



SAR-SIFT: A SIFT-LIKE ALGORITHM FOR SAR IMAGES

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A F A F DE A F A A E

For D n r D on Y nn o n For n p n

Abstract—The Scale Invariant Feature Transform (SIFT) algorithm is widely used in computer vision to match features between images or to localize and recognize objects. However, mostly because of speckle noise, it does not perform well on synthetic aperture radar (SAR) images. We present here an improvement of this algorithm for SAR images, named SAR-SIFT. A new gradient computation, yielding an orientation and a magnitude robust to speckle noise, is first introduced. It is then used to adapt several steps of the SIFT algorithm to SAR images. We study the improvement brought by this new algorithm, compared to existing approaches. We present an application of SAR-SIFT for the registration of SAR images in different configurations, especially with different incidence angles.

Index Terms—synthetic aperture radar (SAR), remote sensing, SAR image registration, scale-invariant feature transform (SIFT)

n ro n n r r on n or n
on r r on _A F n ppro
propo o 4 or r r r o on
p o A o p Con n A AC _
p or o o n p n or
r pon n r pp n
pro o _ F or o o or
r o n n r r or on pp on _
Y n o or Bo r pr n on o F
r p or o p r or r r o n n o r
on n r o on r _ on
p r or o r n r pr n on o
or r r p or n F r p or Bo _
on no r pp on o F or _
n n r on r r o on op
r n F pon p
r p n n r p o _ o 9 p r or
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on _ o r r orr p
ron p no p n
pro n _ F or o no
p r or on p o _ r pro n
n propo o pro or _ o
o pr r or no or
n n o p no _ r r o o n r n
or o o p o or 4
o pro p r or n _ p r on p n
pon r on r n Fn o ppr
orr pon n _ o r p
DE n or n or on n X op n 9
p r or n pr r r on_ D n on
o or op r n on
C_ o r p r or n o n opp
or r r n n r o
orr no n no o on r o r
pp on n r r on_ o o o no on r
p o p no _Con rn
o pp on o r F or n op
o o r n r o p r or n
F or p o A _

_ D C
n r on o r o r on r pro
n r on o r o on o n op
n n p r r r r A o n r n n
p on o n or r o on n or
n on _ o on p o or on
Dr on r on r p pp n or n on r
ppro o p r r n r n
or n p on _ p p r
n r o r r p or or A n p r r
n r n F r r n or F
r or or n r pon on n
o r r p on_ D o n
n o o p r on o o n
r on o n _ n r n o
n ro on rn on n p r o n on
n n n or on or rn
n o pp on o r r n n
n r r on or o r n _
F or n n r n op on or r o
n n o p r or n n n r n _
or n pp o o op n
r r r r on r _ r
r r on o 4 F pon Con ro
on C o or on o _
no on p o r o n n n
F_D n r D on Y_ o n F_ p n r n n
o o r C_ C 4 r B rr n
Fr n _ r n _ n o p r _ r
C_ E DC A n E o r B n 4 o o Fr n _
or ppor C_ E r n _

propo n p p r o p F or o r r o p p r o o _
 p o A _ on pr n
 o n o F or n o r on
 A _ on n r o n r n o p
 on n F or o p o A _
 E p r n on n p r or n r pr n n
 on _ F n on n po
 o r n or or n n
 r o on on n A n _ An pp on o A
 r r on n pr n r r or n on
 r pr n _
 A on r n pro n r on o or pp r
 n _

_ E E A F E F A A A D
 BE A A A E

n on or n F or n o o
 r n r n r o _ o pr n on n
 pp o A n o o p on o op
 _

A. Presentation of the original SIFT algorithm

F or n n r o n 4
 ' or n o o r n n r _
 or o o o r p r n o o n
 p r r p

1) *Keypoints detection:* Fr po n r o
 n r po n n r r r o on (x, y)
 σ n or n on θ

$$P(x, y, \sigma, \theta).$$

A r n o n Do p n
 p p r o on o p n o n
 on r $\sigma_l = \sigma_0 \cdot r^l$ n $l \in \llbracket 0..l_{max}-1 \rrbracket$
 r n r n on (x, y, σ) r n o
 o n po n n r po on n _
 C n o on r or o on
 r r r r on on n r _
 Ano r po o r r or n r
 or on r r _

A on o r n r po n or n r r
 p o po n n p r o
 r r n on n n o
 or r o on n p
 4 r p n p on o
 o n r n n _ o n n r n
 r r A n n n A n 4 or r n
 o on n r p on on
 on or r r r A F r n
 po n o o r or n on p r r _

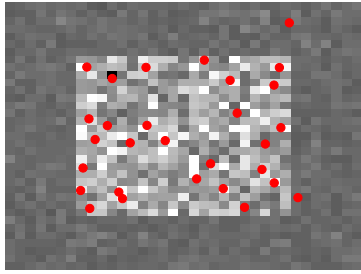
n p p r o p r propo p p r o or po
 po n on on B o po n r o
 o r n (x, y, σ) n p _
 po n r r r r on
 o n o n on or o on r _

2) *Orientation assignment:* o r n n or n
 on o po n o o p
 o o r o r n or n on
 r n n _ or o p on
 p n n n or oo _ n or n on r n
 n p r or o 80% o _ n o r
 r p r r r pon n x n y r on n
 o r pon o p n n or n on
 n o o pr n p or n on _
 n p p r o o n n o
 o o or n on o r n o n on r r o
 p p r o _ A n or n F or r n
 po n n o n po on n
 r n or n on θ _

3) *Descriptors extraction:* A F r p or n o
 po n $P(x, y, \sigma, \theta)$ o r o o r _ A
 q r n or oo n ro n po n
 p n n on σ o o n r n on n n r n _
 n ro n n $-\theta$ o n r ro on n r n _
 nor n or oo n o 4×4 q r
 or pon o r o r n or n on
 r n n r o p _ For
 po n F r p or o n on n n
 n nor n o r _

D r n p on o F r p or n
 propo n r r _ CA F 9 o n
 pp n CA on nor r n n or oo _
 o p on o po r r n pon or
 o r n or n r CA F
 o n r p n r n or
 r r pon n r n or on r on _
 r oo o F r p or o po r
 r o 9 or F _ _

4) *Keypoints matching:* D po n o o r n
 r or n o r r p r p or _ D r n
 n r r n r r o o on
 r or D n o
 _ Fr n n r o p n on
 r p or n on o o r n n r
 n or o n _ o r n o
 on n r o n or r o p r _ A r o
 th pp on r o o o r p n _
 r r r p r or
 p n on D n o D p _
 n pro o r o p or
 n n a contrario o _ p p r o
 o r n or on po n n p r o
 r on p o r n o on o _
 For o p o
 r _



