Precipitation Measurement

VU2: Course Number 707813

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Some Applications of Precipitation Measurements

- Data assimilation, numerical weather prediction, nowcasting, forecasting
- Forecast validation
- Climate change assessment
- Hydrologic modeling/streamflow prediction
- Landslide warning systems
- Avalanche prediction and control work
- Irrigation scheduling
- Urban planning and civil engineering

Tapiador et al. (2012)

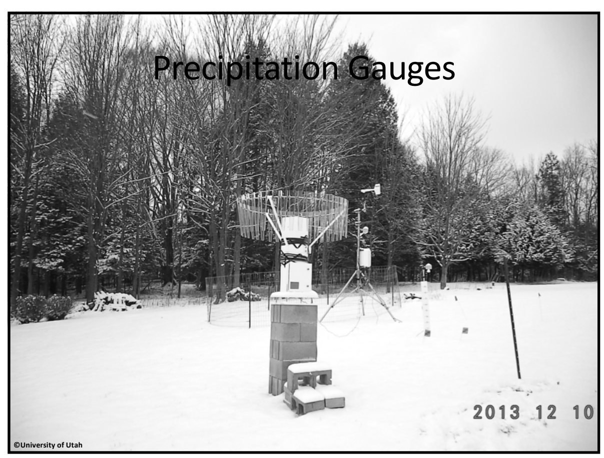
Group Discussion

Why is precipitation difficult to measure or estimate?

Approaches

- *In situ:* Measurements made at the site of the instrument
  - e.g., rain gauges and disdrometers
- *Remotely sensed:* Measurements made with a sensor that does not make direct physical contact
  - *Passive:* Measurement is made of energy that is naturally reflected or emitted from the target
    - e.g., spaceborne microwave radiometers
  - *Active*: The measurement system transmits its own energy and measures the properties of the returned radiation
    - e.g., ground-based or space-borne radar
- *Multisensor*: Analyses integrating precipitation observations/estimates from multiple sources and in some cases NWP guidance
  - e.g., INCA

Precipitation Gauges

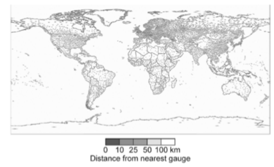


Precipitation Gauges

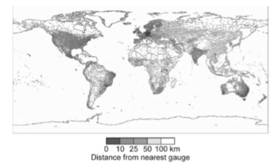
- 150,000+ manual precip gauges in use globally
  - Widely used
    - Nonrecording graduated cylinder
    - Tipping bucket
    - Weighing
  - Less common
    - Capacitance
    - Drop counting
    - Hot plate

Strangeways (2007)

Rain Gauge Density



Distance to nearest Global Telecom System (GTS) "first class" station (typically at least every 3 hours)

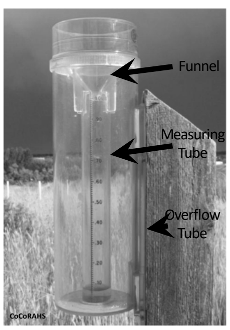


Distance to nearest Global Precipitation Climatology Center station (mainly daily data)

Most of the planet is poorly sampled by gauges
Even in developed countries, precipitation is undersampled by guages

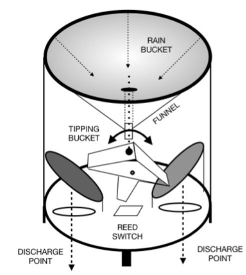
Kidd et al. (2017)

Nonrecording Graduated Cylinder



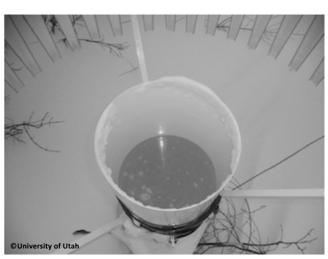
Tipping Bucket

ASOS Tipping Bucket with Wind Shield



Source: Unknown

Weighing Bucket



Discussion

What are the advantages and disadvantages of Nonrecording, tipping bucket, and weighing gauges?

