3 things your robot should know

Rob Seaman
NOAO Science Data Management
Telescopes from Afar
Kohala, HI, 1 March 2011
(Decided to go with Doctor Seuss rather than Doctor Asimov)
Autonomous Infrastructure

1. *What time is it?*
   UTC to be redefined != GMT

2. *How to talk to humans*
   Robotic telescopes funnel data to humans

3. *How to talk to other robots*
   Celestial transient alerts with VOEvent
This talk is dedicated to Father Edward Jenkins, OSA who taught generations of Villanova students the history of Astronomy
1. What time is it?
Pop quiz!

Who recognizes these clocks?
Longitude prize

Harrison’s clock, H1, failed to allow for centrifugal force as ships tacked

(but invented roller bearings & bimetalic temperature compensation)

H4, won the prize by allowing for the inevitable rate error

(also way ahead of its time in the concept of miniaturization)
A goal of this talk

To sound the alarm

UTC is being redefined

UTC != GMT
What would this mean?

• Resets all the clocks in the world
  – no longer the solar (synodic) rate
  – wait long enough and day turns into night

• Astro software is canary in the coal mine
  – 1 sec of time = 15 sec of arc (equator)
  – *very* large expense

• No plan for future adjustments
  – Leap hours?
  – Kaleidoscopic time zones?
Whose decision?

- *Not* the IAU (Time = Comm 31)
- Rather, ownership of UTC is asserted by the International Telecommunications Union
- The IERS (International Earth Rotation and Reference Systems Service) issues leap seconds
Change is one vote away

From: "Matsakis, Demetrios" matsakis.demetrios@usno.navy.mil
Date: October 22, 2010 9:43:30 AM MST
To: Leap Second Discussion List leapsecs@leapsecond.com
Subject: [LEAPSECS] UTC Redefinition Advanced

• “I have now heard from two sources that the revised ITU-R draft recommendation TF.460-6 passed a major hurdle in Geneva last week.
• It will be sent by SG7 to the January 2012 Radiocommunication Assembly meeting. […]
• I presume it calls for the elimination of all future leap seconds after several (5?) years notice.”
UTC was our default time scale

• UT has been the “general equivalent” of GMT
• | UTC – UT1 | < 0.9s very likely to change!
• Precision time community has been seeking a fundamental change to UTC since before Y2K
• Final vote pending in the International Telecommunications Union (ITU)
• Astronomical projects should evaluate alternatives
A Brief History of Time

• The Dawn of Time:
  – Apparent Solar Time
  – Unit = “day”
  – naturally begins at dawn

• Analemma (gr: “sundial”)
  – Sun’s position at the same time-of-day over a year
What is time-of-day?

- **Mean Solar Time**
  - Clocks mark the hours
  - Begins at noon
    - when Sun transits meridian

- **The Equation of time** is the difference between apparent & mean time (same thing as analemma)

Equation of Time due to obliquity of ecliptic and orbital eccentricity – K. Heidom

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Greenwich Mean Time & Longitude

- Latitude = altitude of Sun
- Longitude = time at home
- Prime Meridian provided interoperability in 1884
- Also established Standard Time Zones
- Day begins at midnight

Prime Meridian, Greenwich – M. Reeve
Synodic Day vs Sidereal Day

- Actual day = 23h56m4s
- Actual year = 366.25 days
- Minus 1 day for lapping Sun
Atomic Time

- TAI (International Atomic Time) is a weighted mean of a worldwide ensemble of “atomic” clocks
- The UTC and GPS time scales are derived from TAI
- After redefining UTC, notion is to “suppress” TAI

“Day, n – A period of twenty-four hours, mostly misspent.” – Ambrose Bierce
So how long is a Day?

- Sidereal days are constant length
- Each solar day differs slightly
- Daily residuals accumulate as Equation of Time
- Daily millisecond level epsilon due to 1820 SI epoch
- \( \varepsilon \)'s accumulate as Leap Seconds
Length of Day – Long Term Trend

- Earth and Moon coupled tidally
- As Earth slows, lunar orbit grows ~ 1 mile radius per 1 SI-second increase in LOD
- Need for leap seconds grows quadratically
Time requirements in astronomy

- Many reasons like:
  - The time domain is a key use case for automated observing systems
  - Robotic telescopes need reliable clocks
  - Robotic telescope networks need a coherent standardized timekeeping paradigm
Timekeeping is changing

• UTC is very likely to be redefined
  – No leap seconds
• Significant cost to retrofit software & systems
  – Will dwarf Y2K efforts
• Opportunity to embrace evolving IAU vision on coordinate systems
• Current projects should proactively accommodate projected standards
2. How to talk to humans...
...Efficiently

