The Use of Radar to Improve Rainfall Estimation over the Tennessee and San Joaquin River Valleys

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**Remote Sensing of the Water Budget**
Where is the water and how much is there?

**Coupled Modeling: Diagnostic and Prognostic**
Where is it going today, where will it go tomorrow?

**Overarching Motivation and The Result**
- Improved Water and Energy Management

- **Optimize Storage, Routing, Planning**
  Now, what do we do with it?
Overview collaborative radar rainfall project between Tennessee Valley Authority (TVA), VCSI (The Von Braun Center for Science & Innovation), NASA MSFC and UAHuntsville

- **AREPS: ARMOR Rainfall Estimation Processing System**
  - Demonstration project of real-time radar rainfall using a research radar

- **NREPS: NEXRAD Rainfall Estimation Processing System**
  - Expansion to Tennessee River Valley using operational WSR-88D
  - Objectives, methodology, some results and validation, operational experience and lessons learned.

NASA Earth Science – Applied Science Program’s ARRA Project: Water Supply and Management in California

- NASA MSFC and UAHuntsville to provide NREPS rainfall input to NASA MSFC/USRA distributed hydrological model for soil moisture and evapo-transpiration estimation.
- NREPS challenges, ongoing/future work and opportunities over Central CA and beyond.
Objective and Motivation

- TVA River management and distributed rainfall measurements - reducing dependence on rain gauges.
  - Provide custom-tailored, radar-based rainfall products specific to TVA’s operational river management needs (e.g., 6-hr sub-basin mean rainfall)
  - Potential reduction of costs associated with maintenance of large TVA rain gauge network

- Research & Development → Operations
TVA River Forecast Center
http://www.tva.com/river/flood/center.htm

- Knoxville, TN: staffed around the clock and 365 days a year
- River management duties include
  - Issuing forecasts of reservoir levels and water releases at TVA dams
  - Providing hourly generation schedules for TVA hydroelectric projects
  - Providing special notifications to the public during flood events
  - Evaluating cooling water needs for TVA coal-fired and nuclear plants
  - Monitoring water quality conditions below TVA dams (oxygen levels)
  - POC in event of a river system emergency
- Complex, interdependent and sometimes conflicting set of river management requirements and responsibilities.
  - Forecasters are busy! They need reliable data for decision making.
- Forecasters use lumped hydrologic runoff model tuned to parameters and input data performance, including gauge rainfall mapped to sub-basins using Theissen polygons.
Tennessee River Watershed

TVA River Scheduling Division

- 112 sub-basins
- 1840 km$^2$
- 189 rain gauges maintained by TVA
  - Annual costs: $6K / gauge

Demo project using ARMOR
Objective:
Transition from rain gauge (point) estimation paradigm to radar (distributed) measurement.

CURRENT River Operations
Gauge Rainfall Inputs

Advanced Radar, QPE Applications

FUTURE TVA
River Ops Rainfall Inputs
Point (gauge) vs. areal (radar) rainfall estimates

E.g., Warm season precipitation event
Favorable comparison to gauges- (points)

BUT much of the heaviest precipitation missed at individual gauges (this is fairly typical)!

Heterogeneity of rain field presents problems for point measurements, even for gauge-adjusted radar maps
Conventional Radar *Estimates* of Precipitation

- Radar scans rain/precipitation by sending out a series of microwave pulses along a $1^\circ$ beam while sweeping that beam through a $360^\circ$ circle.
- Executed for several elevation angles and repeated every 5 – 6 minutes.
- Returned power from rain (called reflectivity - “Z”) is typically measured at only one polarization (e.g., horizontal) and related to rainfall via “Z-R” power laws: $Z = aR^b$

- Raindrops (often the target) are deformed by drag as they fall.
- Become more oblate with size (diameter)
QPE: Problem with conventional radar-rainfall approaches: Reflectivity Factor (Z) - Rainfall Rate (R) Relations

- Problem: Numerous rainfall-reflectivity relationships, which one is correct?
- Random error up to 100% (instantaneous) can occur. Typical space-time smoothing reduces to say 20%-40%.
- Measurement sensitive to rain drop size distribution, presence of hail/ice/snow, and radar calibration.
- Without care, unacceptable errors/bias can be incurred for high resolution hydrological applications.
- Even gauge corrections are still beholden to gauge calibration/error/sample mismatch - a problem at times (more often then we would like to admit).

