

FFRF description and result synthesis

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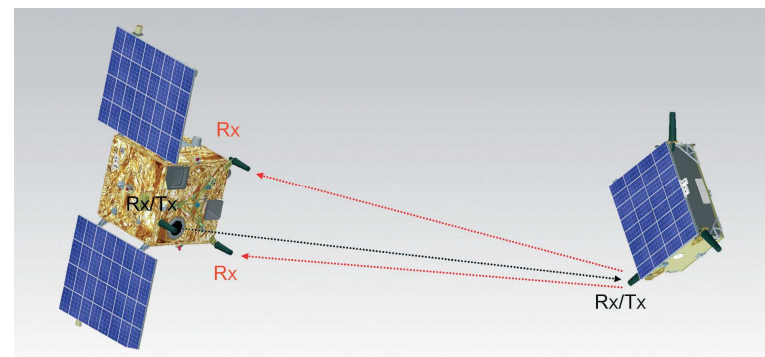
SUMMARY

- FFRF overview
- Position computation
- On-ground FFRF validation and calibration
- Flight result synthesis
- Conclusion

Used for autonomous relative navigation of a group of 2 to 4 satellites which are flying in formation

Services

- Intersatellite distance : 3 m - 30 km
- Omnidirectional coverage
- Distance/LOS fine performance: 1cm / 1°
- Synchronization of on-board times
- Intersatellite link : 4/12 kbps



Principle

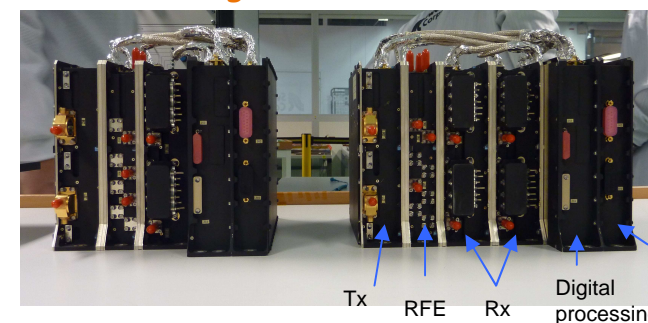
- One terminal (emitter/receiver) on each satellite
- Alternate emission (TDMA)
- Distance : half-sum of two pseudoranges
- Line of sight : differential measurement on antenna triplet
- Autocalibration loop for electrical bias correction

Signal

- GPS modulation in S-band (2.0-2.3 GHz)
- Dual frequency for carrier phase integer ambiguity resolution

FFRF Tango

FFRF Mango



Development history

- TRP ESA from 2002 to 2004, followed by R&T CNES in 2005
- FFRF on PRISMA : start of phase B in oct. 2005, phase CD in july 2006, FM delivery in oct. 2009