• Compression (near-optimal representation)
  – Minimize likelihood for misunderstanding
  – Robust against (inevitable) corruption

• Standardized metadata

• Human engineering requirements
  – Robotic telescope networks *emphasize*, not eliminate these
...Efficiently

- Compression (near-optimal representation)
  - Minimize likelihood for misunderstanding
  - Robust against (inevitable) corruption

- Standardized metadata (Thing Three)

- Human engineering requirements
  - Robotic telescope networks 
    *emphasize*, not eliminate these
...Efficiently

• Compression (near-optimal representation)
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• Standardized metadata (Thing Three)

• Human engineering requirements
  – Robotic telescope networks emphasize, not eliminate these

• LEGO Demo
Observing creates data

• Both humans and robots benefit from:
  – **Efficient representations**
    • data compression
  – **Hierarchical organization**
    • FITS tile-compression (*FPACK*) & multi-extension files (*MEF*)
    • WWT TOAST (*HTM*)
      – Tessellated Octahedral Adaptive Subdivision Transform
    • HEALPix (*FITS HPX*)
      – Hierarchical Equal Area isoLatitude Pixelisation
  – **Standardization**
A goal of this talk

To convince you:

Compression != Voodoo
Compression insights gained

• Through an ongoing collaboration with Bill Pence (NASA/GSFC) & Rick White (STScI)

• And informed by cogent (if sometimes obscure) contributions in the literature
It *isn’t* about optimization

- The goal of system engineering is rather to *satisfice* an *adequate* solution

- The efficiency of the process of finding a solution matters, not just the efficiency of the solution that is found

- Stealing a solution is very efficient
  - Please, steal FPACK
Don’t use gzip...blindly

![Graph showing NEWFIRM compression with a 29% improvement in 32-bit int pixels.](image)
Think throughput

• Storage savings are important, but

• Compression also widely benefits:
  – Data transport
  – Data handling
  – Data access

• Speed matters, too!
Just a 15% improvement in network throughput and storage efficiency is the same as eliminating the overhead of one whole copy of the archive and the perpetual latency of one replication leg.
FITS tile compression

• FITS Convention v2.1, 2009
  – ADASS 1999 (*Pence, White, Greenfield, Tody*)
  – Interoperates with **FITS Checksum convention** (1994)

• Images mapped onto FITS binary tables
  – Supports multiple compression algorithms
  – First & every copy can be compressed

• Tiling permits rapid RW access

• Headers remain readable
Rice algorithm

• Fast (difference coding)
  – near optimum compression ratio
  – throughput is key, not just storage volume

• Numerical, not character-based like gzip

• Depends on pixel value so
  \[ \text{BITPIX} = 32 \]
  compresses to same size as
  \[ \text{BITPIX} = 16 \]
CFITSIO / FPACK

- \textcolor{red}{http://heasarc.gsfc.nasa.gov/fitsio/fpack}\textcolor{black}{k}

- Fpack can be swapped in for gzip and funpack for gunzip

- But library support (CFITSIO) provides Jpeg-like access
  - compression built-in
  - Read/write directly
IRAF and community software

• Tile compression can & should be supported by all software that *reads* FITS

• Instrument and pipeline software may benefit strongly from *writing* compressed FITS

• Transport & storage always benefit

• IRAF fitsutil package released
  – new IRAF FITS kernel next
“Data” are not generic

• Astronomical data are specific to astronomy:
  FITS arrays = images
  – of astrophysical sources
  – taken through physical optics
  – recorded by physical electronics
  – digitization constrained by information theory
  – with a distinctive noise model
The ubiquity of noise

• Noise is incompressible

• Signals are correlated (often with high redundancy)
  – physically
  – instrumentally

• Shannon entropy: $H = - \sum p \log p$
  – depends only on the probabilities of the states
  – measures “irreducible complexity”
Compression correlates closely with noise

Distinctive functional behavior

For three very different comp. algorithms

For flat-field and bias exposures as well as for science data

That is, for pictures of:
- the sky
- a lamp in the dome
- no exposure at all

Signal doesn’t matter!
The sparsity of celestial signals

• For most astronomical data, compression ratio depends only on the background noise
  – Sparse signals are negligible (even if transformed)
  – Noise is incompressible

\[ R = \frac{\text{BITPIX}}{N_{\text{bits}} + K} \]

K is about 1.2 for Rice

where \( N_{\text{bits}} = \log_2 (\sigma \sqrt{12}) = \log_2 (\sigma) + 1.792 = H \)
A better compression diagram

R = \frac{\text{BITPIX}}{N_{\text{bits}} + K}

Effective BITPIX:

\text{BIT}_{\text{EFF}} = \frac{\text{BITPIX}}{R}

\text{BIT}_{\text{EFF}} = N_{\text{bits}} + K

Line with:

Slope = 1

Intercept = K
Rice output is same size whether input is 16-bit or 32-bit.