F _ ' o 9 po n on o pp
on r n orr p p no n ' oo p
po n -

B. Limitations of the SIFT algorithm on SAR images

F or o no p r or on A -
n po n on o r
n p r r p no on ro on
o F _ ' - n op no on
or n po n r n p r o
o o on n o on r p n n -
o r A pr n r n r n n
p no o ron r r n n on
o o n o r r F r _ F
on on on r r no ppr n
F r ' - p o r n orr p p no
or n on n r p or r o no ro o
p no n r o p on r on
r n r n -

C. Previous adaptations of the SIFT algorithm for SAR images

o on o F or or A
r n propo n r r _ o o
p or pp n or
po n on ' or ppr n or n on
n n ' - pro r o r
n r o on n n o r o
r n n po n r no pr o -
ppr n or n on p o o
r o pro or o p n p -
n ' n n r r o o o n p
n or r po n n o r on
r p or n o n r n p r or n _ B
n n o r p or n pr n
pp on o or on ron n _ n
' 4 n p r pro r o n p n
or po n on n F r p or r p
n pro r on o p Con - r n
or o r p r or n n or n F _
o or propo o r n n o p
r p n n p n n o rop on
or o p n oo ' 9 ' _ B pro
r r o on n o o n or on _

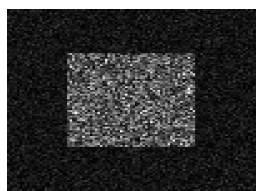
Ano r o on o no r r n or
on ' or n n r E pon n F r EF
n _ D no n on n n n r
r r or - p r or n
o or r r n o o or n F
or r pp o A n r o
orr o o or r o o n _
r o pro p r or n r n
o r _ ' n o o r r on n
on r p r on p o po n
n r r on _ o r p
r pr n n o no o r p n no
ro on _ For r r on pp on r n or on
n ' on orr pon n
r r or ' on - o n F
or n r r r r r o
r n n r n or on _ pro
on n n r r o r r on _
r p n p r or n n
pr r r on ' 9 _ F orr pon n n r o
no n or n or on n no pr
n on o DE _ B n
o n or on r no no n n n pr
r r on on n n o n rpr on
r r or -

o p F or o A n r o
no o n p o A -
o o op r n r n o p on n
o o n n or n on r ro
o p no - r p o or n n
p o A _ A n po n on o
n ro n or n on n n n
A p r p or _ po n n p
no o n o no p n on p o
r r on q o r p or _ on
n ro n op n -

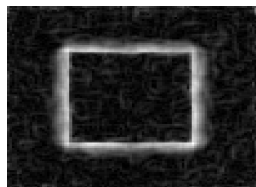
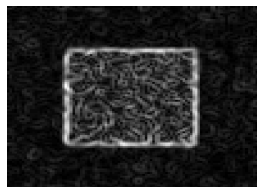
- ED E ' D

A. Gradient computation for SAR images

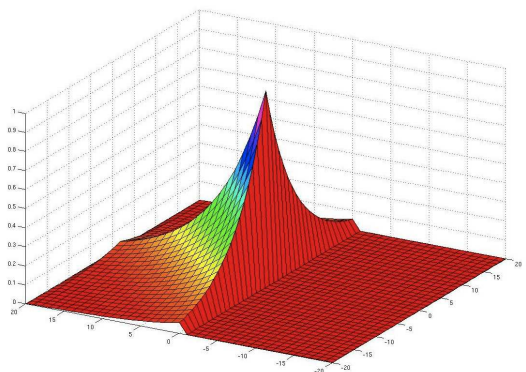
1) State of the art: n or on on
n r n pro o n r n r n on A
- n r n o r n o pon n p n
on n r n r - r on ppro n
on on n r o n r n n -
For A o r r r n
o o n o r o r n n on o
o r - r n r n
no on n r r op r or _
4 o n o r o or o
p no n o r n - r
or n r o n n ro n or r o o n
on n r r on A
• o o A r A on n
o p n r o o o n on oppo o
p on on r on i F r



n or p
p no

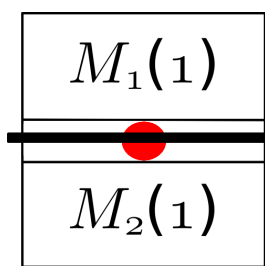


r n r n Eq_ r n o
9 n



F _4 E pon n r or o p on o n _

F _ E p o r n or p p no n
r n n or o r n o p on o _



n or r r on_ o For n r on o
o p r p T_3 T_1 T_2
n T_4_

F _ o A o _

$$R_i = \frac{M_1(i)}{M_2(i)}.$$

r o R_i n nor

$$T_i = \max\left(R_i, \frac{1}{R_i}\right).$$

r o r o p on o r n r on
F r _ r n n D_n^1 n or n on
D_t^1 r n

$$D_n^1 = \max_i(T_i)$$

$$D_t^1 = (\arg\max_i(T_i) - 1) \times \frac{\pi}{4}.$$

E n o n r o n r n
n D_{n-}^1

• o o E pon n A r
E A n pro n o A or
on o n o p n pon n
o n F r 4_ For p n
po n (a, b) n r n or r
r on

$$M_{1,\alpha}(1) = \int_{x=R} \int_{y=R^+} I(a+x, b+y) \times e^{-\frac{|x|+\alpha|y|}{\alpha}}$$

$$M_{2,\alpha}(1) = \int_{x=R} \int_{y=R^-} I(a+x, b+y) \times e^{-\frac{|x|+\alpha|y|}{\alpha}}$$

4

\alpha pon n p r _
A n A r o n nor on or
r on i r n

$$R_{i,\alpha} = \frac{M_{1,\alpha}(i)}{M_{2,\alpha}(i)}$$

$$T_{i,\alpha} = \max\left(R_{i,\alpha}, \frac{1}{R_{i,\alpha}}\right).$$

r o T_{i,\alpha} r o p on or on i =
1 n r i = 3 r on _B n o o
or on op r on r n
o n

$$D_{n,\alpha}^2 = \sqrt{(T_{1,\alpha})^2 + (T_{3,\alpha})^2}.$$

E A or pr n
on n or ro o no n A n
n p r r \alpha o n p oo n
o _

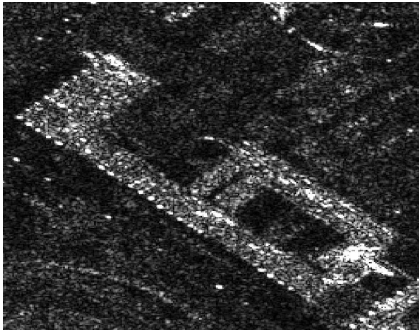
o op r or n n or on n
pro oo o r n n _ o r
o no pr r o r n or n on
n on r on r on r _ o
pro n r n n r o r on o
on n _

