Direct hybrid Navigation based on celestial bodies and landmarks

Yves Robin-Jouan

IFN, ION, IEEE Member

PMBA, MOV'EO & SYSTEM@TIC clusters partner

yrobinjo @ free.fr

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Agenda

- The "New navigation" initiated by A. YVON-VILLARCEAU (1877)
- One century later…
- Sight reduction through Cones for land & sea applications
- Measurement functions for multi-sensor integrating:
  - Stars, Satellites & High Altitude Platforms, Landmarks
  - from loose coupling to tight coupling
- Unified Matrix equation for direct hybridation
- A canonic case with Stars, Satellites and both
- A practical case with 2 Landmarks and a Star
- Outline of an Architecture for Autonomous Vehicles
- Conclusion & References

YVON-VILLARCEAU, pioneer of modern linear methods

- $e = a\,x + b\,y + c\,z$ [$e = \sin h$]
- $e' = a'x + b'y + c'z$ [$e' = \sin h'$]
- $1 = x^2 + y^2 + z^2$

where h & h' are the heights of 2 celestial bodies

"x, y, z represent rectangular coordinates of the location, according to a linear scale, with the Earth radius taken as unity (=1). So the 2 first equations generate 2 planes, and the last equation the Earth sphere itself. Therefore, the problem is reduced to compute the intersection of 2 planes with a sphere.

But in practice, we don't recommend to use the given formulas, because of the associated computing difficulties [on 1877!]. We propose a method which is LESS DIRECT, but quicker to be applied. "

« Nouvelle Navigation Astronomique – Théorie » pp 22-26 (Gauthier-Villars, Paris, 1877)

Marcq Saint-Hilaire method, associated errors and their mathematics were following on.

In 1877, there were alternative methods for a long cruise!

James Tissot
1877

Leaving Portsmouth (UK), "from the gallery of HMS Calcutta"

YVON-VILLARCEAU followers …?

- $e_1 = a_1 x + b_1 y + c_1 z$ $[e_1 = \sin h_1]$
- $e_2 = a_2 x + b_2 y + c_2 z$ $[e_2 = \sin h_2]$
- ……
- $e_n = a_n x + b_n y + c_n z$ $[e_n = \sin h_n]$
- $(1 = x^2 + y^2 + z^2)$, skipped if $n \geq 3$

where h_k is the height of celestial body k (= 1…n)

One century has been spent before using these equations…

… firstly for Celestial navigation:

with HP 25, HP 97 (ENMM, 1976), TI 59 (USNO, 1978)…

then SHARP 1246S & BASIC pocket calculators (1984)

Using CelNav for topography along Sahara coast (1997)

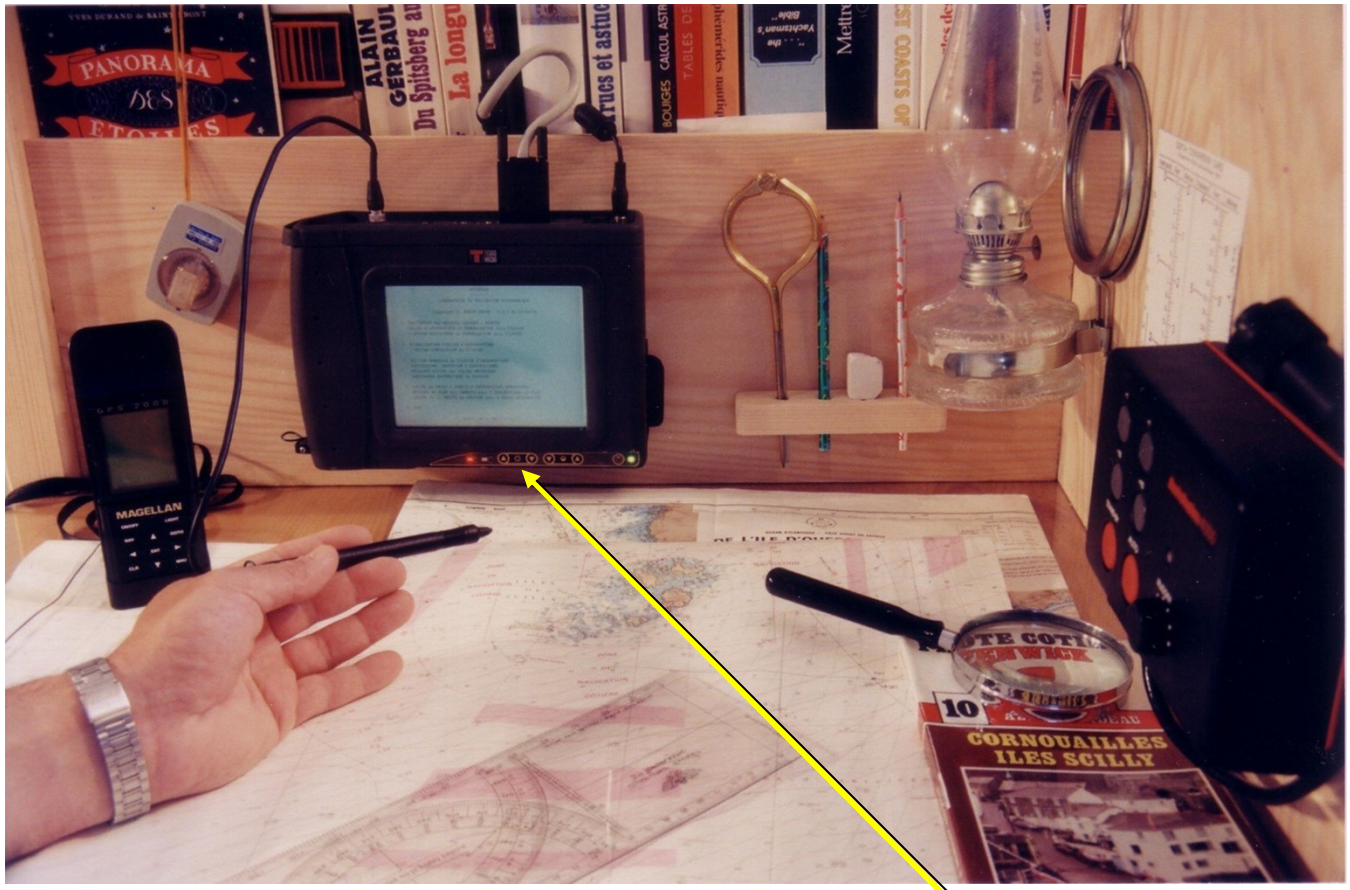
- **Doing some SLAM with better accuracy than GPS under SA !**

- **SOKKIA DT5, connected as a digital theodolite to…**

- **…HP 200LX, palm PC running automatic ephemerids + multi-sight reduction**

for long-range Telecom stations, powered on solar array + batteries

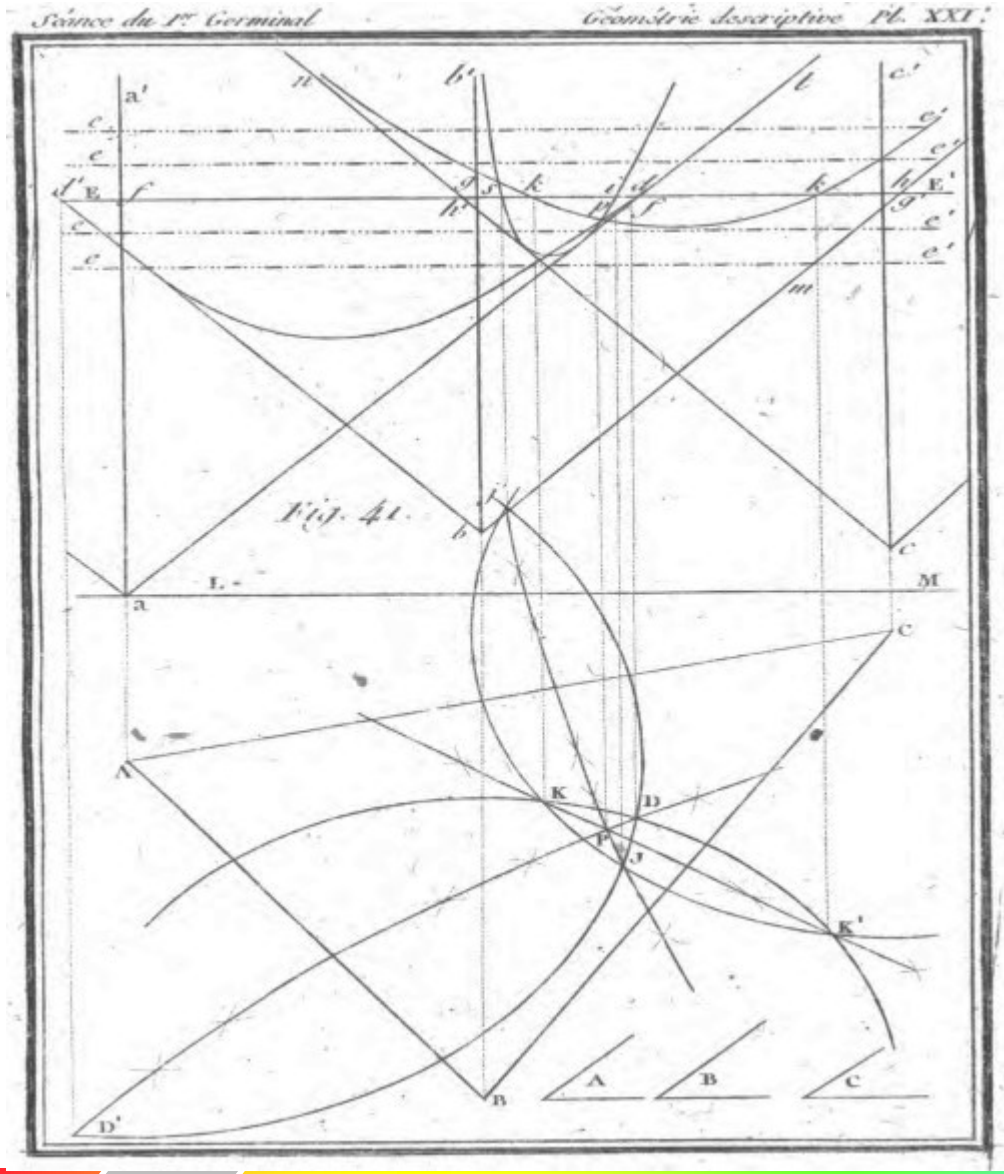
Using CelNav & GPS on board a 36 footer (1998)



Jeanneau Sun-Odyssey

- **MAGELLAN GPS 2000, an early handheld RX**
- **Ruggedized PC running DOS, and ASTROLAB software**