Sample of current operational relationships:
- \( Z = 300 \, R^{1.4} \) - convective rain
- \( Z = 250 \, R^{1.2} \) - tropical rain
- \( Z = 200 \, R^{1.6} \) - summer stratiform rain
- \( Z = 130 \, R^{2.0} \) - winter stratiform (eastern US)
- \( Z = 75 \, R^{2.0} \) - winter stratiform (western US)

How do we correct these issues?
• **Approach:** Provide measurements in both horizontal and vertical polarizations (dual-polarimetric).

• **Advantages:** Better description of various particle types/shapes in a given volume

• Determine size distribution - more accurate rain rates (**improved QPE**)  
  • Rain drop shape related to size

• **Hydrometeor ID** (hail vs. rain) and non-meteorological scatterers (clutter!)

• Consistent **calibration**
Enter Polarimetric Radar

And more variables………

1. **Reflectivity factor** $Z$ at horizontal ($Z_h$) or vertical ($Z_v$) polarization [Conventional radar measure]
   - Measure of drop size and concentration;
     - Most sensitive to drop SIZE ($D^6$)

2. **Differential reflectivity** $Z_{DR}$ ($Z_h/Z_v$)
   - Measure of median drop diameter → SIZE/SHAPE
   - Useful for rain / hail / snow discrimination → SIZE/SHAPE

3. **Specific propagation differential phase** $K_{DP}$ $\Sigma(k_h - k_v)$
   - Measure of water content and drop size → NUMBER/SHAPE
   - Immune to radar calibration, attenuation, partial beam blockage

4. **Correlation coefficient** $\rho_{hv}$
   - Indicator of mixed precipitation → SHAPE/PHASE/CANTING (Depolarization)
   - Useful for identifying non-meteorological scatterers too!

**Advantages:** Better description of various particle types/shapes in a given volume
- Determine size distribution- more accurate rain rates (**improved QPE**)
- **Hydrometeor ID** and non-meteorological scatterers (clutter!)
- Consistent **calibration**
Dual-Polarimetric Radar: Improved QPE through improved description of particles

Rain is Oblate
- Small Drops (1 mm)
- Large Drops (> 4 mm)
Axis ratio decreases with increasing size—more oblate

Hail/Graupel
- Radar "sees" an effective sphere
- Tumbling and lower dielectric strength makes hail look like spheres
- Unless they start to melt...
  - Melting Hail/Graupel (Toroid or ice core; looks like a huge drop)
  - Axis ratio ~ 1
  - Axis ratio < 1

Assessing size and Shape with Dual-Pol
- Particle Size-Controlled
  - Smaller ZDR → Larger ZDR
  - Smaller KDP → Larger KDP

- Number Concentration Controlled
  - Smaller # → Larger #
  - Larger ZDR → Smaller ZDR
  - Small Drops vs Large Drops
  - Small KDP vs Large KDP

Insects vs Rain
- Small Drops vs Large Drops
- Smaller Z vs Larger Z
- Smaller KDP vs Larger KDP
Advanced Radar for Meteorological & Operational Research

- Location:
  - Huntsville International Airport, Huntsville, AL (Altitude 206m)
- C-band *dual-polarimetric* Doppler radar
- Simultaneous transmit and receive of H, V
- Variables: Z, V, W, ZDR, $\Phi_{DP}$, $\rho_{hv}$
- Operations:
  - 24-hrs a day / 7 days
  - Rain volumetric scans at least every 5-min (tilts: 0.7°, 1.5°, 2.0°)
  - Also used in research mode (e.g., RHIs, full volumes, vertically pointing scans)
- Routine calibration:
  - Receiver calibrations
  - Solar scans
  - Self-consistency amongst variables
  - Comparisons with TRMM and rain gauges
ARMOR Rainfall Estimation Processing System (AREPS)

- Clean using $Z$, $\rho_{iw}$, var ($\Phi_{dp}$)
- Filter $\Phi_{dp}$, recompute KDP (adaptive FIR filtering)
- Correct Attenuation ($Z$) [$\Delta Z$ and $\Delta ZDR = \alpha KDP^8$]
- Differential Attenuation (ZDR)
- Compute Hybrid rain rates ($R[KDP,ZDR,Z]$)
- Write UF
- Grid rain rates (1 km$^2$ spacing)
- Summation of rain rates
- Compute point and areal N-hr rainfall estimates
- Optional D
- End-user
AREPS Coverage

- 100 km from ARMOR (HSV)
- 11 sub-basins
- 42 rain gauges
AREPS Distributed Rainfall Products

- Rainfall products created every 5-min:
  - 1-hr and 6-hr basin/sub-basin rainfall statistics (mean, max, min, etc)
  - Rainfall at critical locations (e.g., dams)
  - rainfall accumulation images (1-hr, 6-hr)
- Text files transmitted every hour to TVA
  - Contain previous hour's rainfall
  - used as input by inflow model input