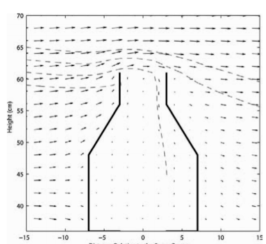
Error Sources

- Unrepresentative siting
  - Major issue for many volunteer observers
- Size of the collector
- Evaporative losses
  - Heated and nonheated gauges
- Outsplash (liquid hydrometeors) and bounce (frozen hydrometeors)

Error Sources

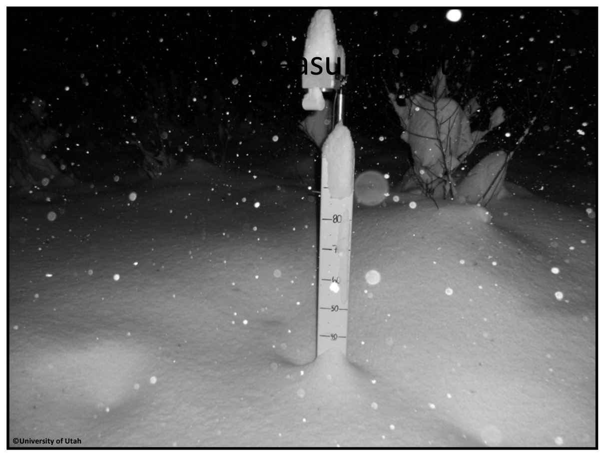
- Wind effects
  - Undercatch, especially for snow with unshielded gauges
- Overfill
- Snow adhesion and clogging
- Datalogging, communications
- Human

Undercatch



Dashed = Snowflake Trajectories

Rasmussen et al. (2012)

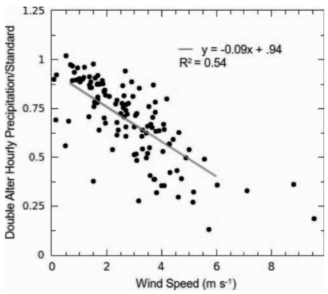


Automated Snow Water Equivalent

Automated Snow Water Equivalent

A number of wind shields have been created to reduce [undercatch], but no shield has yet been invented that has a high collection efficiency and is smaller than 4 m in diameter.

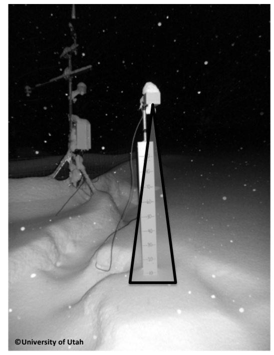
Example



Double Alter Shield GEONOR

Rasmussen et al. (2012)

Automated Snow Depth



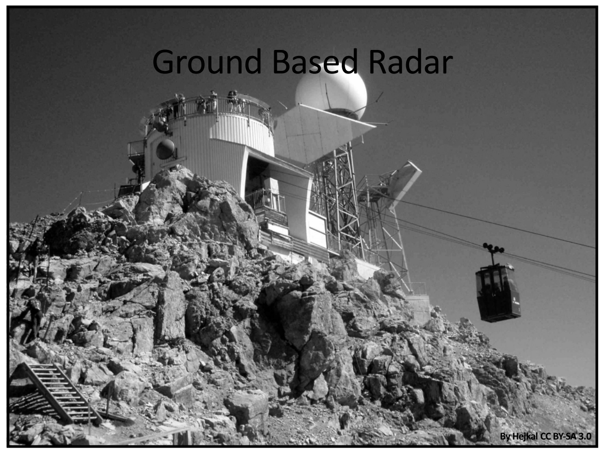
- Common: Ultrasonic snow-depth sensor
- Requires temperature for speed-of-sound
- Interval: Depth since board last wiped
- Total: Depth relative to ground

Manual Snow Measurement

- Difficult to beat!
- Good manual measurements require
  - Dedicated observer
  - Wind-sheltered, level location with a good sky-view factor
  - White, wood snowboard ~40x40cm
  - Ruler
  - Measurement periods vary but should
    - Not be taken more than 4x/day or less than 1x/day
    - Ideally be taken prior to melting or settlement
- Water equivalent can be obtained with a coring tube and spring scale

Steenburgh (2014)

Ground Based Radar



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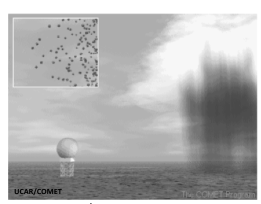
Radar Basics

