Challenges of remote sensing for hydrology: the SMOS and SWOT missions

Selma CHERCHALI
Land and Hydrology Program Manager
CNES – Science, Applications and Innovation Directorate

Ahmad Al Bitar
CESBIO, Toulouse, France
• Introduction
  ✦ The new challenges
  ✦ Space context

• The SWOT mission

• The SMOS mission
Introduction

The new challenges

- What climate shall we have tomorrow?
  - Increases in global sea and air temperatures
  - Widespread melting of snow and ice
  - Rising global sea level

- Global changes - Climate change & increased demand on water resources - are shaping the challenges associated to hydrology that humanity needs to tackle in the next century:
  - food security / flood mitigation / water quality

- How to improve our models at global scale to quantify the changes?
  - What are the observation and accuracy needs for global water cycle & energy budget research?
    - From continental to global scales to augment climate networks

- How to predict at a finer scale to mitigate the impacts (IPCC Report 4)?
  - What are the accuracy needs for water management for flood prediction, reservoir operation, agriculture and drought assessment?
    - Solve regional problems and acquire real-time data to augment operational networks

⇒ There is need to spatialize and to refine the current scale of perception
  - Observations at high spatial and temporal scales
There is still need to understand the processes that govern the production and distribution of water in the compartments of the Earth surface and to evaluating the impact of human activities on them.

What are the data needs and with which distribution scheme?

» programs addressing hydrology and water (GEOS, HYMEX, H2020…) are expecting space-based observations to provide needed observations of sufficient accuracy for water resource applications (Essential Climate Variables, Climate Change Initiative).

How to address the socio-economic benefits?

» Consider end-users requirements
» Benefits of Earth observations applications to decision making
» Develop services
Water balance components

\[
\frac{dS_{SM}}{dt} + \frac{dS_{SW}}{dt} + \frac{dS_{GW}}{dt} = P - E - Q
\]

- Soil moisture
- Surface water
- Ground water
- Precipitation
- Evapotranspiration
- Energy budget
- Discharge
Space measurements for water cycle

\[
\frac{dS_{SM}}{dt} + \frac{dS_{SW}}{dt} + \frac{dS_{GW}}{dt} = P - E - Q
\]

Not all components are observed at the desired resolution and accuracy.
The « revolution » in space missions for hydrology

Increase in accuracy (more adapted spectral bands)
example of soil moisture:
*from* AMSR-E (C-Band) *to* SMOS (L-Band)

Increase in spatial resolution
example of altimetry:
*from* Jason (kilometric) *to* SWOT (100m)

Increase in temporal resolution
example of visible:
*from* SPOT5-6 (local) *to* Sentinel 2 (5 days)

Increase in accessibility of data
Vast majority (S2,3, SMOS, LandSat) are *freelly accessible*

The SWOT and SMOS missions that we present here pertain to the newest generation of sensors.
The SWOT mission

A wide swath altimeter for observing Surface Water and Ocean Topography
SWOT - MISSION GOALS

● Science Goals
- study hydrological processes by determining the storage and discharge rate of water on land.
- study the oceanic mesoscale and submesoscale processes that determine the kinetic energy of ocean circulation and its transport of water properties.

● Societal Benefits
Address two key issues facing a warming planet:
- the variability of fresh water resources.
- the capacity of ocean circulation in regulating the rate of warming.

● Technology Goal
Set the standard for future operational altimetry missions.
The SWOT mission is a partnership between the hydrology and oceanography scientific communities.

