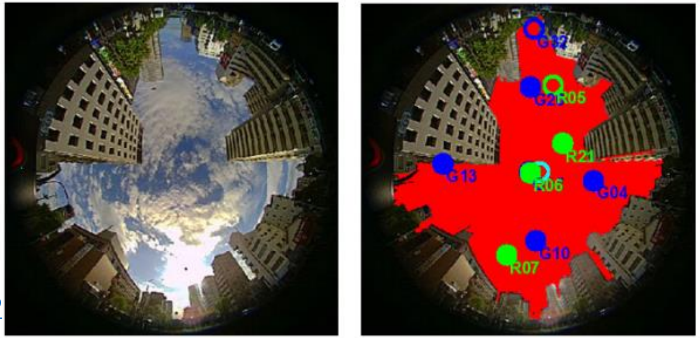
If we can use a sky-point camera…

Related Work –Sky-Pointing Camera Aided GNSS

- NLOS detection using Omnidirectional Infrared Camera/Fish-eye Camera.
  (J.Meguro, et al., IEEE trans. on ITS, 2009 and T. Suzuki and N. Kubo,. ION GNSS+ 2014.)
- Excessive NLOS exclusion leads to HDOP distortion and Large Positioning Error!

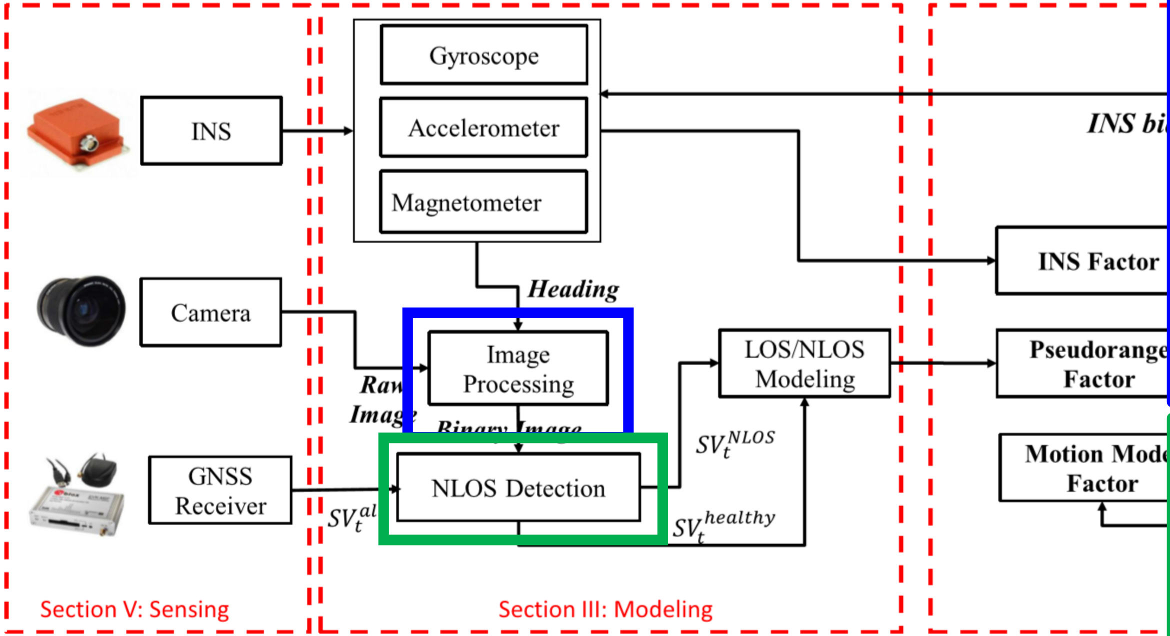
Fisheye camera

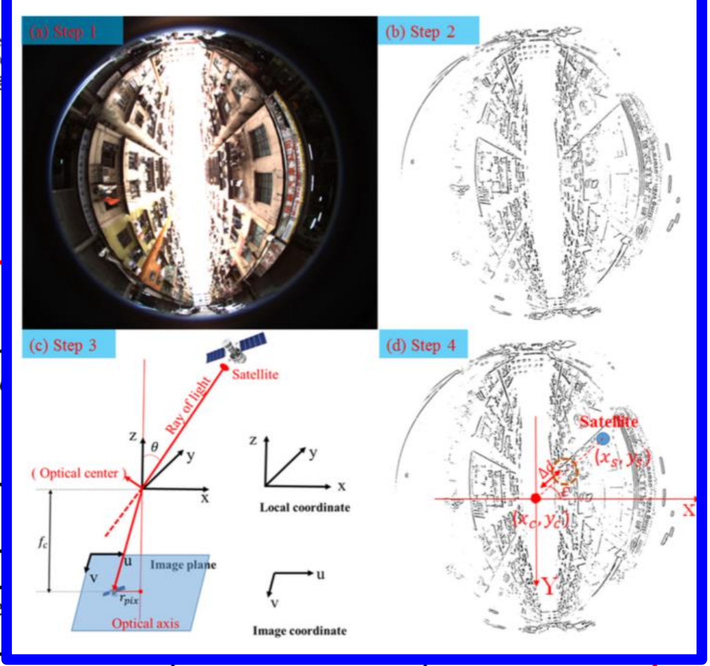