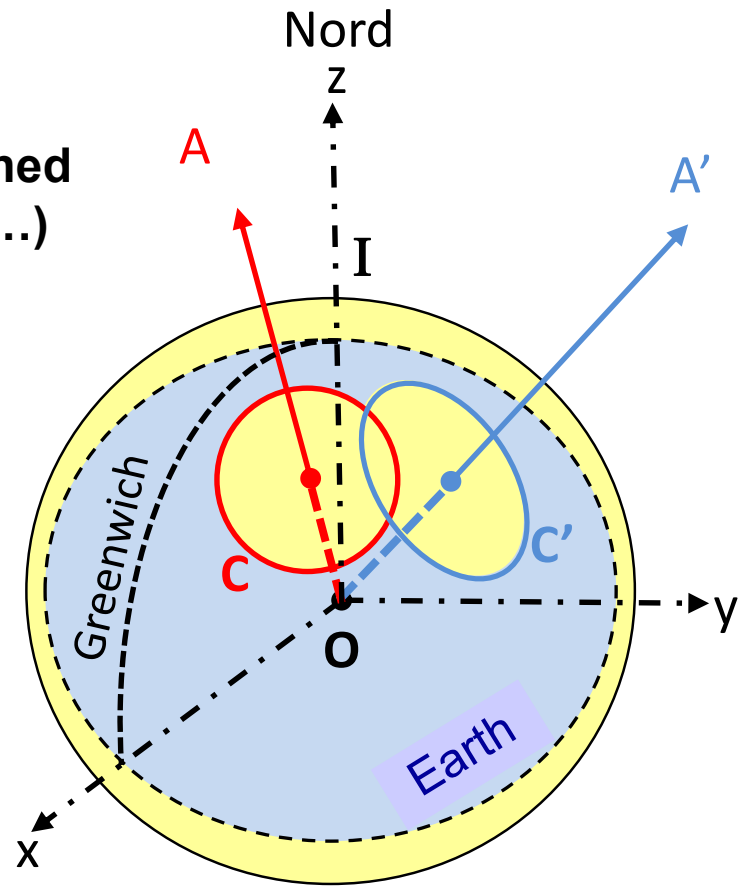
Monge Descriptive Geometry and positioning by cones



- Can you **find the projections of a point** when you know the zenith angles of 3 marks in space ?
- The position is given by intersecting **3 circular cones**
- (Then Monge proposed a similar approach with multilateration !)
- Séances des Ecoles Normales, *Paris, Imprimerie du Cercle Social, Rue du Théâtre Français, N°4* French Republic Germinal 1 an IV (March 21, 1796)

Geometry basis for a multi-sensor integration (1/2)

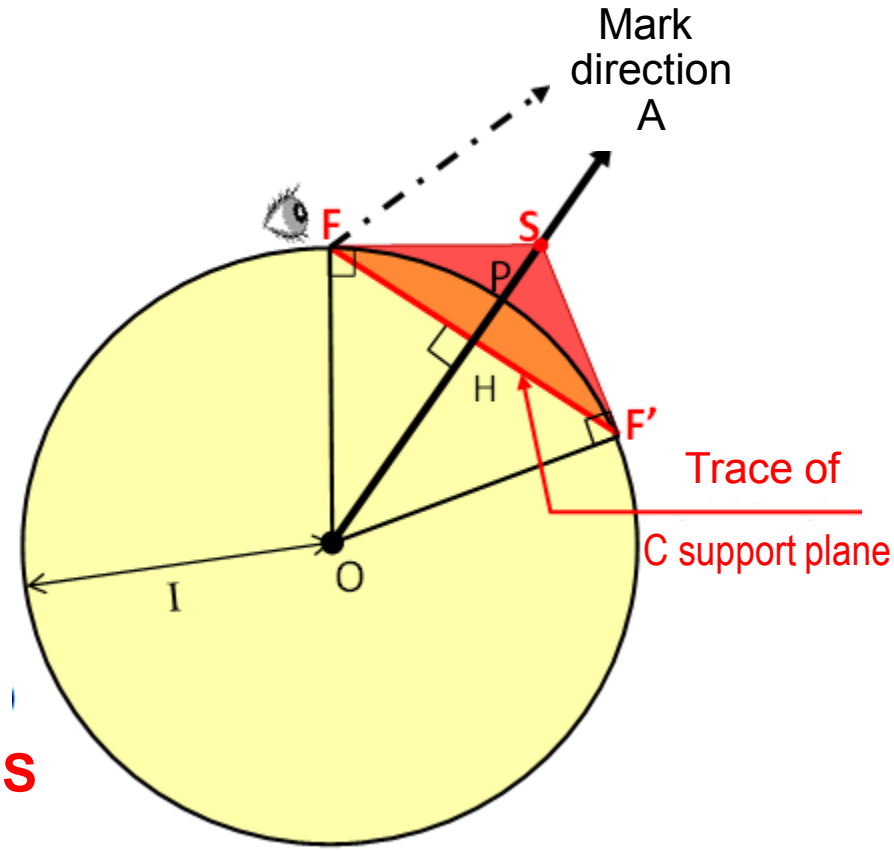
- **Around the Earth, a local reference sphere can be considered:**
  - this is "spherical Earth", with radius = 1 for Celestial (and coastal) Navigation
  - but it can be a virtual sphere, with a radius I to be defined for Navigation using Satellites or HAP (UAV, balloons…)
    I remains near 1 in conventional aviation airspace
- **Such a reference sphere gives a circular geometry to locus of points with an equal measure of a mark:**
  - around this mark or its vertical projection on the sphere
  - locus is a small circle C of the sphere,
  - circle C is centered in the OA axis to a celestial mark
  - it may be centered or not to a group of landmarks (if not, the shift vector is known)



ECEF coordinate system
Earth Centered, Earth Fixed

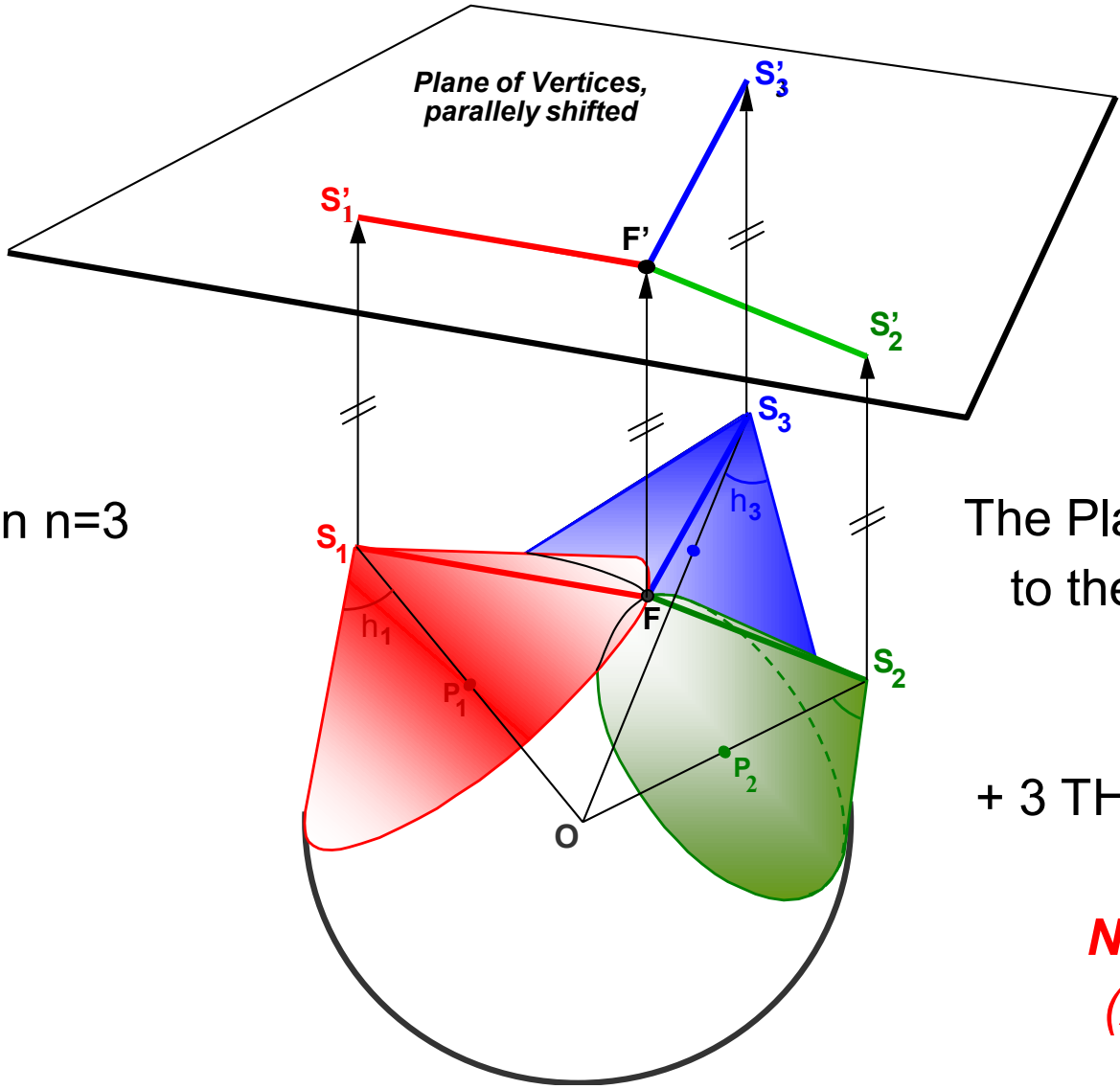
Geometry basis for a multi-sensor integration (2/2)

- The envelope of horizontal planes following a circle C is a cone:
  - with the same axis OA than the circle C
  - tangent to the sphere I by definition
- The vertex S of the cone is:
  - in the horizon plane of the observer (if measure is exact)
  - representative of the mark via its 2D location (P on the sphere)
  - representative of the measure via its altitude
- $\overline{OS}$ radius is directly tied to the measure of:
  - time or distance (satellite, HAP,…Radar)
  - angle (star, height or aperture between landmarks)
- In every case, marks can be exchanged with S in the horizon plane of the observer
  - celestial bodies are lowered (as with a sextant)