Partnered mission: NASA / CNES / CSA / UKSA

Ka-band SAR interferometric (KaRIn) system with 2 swaths, 50 km each

Jason-class altimeter for nadir coverage,
Radiometer for wet-tropospheric delay
GPS/DORIS/LRA for POD

Science mission duration of 3 years
Calibration orbit: 857 km, 77.6° Incl., 1 day repeat
Science orbit: 891 km, 77.6° Incl., 21 day repeat

Target Launch Readiness: Apr. 2021
SWOT mission will address challenges and shortcomings of conventional altimetry (e.g., spatial coverage and resolution) in both oceanographic and hydrologic applications and will enable a wide range of research opportunities in oceanography and land hydrology.
SWOT – Requirements rivers

- Inundated Area/River Width:
  - 15% error for 100 m wide rivers over 10 km reach (baseline)
  - 15% error for 170 m wide rivers over 10 km reach (threshold)

- Water surface elevation/height:
  - 10 cm error for 1 km² area and 25 cm error for between (250 m)² and 1 km² (baseline)
  - 11 cm error for 1 km² area (threshold)

- Water surface slope:
  - 10 μrad error for 100 m wide river over 10 km (baseline)*
  - 20 μrad error for 100 m wide river over 10 km (threshold)*

*Nominal

From Allen et al., in press, GRL
SWOT Mission Requirements lakes

Inundated Area:
- 15% accuracy for lakes larger than (250 m)$^2$ (baseline)
- 15% accuracy for lakes larger than 1 km$^2$ (threshold)

- Lake Water Surface Height:
  - 10 cm accuracy for lakes larger than 1 km$^2$ and 25 cm accuracy for lakes between 1 km$^2$ and (250m)$^2$ (baseline)
  - 11 cm accuracy for lakes larger than 1 km$^2$ (threshold)
KaRIn will generate about 7Tb of data per day, which will be processed on ground to generate the following products:

- **Level 0**: Instrument Telemetry
- **Level 1**: Sensor data.
  - SWOT Low Resolution (Ocean Data) – OBP partial interferograms.
  - SWOT High Resolution (Land data) – full resolution complex interferograms in radar coordinates, phase flattened. (Images are internal product)
- **Level 2**: Users level.
  - SWOT Low Resolution (Ocean Data): Swath of sea surface height, slope, height uncertainty and backscatter
  - **SWOT High Resolution (Land data)**: Geolocated water mask with Surface Water height, slopes with uncertainties,
  - **SWOT High Resolution Enhanced**: Discharge on river database, flood plain on long-term data collection
Outreach: Inform the stakeholders about the SWOT capabilities (website, workshop), develop communication strategies to target and support requirements of the user community etc…

The improvement of the existing applications
- Sea transport shipping, fisheries, prediction of ENSO, forecast of extreme events (cyclones, storms) and the monitoring of climatic parameters

Innovative applications for coastal areas
- In particular for coastal management and off shore resource exploitation mining, oil continental shelves

The creation of new environmental services
- For inland waters (lakes, reservoirs, major rivers) at global scale to leverage opportunities for water resources management, estuaries, the risk prevention of flood, the prevention of the propagation of epidemics

An open data policy
- This will strengthen the existing services for oceanography and create new services in for water resources
The “French” SWOT application program support

**Hydrology**

- Storage of water in lake, river and wetlands
- Variation in the water storage
- Rivers Discharge estimation

**Oceanography**

- Coastal currents
- Representation of eddies at mesoscale
- Global ocean altimetry at high resolution

**Potential applications**

1. Transboundary rivers management (international & interregional)
2. A better modelling of flood
3. Clear water management for urban, industrial and agricultural sectors
4. Hydroelectricity production management
5. Prevention of the propagation of epidemics
6. Fluvial navigation support
7. Climate and weather forecast with better accuracy
8. Marine operations
9. Fisheries
10. Aide aux plateformes pétrolières
SWOT-Aval – pushing forward the SWOT applications

A multi-sensor approach to support high-end applications from SWOT

SMOS/SMAP

GPM/ MGT

JS3/S3/S6

S2/LDCM/S1…

Dynamic wetlands surfaces and volumes (credits Cesbio / Legos)

A multi-sensor flood prediction system for the Niger Basin (credits: GET)

Lac Poyang water balance (credits: Sertit)

A priori-discharge db based on SWOT simulator (credits: Legos/UFRGS)
The SMOS mission

A 2D interferometric L-Band radiometer for Soil Moisture and Ocean Salinity
SMOS mission fact sheet

