Technically supported by:

JACOBS UNIVERSITY

The rasdaman Array DBMS: Concepts, Architecture, and What People Do With It

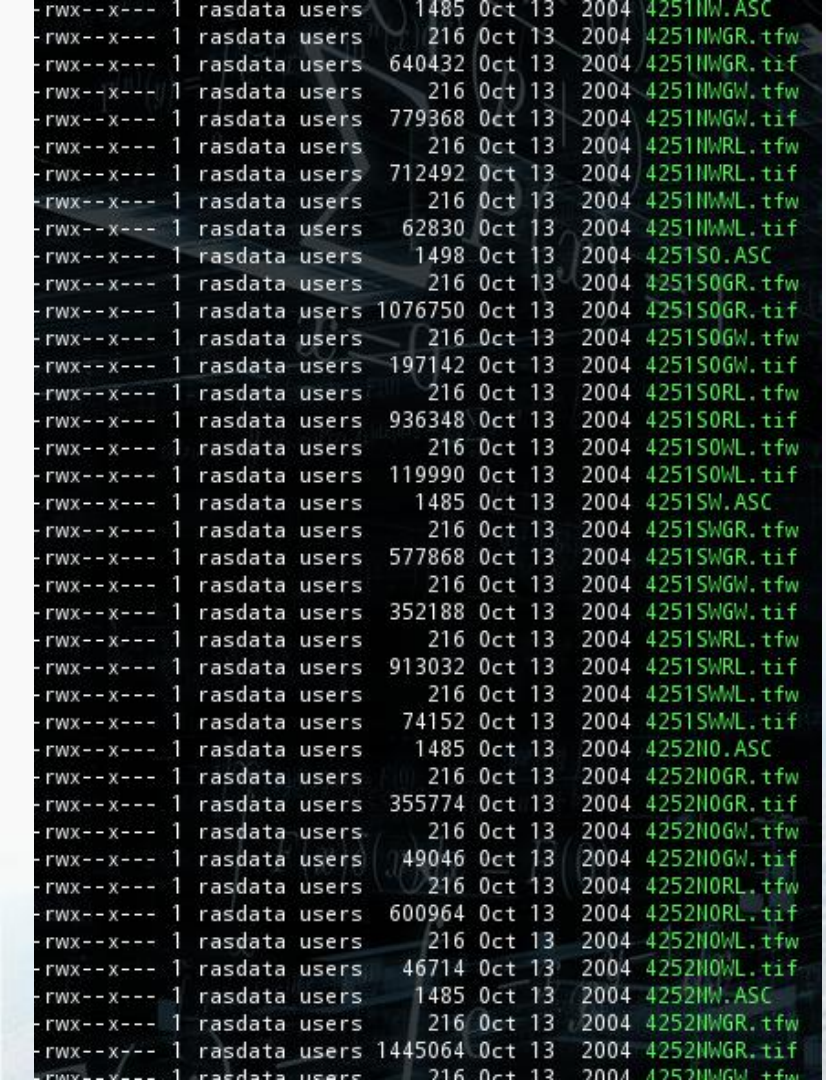
SSDBM, Copenhagen, 2022-07-08

Peter Baumann

Jacobs University | rasdaman GmbH

Array DB Research @ Jacobs U

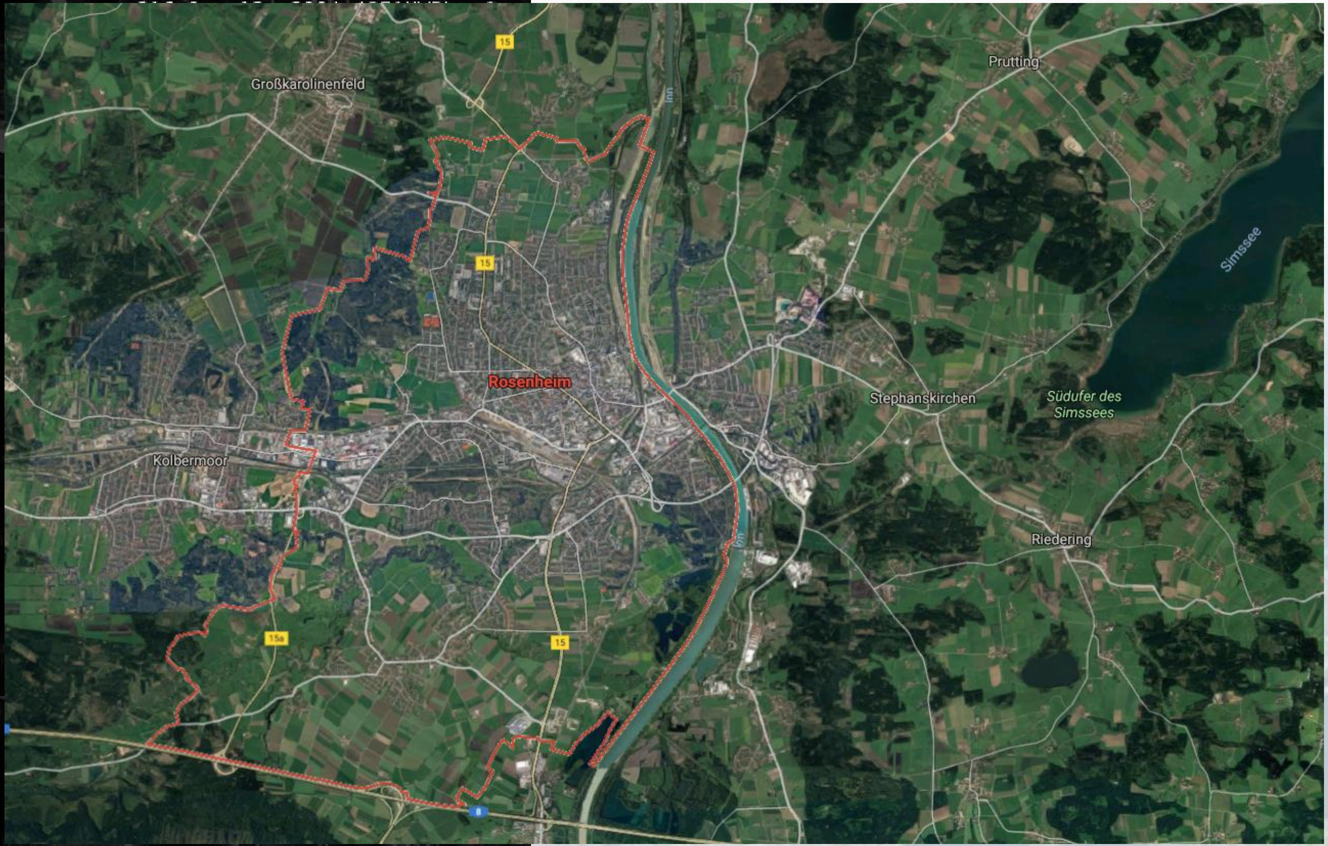
- Large-Scale Scientific Information Systems research group
  - large-scale n-D raster services & beyond
  - https://l-sis.org
- Spin-off company: rasdaman GmbH
- Main visible results:
  - pioneer Array DBMS, rasdaman
  - Datacube standards



JACOBS UNIVERSITY

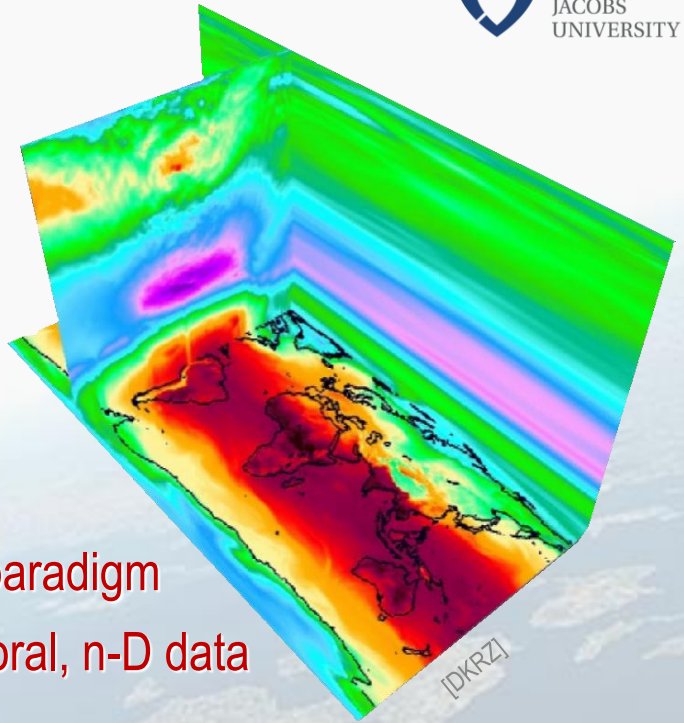
JACOBS UNIVERSITY

```
-rwx--x--- 1 rasdata users    1485 Oct 13  2004 4251NW.ASC
-rwx--x--- 1 rasdata users     216 Oct 13  2004 4251NWGR.tfw
-rwx--x--- 1 rasdata users  640432 Oct 13  2004 4251NWGR.tif
-rwx--x--- 1 rasdata users     216 Oct 13  2004 4251NWGW.tfw
-rwx--x--- 1 rasdata users  779368 Oct 13  2004 4251NWGW.tif
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata
-rwx--x--- 1 rasdata users    1485 Oct 13  2004 4252NW.ASC
-rwx--x--- 1 rasdata users     216 Oct 13  2004 4252NWGR.tfw
-rwx--x--- 1 rasdata users 1445064 Oct 13  2004 4252NWGR.tif
-rwx--x--- 1 rasdata users     216 Oct 13  2004 4252NWGW.tfw
```