r propo o n r n or on
r n r p T_{1,\alpha} n T_{3,\alpha} -B n o o
r n or or op r n
n n or n on r

$$D_n^3 = \sqrt{(T_{1,\alpha})^2 + (T_{3,\alpha})^2}$$

$$D_t^3 = \arctan\left(\frac{T_{3,\alpha}}{T_{1,\alpha}}\right).$$

▼



F₁ Er Co o 34° o n
n n n l r o on

n on o or n on q on n
T_{1,α} n T_{3,α} po n D_t³ n
on n 0 n $\frac{\pi}{2}$ or o r r n
o p on on r r m_a n m_b F₁ r n r n pp on o F₁
m_a < m_b n r o σ = 2

$$T_{1,\alpha} = \frac{m_a}{m_b}$$

$$T_{2,\alpha} = 1$$

$$D_t^3 = \arctan\left(\frac{m_b}{m_a}\right).$$

r or r n or n on r r r
p n n on r o r
p o q o ro nor r o T_{1,α} n
T_{3,α} o no r o o p r n
or n on

2) *Proposed approach:* propo r o n
or on n r r n

$$G_{x,\alpha} = \log(R_{1,\alpha})$$

$$G_{y,\alpha} = \log(R_{3,\alpha})$$

n o o p r n n n or n on n

$$G_{n,\alpha} = \sqrt{(G_{x,\alpha})^2 + (G_{y,\alpha})^2}$$

$$G_{t,\alpha} = \arctan\left(\frac{G_{y,\alpha}}{G_{x,\alpha}}\right)$$

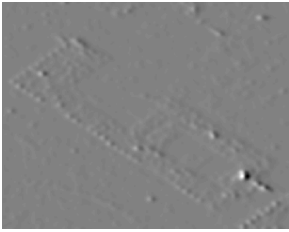
α p r r o pon n o
o p o n
B n o r pro n on o or
r n or n on on r o n
o p on

$$G_{x,\alpha} = \log(m_a) - \log(m_b)$$

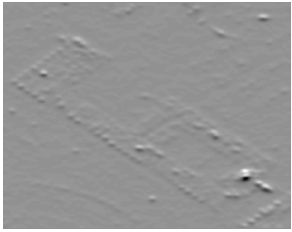
$$G_{y,\alpha} = 0$$

$$G_{t,\alpha} = 0.$$

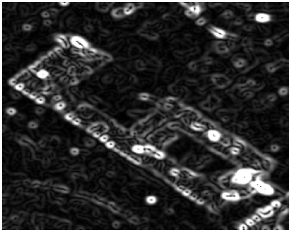
r no nor on n or
n r o n n r n or r o o n n
n po r n ppro o
po o or n on r n n o o n
A o n n p r r α o o oo



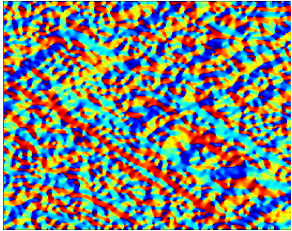
or on o pon n



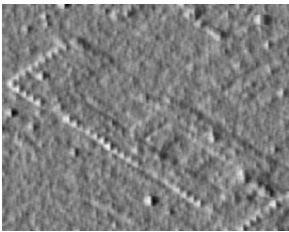
r o pon n



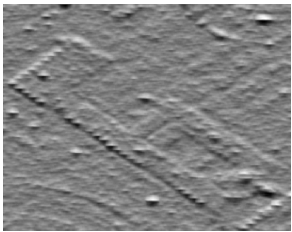
n



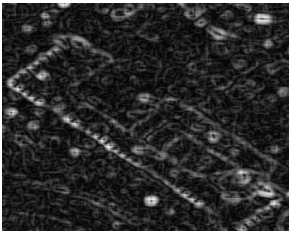
r n on



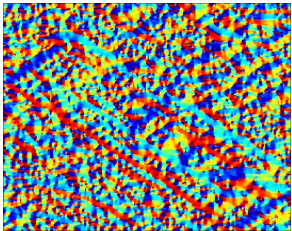
or on o pon n



r o pon n



n



r n on

9 F₁ r n o p on r n o pp
on o F₁ α = 2

r n r n pp on n o p r o
r n n r n o p on o *Gradient*
by Ratio

F r pr n r n n on r n
orr p p no or o r n o p on
o r n o o Eq₉ o no
pro or on r r n on
on o o r n r n r n

r n o o F r r pr n
or r n n on F r
pp r r n r n

pr n r r on o p no r n
 n n r n or on o pon n
 r r on r r n on o r
 on _For o o r r n r pon r no
 r on o r _

n r n o p on o no p o
 p F or o A _

B. A SIFT-like Algorithm adapted to SAR images

o n o n or
 SAR-SIFT pr n n F r _A n on or
 r r p o or r p o A
 n on on n n n _

1) Keypoints detection: A r p ppro o
 po n on A o o pp o
 on o r o o _ o o
 n no n o p on n o
 ppr on on r r _
 A o pp n o p ppro
 no ro no o no n o no pro
 p r or n o or n ppro F _ _
 p o r n orr p p no on F r
 9 o po n r n o n n r orn r
 p o _ r r r on
 n n pp r on p F _
 n o pp n q on n o r
 r r n ro _B p n p r r
 on on r r on n r o
 on n r o n r o orr
 on _