- An **ESA earth explorer** mission with the contributions of **CNES** and **CDTI**
- Main products are **Soil Moisture (0-5cm)** and Sea Surface Salinity
- An **L-band (1.4Ghz)** passive instrument
- **2D Interferometric** radiometer (std: 2.4 k)
- **Full polarimetric** acquisitions
- **Multi-angular** acquisitions (0° - 60°+)
- **3 days global coverage** at 6 am and 6 pm
- Spatial resolution (**27 -55 km**)
- RFI mitigation at ground segment
- Operational since **Nov. 2009**

- Similar missions SMAP (NASA) operational since 2015
The CATDS SMOS center

A data production center & two scientific centers for SMOS high-end Level 3 & 4 products from CNES.

CATDS data over land:
- Multi-temporal retrievals of surface soil moisture (0-5cm)
- Root zone soil moisture and Drought monitoring
- Dynamic Wetlands maps
- High resolution products using optical and radar sensors

Applications to Drought / flood monitoring and interdisciplinary sciences
Root zone soil moisture is a very useful information to access agricultural drought in an early warning system.

At CESBIO SMOS surface soil moisture and MODIS LAI are assimilated into a double bucket model to compute root zone soil moisture. (Al Bitar et al. 2013, Kerr et al. 2016)
SMOS monitoring 5 major droughts in 2015

- CA, USA Sept. 2015
- Brazil May 2015
- South Africa April 2015
- India Oct. 2015
- Australia June 2015

Root zone soil moisture

- Drought index: moderat, mild, extrem

ahmad.albitar@cesbio.cnes.fr
Droughts preceding the Canada fires were well depicted in SMOS drought index.
Reaching sub-kilometric Soil Moisture resolutions

A kilometric resolution is essential for many hydrological applications. SMOS resolution is enhanced by merging it with data from other sensors.

SMOS & optical sensors

- Muren Bidge basin Australia
- Kabini Basin, Karnataka, India

SMOS & C-Band radar

- 25 km
- 1 km

(Merlin et al. 2012) (Molero et al., RSE, 2016) (Tomer et al., RS, 2015, 2016) sat@aapahinnovations.com
SMOS Flood Risk Forecast

Methodology

Leveraging inundation risk based on SMOS soil moisture prior knowledge

Rainfall forecast → Rainfall probabilities → Precipitation Flood Risk → Precipitation Inundation risk → Flood Risk (Precip + SMOS) → SMOS Inundation Risk

Soil Moisture quantile for prob. of 0.95 for all dataset

Al Bitar A., Chone A., S. K. Tomer, CESBIO
SMOS Flood Risk Forecast

Results

- Compare with the Dartmouth Flood Observatory
- Dartmouth magnitude of the flood against the Precipitation inundation risk and the SMOS inundation risk.

Results show that the Precipitation Inundation risk is underperforming.
But also that the use of SMOS globally enhances the risk product except in A

Al Bitar A., Chone A., CESBIO.
Operational implementation
by CapGemini and CESBIO

SMOS flood risk 07 Oct. 2014 at 12h45 for the next 5 days

Storm risk by NOAA 07 Oct. 2014 at 12h45
Monitoring of wetlands in Tropical basins

(Parrrens et al. 2015, Al Bitar et al. 2015
CNES TOSCA-SOLE)
SMOS - Monitoring drought in Tropical regions

The 2010 South-Amazon drought

Clim. Water. Index

Anomaly of water fraction
Jul. – Sept. 2010

Current impact of ENSO

Anomaly of water fraction
Oct. – Dec. 2015

water deficit
from Lewis et al. (Science 2011)

anomaly of SMOS water fraction

abnormaly dry abnormaly wet
Impact of ENSO on hydrological dynamics

Time-lag between SMOS water fraction & TRMM rainfall

- All years
- Normal years
- ENSO years

Time-lag between SMOS water fraction & in-situ discharge at outlet

- All years
- Normal years
- ENSO years
Conclusions
The future of Hydrology... a strategy for integrated observations

- Integrating observations (CATDS, SWOT aval, ....)  
  - to establish a more complete system description

- Integrating model components  
  - to build an earth modeling system

- Integrating research results  
  - to establish end-user solutions

- Data Integration  
  - to allow for spatial and temporal rectification and to allow for the intercomparison and quality evaluation of different models and observation data

- Data-Model Integration  
  - to constrain data and its errors by physical processes using four dimensional data assimilation techniques

- Solution Integration  
  - to develop water cycle solutions by integrating observations into applications
The hydrological sciences community is making it’s mutation, as the atmospheric and ocean silences did before, by moving to global multi-model and multi-sensors integrated modeling and assimilation systems.