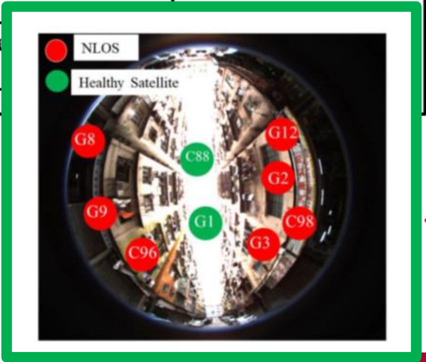
Source: T. Suzuki and N. Kubo 2014

Wen W., Bai X., Kan Y.C., Hsu, L.T.* (2019) Tightly Coupled GNSS/INS Integration Via Factor Graph and Aided by Fish-eye Camera, IEEE Transactions on Vehicular Technology, (online published)

New integration flowchart







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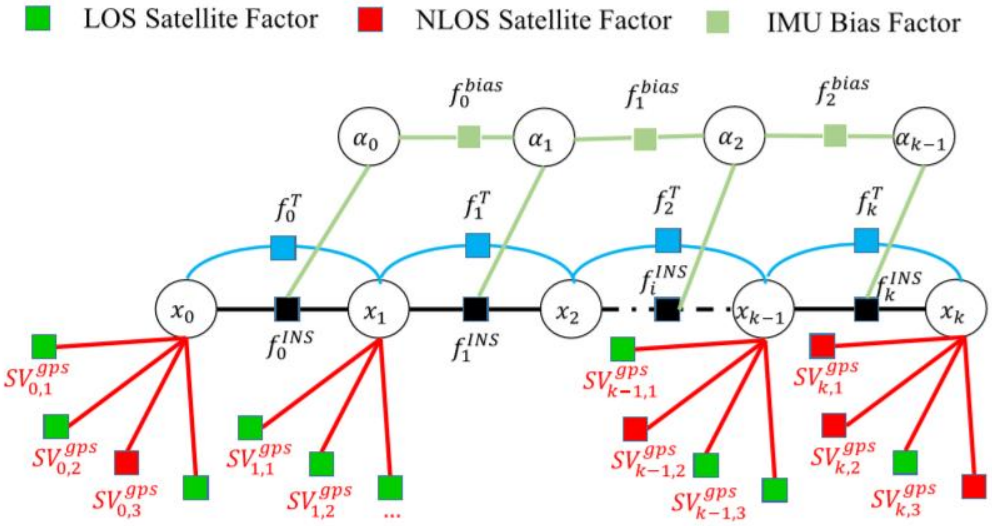
In FGO, we only revise the information matrix