Diametral cross view

n measures with associated cones ⇨ Plane of Vertices



Case when n=3

THEOREM 1

The Plane of Vertices is tangent to the reference sphere in F for n = 3 and ∀ n

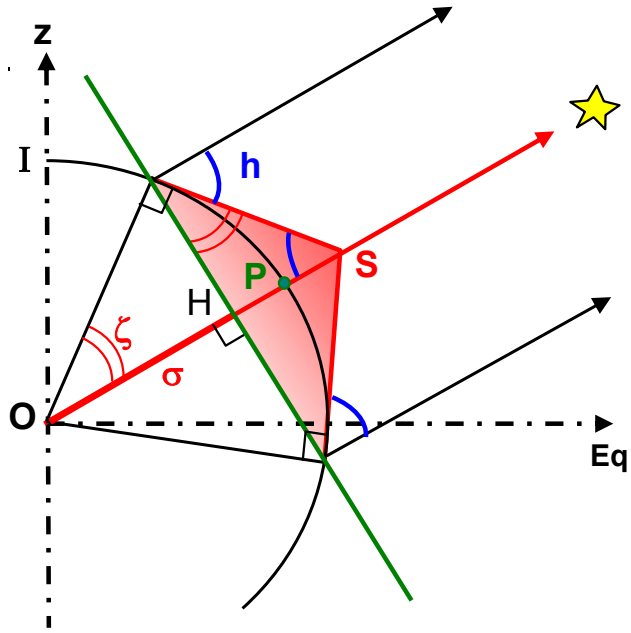
+ 3 THEOREMS in succession

No Need for any AP

(Assumed Position)

How to decline it with respect to the type of mark (1/2)

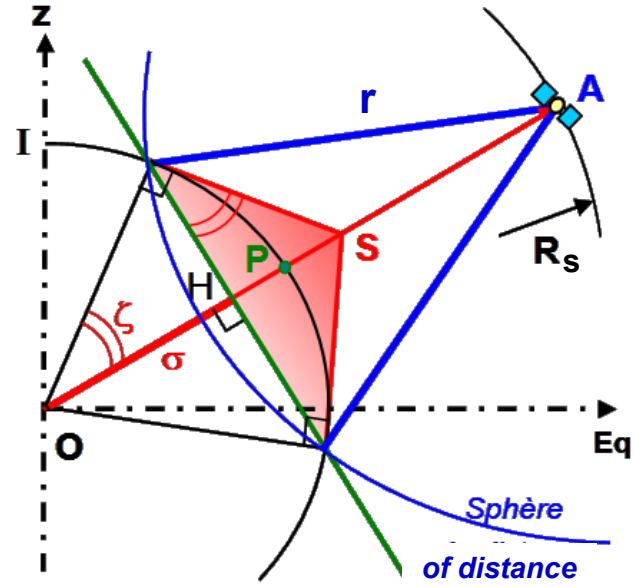
- **Case ① with a Star**
  - **measured variable: h**



$$\Sigma = \overline{OS} = \frac{I}{\sinh} \qquad \text{where } I = 1$$

$$= I \,.\, \operatorname{cosec} h$$

- **Case ② with a Satellite (or HAP)**
  - **measured variable: r**

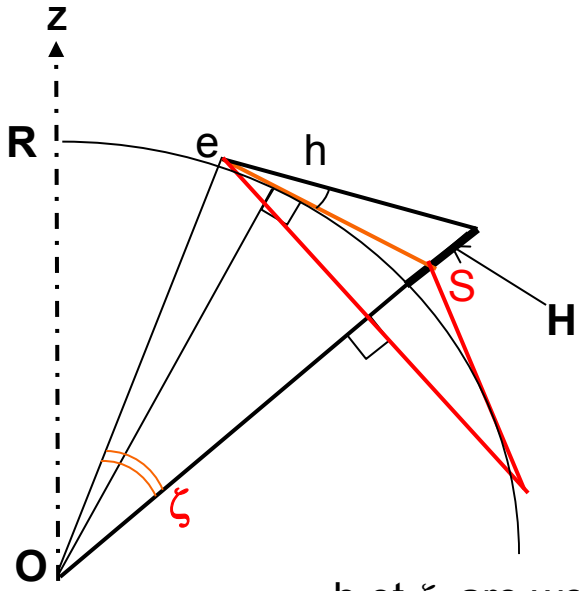


$$\Sigma = \overline{OS} = \frac{2 \cdot R_s}{1 + \dfrac{R_s^2 - r^2}{I^2}} \qquad \text{where } \mathbf{r = \rho + c.\tau}$$

ζ = zenith distance

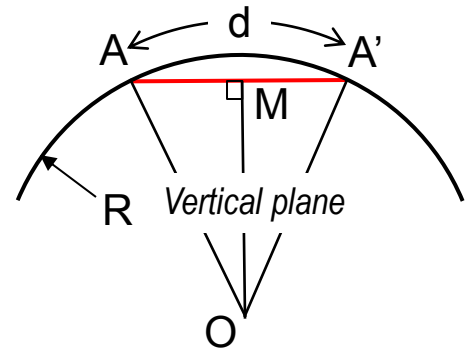
How to decline it with respect to the type of mark (2/2)

- **Case ③ with an isolated Landmark**
  - **measured variable: h**

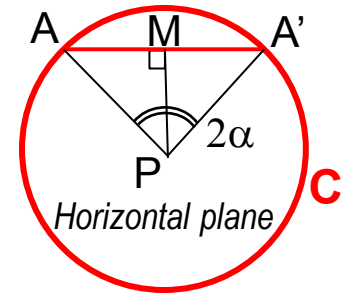


h et ζ are weak

- **Case ④ with a pair of Landmarks A, A'**
  - **measured variable: α**



M: middle point of AA'



$$\sin\zeta = \frac{d}{2} \cdot \frac{1}{\sin\alpha}$$

ζ weak except if α is weak also

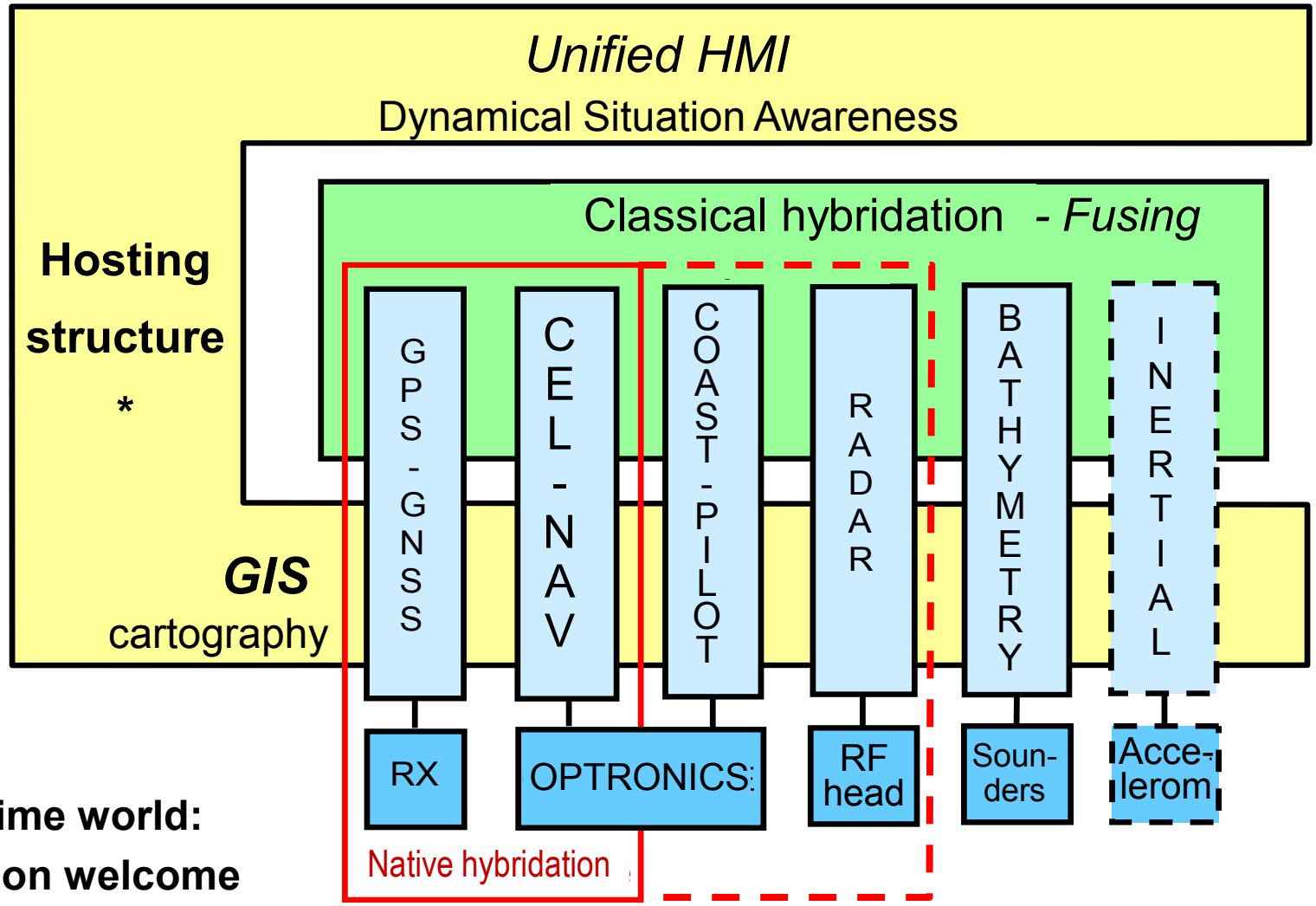
$\Sigma = 1 / \cos\zeta$

P is the center of the arc of **C** which subtends α

For P location computing return to case ①

ζ

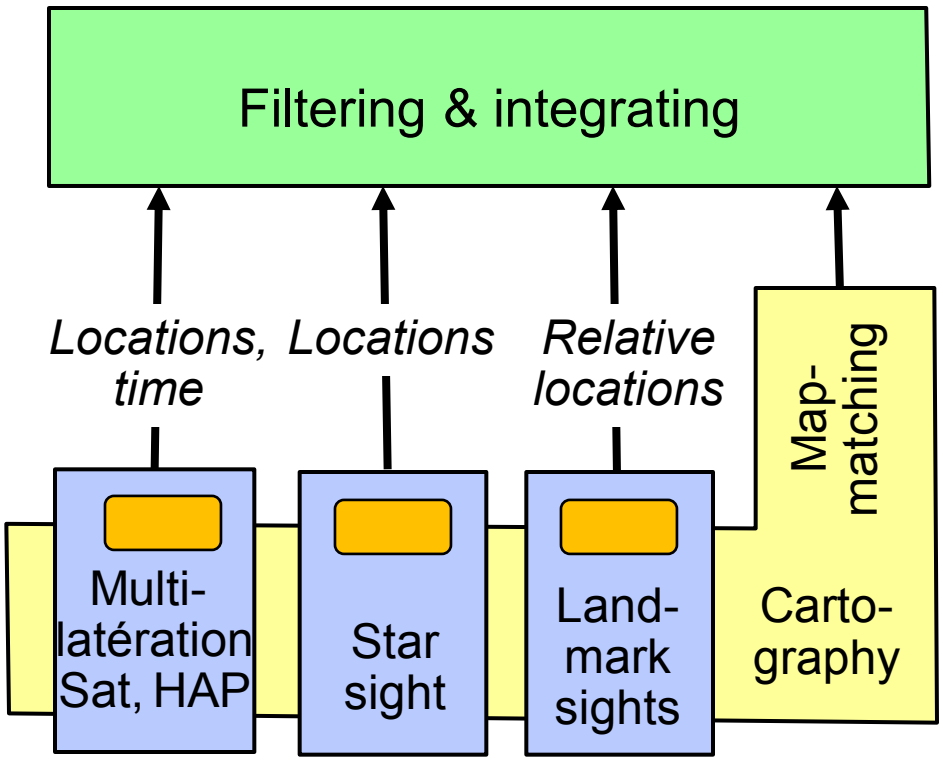
Principle of multi-sensor Hybrid Navigation