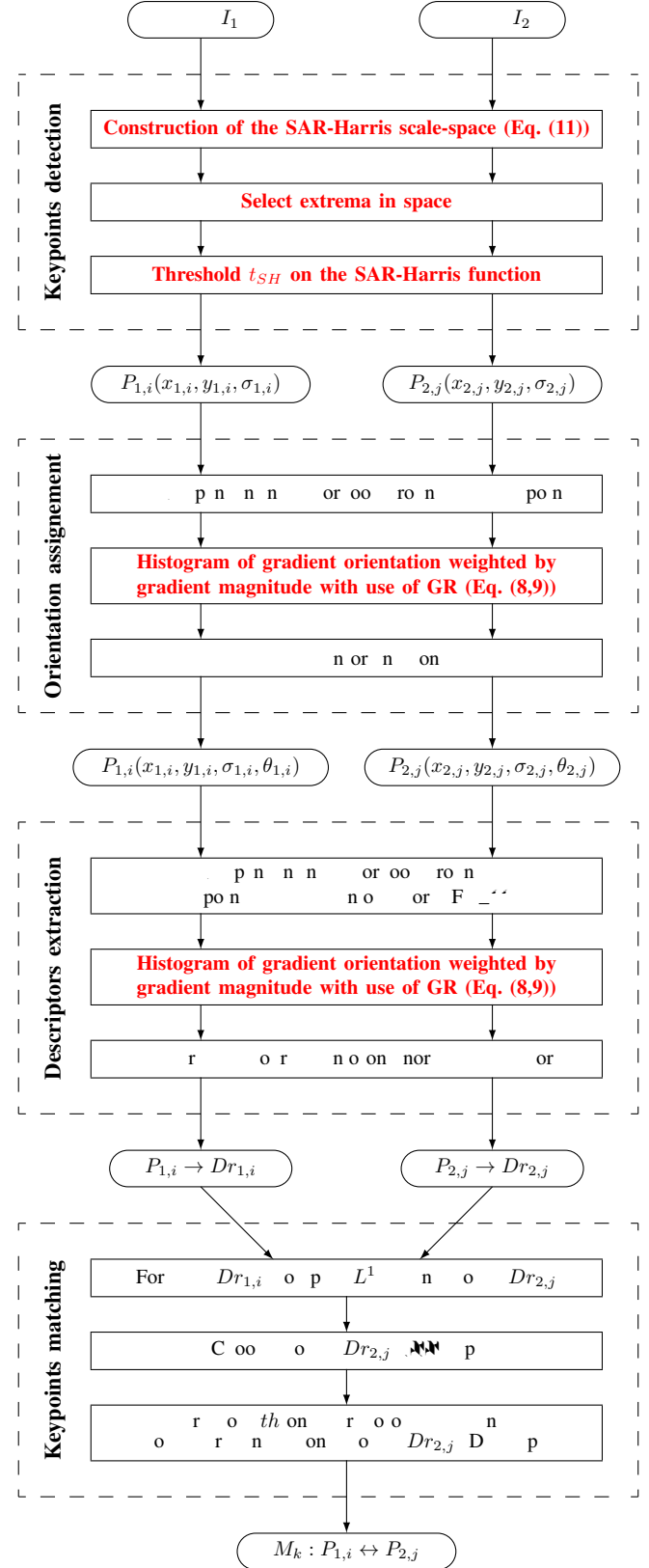
n . n r o no on n n n
 o p o p no n r on on
 r _ r n on n on r
 on r r _ Fro n r n
 o p on p o A op
 n on A propo n ppro on
 or_

. r r r n n on r n or
 op r p

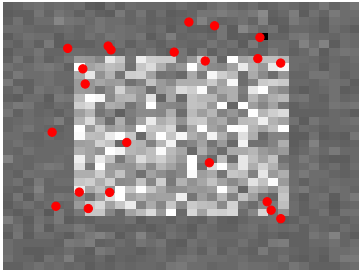
$$C(x, y, \sigma) = \sigma^2 \cdot \mathcal{G}_{\sqrt{2} \cdot \sigma} \star \begin{bmatrix} (\frac{\partial I_\sigma}{\partial x})^2 & (\frac{\partial I_\sigma}{\partial x}) \cdot (\frac{\partial I_\sigma}{\partial y}) \\ (\frac{\partial I_\sigma}{\partial x}) \cdot (\frac{\partial I_\sigma}{\partial y}) & (\frac{\partial I_\sigma}{\partial y})^2 \end{bmatrix}$$

$$R(x, y, \sigma) = \det(C(x, y, \sigma)) - t \cdot \text{tr}(C(x, y, \sigma))$$

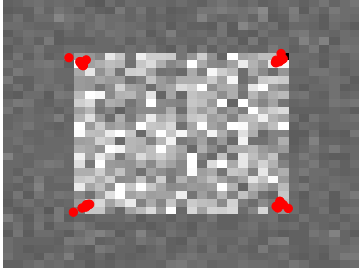
$\mathcal{G}_{\sqrt{2} \cdot \sigma}$ n rn n r on $\sqrt{2} \cdot \sigma$
 * on o on op r or I_σ on o on o or n
 n rn n r on σ n t
 n r r r p r _ r σ^2 n
 r or nor on _ n o
 n r r r on o o ppr o on r
 n po n pp n r o d_H on $R(x, y, \sigma)$ _



F _ n o A F or _Con r on pr
 n n p p r r n r _



o pp on o r
po n



A . rr o po n

F _9 D on o po n on r n orr p
p no o pp on o r
o n A . rr o _

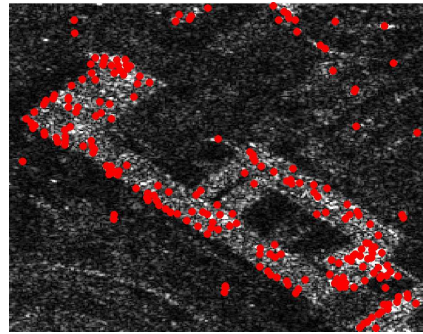
Con rn n on n r n o
propo n A . rr r n A
. rr n on r p

$$C_{SH}(x,y,\alpha) = \mathcal{G}_{\sqrt{2}\cdot\alpha} \star \begin{bmatrix} (G_{x,\alpha})^2 & (G_{x,\alpha}) \cdot (G_{y,\alpha}) \\ (G_{x,\alpha}) \cdot (G_{y,\alpha}) & (G_{y,\alpha})^2 \end{bmatrix}$$

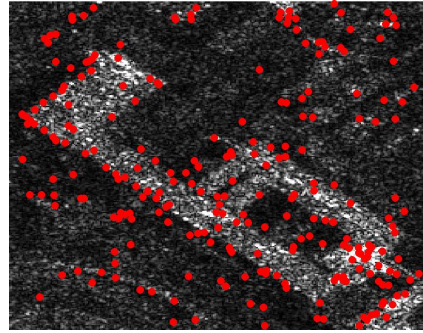
$$R_{SH}(x,y,\alpha) = \det(C_{SH}(x,y,\alpha)) - d \cdot \text{tr}(C_{SH}(x,y,\alpha))$$

d n r r r p r r n r r G_{x,α}
n G_{y,α} r o p n Eq_ _
n n n o n p on σ²
no n n or o n r n r n _