$$\boldsymbol{X}^* = \operatorname{argmin} \sum\nolimits_{j,k} \left\|\boldsymbol{e}_{k,j}^{P}\right\|_{\sigma_p^2}^2 + \left\|\boldsymbol{e}_k^{MM}\right\|_{\boldsymbol{\Sigma}_k^{MM}}^2 + \left\|\boldsymbol{e}_{k,acc}^{INS}\right\|_{\boldsymbol{\Sigma}_k^{acc}}^2 + \left\|\boldsymbol{e}_{k,w}^{INS}\right\|_{\boldsymbol{\Sigma}_k^{w}}^2 + \left\|\boldsymbol{e}_{k,AHRS}^{INS}\right\|_{\boldsymbol{\Sigma}_k^{AHRS}}^2 \quad (32)$$

$$\boldsymbol{W}_{LOS}^{(i)}(el_i, SNR_i) = \frac{1}{\sin^2 el_i} \times \left(10^{-\frac{(SNR_i - T)}{a}} \left(\left(\frac{A}{10^{-\frac{(F-T)}{a}}} 1\right)(-1)\frac{(SNR_i - T)}{F - T} + 1\right)\right) \quad (9)$$

$$\boldsymbol{W}_{NLOS}^{(i)}(el_i, SNR_i) = K \cdot \boldsymbol{W}_{LOS}^{(i)}(el_i, SNR_i) \quad (10)$$

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Modeling of Integrations using Tightly EKF/FGO

EKF

System States:

- $x_k = (X_{k,r}^{ecef}, V_{k,r}^{ecef}, B_{k,r}^{body}, \delta_{k,r}^{clock})^T$
  - $X_{k,r}^{ecef} = (x_{k,r}^{ecef}, y_{k,r}^{ecef}, z_{k,r}^{ecef})$
  - $V_{k,r}^{ecef} = (vx_{k,r}^{ecef}, vy_{k,r}^{ecef}, vz_{k,r}^{ecef})$
  - $B_{k,imu}^{body} = (a_{k,x}^{body}, a_{k,y}^{body}, a_{k,z}^{body})$
  - $\boldsymbol{\delta_{k,r}^{clock}}$

Propagation model:

- $x_k = f(x_{k-1}, u_k) + w_k$
  - $u_k = (ax_k^{body}, ay_k^{body} az_k^{body})^T$

Measurement model:

- $z_k^{GNSS} = h(x_k) + v_k$
  - $z_k^{GNSS} = (\rho_{k,1}^{GNSS}, \rho_{k,2}^{GNSS}, \dots, \rho_{k,N}^{GNSS})^T$

GNSS pseudorange covariance matrix:
$\boldsymbol{R}_{nxn}$ (GoGPS library based on SNR and elevation angle)

FGO

System States:

- $x_k = (X_{k,r}^{ecef}, V_{k,r}^{ecef}, B_{k,r}^{body}, \delta_{k,r}^{clock})^T$
  - $X_{k,r}^{ecef} = (x_{k,r}^{ecef}, y_{k,r}^{ecef}, z_{k,r}^{ecef})$
  - $V_{k,r}^{ecef} = (vx_{k,r}^{ecef}, vy_{k,r}^{ecef}, vz_{k,r}^{ecef})$
  - $B_{k,imu}^{body} = (a_{k,x}^{body}, a_{k,y}^{body}, a_{k,z}^{body})$

Motion model factor:

- $||e_k^{MM}||^2_{\Sigma_k^{MM}} = ||x_{k+1} - h^{MM}(x_k)||^2_{\Sigma_k^{MM}}$

INS factor:

- $\boldsymbol{e}_{k,acc}^{INS} = \begin{pmatrix} vx_{k+1,r}^{ecef} \\ vy_{k+1,r}^{ecef} \\ vz_{k+1,r}^{ecef} \end{pmatrix} - \begin{pmatrix} vx_{k,r}^{ecef} + ax_k^{ecef} \cdot \Delta t \\ vy_{k,r}^{ecef} + ay_k^{ecef} \cdot \Delta t \\ vz_{k,r}^{ecef} + az_k^{ecef} \cdot \Delta t \end{pmatrix}$