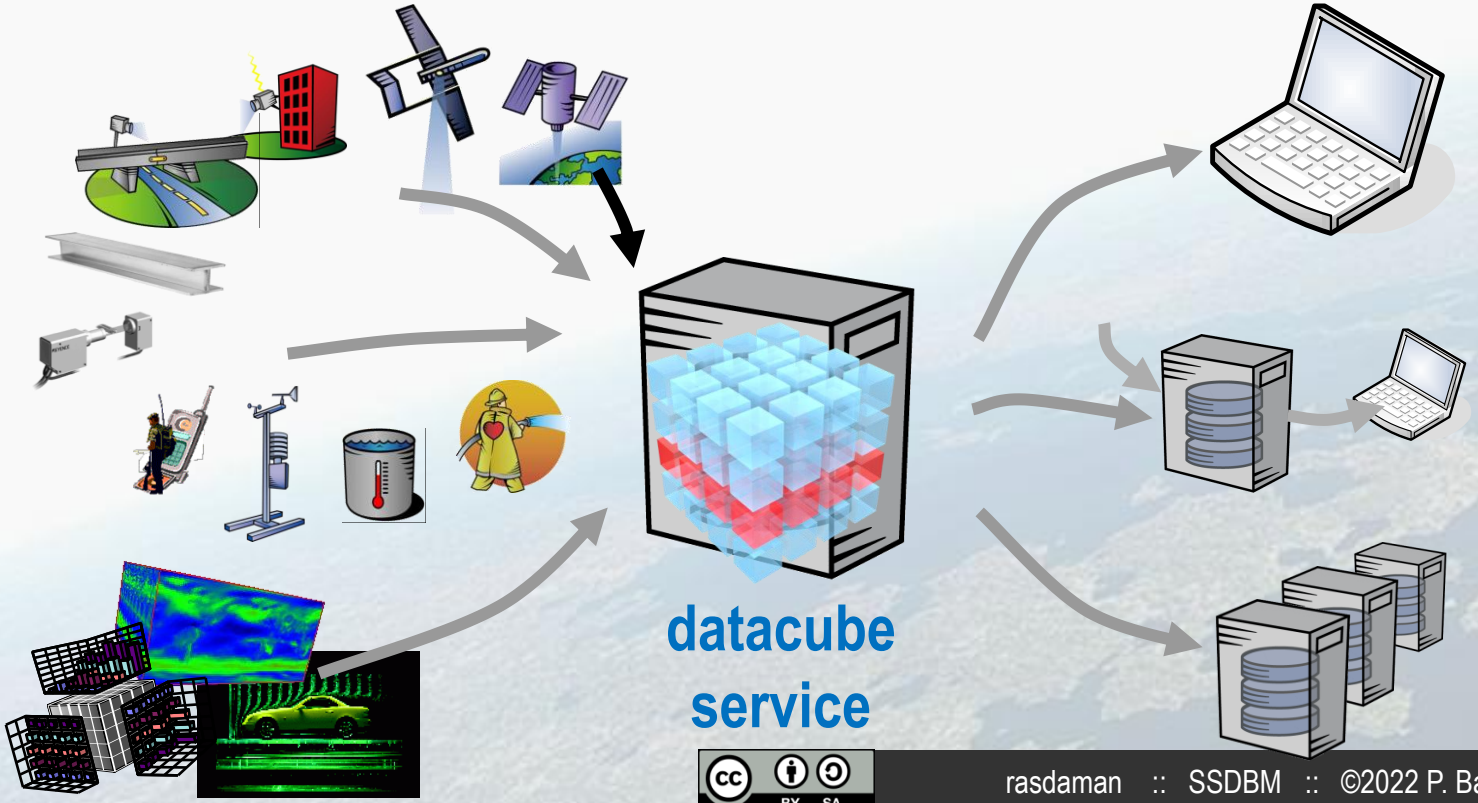
JACOBS UNIVERSITY

Datacubes?



- Sensors & simulations
  -> gridded („raster“) data
- Datacubes are the natural paradigm
  to interact with spatio-temporal, n-D data
- Avoid undue complexity
  -> data + service on high semantic level

Homogenized, Analysis-Ready Datacubes

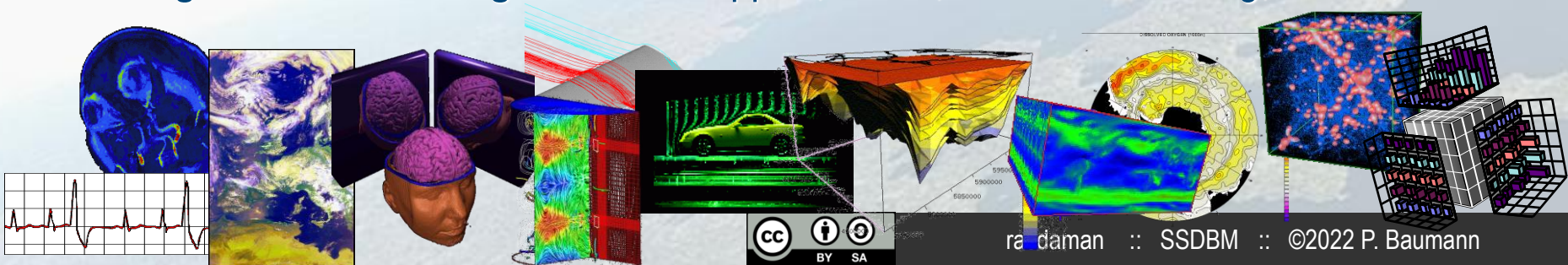


JACOBS UNIVERSITY

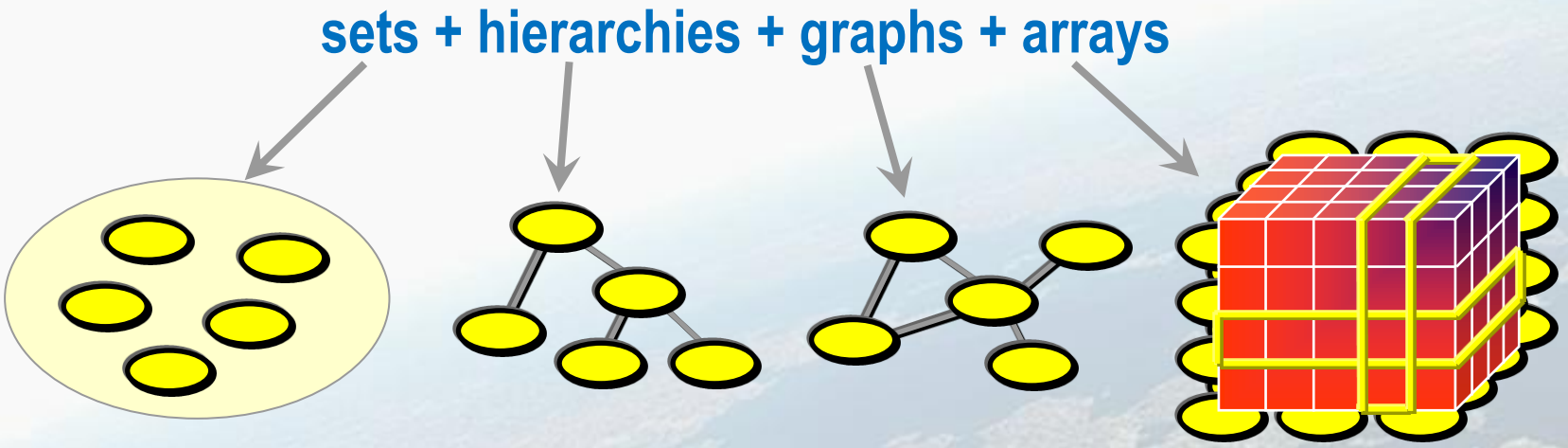
An Array Databases Perspective

Arrays: *Sensor, Image, Model, Statistics Data*

- **Life Sciences:** Pharma/chem, healthcare / bio research, bio statistics, genetics, ...
- **Earth Sciences:** Geodesy, geology, hydrology, oceanography, meteorology, remote sensing, ...
- **Space Sciences**: Astronomy, planetary science, astrobiology, ...
- **Engineering:** Simulation & experimental data in automotive / shipbuilding / aerospace industry, turbines, process industry, ...
- **Management/Controlling:** Decision Support, OLAP, Data Warehousing, fintech, ...

