid) is a fundamental parameter for radargrammetric processing. It must have a minimum value of about 8-10°; greater values are preferable for mountainous zone. Doppler Centroid is approximatively zero.

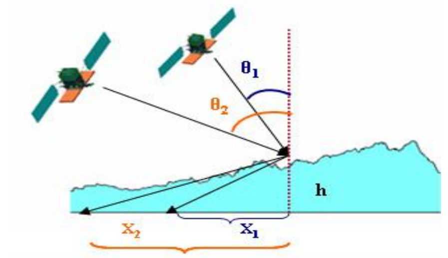


Fig. 8d

From Fig. 8d we can see how target point is viewed from two satellites with different view angles (θ_1 e θ_2 respectively) from its real position, effect caused by foreshortening effect. So we have [4]:

$$X_1 = h \cdot \cot \theta_1 \qquad (1)$$
$$X_2 = h \cdot \cot \theta_2 \qquad (2)$$

and $|X_1 - X_2| = p$, with p representing image spatial resolution. Replacing (1) and (2) in previous relation and resolving for h minimum, one get minimum height difference

$$h = p \,/\, (\cot \theta_2 - \cot \theta_1) \,. \qquad (3)$$

Range-Doppler algorithm has been implemented for image formation [4], [6]:

$$X_S = a_0 + a_1 T + a_2 T^2$$
$$Y_S = b_0 + b_1 T + b_2 T^2$$
$$Z_S = c_0 + c_1 T + c_2 T^2$$
$$V_{SX} = d_0 + d_1 T + d_2 T^2$$
$$V_{SY} = e_0 + e_1 T + e_2 T^2$$
$$V_{SZ} = f_0 + f_1 T + f_2 T^2$$

Range Equation $\quad R_S = |(\mathbf{P} - \mathbf{S})|$

Doppler Equation $\quad f_D = - [2 \cdot (\mathbf{P} - \mathbf{S}) \cdot \mathbf{V}_S] / [\lambda \cdot R_S]$

Where $\mathbf{P} = (X_P, Y_P, Z_P)$ is the ground point coordinate, $\mathbf{S} = (X_S, Y_S, Z_S)$ and $\mathbf{V}_S = (V_{XS}, V_{YS}, V_{ZS})$ are satellite position and velocity respectively; R_D is the slant range distance while f_D is the Doppler centroid frequency. Ground point positions P can be computed, knowing their respective satellite positions and velocities, resolving a simple linear system via LU decomposition (see fig. on the left).

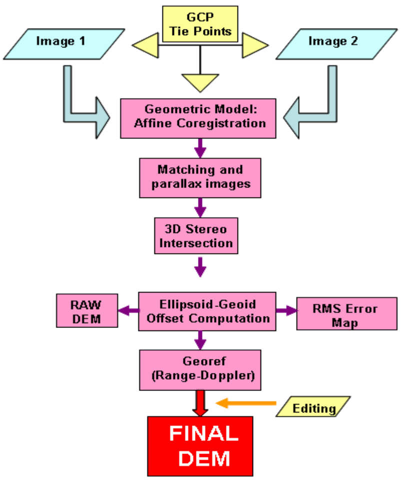


Fig. 9: *Processing Steps*

Radargrammetric processing chain is described schematically in Fig. 9. Having used complex images (spotlight) we have applied a Gamma Filter to stereo-pair (Table 4) for speckle reduction purpose and rescaled them to 8-bit.
For a good stereo-pair coregistration we have collected 26 Tie Point, discarding the implementation of an automatic coregistration.
Matching step is the crucial point of processing: it consists to build a good correlation matrix with values depending by scene orography and parallax value, obtained by tie point used for affine coregistration (quasi-epipolar images). In this way we can implement a specific matching algorithm and compute the best correlation between stereo-pair images.
The output of matching process is represented by a correlation image and two parallax images that we have used for height image extraction. Finally we obtain a final DEM.

6. Results and validation

Radargrammetric process has been applied in various test area for validation purpose (e.g. Matera, Bernalda, Italy), finding optimal acquisition configuration and specific matching parameters. Afterwards we have chosen Parkfield as test area (Fig. 10a). Dataset used is described in Table 4. We have processed a stereo-pair formed by two complex COSMO SkyMed acquisition whose amplitude are showed in Fig. 10b and Fig.10c with intersection angle of about 20°.