![1-hr rainfall (also create 6-hr rainfall)](http://vortex.nsstc.uah.edu/armor/webimage)

![6-hour accumulation statistics](http://vortex.nsstc.uah.edu/armor/webimage)
Verification: Point Comparisons
AREPS vs. TVA rain gauges
(October 2007 – June 2008)

Before Calibration Correction

Bias = -17% (-1.80 mm)
Error = 18%

After Correction

Bias = -10% (-0.99 mm)
Error = 12%

Radar Rainfall Estimate Improved

- Original bias and error targets achieved (+/-20%, +/-25% respectively)
- Constant monitoring of calibration maintains precision and accuracy of product
Verification: Sub-basins
AREPS vs. rain gauge-derived areal mean
(January 2008 – July 2008)

- Inflow model uses rainfall estimates averaged over each sub-basin
- Radar estimates average over sub-basin
- Rain-gauge network used by TVA to compute Theissen polygon values to represent each sub-basin
- Radar underestimates sub-basin rainfall by only 8%
- Random error = 20%
  - Largely attributed to Theissen polygons (i.e., density of rain gauge network with respect to sub-basin boundaries)

Demonstration successful….but what about the rest of the watershed?
Expansion of radar rainfall maps across entire TN River watershed

NEXRAD coverage across TVA watershed grid
(Number of radars within 200 km of a gridpoint)
(Yellow and red gauges are owned by TVA; red=critical)

With River Basins and Rain Gauges

→ Sufficient radar coverage
NEXRAD Rainfall Estimation Processing System (NREPS)

1) Time matching
2) QC/rain rate algorithm
   • AP, Sun strobe removal
   • C-S partitioning (37 dBZ)
   • Z – R relation
   • Melting level correction
3) Gridding 2 km²
4) Merge radars
5) Hourly accumulation

WSR-88D Level II
Unidata LDM (IDD)

HRAP 2
NREPS

NCEP Stage II
Precipitation Analysis

FTP

LDM outage
NREPS Processing

- VCP-based sweep selection (e.g., 1st SUR and Doppler scans of each elevation)
- Beam blockage correction for occultation
- Clutter mitigation (NEXRAD ORPG 3)
  - Notch width filter
  - Sun strobe removal
- Non-precipitation mitigation (Steiner and Smith 2002)
  - Vertical extent and structure
  - Spatial variability
- Additional checks using VCP mode and RUC analysis melting level
  - Clear-air VCP + 0°C height > 100 m → no precipitation
  - Clear-air VCP + 0°C height ≤ 100 m → snow
- Rainfall from individual radar interpolated to 2 km x 2 km Cartesian grids using NCAR reorder at 1.0, 1.5 and 2.0 km ARL for TVA (more vertical levels every 0.5 km for CA domain).
  - Use lowest available “good” rainfall rate for each radar grid point
  - Individual radar grids are composited to a single mosaic using an inverse exponential weighting
Beam Blockage Correction

- DEM vs ray path model → regions of occultation
- Visibility correction factor (Germann et al. 2006)
  \[ f = (1 - \text{blockage})^{-1} \]
- Adjust reflectivity field for blockage of 5% to 90% (Lang et al. 2009)
Non-precipitation mitigation

- Steiner and Smith (2002)
- Reduce AP
- Decision tree methodology performed in polar coordinates
  1. ECHOtop → echoes separated from precip
  2. SPINchange → echoes embedded in precip
  3. vertGRAD → limits echo removal around edges of storm cells
- Computationally fast and efficient
- Difficulties with widespread clear-air echoes
NREPS Rain Rate Algorithm

Reflectivity (Z) = GOOD (and passed QC)

- YES: Hail? (Z > 72 dBZ)
  - YES: Avg surrounding: <Z (θ 1, r ±1)>
  - NO: Stratiform? (Z < 37 dBZ)
    - YES: Marshall-Palmer 
      \[ Z = 200 R^{1.6} \]
    - NO: Default NEXRAD
      \[ Z = 300 R^{1.4} \]

- NO: Snow?
  - YES: 0°C height < beam height
    \[ R = R (Z_h) \] / SLWE
    \[ SLWE = \text{snow} / \text{liquid} \] (SLWE = 8 for TN Valley)
  - NO: \[ R = R (Z_h) \]
NREPS Performance

- Error = 20%
- Bias = -7%
- $R^2 = 0.93$
- NREPS has been implemented by TVA
  - used routinely in river scheduling operations
- TVA rain gauge removal
  - Gauges selected after extended NREPS validation
  - 18 gauges removed thus far
  - Additional gauges (TBD) next year
Coverage: Radar vs Rain gauge

- Intense isolated rainfall in west-central TN (sub-basin 3911)
- Amounts: (6pm-midnight)
  - Gauge = 38.1 mm (1.5 in)
  - Radar = 125 mm (4.9 in)
- Which was right?
  - radar beam < melting level
  - max reflectivity < 50 dBZ
  - stationary thunderstorm
  - no rain gauges in 3911

→ Advantage: Radar
May 2010 “1000-year flood” in Middle and West Tennessee

2 May 2010: NREPS 24-hr Rainfall

Downtown Nashville TN flooding, especially near Cumberland River, which crested at 52 ft there, and tributaries.