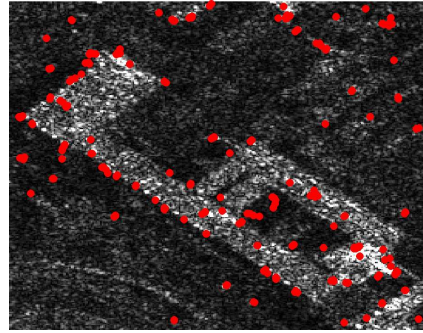
For po n on o r p o
p o n r pr n on o or n
o n o p n A . rr
n on Eq_ '' r n α_k = α₀ · c^m
m ∈ [0..m_{max} - 1]_ o r n p r n
o po n n _ p po on o
po n r r n p r or n n r n rpo on
o A . rr r r on ro n o r _ A
r o d_{SH} on A . rr n on o
o r n o on r po n _ o n po n
r r r po on (x,y) n r α_
ppro A . rr o r
o p o o n or r o o o
on or r r _ A r o
n o n n p n n o on r _
no p r r r r
n n on _ o o r on op



o pp on p
po n



o pp on o r o
po n



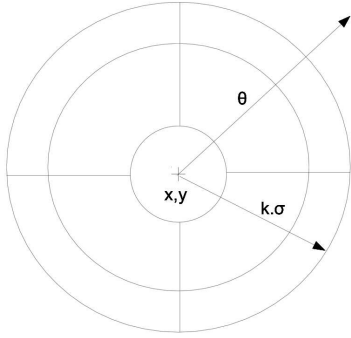
A . rr o 4 po n

F _' D on o po n on o F _
o r o o pp on p n
r o d_H n d_{SH} r o o n
n ro po n r r n po n on o
_

_ n r n p r _ r
on n no r po on or r n
_*o r o o r ppr r o n
A . rr n on_

p o r n orr p p no on
F r 9 o n o po n
r on o n on orn r p n r r no
on _

F r ' pr n n p o po n on or
r n o _ A p o r po n



F _ '' o r r r p or_ k
p r _ o o n n r o o r r r r p
0.25 n 0.73_

o pp on p
r n on r n
o o on o r on o o n o r -
Con rn n po n o
pp on o r o o o on
r o on on o o n o r pp n o
on n o r r _ o r po n
A _ rr o r o o on
orn r n r po n n n r o on
on o o n o r r o _

2) Orientations Assignment and Descriptors Extraction:

n or n F or o p o or n on
n n n r p or r on r on o r o
r n or n on_ o r r o p on
n or oo o po n n r n

n -
r propo o r n o o
n ro n on A o o p o o r _
n o n q r n or oo n 4×4 q r o
or n or n F r p or r on
r r n or oo o 6σ n o po r or
n F r _ r n r p or Ratio

Descriptor_ o r o o o p
r n o r or r p o o r p
on r on o or on o or n F _ n
n or r o pr n p or n on r on n a on
contrario ppro _ p o o or n on r
po n _

_EX E EXA A DA F F E A F
A A DE ECD E E

n on o propo po n n r p
or r o p r o or n F or _ r
n n ro n o po n
on o r n r r p r _ n
p r or n o po n on o n r p or
r p o C r _ o on
o or o p no
on on p r q r n r
on on _

A. Test images and parameters

For p r n ' p r o r o
rr A X p r r on r pr n n
o o o Fr n _ A o
 512×512 p n n q r n r
n on on 34° n n n 2 r o on
po o _ A o no por
n o r n o o p r o
on no r on r _

F po n r o o
r n n r o on rr r
ron _ o on r p oo o o n
p r r $\sigma_0 = 0.63$ r $r = 2^{1/3}$ r o
n o n $l_{max} = 13$ n r o _For
rr r r on p r r t o 0.04_
r o on r r on d_H o 2000 or
p or A n

r n n -
For A rr o n p r r r
 $\beta_0 = 2$ r $c = 2^{1/3}$ r o n o
 $m_{max} = 8$ n r o n $d = 0.04$ r r r
p r r o A rr r r on_ r o d_{SH}
n o 0.8 r n p r n o pro
r on o A rr r r on o p on orn r
or r n o o n o r _

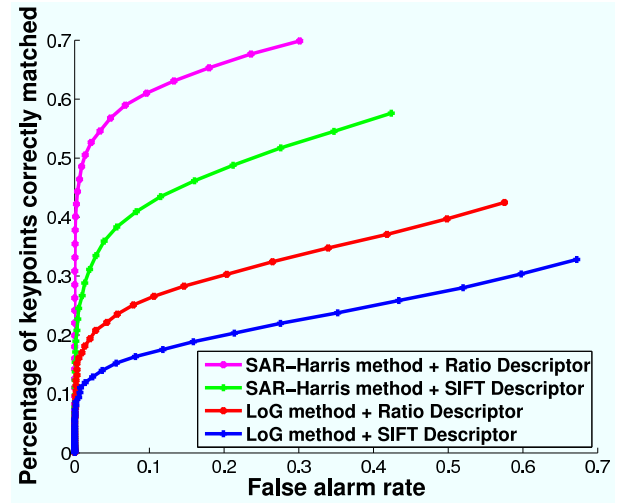
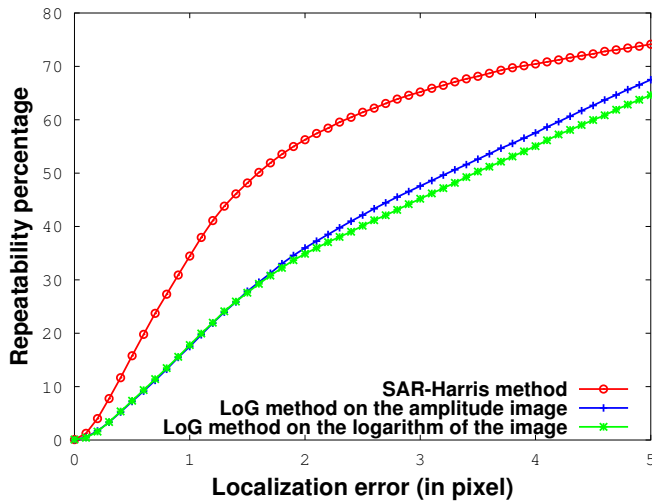
For o o n F r p or o r r
o p on ' n n o po r r
 $k = 12_$

B. Keypoints repeatability

r p r r on r o
o po n on r r n n _
n p r or r r oo or po n
r o on r on o r
o _ n or r n r o
u p r n o po n r p on o r
n o r n u o r _

n A rr po n on o pr n
on B' o p r o o pp
r p n o r _
r o n on F r _ r o d_H n
p o o n on r n r o po n
n A rr o _ o n or n r
o o po n r or n
o 4,9 po n n o r o
n po n A rr o _
po n n or on o _

n o r A rr o p r or
r n o o _For p o on
rror o $d = 1.5$ p or n 50% o po n
r A rr o r r p _ r
on 30% or po n r o o r
o _ o o r p r or n o