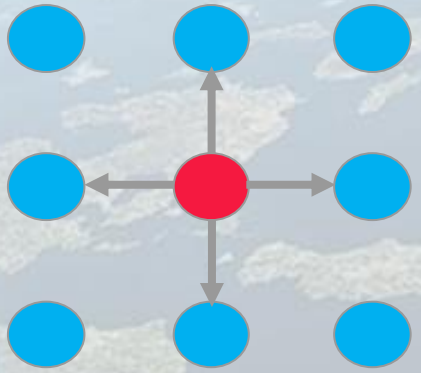


Fundamental Information Categories



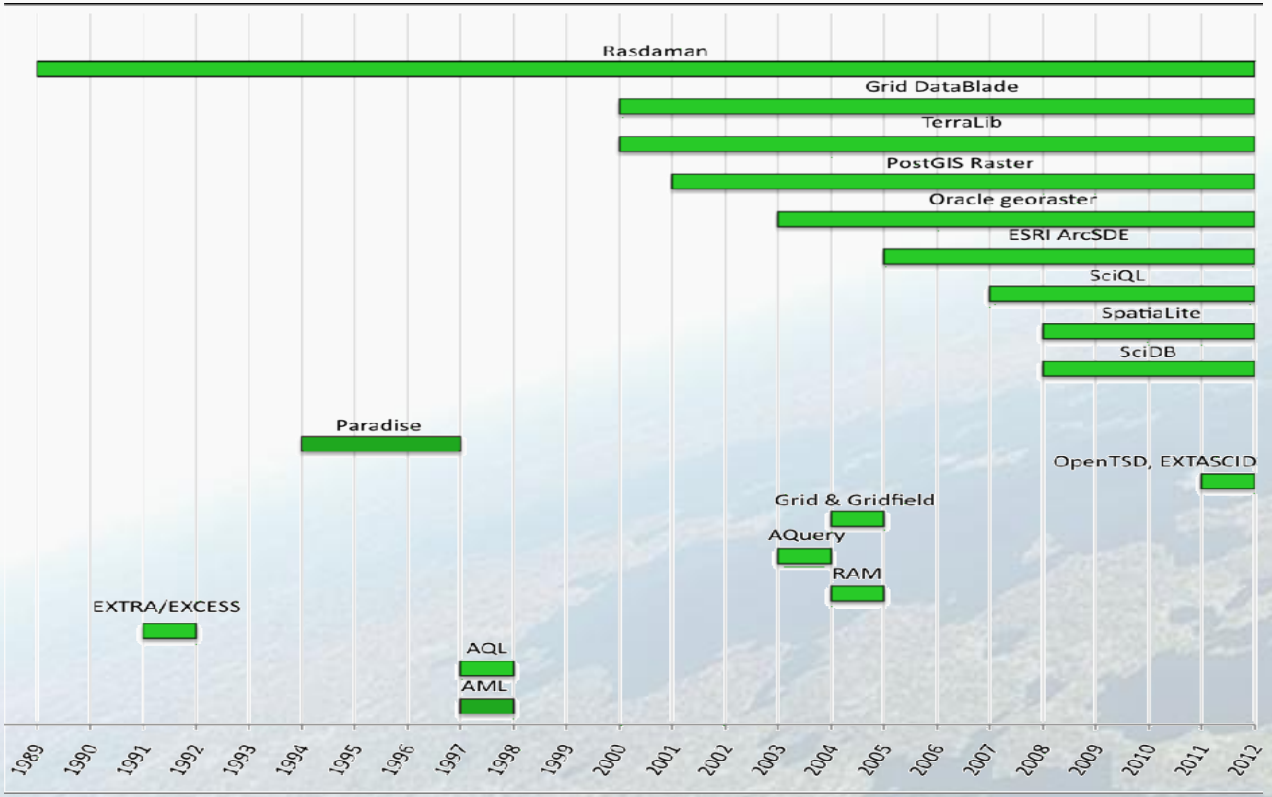
Array Analytics

- Array Analytics :=
  Efficient analysis on multi-dimensional arrays of a size orders of magnitude above evaluation engine's main memory
- Essential data property: n-D Euclidean neighborhood
  - Secondary: #dimensions, density, ...
- Operations: Linear Algebra++



[EDBT/ICDT Array Databases Workshop, 2011]

A Brief History of Array DBMSs



State of the Art

- Actionable datacubes: Baumann 1991, 1994
- OLAP: Business & statistics datacubes: Inmon 1992
- Today:
  - Array Databases
    - *rasdaman, SciQL, SciDB, Oracle GeoRaster, PostGIS Raster, EXTASCID, Teradata Arrays, ...*
  - Libraries & programming tools
    - *Xarray: OpenDataCube, CubeX, …*
    - *Wendelin.core, boost::geometry, Ophidia, Google Earth Engine, ...*
  - MapReduce based: SciHadoop, GeoTrellis, ClimateSpark, SciSpark, ...
- Research Data Alliance report: 19 tools deep-comparison, 4 benchmarked
  - https://rd-alliance.org/system/files/Array-Databases_final-report.pdf

rasdaman 1: Concepts

rasdaman

= „raster data manager“: n-D datacubes in SQL

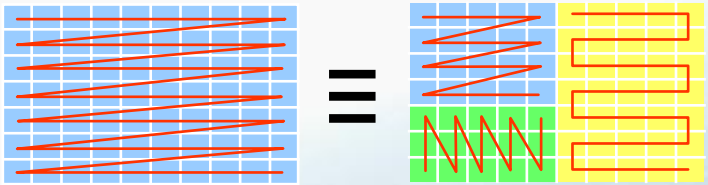
- pioneered actionable datacubes; publications & patents

- massively scalable Big Datacube Management & Analytics engine, aka Array DBMS
  - full-stack implementation

- standards blueprint, reference implementation, awards

QL Foundation: Array Algebra

- Minimal algebra for model, QL, storage mapping, optimization
  - Array constructor & condenser & sorter
  - Array iteration implicit → no explicit loops → declarative, safe



- Array QL = SQL with array expressions
  - Expressiveness up to, eg, Discrete Fourier Transform

[VLDBJ 1994, NGITS 1998]

Array Algebra Ops: Constructor

- Generate new array, initialize:

  $MARRAY_{X,x}(e|_x)) := \{ (x,f): f = e|_x, x \in X \}$

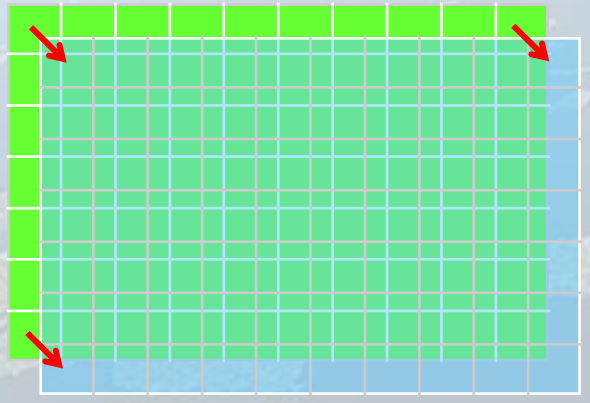
  - expression $e|_x$ potentially containing occurrences of x, of result type F

- Ex: image addition

  addition of cells

  - $a + b := MARRAY_{X,x}(a[x] + b[x]) := \{ (x,f): f = a[x] + b[x], x \in X \}$

```
marray x in [0:99], y in [0:99]
values a[x,y] + b[x,y]
```



- Shorthands: `a[x0:x1,y0:y1,t]` `a.red + 5`

[VLDBJ 1994, NGITS 1998]