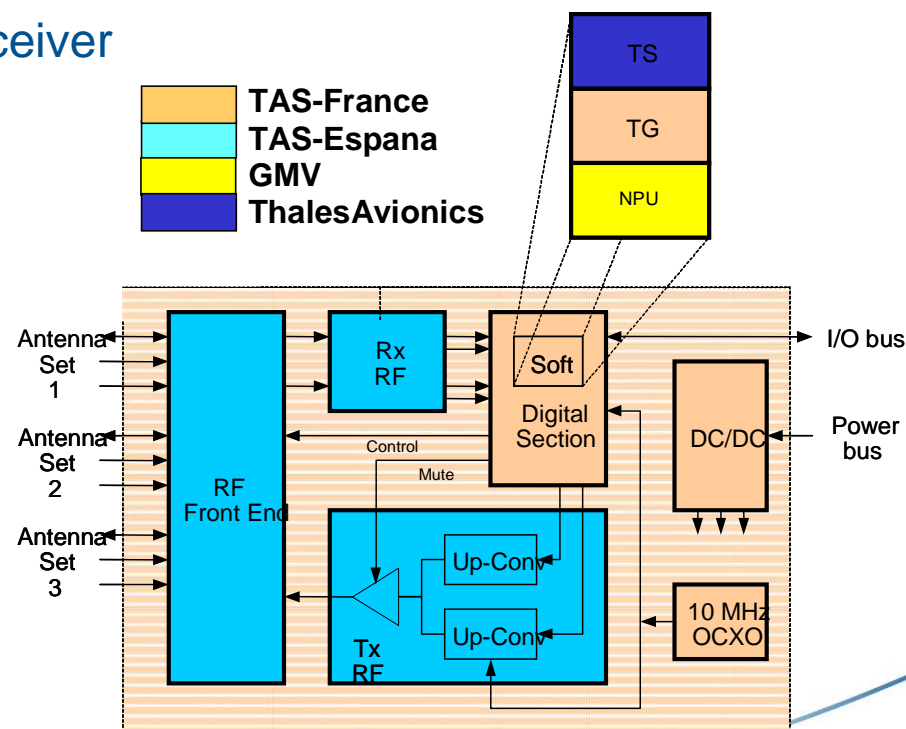
Equipment architecture

- Heritage from GPS TOPSTAR 3000 receiver
- New and complex architecture and SW

Development aleas

- RF module imperfection
 - ◆ Accepted because of planning constraints and limited impact on final performance

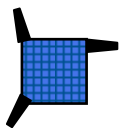
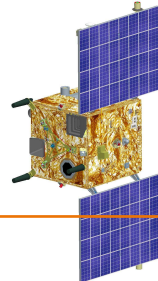
Organization



Position computation (1/2)

Two different PVT computations: coarse and fine mode

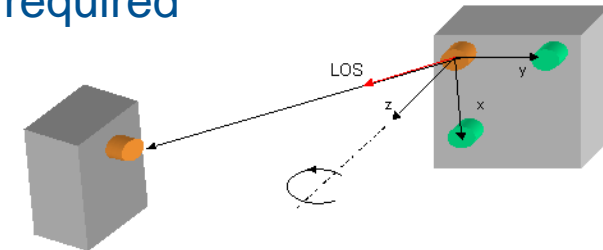
- Processing of raw measurements (code, carrier phase F1 and F2)

	Coarse mode	Fine mode
Distance	Computed from Code measurements	Computed from ambiguous carrier phase measurements
Line of sight	Computed from RF power signature over 4 antennas → Partly available on Tango 	Computed from path difference of carrier phase along 2 baselines of antennas (triplet) → Available on Mango 
Accuracy	1m, 45°	1cm, 1°
Availability	Instantaneous once signal has been acquired → 1min	Reached after a sequential process which raises carrier phase ambiguities → 19 min

Position computation (2/2)

Fine mode accuracy is based on carrier phase (CP) measurements which are initially ambiguous:

- Carrier phase differences are ambiguous modulo $\lambda \rightarrow \sim 15^\circ$ in LOS angle
- Distance CP is ambiguous modulo $\lambda/2 = 6.5\text{cm}$
- Carrier phase Integer Ambiguity Removal (IAR) is required
 - ◆ LOS: satellite rotation (50° -magnitude) is performed to solve the 2 CP differences ambiguities
 - ◆ Distance : performed through combining of filtered raw measurements (code, dual frequency CP measurements)
- IAR duration: 5 min for LOS + 13 min for distance



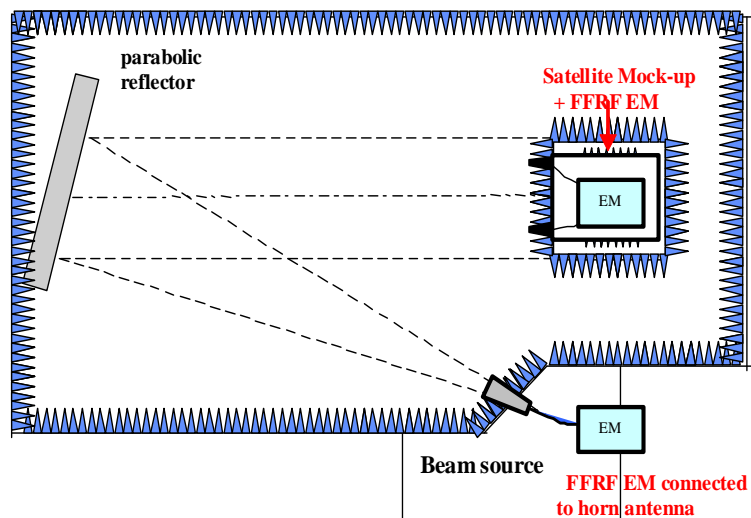
However IAR process is very sensitive to errors (electrical, multipath, antenna phase center modelization) \rightarrow results in biased final distance/LOS

Validation in conducted mode / static conditions performed by TAS on Engineering Model (EM) and Flight Model (FM)