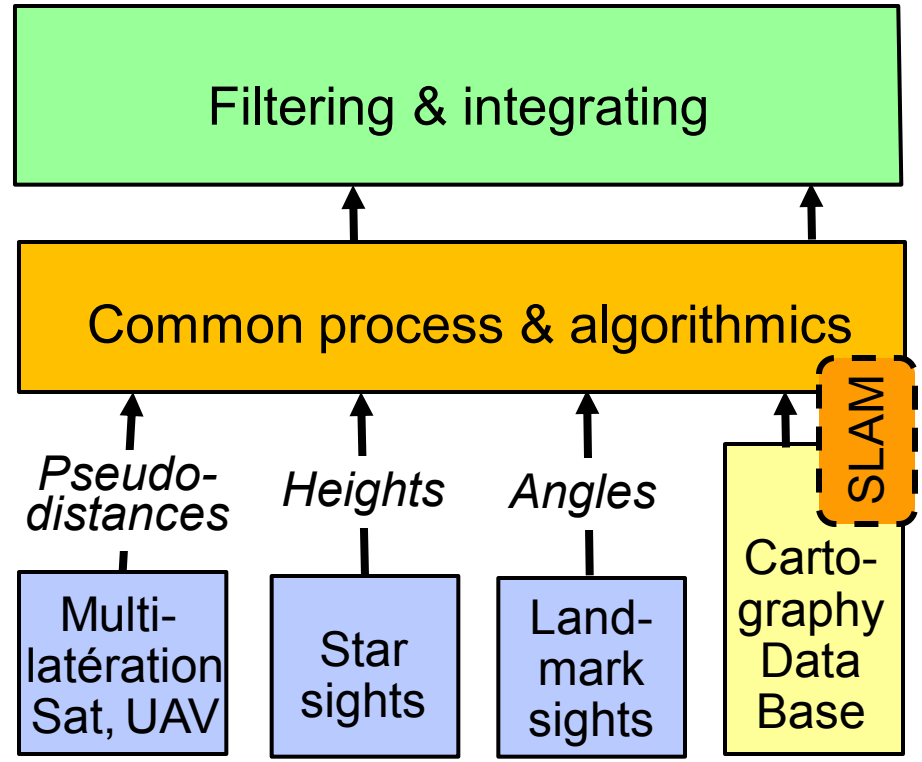
* In maritime world:
ECDIS station welcome

From loose coupling to tight coupling

- **Fusing pre-processed data or raw data (which is better)**



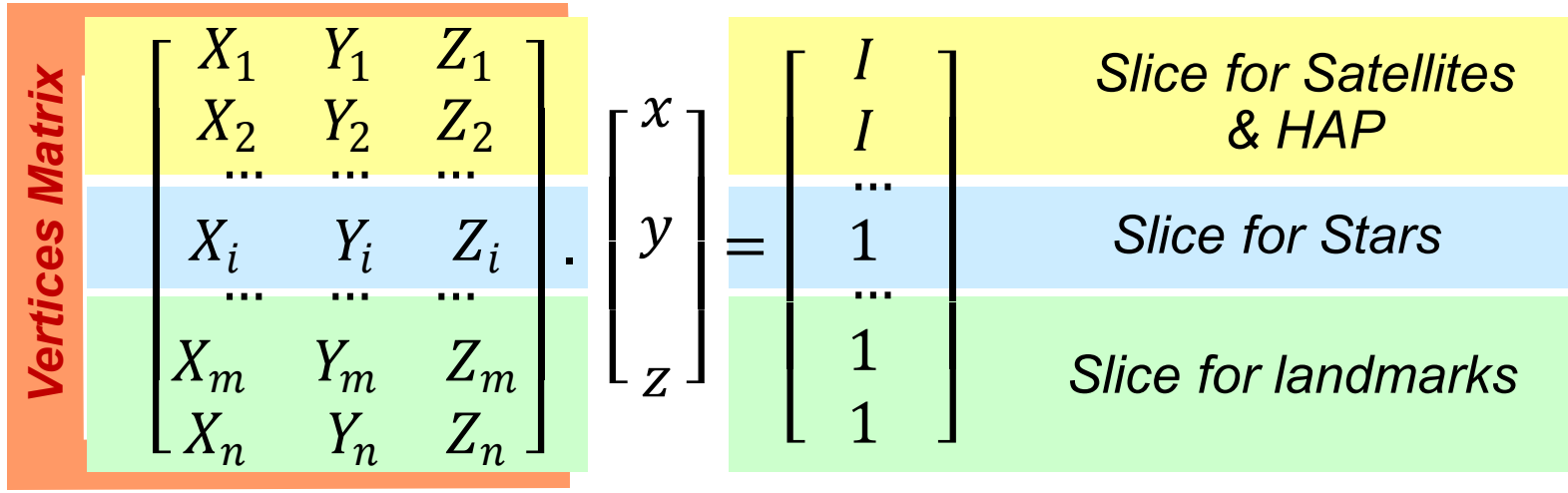
- **Loose coupling**



- **Tight coupling**

(SLAM = Simultaneous Localization & Mapping)

A single and polyvalent matrix equation using Vertices

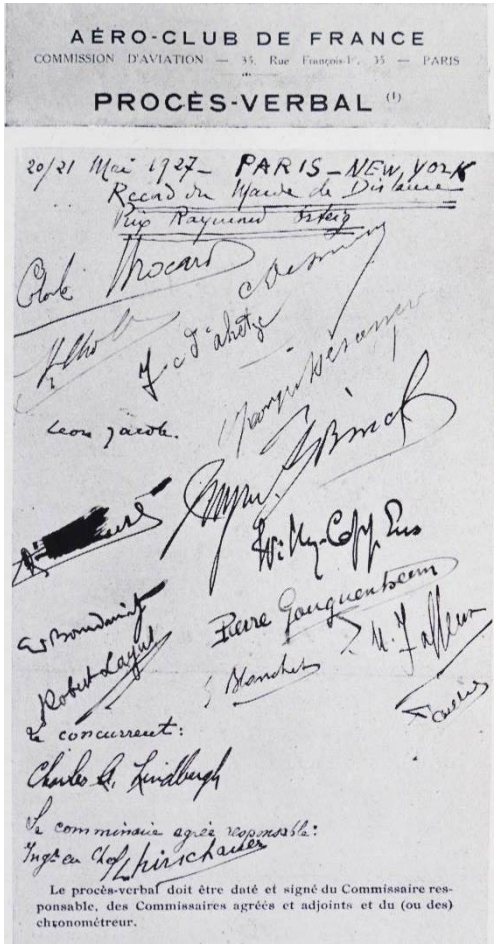


- **Size of Vertices matrix: n x 3**
  - 3D coordinates of n Vertices (including their Σ_k) are distributed according to lines
- **Without satellites (or HAP) ⇨ pseudo-inversing the Vertices matrix**
  - pseudo-inversing is equivalent to LMS solving
- **With satellites (or HAP): favor is set to horizontal (2D) coordinates**
  - Σ_k are parametrized with altitude I and time τ ⇨ iterative process is necessary
  - Solving through relaxation : pseudo-inversing once, I & τ matched at each iteration
    or incrementation : pseudo-inversing at each iteration

Minimum conditions about the number of marks

- Satellites only:
  - 4 for 3D location (aviation)
  - 3 for 2D location (on ground or at sea)
- Satellites + Stars (or planets):
  - 2 Satellites : i.e. the 2 GEO of new generation WAAS…
  - and 1 star : Sun, Moon or Venus
- Star and Landmark: 1 of each for a landing from high sea
- Satellites and Landmarks: sea straights and urban canyons
  - 2 Satellites + 2 Landmarks (or urban objects)
- Landmarks only:
  - 2 to 3 coastal landmarks
  - 3 urban objects

3 pages of Navigation history… for a canonic case



AÉRO-CLUB DE FRANCE

COMMISSION D'AVIATION — 35, Rue François-Ier, 35 — PARIS

PROCÈS-VERBAL (1)

20/21 Mai 1927 – PARIS – NEW YORK

Record de Vitesse

Le concurrent:

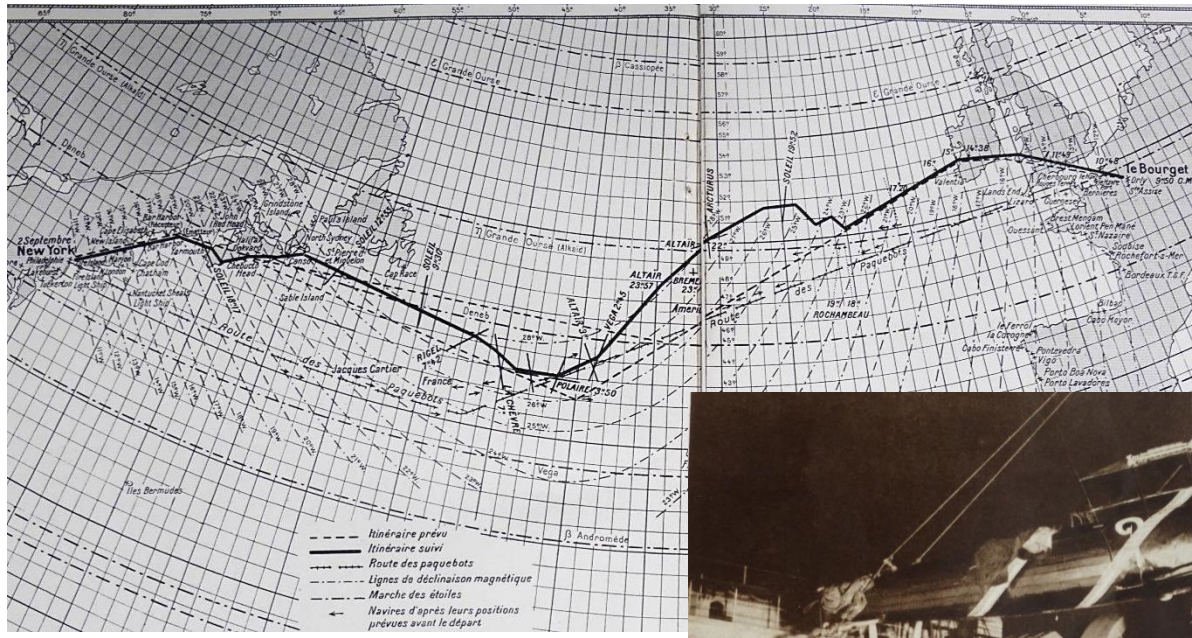
Charles A. Lindbergh

Le commissaire agréé responsable:

Ingénieur Col. Thirchaules

Le procès-verbal doit être daté et signé du Commissaire responsable, des Commissaires agréés et adjoints et du (ou des) chronométreur.