Array Algebra Ops: Constructor

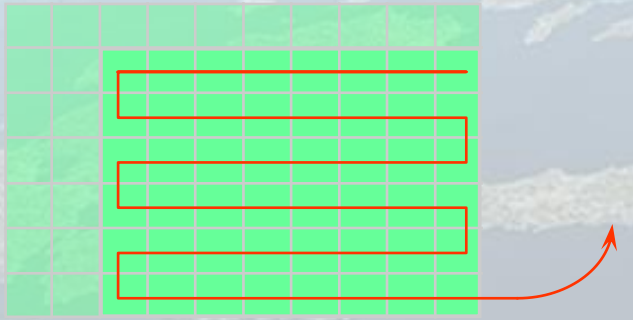
- Summarize over (part of) an array:

  $COND_{o,X,x}(e|_{a,x}) := e|_{a,p_1} \; o \; e|_{a,p_2} \; o \ldots o \; e|_{a,p_n}$

  - x visits each coordinate in $X = \{ p_1, \ldots, p_n \}$ exactly once, accessing array a
  - o Monoid

```
condense +
over     x in [0:99], y in [0:99]
[ where  P ]
using    a[x,y]
```

- Shorthands: `max_cells( a )`

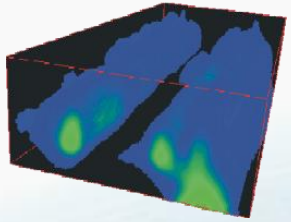


[VLDBJ 1994, NGITS 1998]

From Algebra to SQL: Operations

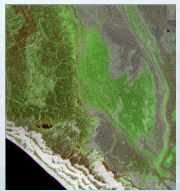
- selection & section

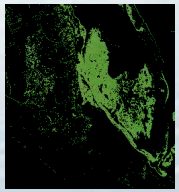
```
select c.data[ *:*, 100:200, *:*, 42 ]
from   ClimateSimulations as c
```



- result processing

```
select ls.img * (ls.img.green > 130)
from   LandsatArchive as ls
```





- search & aggregation

```
select mri.data
from   MRI as img, masks as am
where  some_cells( mri.data > 250 and m.valid )
```

- data format conversion

```
select encode( c.data[*:*,*:*,100,42], „image/png“ )
from   ClimateSimulations as c
```

Linear Algebra Beginnings in Array Queries

JACOBS UNIVERSITY

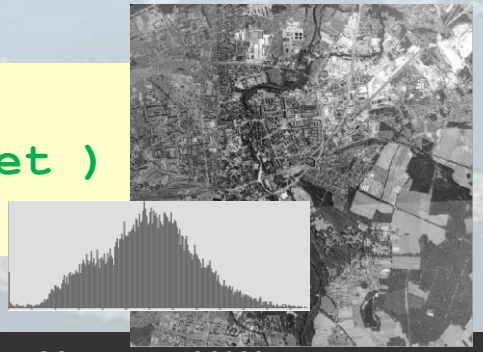
- Matrix multiplication

```
select mdarray i in [0:m], j in [0:p]
       values  condense +
               over     k in [0:n]
               using    a [ i, k ] * b [ k, j ]
from   matrix as a, matrix as b
```

$$(\mathbf{AB})_{ij} = \sum_{k=1}^{m} A_{ik} B_{kj}$$

- Histogram

```
select mdarray bucket in [0:255]
       values  count_cells( img = bucket )
from   img
```



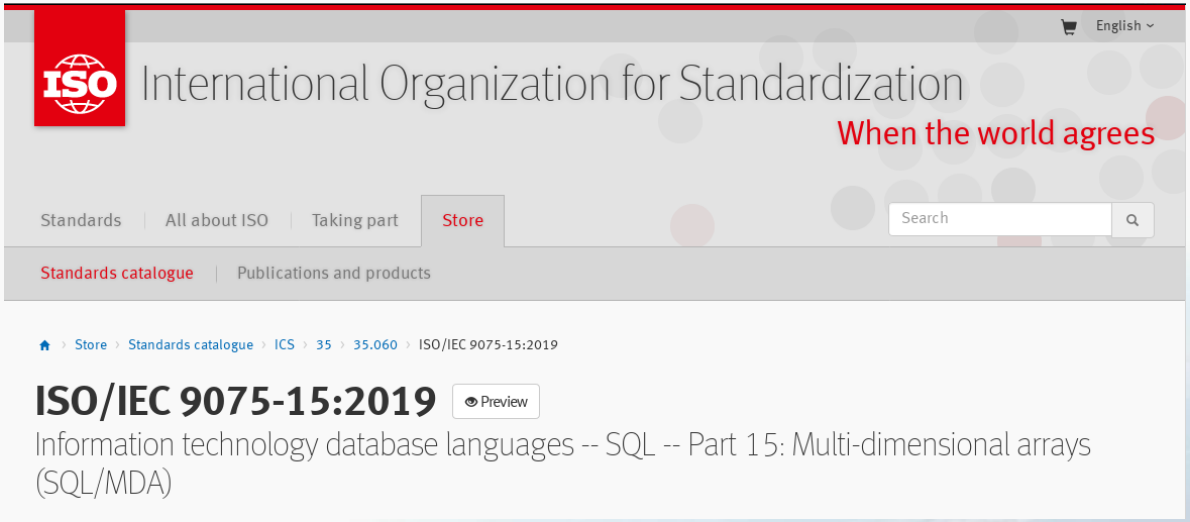
User-Defined Functins (UDFs)

- external code dynamically linked into server, callable from query
- UDF API = client API + auto-generated adapter → easy to use
- integrated with server-side tile management, parallelization, ...
- Ex: use OpenCV for histogram equalization on RGB image

```
select encode( cv.equalize_hist( c[0:999,0:999]/16) ), "png" )
from AGDC_2D as c
```

Standardization

ISO SQL/MDA




```
create table LandsatScenes(
   id: integer not null, acquired: date, scene: row( band1: integer, ..., band7: integer ) mdarray [ 0:4999,0:4999] )
```

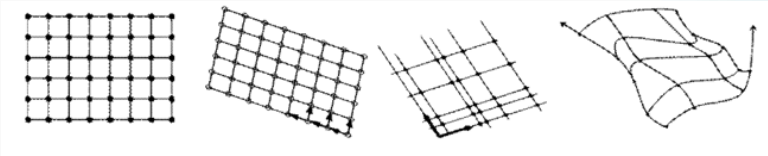
```
select  id, encode(scene.band1-scene.band2)/(scene.band1+scene.band2)), „image/tiff“ )
from    LandsatScenes
where acquired between „1990-06-01“ and „1990-06-30“ and avg( scene.band3-scene.band4)/(scene.band3+scene.band4)) > 0
```

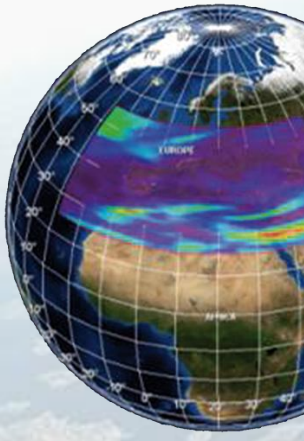
OGC WCPS: Space/Time Datacubes

- Web Coverage Processing Service (WCPS)
  - spatio-temporal datacube analytics language

```
A[ Lat(10.2),Long(8.4),date("2017-12-04")]
```