- Types
  - Scanning
  - Profiling
- Wavelengths (Approx)
  - S-band: 10 cm (US NEXRAD)
  - C-band: 5 cm (Austria)
  - X-band: 3 cm (Portable, Gap filling)
  - Ku (2.3 cm), K (1.25 cm), Ka (.75-1 cm)
    - Primarily used for profiling radars
- Short wavelengths attenuate more but require a smaller dish
- Long wavelengths attenuate less, but require a large dish
- Single Pol
  - Radar transmits and received radio waves with a single polarization (typically horizontal)
- Dual Pol
  - Radar transmits and receives radio waves with both horizontal and vertical polarization

Radar Equation



- Assumptions
  - Targets are distributed – i.e., comprised a large number of small water droplets
  - Targets are evenly distributed
  - No attenuation between the radar and the target

$$Z_e = \frac{C_R P_r r^2}{0.93}$$

- Z_e: Equivalent radar Reflectivity factor
- C_R: Radar constant (function of beamwidth, antenna gain, transmitter power, & other characteristics)
- P_r: Power returned/measured
- r^2: Range squared
- 0.93: Constant based in part on Index of refraction of water

Houze (2014)

Radar Equation

$$Z_e = \frac{C_R P_r r^2}{0.93}$$

Z_e called "effective" since it assumes the reflectors are water droplets

Units = mm^6m^{-3}

In practice this is used since composition of scatters is not known with certainty

For liquid water

$$Z_e = \int_0^\infty D^6 N(D)dD$$

Diameter to the 6th power　　Number of drops of diameter D

∴ Z_e very sensitive to particle size and spans many orders of magnitude

Houze (2014)

Radar Equation

Effective reflectivity typically expressed in decibel units

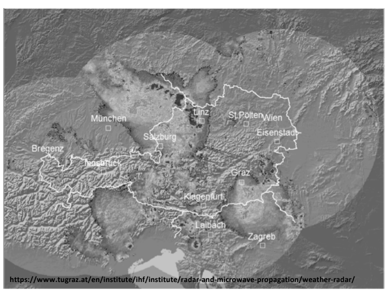
$$dBZ_e = 10log_{10}Z_e$$

Typical values and precipitation characteristics

dBZ_e	Precipitation
0-10	Drizzle, very light rain, light snow
10-30	Moderate rain, heavy snow
30-45	Melting snow (bright band)
30-60	Heavy rain
60-70+	Hail

Houze (2014)

Examples



Real-time examples from Europe and US

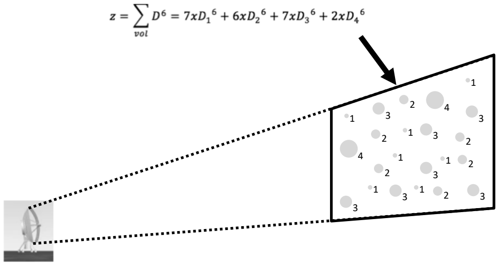
Old School Precip Rate from a Radar

- Used for single pol radars
  - Rainfall rate estimated from Z_e each volume scan
  - Integrate rainfall rates over time period of interest
  - Easy right?

Old School Precip Rate from a Radar

Problem: Radar reflectivity factor is dependent on the drop-size distribution

$$z = \sum_{vol} D^6 = 7xD_1{}^6 + 6xD_2{}^6 + 7xD_3{}^6 + 2xD_4{}^6$$



But we don't know the drop-size distribution

Old School Precipitation Estimation

Solution: Assume a drop-size distribution or use gauge-based precipitation rates

These approaches typically yield a power law relationship between z and rainfall rate, R

$$z = aR^b$$

Known as a "Z-R" relationship
a and b empirically derived with Best values dependent on situation
For US WSR-88D network

Relationship	Optimum for:	Also recommended for:
Marshall-Palmer ($Z = 200R^{1.6}$)	General stratiform precipitation	
East-Cool Stratiform ($Z = 130R^{2.0}$)	Winter stratiform precipitation - east of continental divide	Orographic rain - East
West-Cool Stratiform ($Z = 75R^{2.0}$)	Winter stratiform precipitation - west of continental divide	Orographic rain - West
WSR-88D Convective ($Z = 300R^{1.4}$)	Summer deep convection	Other non-tropical convection
Rosenfeld Tropical ($Z = 250R^{1.2}$)	Tropical convective systems	

Chilson (2018)

Old School Precip Estimation

- Other issues
  - Precipitation particles are not necessarily spherical as assumed (e.g., snow)
  - Melting enhances reflectivity, resulting in overestimates
  - Radar reflectivity also produced by non-meteorological targets (birds, bugs, etc.)
  - Radar beam can bend, hit mountains, attenuate, etc.