Fig. 10a *- Study Area*

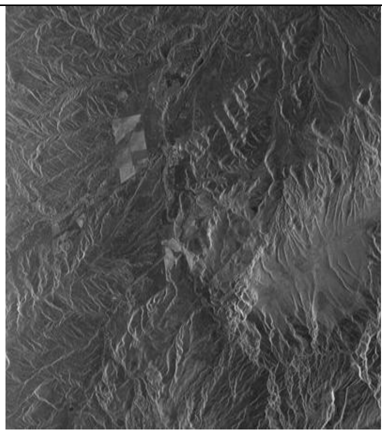


Fig. 10b *- Reference Image*

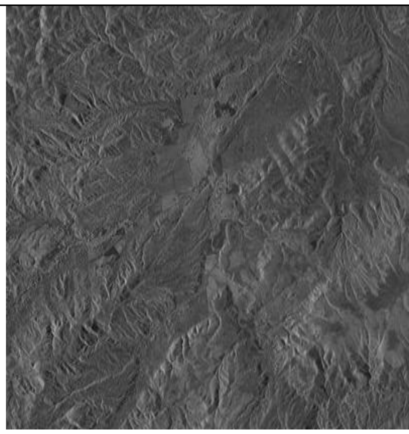


Fig. 10c *- Match Image*

Stereo-pair general dataset				
	Reference Image		Match Image	
Product Type	SCS_B		SCS_B	
Acquisition	Spotlight 2		Spotlight 2	
Sat ID	CSKS1		CSKS1	
Scene Sensing Start	2010-04-15, 13:55:27		2010-04-16, 14:13:29	
Scene Sensing Stop	2010-04-15, 13:55:34		2010-04-16, 14:13:37	
Scene Centre Lat-Lon (deg)	35.912056	-120.43818	35.9052571	-120.440959
Incidence Angle (Near-Far)	29.379148	30.185284	53.6910839	54.1285177
Look Angle (Near-Far)	26.5349863	27.249378	47.2087288	47.5552837
Azimuth Pixel Size (m)	0.70216496379		0.7026818864	
Range Pixel Size (m)	0.312490220229		0.409972592137	
Projection	SLANT RANGE - AZIMUTH		SLANT RANGE - AZIMUTH	
Look Side	RIGHT			
Orbit Direction	AESCENDING			
Orbit Number	15442		5697	
Polariz	VV			

***Table 4** – Stereo-pair General Data*

With this dataset we have obtained a final DEM of 3m resolution (Fig. 11a) with STDV (or equivalently RMS) of about 5m. (Fig.11b). For validation purpose we has performed a comparison of height profiles between Radargrammetric and SRTM (30m resolution) DEM via profile overlap, finding, in general, a good agreement. Radargrammetric DEM show detailed profile due to a best resolution of SAR image used (Fig. 12b).

Some difference between two DEM is due to different epoch of acquisition, various changes induced by seismic activity and different precision between two DEM.

***Fig. 11a** – Radargrammetric DEM*

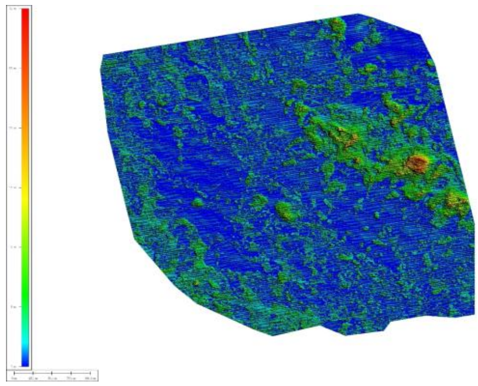


***Fig. 11b** – RMS MAP (STDV)*

STDV (σ) STATISTICS						
TOT RMS	2141270	100%				
Range	Number	%		Range	Number	%
0m< σ <5m	1970503	92,03%		σ =0m	389243	18,18%
6m< σ <10m	99820	4,66%		0< σ <1 m	392024	18,30%
11m< σ <15m	19354	0,90%		σ =1m	261383	12,20%
16m< σ <20m	4392	0,205%		1< σ ≤2m	405557	18,94%
21m< σ <25m	2383	0,11%		2< σ ≤5m	522296	24,39%
26m< σ <30m	122	0,0056%				
σ >31m	0	0				

***Table 5** – σ Statistics*

Afterwards we have made a statistical analysis of STDV data showed in Fig. 12a. The majority of STDV point are less than 5m, 92% respect the total STDV points (Table 5 and Fig. 12b).