  - space & time, regular & irregular grids



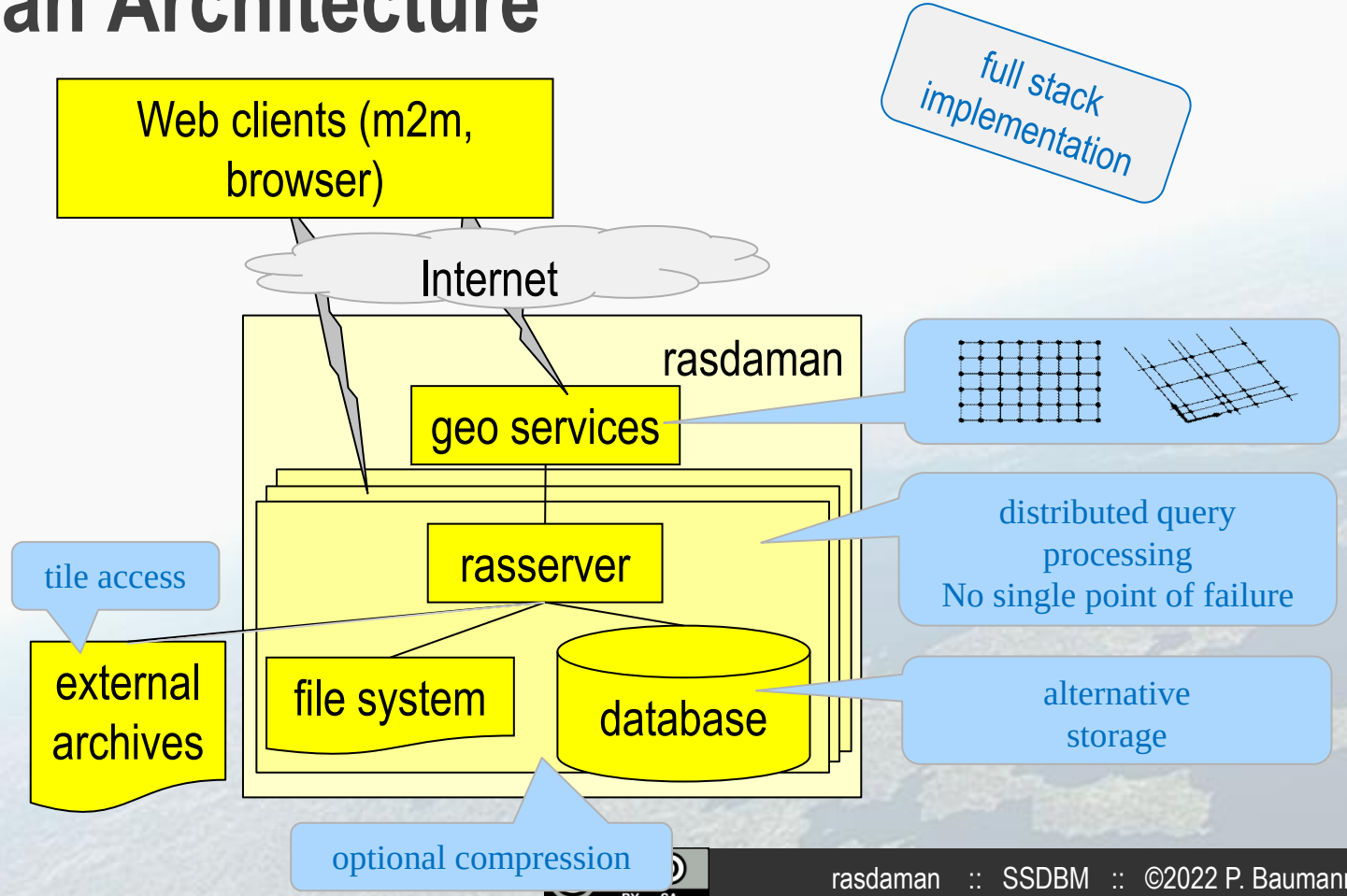


- "From MODIS scenes M1, M2, M3: difference red & nir, as TIFF"
  - "…but only those where nir exceeds 127 somewhere"

```
for $c in ( M1, M2, M3 )
where some( $c.nir > 127 )
return encode( $c.red - $c.nir, "image/tiff" )
```

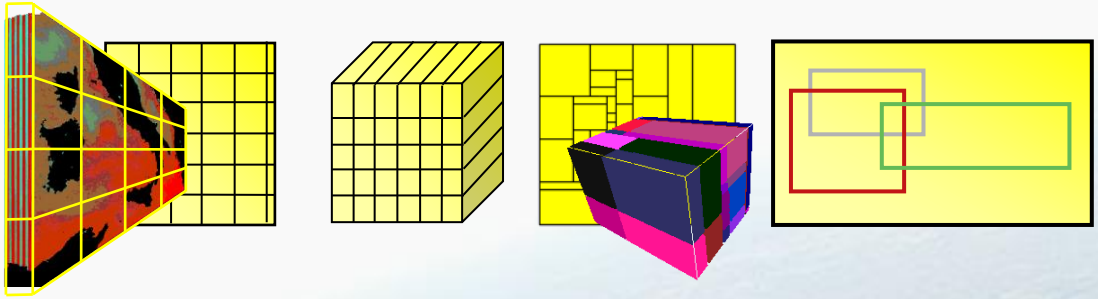
rasdaman 2: Architecture

rasdaman Architecture



Adaptive Partitioning („Tiling“)

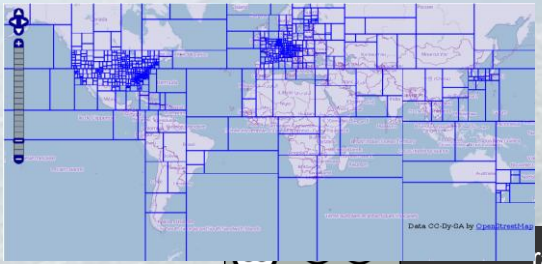
- Any tiling [Furtado 1999]
  - strategies



  - rasdaman storage layout language

```
insert into MyCollection
   values ...
   tiling
     area of interest [0:20,0:40], [45:80,80:85]
     tile size 1000000
     index d_index storage array compression zlib
```

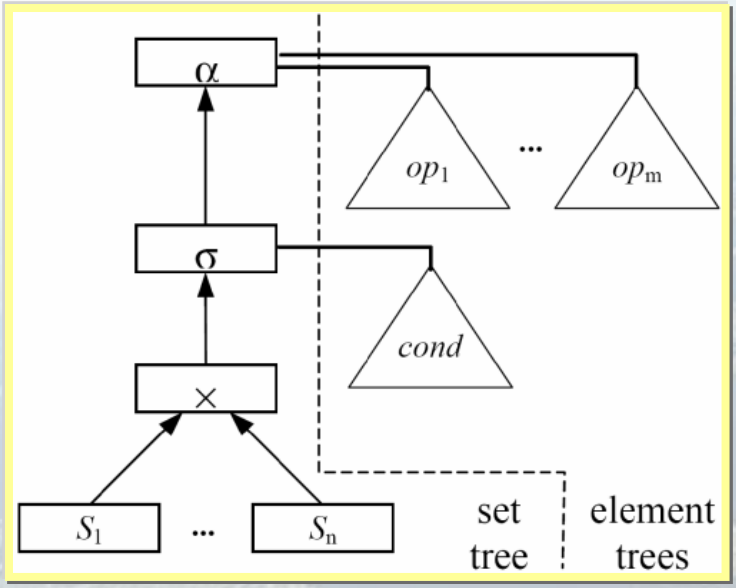
- Why irregular tiling?



[OpenStreetMap]

Array QL Embedding

- Clear separation
  - SQL set tree
  - Array attribute („element“) tree
- Cf: „array-as-table“ vs „array-as-attribute“

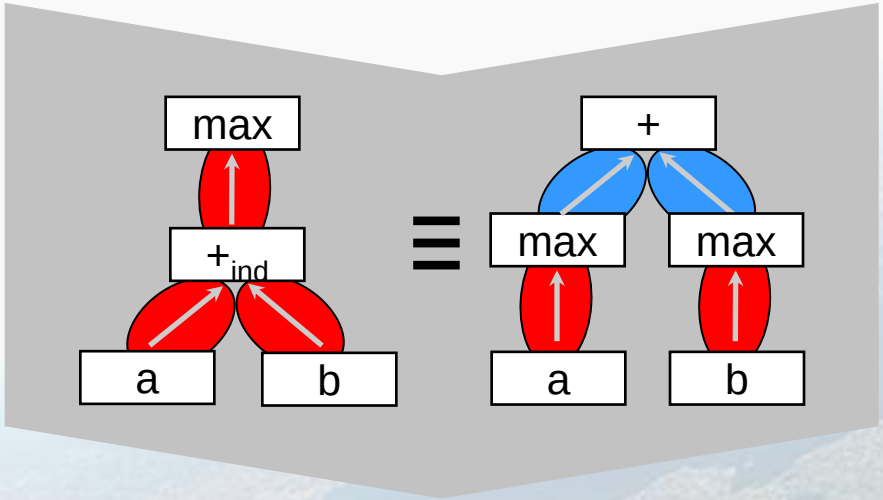


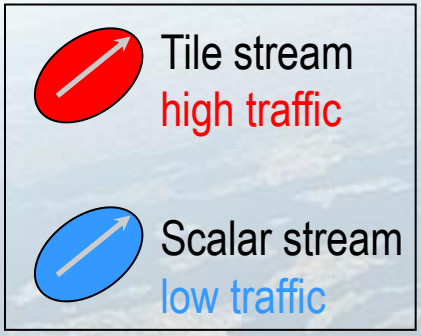
Sample Optimization: Query Rewriting

= find most efficient phrasing for given query

- Algebra based
- 150+ rules, ex:

```
select max_cells( a + b )
from   a, b
```

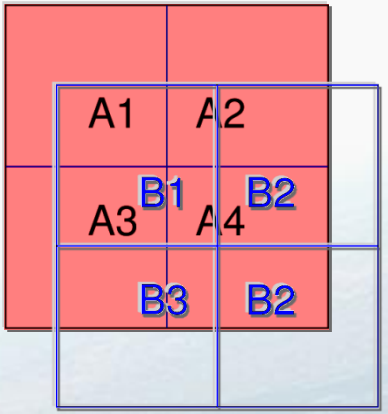




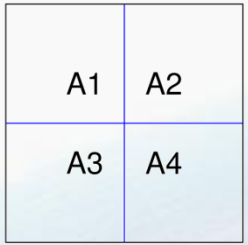

```
select max_cells( a ) + max_cells( b )
from   a, b
```