New School Dual-Pol Approaches

- Dual-pol provides more variables
  - Horizontal reflectivity factor (Z_H)
  - Vertical reflectivity factor (Z_V)
  - Differential reflectivity (Z_{DR})
  - Correlation coefficient (ρ_{HV})
  - Specific differential phase (K_{DP})
  - Differential propagation phase shift (Φ_{DP})
- Advantages
  - More information about drop-size distribution
  - Enables hydrometeor classification
  - Better melting layer detection
  - Better clutter and non-meteorological target identification

Giangrande and Ryzhkov (2008), Kumjian (2013)

New School Dual-Pol Approaches

- US WSR-88D uses 3 equations depending on the melting layer detection and the hydrometeor class
  - R as a function of Z_H within and above the melting layer where ice hydrometeors are detected (multiplicative factors vary depending on hydrometeor type)

$$R = (1.7\text{x}10^{-2})Z^{0.714}$$

  - R as a function of Z_H and Z_{DR} for pure rain

$$R = (1.42\text{x}10^{-2})Z^{0.770}Z_{DR}^{-1.67}$$

  - R as a function of K_{DP} when rain and hail are detected

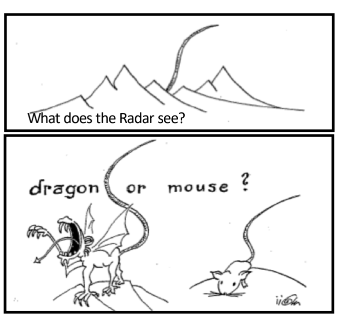
$$R = 44.0|K_{DP}|^{0.822}sign(K_{DP})$$

Giangrande and Ryzhkov (2008), Kumjian (2013)

Group Discussion

What are some of the challenges using scanning radars in complex terrain?

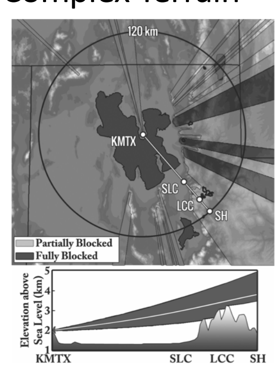
Radar Issues in Complex Terrain



Germann and Joss (2004)

Radar Issues in Complex Terrain

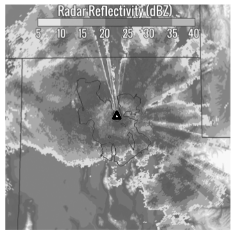
- Factors inhibiting view near ground
  - Shielding
    - No return power
  - Partial Shielding
    - Artificially low dBZ_e
  - Clutter
    - Large, useless dBZ_e due to returned power from terrain

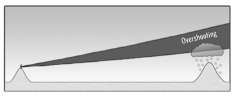


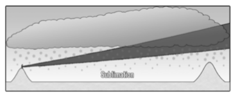
Steenburgh (2014)

Radar Issues in Complex Terrain

- Other Challenges
  - Melting layer bright band
  - Overshooting shallow orographic storms
  - Evaporation and sublimation below lowest tilt

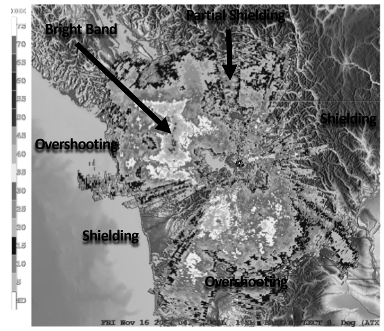




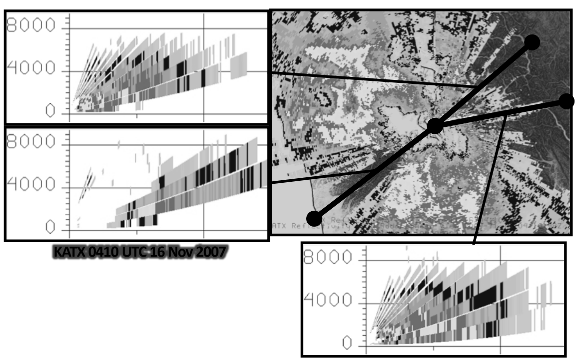


Steenburgh (2014)