- French certificate to Lindbergh, 1927

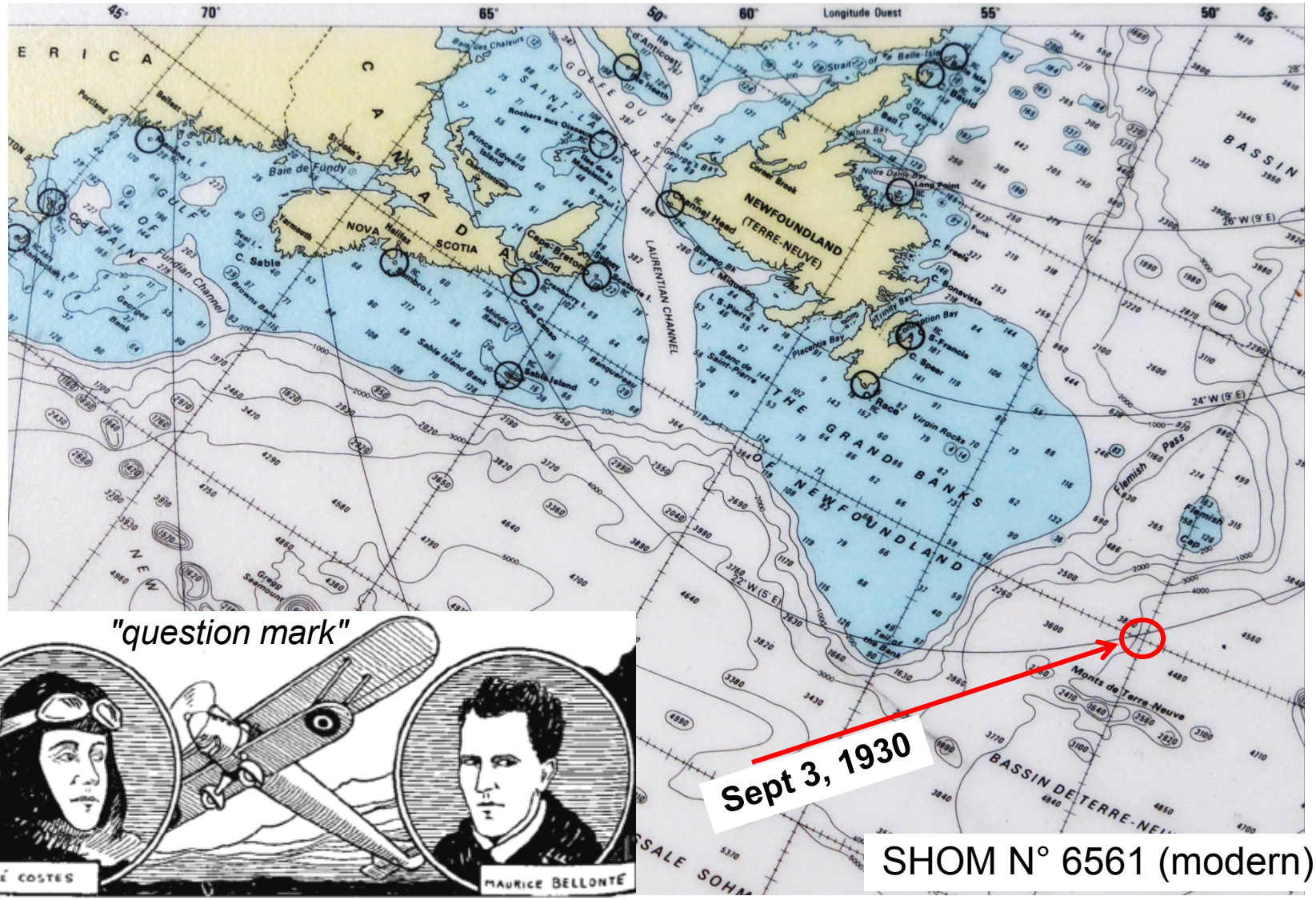


- Atlantic record of « ? » Paris- NY, Costes & Bellonte, Sept 1930

« ? » on board « Ile de France »

- « ? » to day, in Le Bourget Museum

Costes & Bellonte Paris-NY 1st crossing (1930)

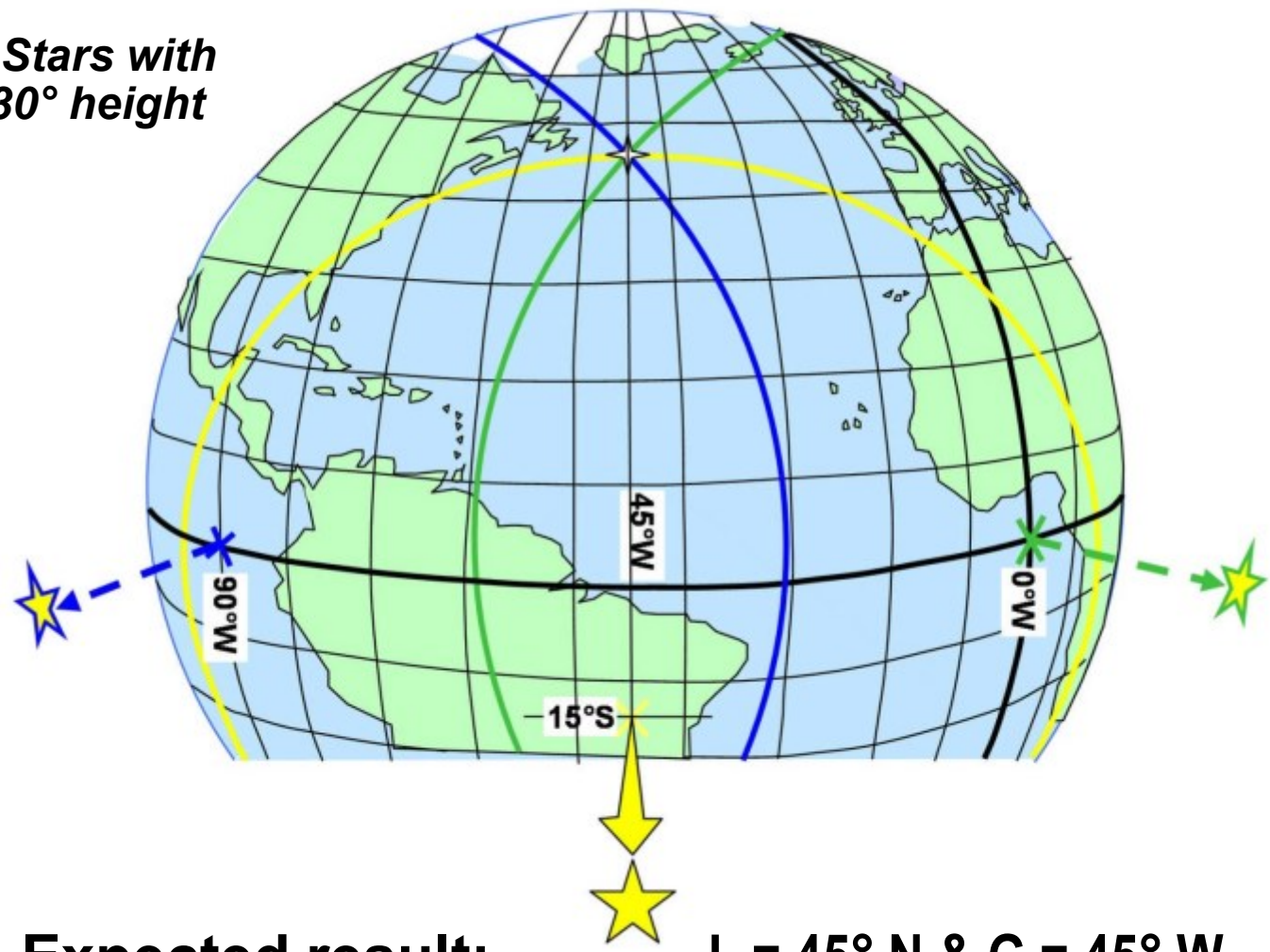


"question mark"

NAVECOM

Costes & Bellonte canonic case with 3 Stars

3 Stars with 30° height



- **Expected result:** **L = 45° N & G = 45° W**

Running ASTROLAB 3.1
(now an old package)