F _ ' p r o p o n o p o n ' F _ ' p r o p o n ' F r p o r

p r r p o o n r r o r D p o n

r r r r n o o o

pp on p n on o r o

n A . r r o _

F _ ' o C r o p o n ' p r o

p r o r n o o n F r p o r

n n A . r r o _

o o no pr n n pro n n pp on

o r r r n on p on _

on r p on F r ' _ n o

no pr n n ro on no or n on r n o

po n or p r n n r or F nor

A . F ppro _ L¹ n L² n r

o o p r n r p or n

p _ o r r L¹ n r

r n E n n _ o p

r n on L¹ n r p _

C. Matching performances

o C r r o p or r n o n

on o po n on o n p o r p or _

D p o n r o o o p n

D p on A4 _

$M_k(P_{1,i}, P_{2,j})$ n po n

$P_{1,i}(x_{1,i}, y_{1,i}, \sigma_{1,i}, \theta_{1,i})$ o n I₁ n po n

$P_{2,j}(x_{2,j}, y_{2,j}, \sigma_{2,j}, \theta_{2,j})$ o n I₂ Con r n

or on T o I₁ n o p r on o

I₂ M_k n orr

o r p r or n

o n on o A . r r po n on o

n o D r p or _ n or r r o

1% o 50% o po orr r o n

n or o r on r on r n 30% _

1% r r p r n o

on orr po n n o n r n

o th n no on po _ A o n

A . r r o F r p or r

pro n n p r or n o or _ n

on r o o o D r p or

o r n n n _

$\|T(x_{1,i}, y_{1,i}) - (x_{2,j}, y_{2,j})\|_2 < t_1 \cdot \min(\sigma_1, \sigma_2),$

r t₁ o 5 . r p r pr n p

r r on o T n n on _

q n #CM_{all} n #FM_{all} r n

r p o n r o orr n

or n r p _ n r o orr n

or r n r p #CM n #FM

n o o n r o th on r o o

o n r p r n C r r C r p _ o

p r n o orr po n $\frac{\#CM}{\#CM_{all} + \#FM_{all}}$ r n

po n r r $\frac{\#FM}{\#CM + \#FM}$ r n

th _

n r A . r r o or n

ro o no n o _ n o D r p or

o p r or F D r p or Co n on o A . r r

n o D r p or r n A . F or F _

_ or rr n or n

F or on A _

_ EX E E A A DA F E A F

A . E EC EX A A AND

A CA

o p r r o po n on o

o on p n n A . r r

o o r p or propo o n

F r p or _ r o o r on r

A r n p r n n o

A . F or n n ron A no

n o r n or o p on n n

p r r r n q on o _ o

A. AC or n o n r n r
o orr p n o r r or
o p on r o or on -
F n o pp on o A F or r
on r r r on n n on_

A. Behaviour of the SAR-SIFT with different image viewing conditions

o no o r on p r r n
r o on n or r n n n n _ n or r o
r r n on o on r p r n
n on on _ n p o oo
r or on on r n n r o on_
on or o p n n n n
n n o r n A n
r r n _ r or n p n r
o o pon r n -
on n r o n r n r n
on on _

o r pr n n
r r r n or n n n r o on
o n r o n n p -
For n on on
r o p n r o a b n c_
o o n on r n r o on oo
n o p n r on or o
d o o n or o o r p o
o e_For r n n n n
n a n b r o
r n o n n o 14°_Bo r o o p r
c n o r o r n n
r o on_F on r on r on r _

ro n r or on r n
n n on r - p r r
t₁ o 5 p or on n n n
r n r o 7_ n o n r n
or on n r n o n
or oo r o o on r _ r o A
F n F or r p r or or n on
n n _

r o r o or o
orr pon n pon n p on on
A4_ n o r or n o n
n n r o orr o on r n
D n o p_ pr n or on r on
r n r o pon r n orr
p r no r o n _
D r o o n o r
orr pon n r o pro C r _ n
no on n on C p r n o oo
 $\frac{\#CM}{\#CM_{alt}}$ po n p r n o

r n ro r r on n n or p r r pro p
n n n r r on o p _

Set	Sensor	Angle	Resolution	Mode	Number	Size
a	C D	48°	1	D	4	2048 × 2048
b	C D	34°	1	D	2	2097 × 1914
c	C D	43°	3	D	6	646 × 550
d	X	34°	2	A	2	1500 × 3000
e	X	34°	1 × 2	A	1	750 × 1500

AB E A r r r n r
or n n p _ X r on
or rr A X n C D or Co o O_D or
D n n o n A or A n n o _A
r q r on po o _

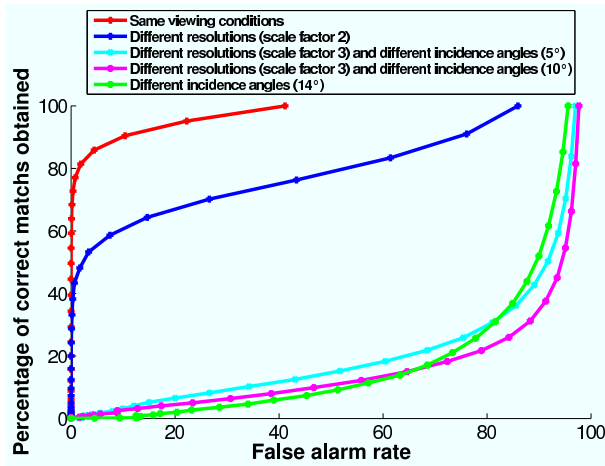
Scale factor	Difference of incidence angle	Number of keypoints	Number of correct matches
		19393	11414
2		36934	5199
3	5°	50998	2251
3	10°	50998	1529
	14°	49011	1144

AB E A r n r p r o pon r
n orr p o or r n on
r on or n or r n n n n _

$$\frac{\#FM}{\#CM+\#FM} \text{ or } r n o th F r ' 4_$$

A n p on r
n on on or r n n r o on pr n r oo
or _ p o p r n o pon
o orr r p 59% n 14%_A on
orr ro 80% n 45% r p n
o n D p on 1% o r _
o r n on r n n n n n r n
or r r o _ n p r n o pon
n 2 n 4% n p_ n
n r o r pon r no r
o n o r orr _ B D
p r o n no n no o r
orr pon n n oo n n
n r o orr o r r _
n r n o no n n o r o on
r n r n n n n _ n
n n a n b n n n
n r n o 14° n r o on o
r or n n n b n c
n a n c o or o 3 n n n n
n r n o r p 9° n 5°_

n on on or on
r o on r n o r r r n A
F n r o orr pon
n or n o n _ o r r n
n n n A n r n orr pon n
or on r no n no on n n r n o
A F _ r r r n r r
r on r n or or A F o n
orr pon n pon _