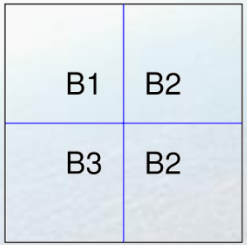
Array Joins

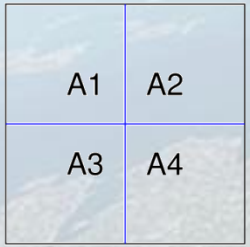
- „A θ B“ in presence of partitioned arrays A, B
  - Challenge: partitions shifted, different size, heterogeneous
  - → inefficient multiple reads of sub-arrays

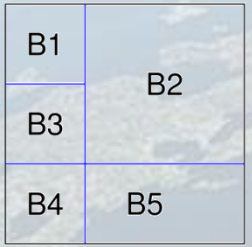


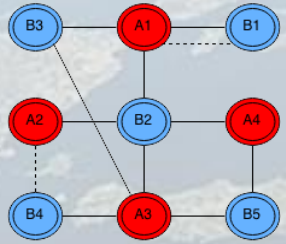
- Goal: optimal partition loading sequence
- Approach: bi-partite graph traversal [Baumann, Merticariu 2015]











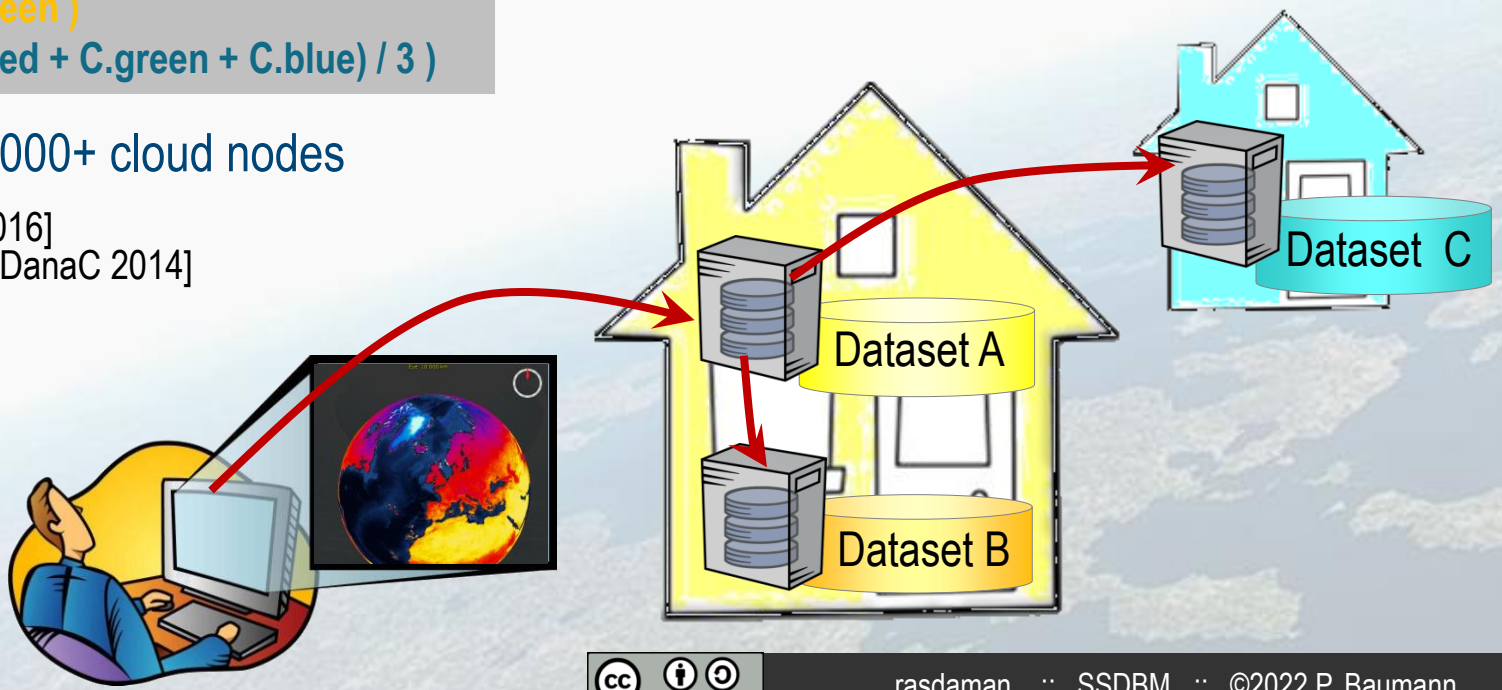
- Also useful for buffer mgmt, parallelization

Parallel, Distributed Processing: Query Splitting

```
  max( (A.nir - A.red) / (A.nir + A.red) )
+ avg( B.green )
+ max( (C.red + C.green + C.blue) / 3 )
```

1 query → 1,000+ cloud nodes

[VLDB BOSS 2016]
[ACM SIGMOD DanaC 2014]



Federation Demo

EarthServer

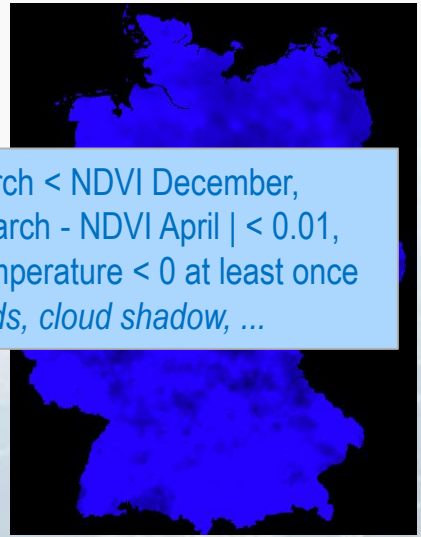
- datacube provider federation
  - 30+ PB location-transparent data space
  - Open standards, zero-coding
- Open, free, transparent, democratic
  - Open & private; free & commercial

https://earthserver.xyz

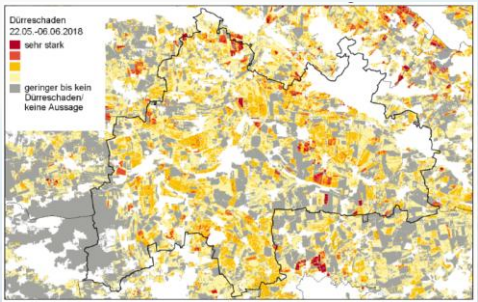
Projects

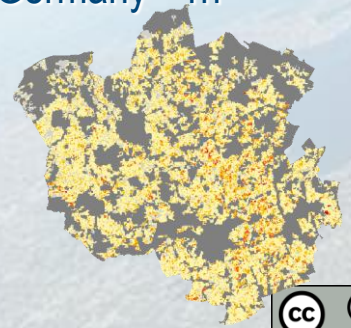
BigPicture

- Rule-based classification of field health, per crop type
  - In-field anomalies, frost, drought
  - complex criteria on timeseries: Sentinel-2a, CORINE land cover, soil data, climate water balance
  - WCPS → flexible, self-documenting
- Lead: Spatial Business Integration, Germany
- Using rasdaman in realtime; Germany ~1h



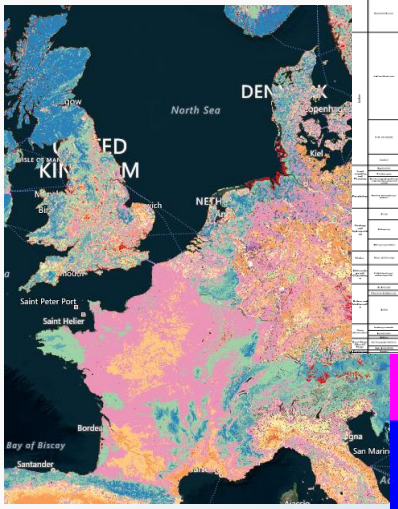
NDVI March < NDVI December,
| NDVI March - NDVI April | < 0.01,
winter temperature < 0 at least once
plus clouds, cloud shadow, ...