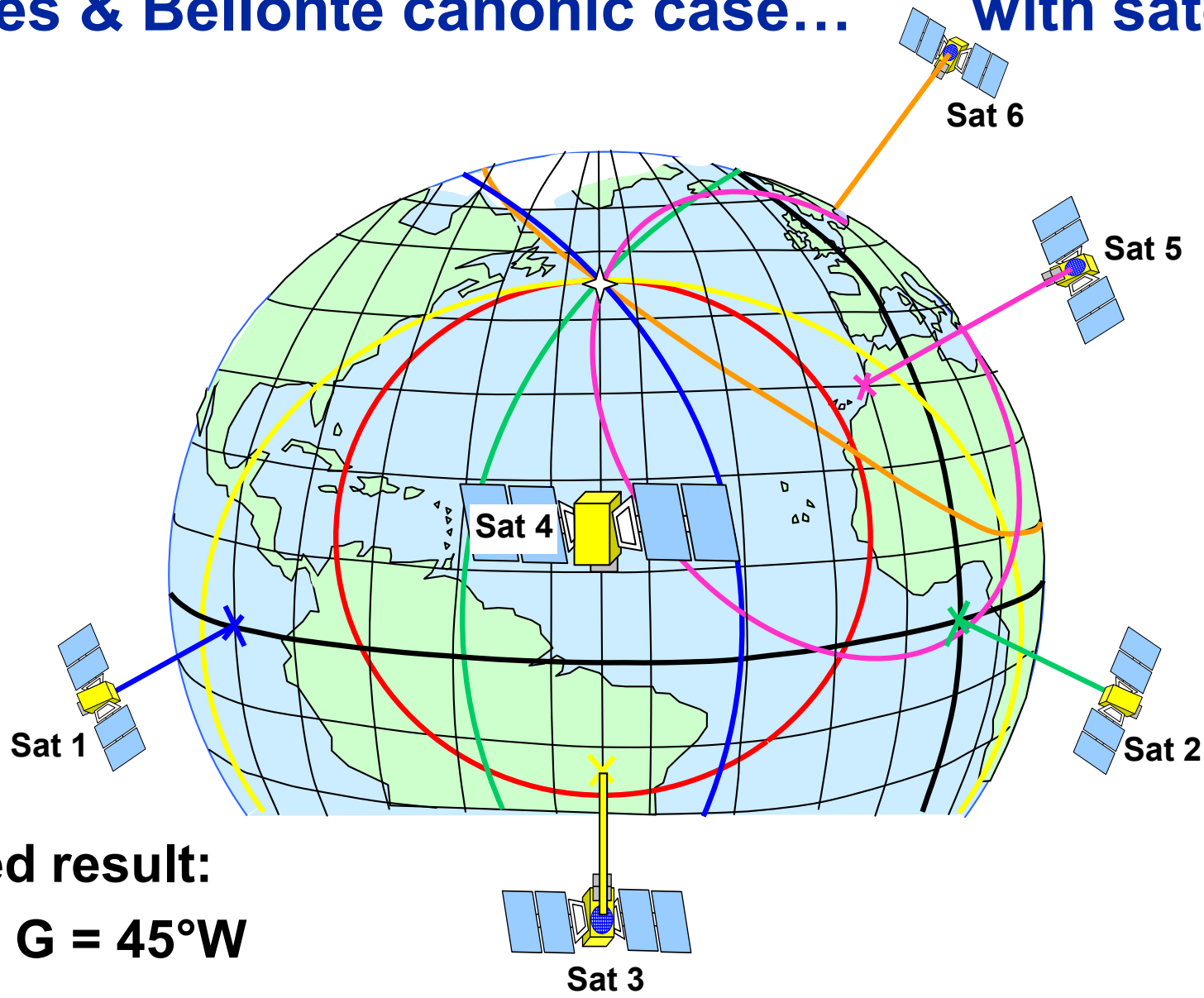
```
Programme de calcul du point - YRJ V5 du 12/07/11
************ METHODE DU PLAN DES SOMMETS ************
 Licence individuelle IM0-12 cédée par Y.ROBIN-JOUAN

Nbre observations= 99
Continuer ? (O/N, Oui par défaut)

N° d'observation choisie dans fichier (0 pour arrêter) ? 4
 2 / 9 / 30  à  5 h 0 mn 0 s
OBSERVATION N° 4 de AMER1
HAUTEUR CORRIGEE = 30.000 Deg déci
DECLINAISON =  +0.000 Deg déci
ANGL HOR GW =  +0.000 Deg déci
LONG ESTIM =  45° 0.0'W
LATI ESTIM =  45° 0.0'N

N° d'observation choisie dans fichier (0 pour arrêter) ? 5
 2 / 9 / 30  à  5 h 0 mn 0 s
OBSERVATION N° 5 de AMER2
HAUTEUR CORRIGEE = 30.000 Deg déci
DECLINAISON =  +0.000 Deg déci
ANGL HOR GW = +90.000 Deg déci
LONG ESTIM =  45° 0.0'W
LATI ESTIM =  45° 0.0'N

N° d'observation choisie dans fichier (0 pour arrêter) ? 6
 2 / 9 / 30  à  5 h 0 mn 0 s
OBSERVATION N° 6 de AMER3
HAUTEUR CORRIGEE = 30.000 Deg déci
DECLINAISON = -15.000 Deg déci
ANGL HOR GW = +45.000 Deg déci
LONG ESTIM =  45° 0.0'W
LATI ESTIM =  45° 0.0'N

N° d'observation choisie dans fichier (0 pour arrêter) ? 0_
```

.....

```
TRANSPORT PAR CAP+DIST entre OBS ? (O/N, Non par défaut)


DEBUT CALCUL
CAS GENERAL
DOP=  5.57

PREDICTION
ALTI =    -0.0 Naut
LATITUDE  = 45 °  0.0'N =  +45.000 Deg déci
LONGITUDE = 45 °  0.0'W =  +45.000 Deg déci

RESULTATS
LATITUDE  = 45 °  0.0'N =  +45.000 Deg déci
LONGITUDE = 45 °  0.0'W =  +45.000 Deg déci
ECART TYPE =   +0.00 Naut

FIN CALCUL

ECART POINT CALCULE A POINT ESTIME:
ECART =     0.00 Naut

ECRITURE POINT CALCULE DANS FICHIER ? (O/N, N par défaut)
```

Result as expected, sharply

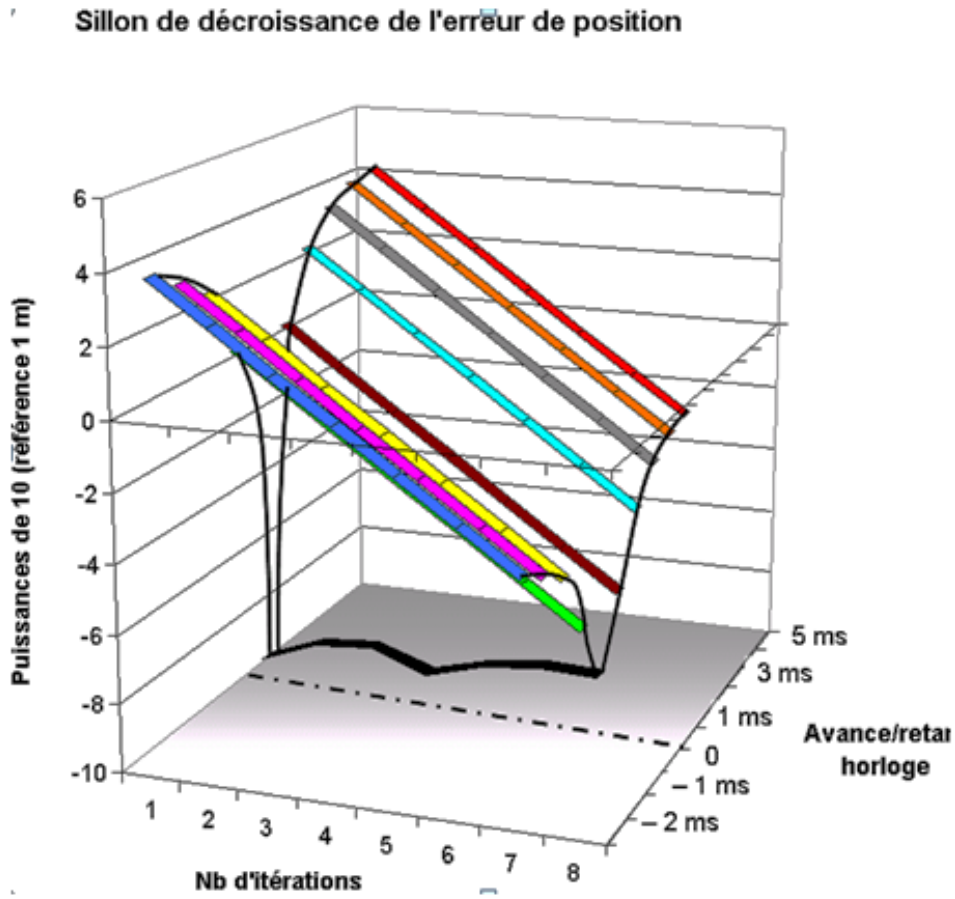
Costes & Bellonte canonic case… with satellites