But this comes with specific challenges that need to be addressed like the complexity of the observed systems (spatial heterogeneity and temporal dynamics), and the impact of anthropogenic activities.

CNES is supporting this dynamic by contributing to innovative missions including the SWOT and the SMOS missions.
Thank you
Extra slides
SMOS

Enhancing Rainfall products
LTHE
Estimated SSM without SMOS assimilation

Motivation:

using TRMM-3B42

Ground measurements (5 cm)
SSM estimates from TRMM-3B42
Rainfall : 624 mm

using CMORPH

Ground measurements (5 cm)
SSM estimates from CMORPH
Rainfall : 2466 mm

Estimated SSM with SMOS assimilation

Results:

Using TRMM-3B42

BENIN-2010, $R^2:0.79$, eff: 0.8, rms: 3.7%

- Ground measurements (5cm)
- SSM estimates from TRMM-3B42
- Rainfall: 2411 mm

Using CMORPH

BENIN-2010, $R^2:0.80$, eff: 0.7, rms: 3.7%

- Ground measurements (5cm)
- SSM estimates from CMORPH
- Rainfall: 2629 mm

From surface to root zone SM using SMOS data

- SMOS daily Surface soil moisture
- Layer 1 model soil model
  - First Layer (5-18 cm)
  - Layer 2 model soil model
    - Second layer (20 - 120 cm)
    - Drought probabilities
    - Root zone probabilities
    - Drought probabilities
    - Drought index

Climate data
EO LAI
(RZSM – 1st May 2016)

SMOS Drought Index – 30 August 2011

(Al Bitar et al., 2013)
Irrigation signal in the SMOS root zone soil moisture
Drought in the horn of Africa

SMOS Drought Index

AVHRR NDVI

Al Bitar, CESBIO
Space measurements for the water cycle

- Precipitation, Energy
- Land Surface
  - Soil moisture
  - Water Surface
  - hydro network, water storage, Discharge, Evapotranspiration
  - Radar and passive microwaves
- Ground water
- Aquifers

Vis, NIR, TIR, Radar
Gravimetry

Direct or indirect measurements
SWOT KARIN main products for hydrology

KaRIn will generate about 7Tb of data per day, which will be processed on ground to generate the following products:

- **Level 0**: Instrument Telemetry
- **Level 1**: Sensor data.
  - SWOT Low Resolution (Ocean Data) – OBP partial interferograms.
  - SWOT High Resolution (Land data) – full resolution complex interferograms in radar coordinates, phase flattened. (Images are internal product)
- **Level 2**: Users level.
  - SWOT Low Resolution (Ocean Data): Swath of sea surface height, slope, height uncertainty and backscatter
  - SWOT High Resolution (Land data): Geolocated water mask with Surface Water height, slopes with uncertainties,
  - SWOT High Resolution Enhanced: Discharge on river database, flood plain on long-term data collection
KaRIN OPERATION

- To form the required baseline, KaRIn will deploy two 5-m-long and 0.25-m-wide reflectarray antennas on opposite ends of a 5 m boom; both antennas transmit and receive radar pulses.

- The interferometer is a dual-swath system, alternatively illuminating the left and right 50 km swaths on each side of the nadir track. KaRIn will make near-nadir measurements at Ka-band (0.84-cm wavelength, 35.75-GHz center frequency).
**Oceanography:** Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 15 km and greater.