- Calibration of Residual electrical bias + RF cable

Validation in radiated mode / pseudo-dynamic conditions performed by CNES on EM in anechoic chamber

- Characterize LOS IAR with rotation
- Characterize and cartography multi-path errors
- Determine antenna phase center locations



Target mock-up with FFRF EM



Mango mock-up

Flight experiment description

- FFRF functional behaviour and performance assessed through 55 (nominal mission) + 15 (extended mission) days of experiment
- In-flight experiments
 - ✦ Signal acquisition
 - ✦ Distance range
 - ✦ Intersatellite link
 - ✦ Line Of Sight and distance accuracy
 - ✦ Multipath calibration
- Performance assessed using GPS POD
 - ✦ GPS POD accuracy = ~1cm at best → very good for LOS characterization but limited for distance characterization
- **Overall good behaviour and performance of RF sensor**
 - ✦ A few anomalies happened (SW correction or “use as is”)
 - ✦ Mission objectives were fulfilled (all GNC experiments successfully performed)

Signal acquisition and distance range

- Acquisition time : less than 1 minute (typically 45 sec)
- Signal acquisition tested up to 22 km
- RF link not fully robust: a few acquisition failures or wrong acquisitions (aberrant distance) were observed
 - ◆ Solved by resetting the equipment
 - ◆ A mechanism of detection/correction of acquisition failures, which was lacking, has been identified
- Once signal is acquired, nominal behaviour between 3m and 30 km

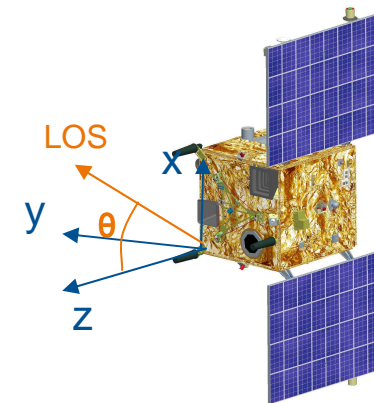
Intersatellite link

- BER is not compliant but this was expected following on-ground tests (RF module NC)
- No impact on FFIORD mission (sensor performance and Tango TM retrieval)

Rate	Distance	Estimated Bit Error Rate	BER spec.
4 kb/s	30 km	8e-6	1e-6
12 kb/s	500 m	<9e-8	1e-7

Line of Sight accuracy (1/2)

- Final accuracy depends on LOS IAR success
 - ◆ in case of IAR failure : error most of the time between $<20^\circ$
 - ◆ in case of IAR success : mean error $=0.9^\circ$ (worst case $=2.5^\circ$)
- Sources of IAR failure
 - ◆ Lateral movement of companion satellite
 - » Particularly impacting at short distances ($<250\text{m}$)
 - ◆ Direction of arrival of signal
 - » Increased failure rate for high elevations ($\theta > 25^\circ$)
- Identified solutions to improve robustness
 - ◆ Modify tuning of algorithm : increase rotation magnitude
 - » For failure configurations, increase from 50° to 100° results in success in 60% of cases
 - ◆ Improve IAR algorithm
 - » Study on-going with TAS
 - ◆ Define specific strategy for IAR
 - » Ex. Make first IAR, then align satellites and finally perform second IAR
 - ◆ Detection of failure by GNC



Line of Sight accuracy (2/2)