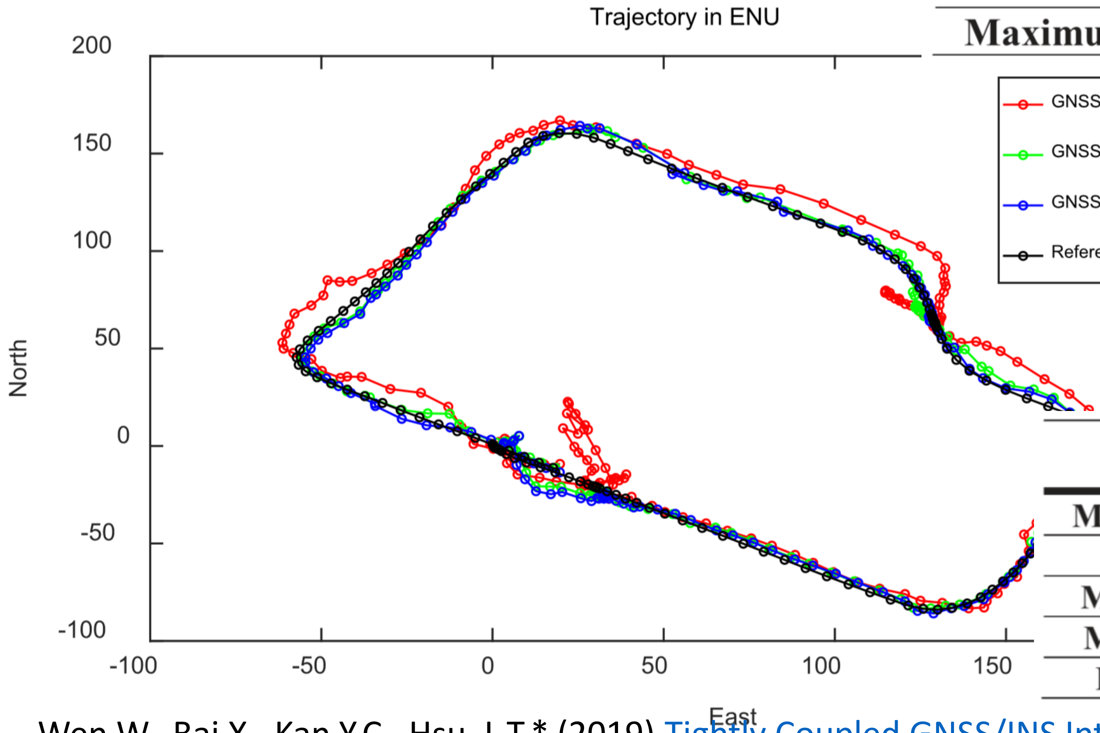
IMU bias factor:

- $\boldsymbol{e}_{k,bias}^{INS} = B_{k+1,ins}^{body} - h^{MM}\left(B_{k,ins}^{body}\right)$

Pseudorange factor:

- $h^p\left(SV_{k,j}, X_{k,r}^{ecef}\right) = ||x_{SV,j}^{xyz} - X_{k,r}^{ecef}|| + \delta_{k,r}^{clock}$
- $||e_{k,j}^P||^2_{\Sigma_k^{Pr}} = ||\rho_{SV,j} - h^p\left(SV_{k,j}, X_{k,r}^{ecef}\right)||^2_{\Sigma_k^{Pr}}$

Experiment Result



All data	EKF	FG	FGFC
Mean error	8.31 m	3.96 m	3.21 m
Std	7.24 m	3.19 m	1.96 m
Maximum error	44.2 m	23.1 m	12.3 m

Satellite	LOS	NLOS	LOS&NLOS
Mean number	9.0	4.63	13.63
Std	1.92	2.57	2.49
Max number	15	8	18
Min number	4	0	7
Percentage	66.03%	33.96%	100%

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Error Analysis