**Hydrology:** To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250\text{m})^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (rivers).
- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

**Mission Architecture**

- Ka-band SAR interferometric (KaRIn) system with 2 swaths, 50 km each
- Produces heights and co-registered all-weather imagery
- Use conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/DORIS/LRA for POD.
- On-board data compression over the ocean (1 km$^2$ resolution).

**Mission Science**

- Partnered mission: CNES/ NASA/ CSA/ UKSA
- Science mission duration of 3 years
- Calibration orbit: 857 km, 77.6° Incl., 1 day repeat
- Science orbit: 891 km, 77.6° Incl., 21 day repeat
- Flight System: ~2000kg, ~1900W
- Launch Vehicle: NASA Medium class
- Target Launch Readiness: Apr. 2021
SWOT Mission Motivations

• Recommended
  - by the US Decadal Survey based on Water/Hydrosphere Concept
  - In the frame of the CNES Scientific Prospective Seminar (Biarritz, March, 2009)

• Cooperation USA/France/Canada
  - An emblematic Project of France-USA cooperation: more than 20 years cooperation in Space Altimetry

• The SWOT mission is a partnership between two communities, hydrology and oceanography
SWOT mission motivations

The Surface Water and Ocean Topography (SWOT) Mission is being jointly developed by NASA and CNES, with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency (UKSA).

The SWOT mission will provide valuable data and information that will benefit society in two critical areas; freshwater on land, and the oceans’ role in climate change.

It will fulfill important observations of the amount and variability of water stored in global lakes, reservoirs, wetlands, and river channels and will support derived estimates of river discharge.

SWOT will also provide critical information necessary for water management, particularly in international hydrological basins.

SWOT is scheduled to launch in April 2021 with newly developed wide-swath altimetry technology, the Ka-band Radar Interferometer (KaRIN) instrument.
THE SWOT MEASUREMENT PAYLOAD

The core technology for SWOT is the KaRIN SAR radar Interferometer, complemented with a suite of instruments:

- a nadir-looking conventional altimeter, a three-frequency microwave radiometer), as well as global positioning system (GPS) receivers and a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) transponder for precise orbit determination.

KaRIN will measure elevations at high precision and spatial resolution. The payload complement will be used for calibration and to obtain a cross calibrated data set with traditional altimeters.
SWOT – An ambitious and challenging mission

• **Scientific Stakes : Leading scientific innovation**
  – New technologies on board SWOT allow the collection of unprecedented oceanographic and hydrographic data on a global scale
  – Essential contribution of SWOT: spectacular gain in spatial resolution from ~100 km to 100 m or more

• **Applications Stakes: Providing information on freshwater**
  – Beyond the scientific contribution to a better understanding of the water cycle, SWOT could have an economic and social impact through the development of new applications

• **Technological Stakes: New path for satellite altimetry**
  – The SWOT mission is a breakthrough in the field of space altimetry
  – The instrument KaRIN is the main innovation of the SWOT mission and presents a significant technical challenge
Flood Risk mapping

Motivation

- Flood can be classified to several types: Hurricanes, storm surge, heavy rainfall ...
- Soil moisture is expected to play a role for heavy rainfall flood, but this remains an open question in hydrology.
- Here we consider that soil moisture conditions can increase or decrease the flood risk:
  - saturated soils increase risk for floods
  - Soil moisture is a proxy for rainfall
  - Land surface / atmospheric coupling (Koster et al.)
SMOS Flood Risk Forecast

Methodology

Leveraging inundation risk based on SMOS soil moisture prior knowledge

Al Bitar A., Chone A., S. K. Tomer, CESBIO
SMOS Flood Risk Forecast

Results

- Compare with the Dartmouth Flood Observatory
- Dartmouth magnitude of the flood against the Precipitation inundation risk and the SMOS inundation risk.

- Results show that the Precipitation Inundation risk is underperforming.
- But also that the use of SMOS globally enhances the risk product except in A

Al Bitar A., Chone A., CESBIO
Operational implementation by CapGemini and CESBIO

SMOS flood risk Today 07 Oct. 2014 at 12h45 for the next 5 days

Storm risk by NOAA Today 07 Oct. 2014 at 12h45