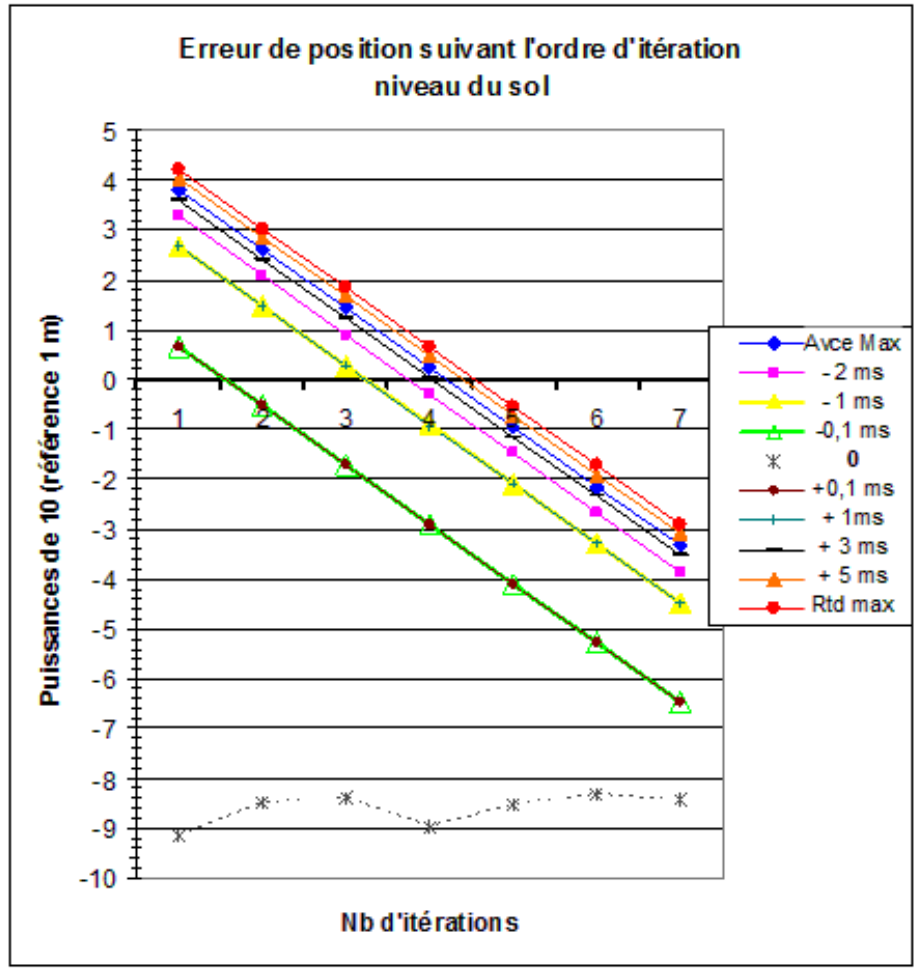


- **Expected result:**

L= 45°N & G = 45°W

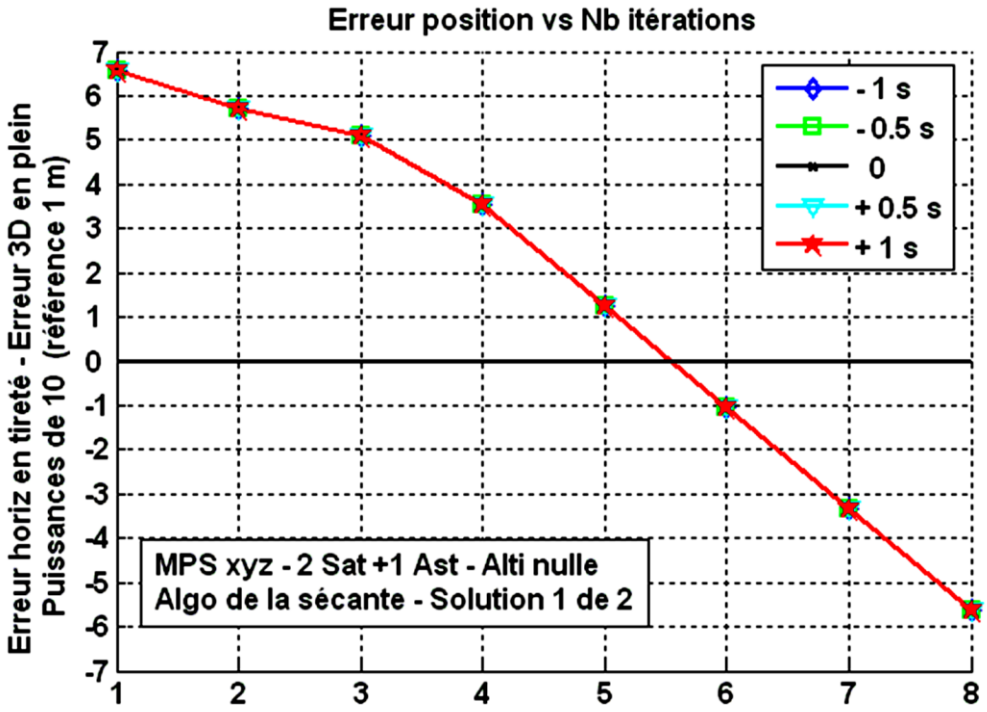
Costes & Bellonte results with 4 GPS satellites (time shift $\tau \neq 0$)



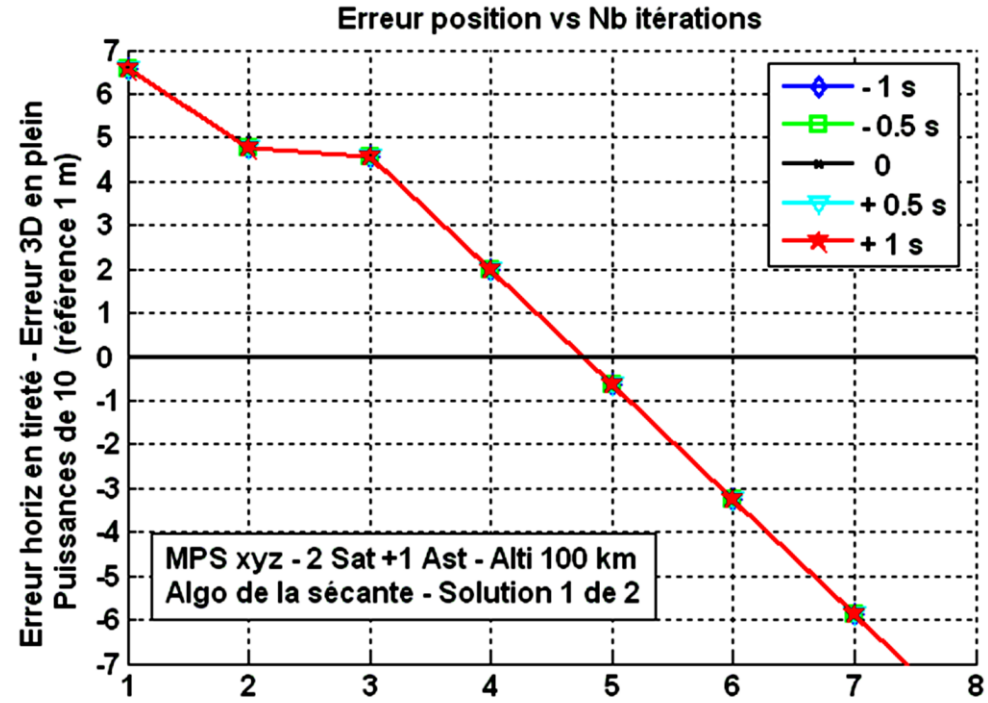


Solution via MPS running Matlab (2006)

Costes & Bellonte results when hybridizing 2 Sat + 1 Star



Low altitude condition



High altitude condition

τ as a parameter in secondes (curves are superimposed)

Solution via MPS running Matlab (2013)

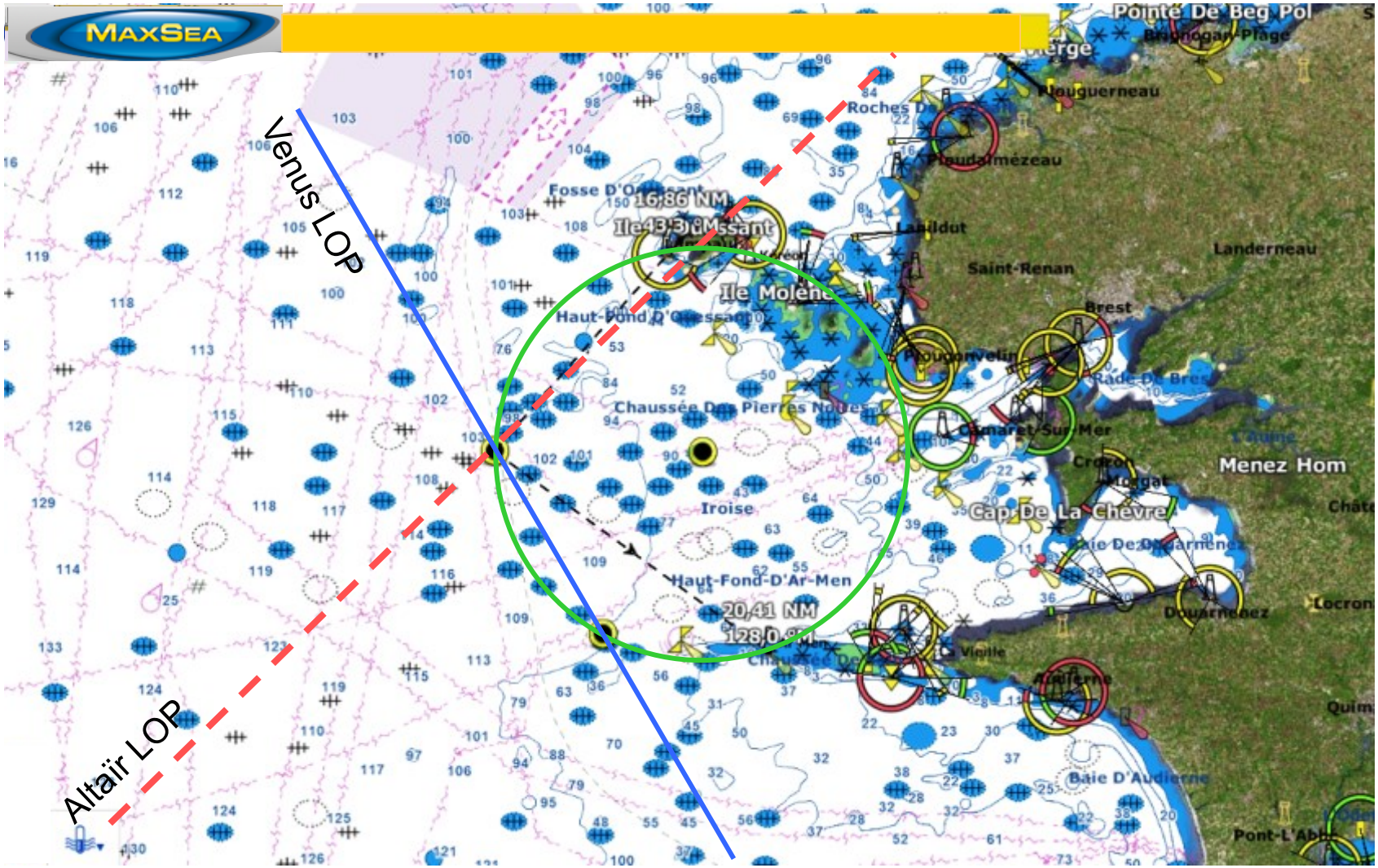
A pragmatic case of landfall in Iroise sea (Brittany)

- **Hybrid location based on 1 Star + a pair of Landmarks**
  - **Venus : Ho = 10° 53,8’ at 18:00 on September 22, 2016 *(as an example)***
  - **Aperture angle sight between Créach & Armen lighthouses: α = 84° 44,9’**
  - **Computation of ζ = 12,6’**
  - **ASTROLAB is run twice sequentially.**

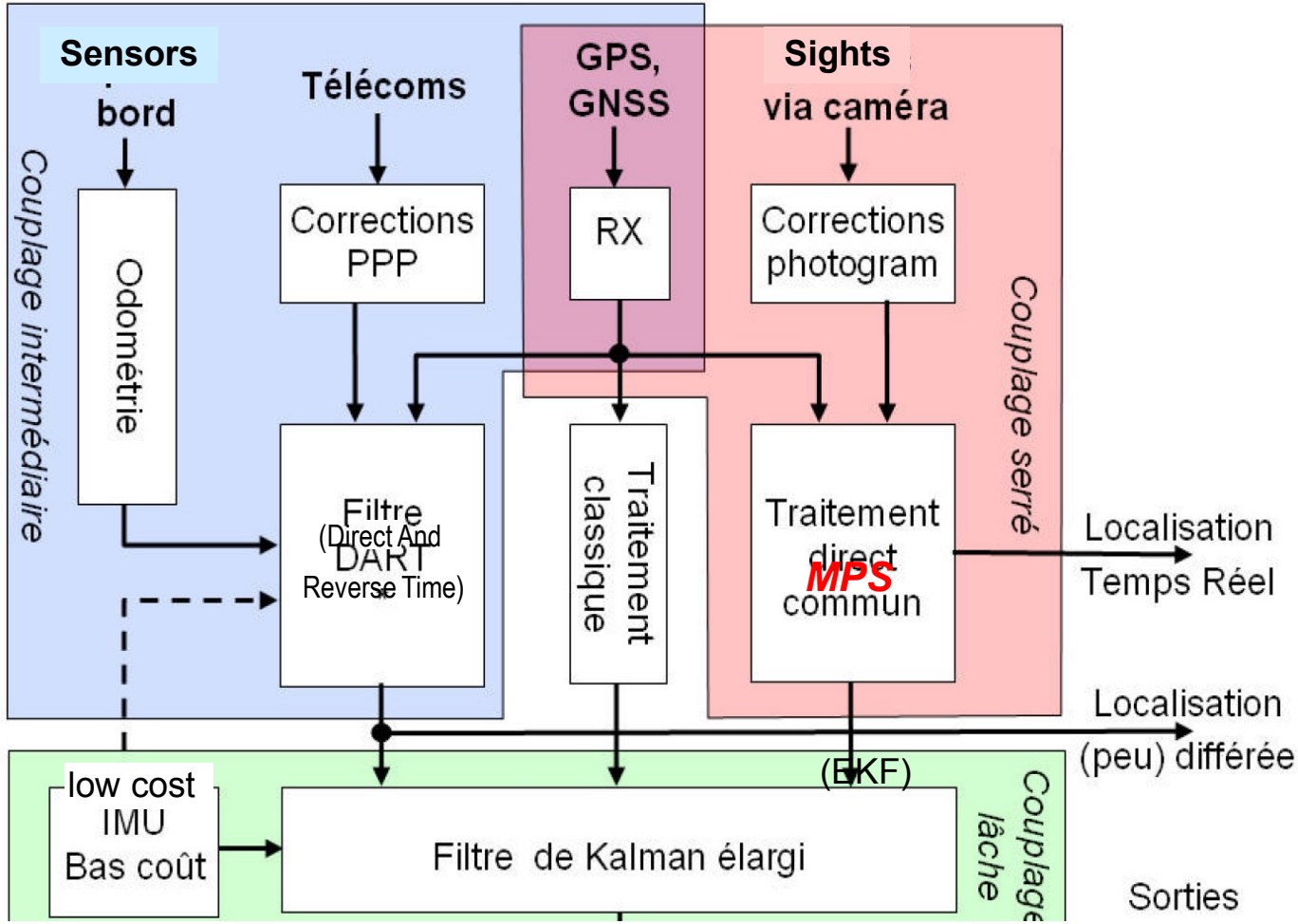
- **Result : 48° 15’ N 5° 24,5’ W, 34 NM W from "Goulet de Brest"**