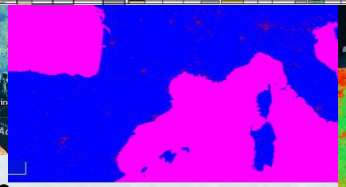


With support from
Federal Ministry of Food and Agriculture
by decision of the German Bundestag

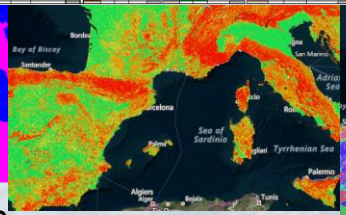
Analytics for Land Management



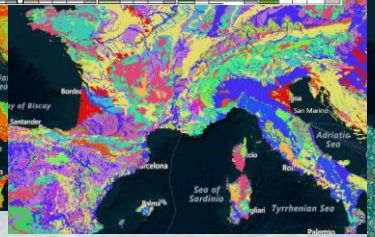
Soil organic carbon



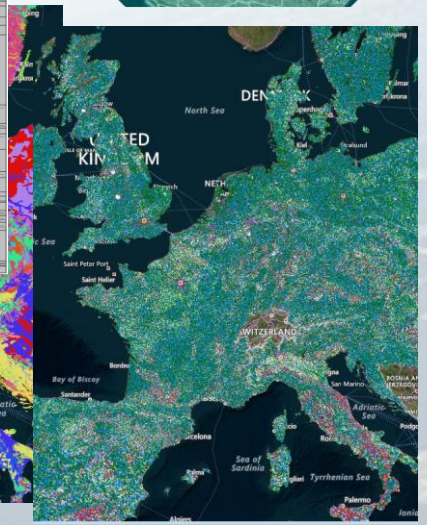
Imperviousness



Landslides susceptibility



Lithology



Soil erosion

https://landsupport.eu

Radio-Networks Planning

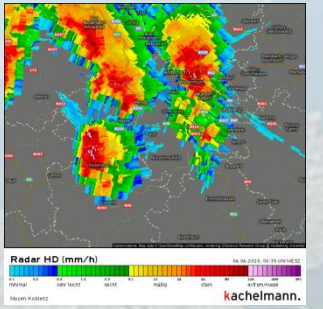
- Telefonica:
  Several 3D x/y/t datacubes
  of their German mobile networks
  - original resolution
  - space/time coverage analysis
- Analytics & marketing (!)

DeepRain: ML for Rain Forecast

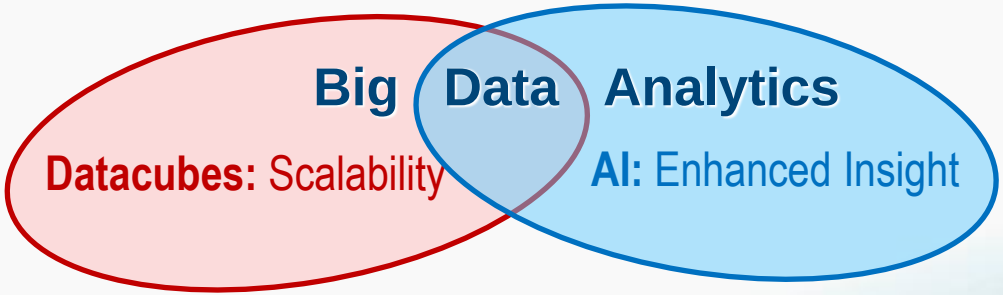
- Goal: improve rain prediction for mountaneous areas

- Approach: ML + Array DBMS
  - numerical weather forecast models
    + precipitation radar + lightning + station measurements + topography

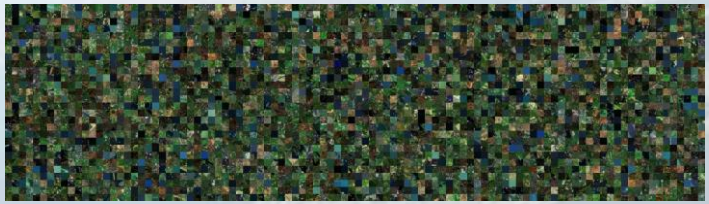
- Lead: Jülich Research Centre, Germany



AI-Cube

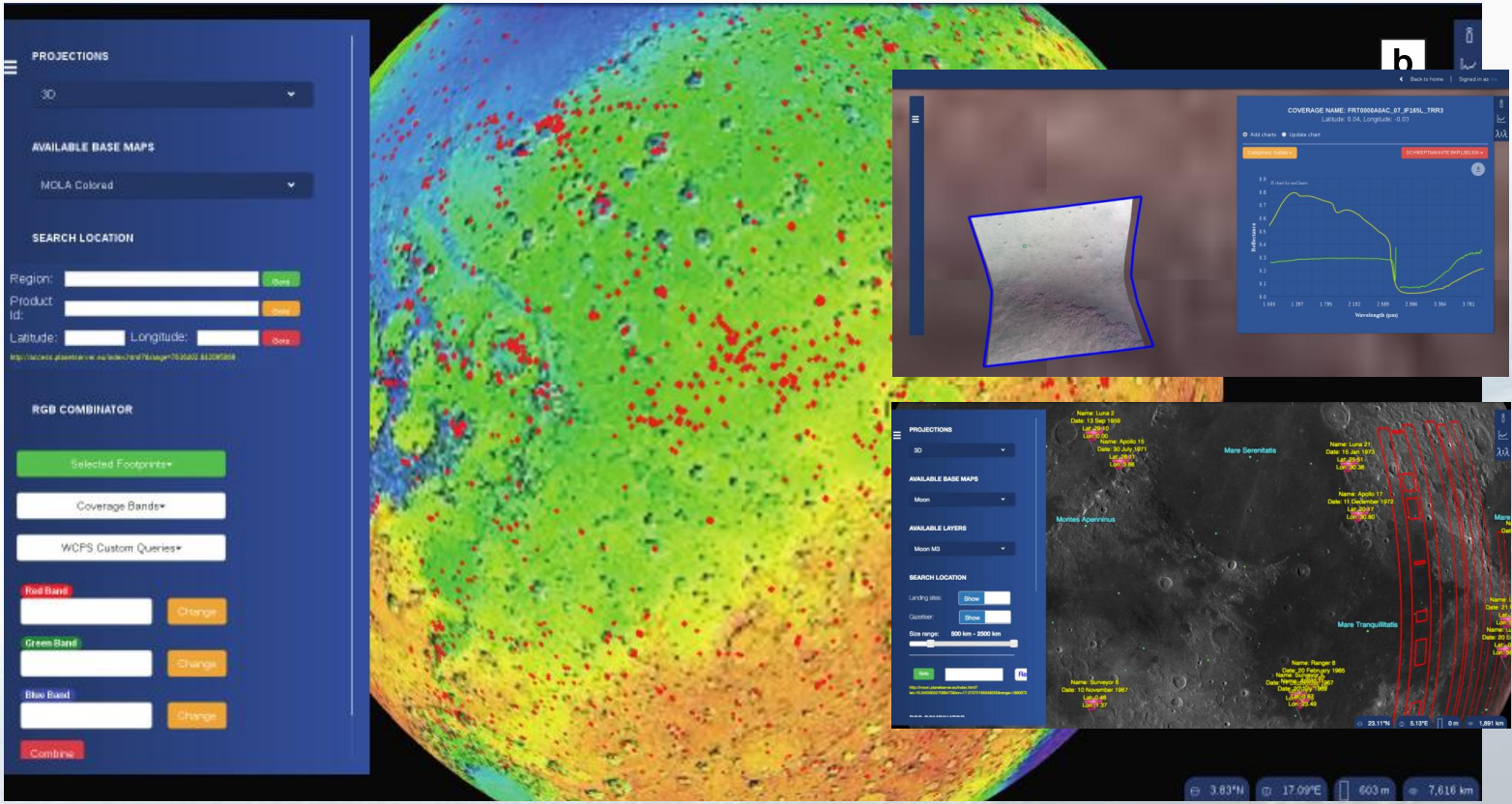


- Jacobs U, TU Berlin, rasdaman GmbH
- Selected challenges:
  - Huge training base: BigEarthNet http://bigearth.net, 590000 tagged S1/S2 patches
  - Query language + NLP integration
  - Space/time training, ex: 3D CNN
- User benefit: easier, faster, more flexible