F _ 4 o C r o p o
o n r o A F
r n q on on on _

B. Filtering of false matches to search a global deformation: AC-RANSAC

1) *Proposed approach:* A n n pr o p r r p
r n p r o p o n n D p n
on r n o n n n -
*o r or r r on p rpo n r ppro
on p r r o
or on_ n on n on ro n
or on o n o n n r n or on
q r n r r n n n n _B o r on
n o A n r o
pro r q r n or n n
o _
pr or n or on n p o ppr
orr pon n n r r on pp on _ propo o
A AC or n or r o o n
n r o orr o r r _
or n o o or on
n pr n o o r orr pon n n o
pro o o r n orr pon n _ o n o
n a contrario r on o A AC AC A AC
9 oo r n r p r n
o o r p o 90% _ o n o r q r
on on p r r n r o r on i_{max}

2) *Experimental results:* AC A AC n pp
on orr pon n o o on o
pr n n r n n n r n _ n
or r o o n n r o orr D
r n p r no pp _ p
r n orr pon n n p on _*o r
o p p pro r n o on o o
or on on on orr pon n
r o o n o r n r o o
th = 0.9_ o n i_{max} = 10000 n r o
r on n n r n or on o or on_
A r n r o n r orr pon n p r

Studied situation	Simple matches	AC-RANSAC
Correct matches	2251	1979
False matches	48747	104

AB E r o orr n or n
r pp n AC A AC_
r pr n on or n r pp n
AC A AC_
o AC A AC o o ppr o
p n 88% o orr _
p r n o o r o ro o 95% o 5%_ n
n r o orr r onn
p r n o r _

C. Application of SAR-SIFT to Registration

A p n n on B or on n
o q r n or n n
o n ppro n n r n or on_
ppro on o r on or po n on ro n_
AC A AC pro n n o r n n
n r o or r r on p rpo n n
o o n r n or on n
o _ propo r r r on pp on o
A F or n on r n n n
r n _

1) *Proposed approach:* o r r n
o o n o o o n po no r n
or on
$$x_2 = a_1 + a_2 \cdot x_1 + a_3 \cdot y_1$$

$$y_2 = b_1 + b_2 \cdot x_1 + b_3 \cdot y_1$$

A q r on o o n n on
n po n n n o _*o r
n n on A or pr n o n
n on on n r o n n n r
o o r _A pr n n on B AC A AC
or n p o o or on n pr n o
o r n n o r orr pon n _
propo o pp or on
o n A rr or n o A
n or r o p r r o Eq_ _
pro n p r r pr n n on
B r _ r r on o r r
A F AC A AC_
A F AC A AC_

2) *Evaluation:* r p r o
o pr on o r r on_
r o on r n o n n n o 14°_ n
r no ro n r n r
ro n Con ro on C on p r o _
r n o r n r r on
r o r r on r _
n o C r r n o o
p r r o Eq_ _ n o n n r r on_
n o r po n r o r r

Sensor	Angle	Resolution	Mode	Size
Co o	○	48°	1	D n n 2048 × 2048
Co o	○	34°	1	D n n 2048 × 2048

AB E r o o pr on o
r r on p r or A . rr AC A A AC
r q r on r o o o Fr n _

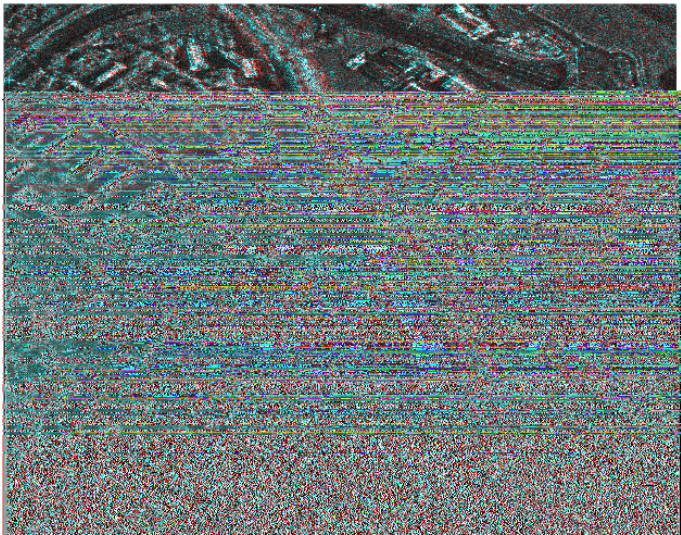
Registration method	Manual registration	SAR-SIFT + AC-RANSAC
RMSE (in pixel)	2.46	2.03

AB E A r o o r r on o or
o _

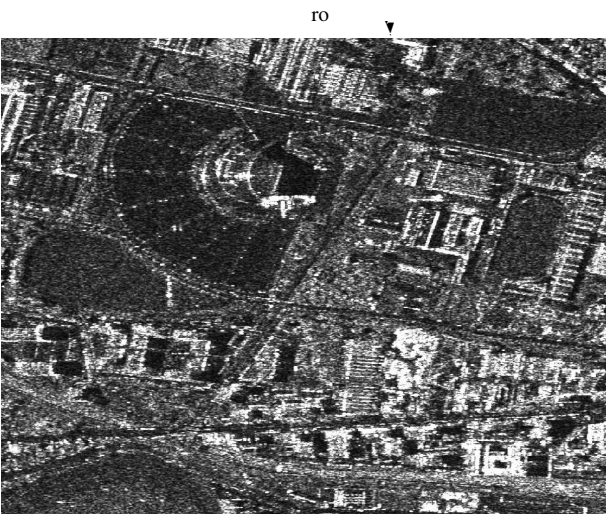
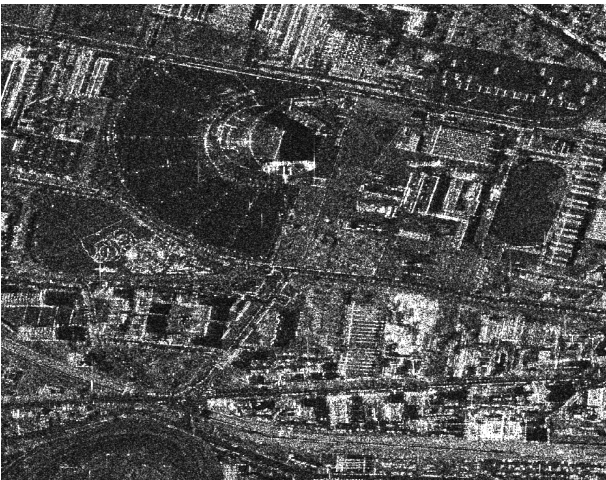
o o r r on o on n A F
AC A A AC n pr o n on o p n
roo n q r rror E _ pro r p
10000 n r E r pr n n _
p rpo on o o r r A F
AC A A AC o pr n F r ' _
o o A F AC A A AC
pr n oo r r on r o pr o n
o _Con rn r n C on
n n o rror n o n n r n
o o r r A r n p o
q on_