Example

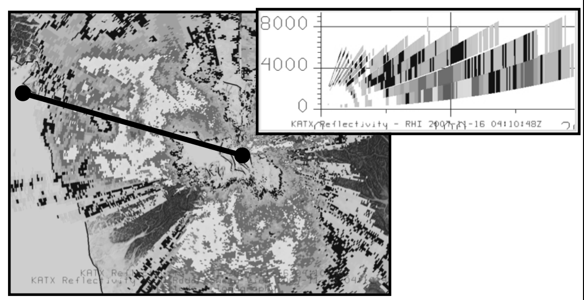


Shielding

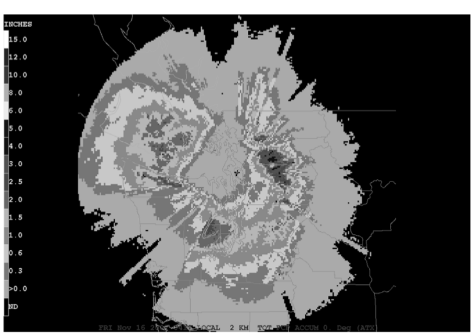


KATX 0410 UTC 16 Nov 2007

Bright Band



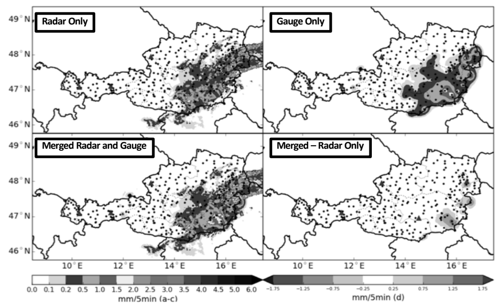
Impact on Precipitation Estimate



Group Discussion

How do these issues affect radar interpretation in Austria?

Merged Radar/Gauge (e.g., INCA)



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Integrated Nowcasting through Comprehensive Analysis

Kann et al. (2015)

Space Borne Remote Sensing

- Critical since gauges and ground-based radar poorly sample vast areas of the Earth
- NWP models cannot fill this void since they struggle with quantitative precipitation forecasts
- Satellite estimates of precipitation based on passive IR/Visible, passive microwave, active radar (microwave or millimeter — e.g. TRMM, GPM, Cloudsat), and fusion/blended techniques

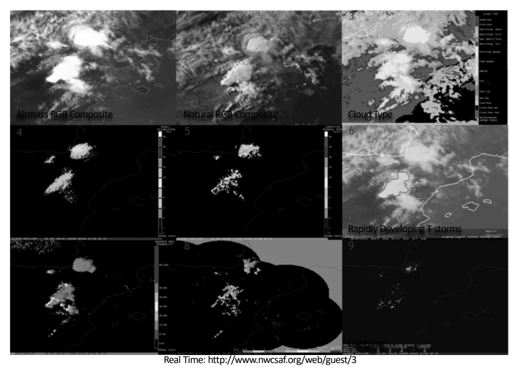
Tapiador (2018)

Passive IR/Vis

- Utilizes relationship between cloud top brightness temperature and precipitation
- May utilize some input from NWP analyses/forecast variables (e.g., 3-D temperature, humidity, etc.)
- Advantage: Broad coverage, modest spatial resolution (kms), high frequency for geostationary satellites
- Disadvantages: Precipitation not always correlated with coldest/brightest cloud tops (orographic and non-convective precipitation), internal cloud structure hidden

Tapiador (2018), Marcos (2015)