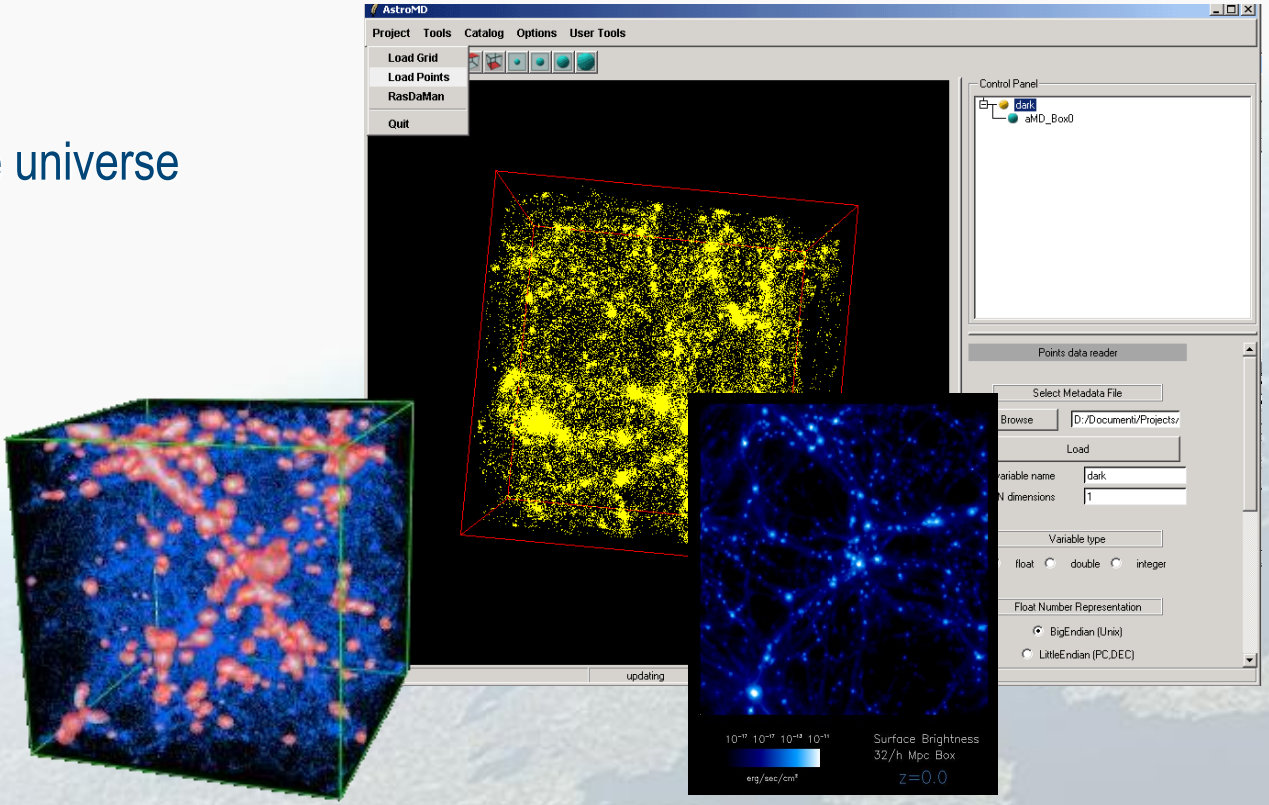
ai-cu.be

PlanetServer



Cosmological Simulation

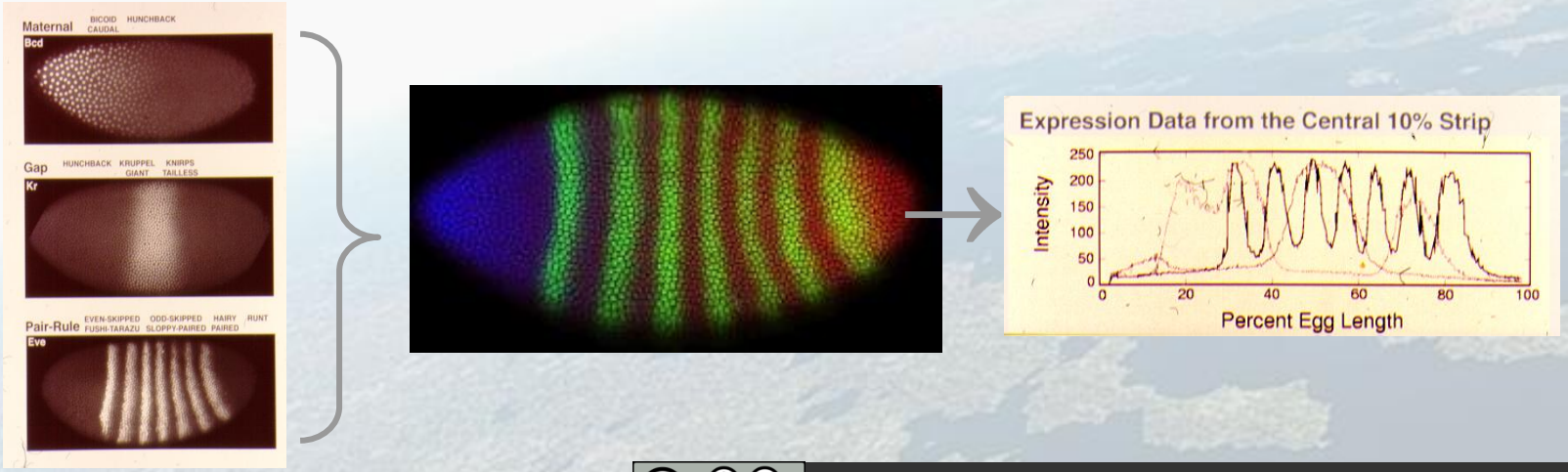
- 3D/4D regions from the universe
- Screenshots: AstroMD
  [Gheller, Rossi 2001]



Gene Expression Analysis

[Samsonova et al]

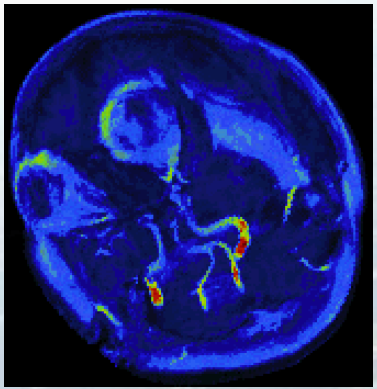
- Gene expression = reading out genes for reproduction
- Goal: capture spatio-temporal expression patterns in Drosophila genes

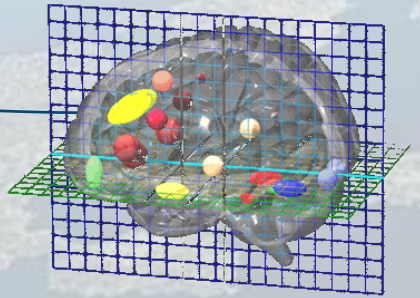


Human Brain Imaging

- Goal: structural-functional relations in human brain
- Experiments (PET, fMRI) → activation maps
- Ex: "*a parasagittal view of all scans containing critical Hippocampus activations, TIFF-coded*."

```
select tiff( ht[ $1, *:*, *:* ] )
from   HeadTomograms as ht,
       Hippocampus as mask
where  count_cells( ht > $2 and mask )
       / count_cells( mask )
       > $3
```





ORBiDANSe

= *Orbital Big Data Analytics Service*

- Big Data idea: „Process close to source“
  → datacube engine on satellite
  - Answer analytics = avoid full download
- rasdaman → ESA OPS-SAT
  - ARM 1-core, 1 GB, 16 GB

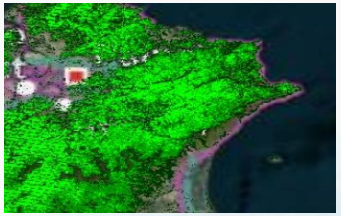
Supported by:
Federal Ministry for Economic Affairs and Climate Action

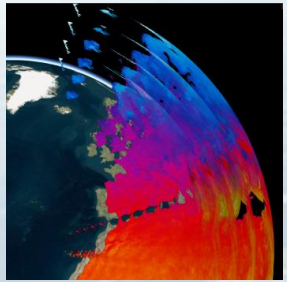
Conclusion

Conclusion & Outlook

- Arrays, aka datacubes, everywhere: science, engineering, business, ...
- Databases are primary Big Data tools – for management and analytics
- rasdaman: management & analytics = database approach
  - High-level datacube query language
  - DBMS goodies: Optimization, parallelization, distributed processing, federation, self-tuning
  - Performance competitive over silo solutions
- Ongoing research:
  - Array Database support for Machine Learning / Linear Algebra
  - Satellite swarm federations
  - Optimization
  - *...and more*

Selected Further Projects





- Societal Benefit:
  - AgriCube (Germany / Taiwan): climate & vegetation analytics
  - DeepRain (FZ Juelich): ML for Improved local rain prediction for mountaneous areas
  - DynAWI (JKI): Weather Indicators for Extreme Weather Forecasts in Agriculture
  - LANDSUPPORT (U Napoli): Land Management
- AI:
  - AI-Cube (TU Berlin): space/time CBIR
  - ML-Cube (NASA): ML on US/EU federated sat datacubes
  - CENTURION (OPT/NET): AI Knowledge Packs on Datacubes