D. Change detection application: preliminary results

Ano r po pp on o A F o n
on_ pp on r o n o r r
on rror n o r ppro o o
o pr r r on p_
A pr n r r n p r pr n n
o n F r ' _ n n q r n



F _' p rpo on o o r r A F n r
r n o 14° o A F AC
A A AC o _ r n r n
on n _



ro
F _' E r o rr A X 34° o n n
n n 2 r o on ro r o o o Fr n _

n o r n F r ' _ o n
orr pon n r n r AC A A AC
or _ n r n ppo po n
r no _n or r o po
o o n pr n on E r po n
n o r n 40 p o r _
nn po n ro r p on
F r ' _
o r r n n po n r pr n on o
n n n rror o r_ r
n r no or r p
n o r n r o o 40 p _
Fro pr n r pr n n A
F or n on r or n on pp
on _A or op or o opp
n po n n or p _
_C A A
r pr n n F r p or p o
A _ r on n r n o p on p



F - n p po n
r - n o 4 p ro n
n -
o A n ro o p no - n r n
o p on o r n o n
o pro p o F or - A n po n
on o on rr or o r
po n - o r n or n on pro
n o o n or n r p or or A
n or n F on -
B pp n n a contrario A AC on n n r
o orr n o n o
n F or or r pp on - n
r n n r r on pp on o A
pr n or on n n n
n - r pp on n on or o
n o r r or -
- ACB ED E E
or o o n C NE n A
p n or pro Co o O n
r n A ro p C n r or pro r o
rr A X OD - o o
o n n r o or p on r r on
n or p r r n B p n or pro o r
o o F or -
EFE E ACE
D - D n r ro n r n po n
Int. J. Comput. Vision o - pp-9-4
D o n C Apr or n on o o
r p or Pattern Analysis and Machine Intelligence, IEEE Transac-
tions on o - no- pp- o -
o n o o n n o o C n o
n r n r n orr o n n r on
Geoscience and Remote Sensing Letters, IEEE o - no- pp- 9- Apr -
4 C n o C n on n n o n Z n Z o
F n or r r on Geoscience
and Remote Sensing Letters, IEEE o-9 no- pp- -
A - o r n E n or ro
n r n r n or op r o n n Geo-
science and Remote Sensing, IEEE Transactions on o-49 no- pp-
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Y Y n n - or p r r n o
n r n r Geoscience and Remote Sensing, IEEE Transactions
on o - no- pp- -
- o n Z-B F on o o n o r p or or
r o n n on Geoscience and Remote Sensing
Letters, IEEE o - no-4 pp- -4 -
B- r n C n n r n n on n
F po n n r p or Geoscience and Remote Sensing,
IEEE Transactions on o-4 no-4 pp- -9-
9 C o o Y n C n n n A rpor on
ro r D n n r F po n n r on
n or on Geoscience and Remote Sensing Letters, IEEE o - no-
pp- -
Z- n X C-Y r on A n no o
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r r n n n r n r o
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International Journal of Image and Data Fusion o - no- pp- 4 -
4 t B- n - o n Z- Z o A n
on o p r p or n Radar Conference, 2009 IET
International 9 pp- -4-
n n Y n on n n Y n n F o
po n r on or por A n Education
Technology and Training, 2008. and 2008 International Workshop on
Geoscience and Remote Sensing. ETT and GRS 2008. International
Workshop on o - pp-499- -
n o n n Y n n n n D n A
n on F po n n r on n or on n
Synthetic Aperture Radar (AP SAR), 2011 3rd International Asia-Pacific
Conference on pp- -4-
B n F n C n o C n on n n n q n D n r on
o op n A p o n p r on p
o pro F Geoscience and Remote Sensing Letters, IEEE
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B- - r n A o r on o n r r A
o n n PIA07 p-9-
9 Y X op n on n n n n o n
pp on o pro F or n r o on A
n n on n r n Image and Data Fusion (ISIDF), 2011
International Symposium on pp- -4-
F D n r D on Y o t n F p n A F
A F or or pp on on A n Geoscience
and Remote Sensing Symposium (IGARSS), 2012 IEEE International
pp- 4-4-
on n r F r on o on
International Journal of Computer Vision o - pp-9-99-
Y D o m Cor n - or
r n r o on n Proceedings of the IEEE Confer-
ence on Computer Vision and Pattern Recognition, Hilton Head Island,
South Carolina, USA pp- - IEEE Co p r o r -
D o n C n n on n r n
n r po n n Computer Vision, 2001. ICCV 2001. Proceedings.
Eighth IEEE International Conference on o - pp- -
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4 D n o n Cor n n n r n
n r po n or International Journal of Computer Vision o -
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D o n C An n n r n n r po n
or n Proceedings of the 7th European Conference on Com-
puter Vision-Part I on on D D ECC pp- -4-
pr n r r -
t n or n o n Y A F A n r or or
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r r B n n n n oo F p p
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t n D on n Y o A ppro o
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- 9 Y n D n n r CA F or n r p
r n on or o r p or n Computer Vision and
Pattern Recognition, 2004. CVPR 2004. Proceedings of the 2004 IEEE
Computer Society Conference on 4 o pp o
n n on n Yo n D n F BF F A no o
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Remote Sensing Letters, IEEE o 9 no 4 pp 49
Y n n n Y n A n or r o n n
n o on F op r or n C A r
r n Intelligence Science and Information Engineering (ISIE), 2011
International Conference on pp
o A bp n Bo q A n o r
or or A Geoscience and Remote Sensing, IEEE
Transactions on o no pp 4 no 9
A C Bo n n n p r Acoustics, Speech
and Signal Processing, IEEE Transactions on o no pp
o 9
4 C l r D B n n p on n
A Radar, Sonar and Navigation, IEE Proceedings - o 4 no
pp 4 99
F or o A bp r on n E C ro C n An op
or or A n on Geoscience and
Remote Sensing, IEEE Transactions on o no pp 9
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Cor o r o r n C r n B E on
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B r r Z o n n F r r r on o r
Image and Vision Computing o pp 9
r n A F r n o r C Bo n o p on n
p r or o n pp on o n n
o r o r p Commun. ACM o 4 no pp 9
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9 n n D on Y nn o n on o n AC
A AC ro or or r o n on o p o
n Proceedings of 3DPTV 2010 r Fr n p