- **There is an alternative solution close to W Sein buoy**

Landing in Iroise Sea: result put on a digital map



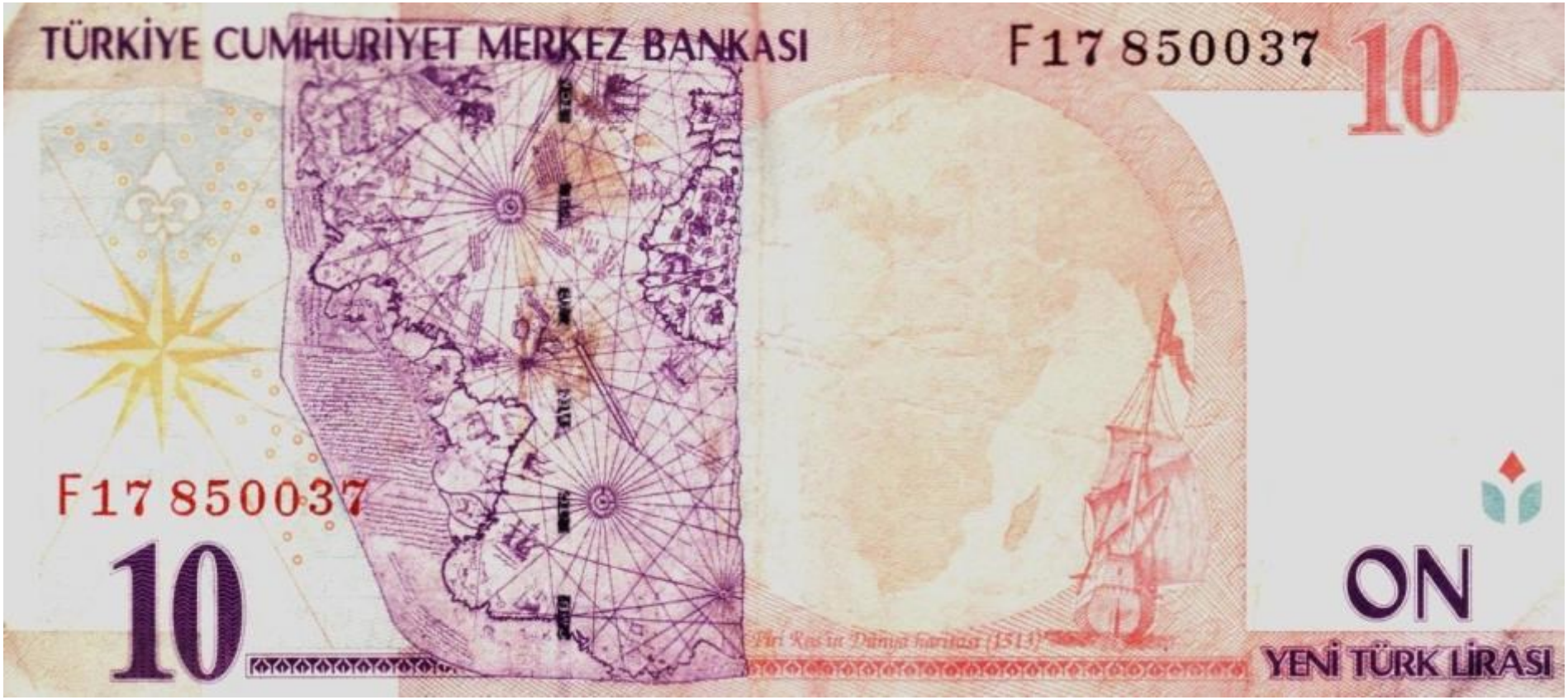
A project for Autonomous Vehicles in ITS framework



3 levels of coupling: tight + intermediate + loose (2016)

As a conclusion 1

- **Exemple of an impact of Navigation history into modern life:**
  Piri Reis Map (1513) on Turkish banknotes !

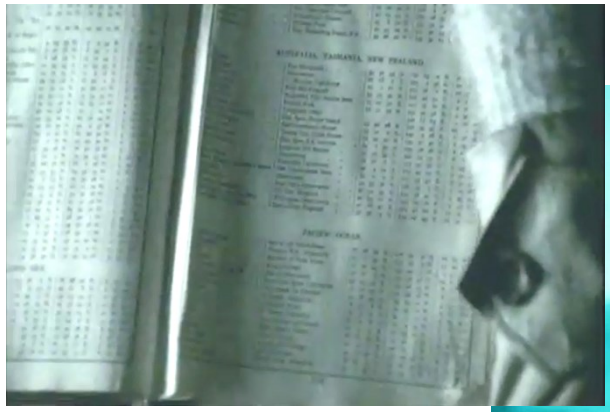


The lost part of Piri Reis map has been sketched on the right side

As a conclusion 2

- **From paper documents of F.Worsley & R.F.Scott, degraded by water…**

…to modern ruggedized tablets



On board J. Caird,
TV movie, 2012

"We had reached the naked soul of man"
Sir E. Shackleton
1916

Fieldbook® CZ80,
running Win or Androïd,
as an example

Bibliography References

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- « L'avenir de la navigation astronomique dans la Marine Marchande », prix Daveluy 2013, Loïc Barbot, Professeur à l'Ecole Nationale Supérieure Maritime
- "Hybrid Navigation using celestial bodies and landmarks with the Method of Coplanar Vertices", Y. Robin-Jouan, NAVIGATION IFN, Vol 64 n°252, May 2017
- « Navigation aux Astres et aux Satellites par la Méthode du Plan des Sommets » Y. Robin-Jouan, Marines Editions, Jan 2013, ISBN 978-35743-088-4

I recommend this good book !...

Montrer la complémentarité entre navigation astronomique et navigation par satellite – entre tradition et modernité – est l'objectif principal de cet ouvrage. Les deux filières traitent de la même problématique, l'une en 2 dimensions et l'autre en 4 dimensions. En pratique une méthode suffisamment puissante doit pouvoir traiter un même problème, en mode astronomique puis en mode satellitaire. Comment ensuite ne pas envisager une entraide des filières dans des circonstances difficiles ?

Dans une démarche unifiante, cet ouvrage reprend les bases classiques de la navigation, puis présente la méthode du plan des sommets, et son application aux astres comme aux satellites. Cette méthode est fondée sur des propriétés géométriques simples, auparavant inexploitées. Elle met à profit la cohérence et la dualité qui existent entre les deux filières de navigation, jusqu'à ébaucher leur intégration. Découpé en chapitres courts, l'ouvrage guide efficacement le lecteur dans l'historique et l'élaboration des méthodes de calcul.

Yves Robin-Jouan est un entrepreneur, inventeur à ses heures. Ingénieur de formation, il s'est impliqué dans de nombreuses réalisations technologiques, au sein de trois grands groupes industriels successifs. Il a publié des articles et dispensé des cours en navigation et en télécommunications. Il a fondé et dirige la société Navecom.

Le logiciel ASTROLAB v3 est fourni sur CD-ROM, pour laisser au lecteur, s'il le souhaite, le soin de reproduire certains exemples démonstratifs traités dans le texte.

Prix : 45 euros (TVA incluse)

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Yves ROBIN-JOUAN

Navigation aux Astres et aux Satellites

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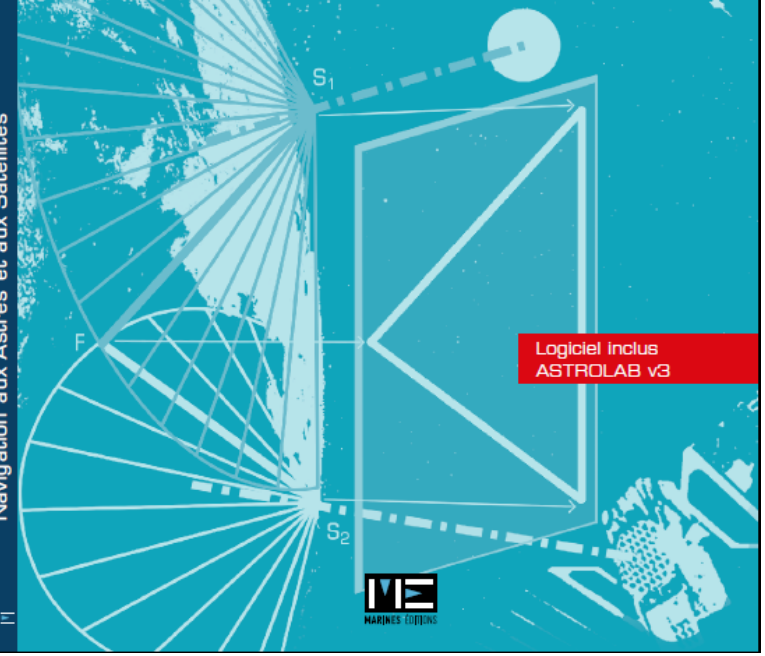
Navigation aux Astres et aux Satellites

PAR LA MÉTHODE DU PLAN DES SOMMETS



Logiciel inclus
ASTROLAB v3

MARINES EDITIONS

ASTROLAB for maximum SW portability

ASTROLAB v3.2 =
MPS for Celestial Navigation
and Coastal Navigation