Tennessee River Basin: April 30 – 3 May 2010

TVA: Gauges with Theissen polygons to-sub-basin 6-hr mean to basin mean
Radar: NREPS grids to sub-basin 6-hr means to basin mean
In many sub-basins, there is good agreement between TVA-gauge and NREPS 6-HR cumulative rainfall.

Figures are courtesy of Mr. Adam Cissna, TVA
More good agreement…

Sub-basin 6-HR Rainfall

Savannah Perryville

Tenn Johnsonville Kentucky

Sub-basin Cumulative Event Rainfall

Savannah Perryville Cumulative

Johnsonville Cumulative

Figures are courtesy of Mr. Adam Cissna, TVA
And some more (including one with less rain)…

Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall

Cheatham to Clarksville

Cheatham Cumulative

Scottsboro Guntersville

Scottsboro Guntersville Cumulative

Figures are courtesy of Mr. Adam Cissna, TVA
But, as seen in the Basin mean, there was a tendency for the radar < gauge rainfall in some sub-basins, especially in “2nd wave” of heavy rain on May 2nd.
Some more sub-basins with radar < gauge in 2nd peak...

Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall

Duck above Manchester

Normandy

Normandy Cumulative

Figures are courtesy of Mr. Adam Cissna, TVA
And there are almost always a couple of exceptions to the rule! Radar > gauge, especially in the 1st wave of heavy rain on May 1st.

Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall

Little River Cadiz

Cadiz Cumulative

Dover to Barkley

Dover Cumulative

Courtesy Mr. Adam Cissna, TVA
TVA-VCSI Project Practical Experience

- Detailed developer (user) knowledge of user requirements, priorities and computing environment (tool capabilities and limitations) is key.
  - With diverse backgrounds, takes time and committed project team to develop productive communication and working relationship to solve complex issues.
  - Active user participation in system testing and improvement is very helpful.

- In an operational hydrological setting like the TVA River Forecast Center, rainfall data availability is the primary priority.

- Implications for robustness of
  - WSR-88D data pathways (Internet and LDM stability, back-up),
  - Software design (exception handling, stability, quality assurance)
  - Hardware design (memory, CPU and storage specifications to worst case scenarios; redundant systems)

- Data accuracy is important but secondary.
  - Because of river management complexity and model uncertainty, it is difficult for TVA to provide 6-hr sub-basin rainfall accuracy guidelines.
  - Forecasters manually adjust model hydrographs to stream flow gauge data in real time. Model output is tuned to measured river response.
California Water Resources Project

- Funded by NASA through American Reinvestment & Recovery Act
  - Through June 2011
- Develop integrated tool to assist water management within the San Joaquin River Valley
  - Radar precip estimates
  - Distributed hydro model
  - Snowfall measurements
  - Surface temp / moisture
- NREPS was selected to provide precip component
Challenges

- Residual non-precip contamination
- Nature of precipitation
  - Shallow, non-bright brand
  - Snow vs rain
- Terrain and remaining occultation
  - Non-standard refraction
- Beam height vs melting level

Map of lowest usable beam height in Central CA
Radar vs rain gauge comparison during mixed-precip events

Jan 29-30 2010
Radar vs Gauge (GID: 383 Petersburg, TN)

- What can this lag cause?
  - Invalid performance conclusions
  - Inflow model initialization errors

1-HR Rainfall Amount (inches)

Time (EST)

Gauge ?

Radar = 0.78

Snow melt
Future NREPS plans

- Vertical profile of reflectivity (bright band mitigation, ice vs. rain, rain rate vs. beam height)
- Explore more sophisticated precipitation type (C/S) identification methodology
  - Other categories for Coastal California – shallow, non-convective, non-bright band?
  - z-R’s for the appropriate regime and precipitation type
- For CA ARRA NREPS: Integration with NASA distributed hydrologic model for soil moisture and evapotranspiration estimates
- Back to the future – As WSR-88D network is polarized, transition z-R algorithm to dual-polarization hybrid R[Z,Zdr,Kdp] methodology at S-band?