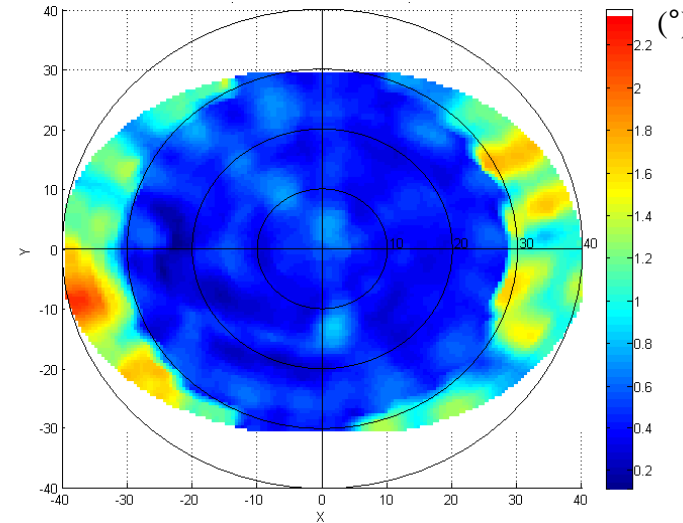
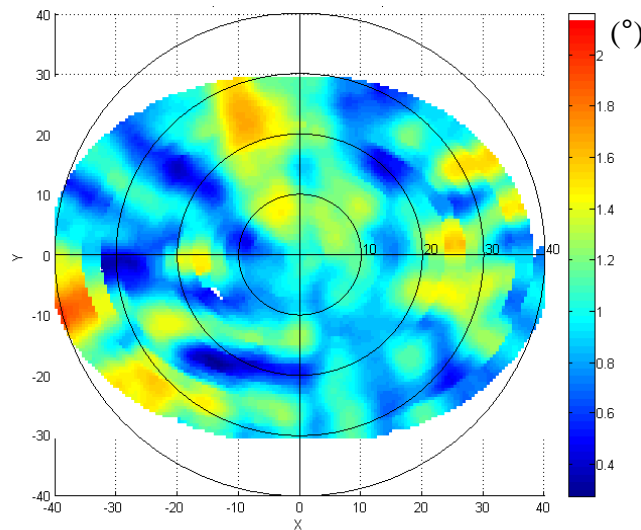
- Good accuracy but performance can still be improved by mitigating some error sources
 - ◆ Temperature variations
 - » Sensitivity of carrier phase differences to temperature
 - » Variation rate equal to approximately : 0.1°C
 - » Mango temperature range $[23\text{-}30^\circ\text{C}]$ → Slowly varying LOS error, almost 1° -LOS angle variation
 - ◆ Multipath error (spatially dependent)
 - » Characterized for elevations $<40^\circ$
 - » Std. Dev. of LOS angle error = 0.3°
 - » Quick spatial variations of multipath error: for a LOS variation of 3° , up to 1° of error on LOS
- Residual bias can be calibrated if necessary using reference data (ex: second stage metrology) or estimated by navigation filter (FFIORD)

Distance accuracy

- Absolute accuracy depends on distance IAR outcome:
 - » Typical absolute error < 10 cm
 - » Maximum absolute error of 1 meter (IAR failure)
- ✦ Impacted by two major sources of error
 - » Residual electrical bias on code distance: AGC correction tables do not correct properly
 - Residual error between +/-1m (depends on distance)
 - Potential origin: imperfect RF modules, on-ground calibration process
 - » Radiated error (Multipath + antenna)
 - Multipath: $\sigma = 4\text{mm}$ for carrier phase, $\sigma < 10\text{cm}$ for code measurement for $\theta < 40^\circ$
 - Error can be minimized by aligning FFRF antennas
- ✦ Other sources of error (temperature, ionospheric) less than 1 cm (GPS POD accuracy)
- ✦ Risk of IAR failure depends on formation geometry
- ✦ Calibration of biases is necessary for accurate absolute distance
 - » Requires reference measurement (POD)
 - Residual bias not critical for RDV or formation acquisition purposes
- Relative accuracy
 - ✦ Very accurate : $\sigma = 7\text{mm}$ for $\theta < 40^\circ$

In-flight multipath calibration

- GPS used as reference + averaging of measurements to remove other errors
- Unreliable distance multipath mapping because of POD insufficient accuracy
- LOS error : magnitude is between $[0.4-2.0]$ for elevation up to 40°
- Correction tables are uploaded for real time correction
- After correction, LOS error is divided by two



- Comparison with on-ground calibration (for LOS)
 - ◆ Same magnitude of error but different values
 - ◆ Explanations: limited representativity of mock-ups, inaccuracy of on-ground test means
- Performance without multipath characterization is sufficient for RDV purposes

Conclusion

Equipment was exhaustively tested over a wide range of configurations

- Test in flight conditions (geometry, satellite) was essential for complete validation and performance assessment (calibration)

Good functional behaviour and performance of FFRF sensor

- All GNC experiments could be successfully performed
- Identified weakness : lack of robustness of initialization process (acquisition and LOS IAR) → can be corrected by algorithm improvement

To reach the mission objective of 1 cm / 1°

- Fine calibration of distance biases
 - ◆ Internal electrical bias → RF module rework + improvement of on-ground calibration
 - ◆ Residual bias → in-flight calibration is required using GPS
- Mitigation of sensitivity to multipath and temperature variations
 - ◆ Rework of RF modules may limit temperature sensitivity. Otherwise temperature calibration or limitation of temperature range
 - ◆ Antenna accommodation to limit multipath errors