EUMESAT IR-Based Conv Rain Rate



Real Time: http://www.nwcsaf.org/web/guest/3

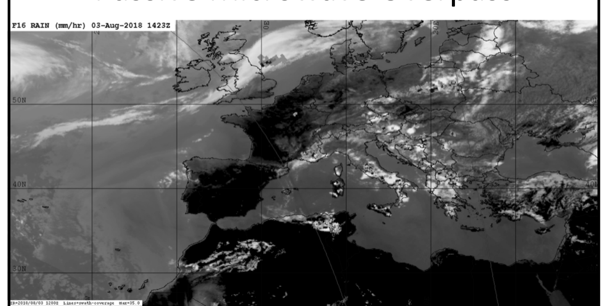
Tapiador (2018), http://www.nwcsaf.org/crr_20090520

Passive Microwave

- Typically based on frequency bands between 10 and 183 GHz (.15-3 cm)
- Radiometers measure TOA emissions from low-Earth orbiting, non-stationary satellites
- “Easiest” over water where emissivity is known
  - Ocean cool radiometrically, precipitation warm
- Resolution typically coarse (> 5km)

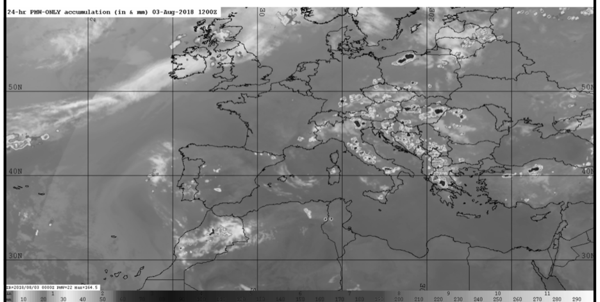
Ciabatta et al. (2017), Tapiador (2018)

Passive Microwave Overpass



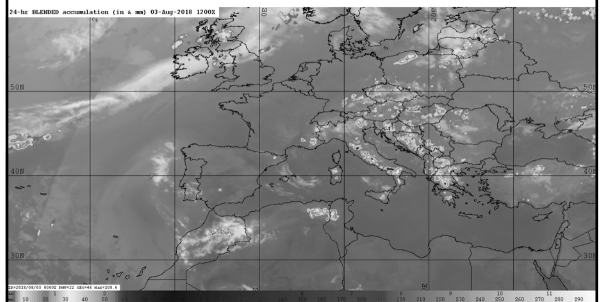
https://www.nrlmry.navy.mil/sat-bin/rain.cgi?GEO=med

Passive Microwave Daily Estimate



https://www.nrlmry.navy.mil/sat-bin/rain.cgi?GEO=med

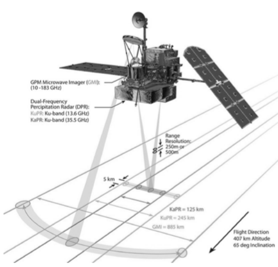
Blended IR/Passive Microwave Daily



https://www.nrlmry.navy.mil/sat-bin/rain.cgi?GEO=med

Active Microwave/Radar

- Tropical Rainfall Measurement Mission (TRMM)
  - Ku-band (13.8 GHz, 2.2 cm)
  - 4.3-km footprint/500 m range gate at nadir
  - 220 km swath width
  - 17 years data ending April 2015
- Global Precipitation Measurement Mission (GPM) Core Observatory
  - Ku-band (13.6 GHz, 2.2 cm)
    - 5-km footprint/250 m range gate at nadar
    - 245 km swath width
  - Ka band (35.5 Ghz, .85 cm)
    - 5-km footprint/250 m range gate at nadir (500 m outer swath area)
    - 120 km swath width
  - March 2014-present



https://pmm.nasa.gov/gpm, https://pmm.nasa.gov/gpm/flight-project/dpr

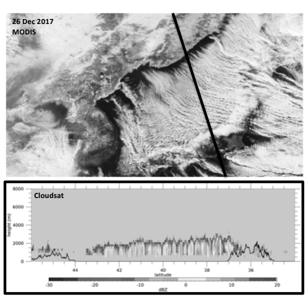
GPM Microwave/Precip Radar

Tropical Cyclone Cebile 2018 (Southern Indian Ocean)

https://www.youtube.com/watch?v=f3oz_ig9phE

Active Microwave/Radar

- Cloudsat
  - W-band (94 GHz, 3 mm)
  - 1.4/1.7 km cross-track/along-track footprint
  - Single "curtain" of data
  - Late 2006 – present (?), with gaps



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