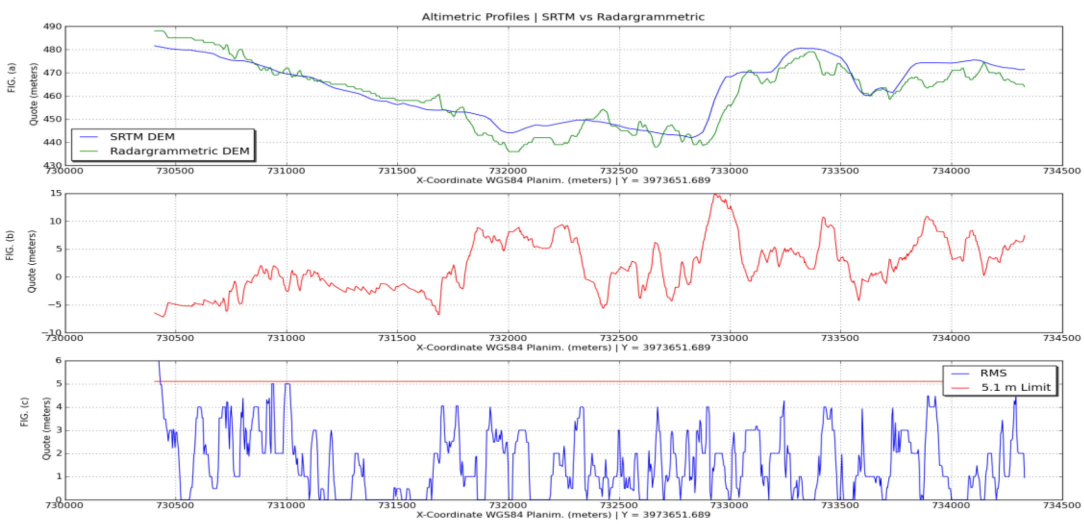


Fig. 12a

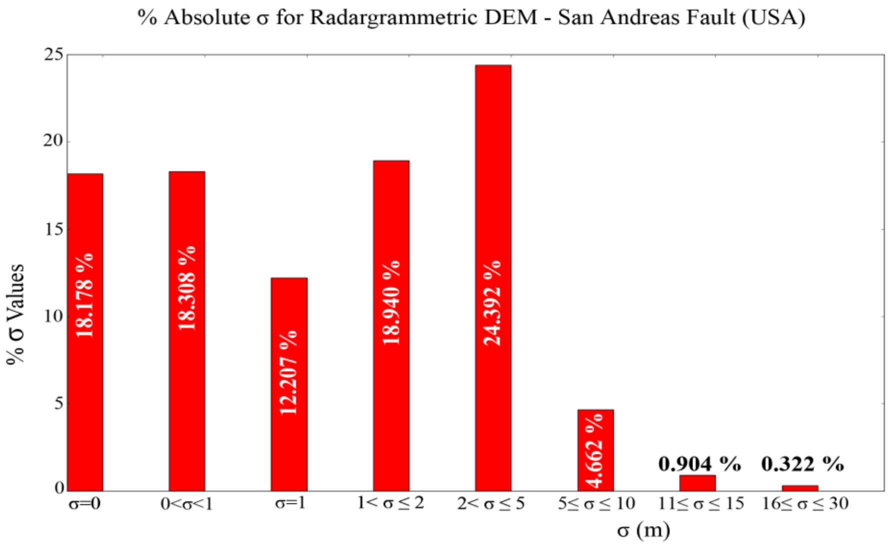


Fig. 12b

7. CONCLUSION

Validation results obtained from interferometric and radargrammetric COSMO-SkyMed DEM prove the high performance which can be reached.
GPS and SRTM interferometric DEM validation measurements, concerning a wide area 40x40 km, show a 10 meters spatial resolution DEM with a height accuracy of 5-15m. 5-9m. STDV values regard flat area where SAR images are not afflicted by geometrical distortion while 9-15m concern mountainous area. The fact that no filtering steps have been applied to the generated DEM involve in further studies focalized on the correction of geometrical SAR distortion. All interferometric GPS validation results do not consider atmospherical effects which afflicts phase interferogram, in this way a better accuracy can be reached using more SAR images.
Radargrammetric results, demonstrate the validity of the technique applied to COSMO-SkyMed data with production of high precision DEM with STDV less than 10 m. This scenario induce us to exploiting new techniques for improving radargrammetric process to implement a complete chain of processing where interferometry technique exploits high precision Radargrammetric DEM.

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