GZIP is 20% larger than 16-bit Rice, but 57% larger for 32-bit data.

Solid lines are synthetic data with \( N_{\text{bits}} \) of uniform random noise. Symbols are data with \( N_{\text{bits}} \) equivalent gaussian noise.
Speed matters

Pack time relative to Rice

Unpack time relative to Rice

(GZIP means tiled “gzip -1”)

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Lossy compression

• What does this mean?
  – “lacking idempotency”
  – i.e., repeated operations aren’t conserved/reversable

• But what does it mean for astronomical data?
  – Only technically lossy if original representation is artificially precise
  – Really a question of proper data representation
  – of rounding to preserve appropriate precision

• Subsequent copies can be idempotent
FPACK “q factor”

• Requantize pixel values
  – Bin into levels proportional to noise
  – q bins per sigma

• Equivalent in recent papers from JDEM team (Bernstein, et al.) and astrometry.net (Price-Whelan & Hogg) is $q = 1$
  – Kepler telemetry uses $q \sim 1.15$

• Default for FPACK is conservative $q = 4$
Quantization is well understood

Fig. 1.— Relationship between the compression ratio and the fractional increase in the background noise in an image containing Gaussian-distributed noise for a range of q quantization parameter values.
R is completely determined by q

\[ R = \text{BITPIX} / (N_{bits} + K) \]

\[ N_{bits} = \log_2 (\sigma) + 1.792 \]

but: \( \sigma = q \) after requantization

\[ R = \text{BITPIX} / (\log_2 (q) + 1.792 + K) \]

\[ R \sim \text{BITPIX} / (\log_2 (q) + 3) \quad \text{for Rice} \]

\[ R \sim 6.4 \quad \text{for } q = 4 \]

\[ R \sim 10.6 \quad \text{for } q = 1 \]
Proper rounding uses dithering

Note the bias introduced by binning without proper dithering "Sheppard's correction" = sqrt (1/12)
Subtractive dithering

“Quantization Noise”, Widrow & Kollár:

“When the input to a quantizer cannot be relied upon to meet the criteria for a suitable quantizing theorem, a dither signal can be added to the quantizer input to guarantee satisfaction. Although the dither is beneficial in that it linearizes the quantizer and ensures known properties for the quantization noise, it does make the quantizer output more noisy. A clever idea was proposed by Roberts (1962) to overcome this drawback. He added a dither to the quantizer input, and subtracted it from the quantizer output. The dither thus acted like a catalyst in a chemical process, making the process work better but not appearing in the process output. Roberts’ subtractive dither idea should be used whenever it is possible.”


FPACK dithering strengthens the case for aggressive lossy compression from Kepler, astrometry.net & JDEM
See References within:


OK, maybe a little voodoo...
Recent work

• Proposed FITS convention extending tile-compression to binary tables (eg, catalogs):
  – Transpose into column-major format
  – Improved gzip-based algorithm
  – Usually requires lossless handling
  – Data-type logistics

Shuffling bytes with gzip

- Blue is normal gzip
- Green is shuffled
  - group low bytes separate from high
- Remains slow
CFITSIO v3.27 / FPACK v1.6 update

From Bill Pence:

• Beta support for binary table compression

• Shuffled gzip (for images, too)

• Improved (very conservative) noise estimation for lossy floating-point mode

• Improved NaN handling

• MEF keyword logistics

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Be there or be square

• FITS tile-compression is used or evaluated by:
  – LSST, Pan-STARRS, DES, ODI, NOAO, CADC, ...
• Requantization by:
  – Kepler, astrometry.net, WFIRST \textit{(JDEM)}, NHPPS, ...

\texttt{http://heasarc.gsfc.nasa.gov/fitsio/fpack}
3. How to talk to other robots
A goal of this talk

Reading assignment

*Hot-wiring the Transient Universe 3 in 2012*
VOEvent Architecture

SkyAlert & LSST/CRTS iPhone App

- Registry Interface
- Vocabularies
- STC
- Units
- UCDs
- Resource Identifier
- VOTable
- VOEvent

Simple Event Access Protocol

TCPV, XMPP, ...

Open Source Broker/clients (Bob Denny)

LEVEL 0.5

VOEventStreams

Autonomous Workflows

SimpleTimeSeries

v2.0 (consensus-building)

v2.0 (consensus-building)
VOEvent v2.0 (*draft in progress*)

- SimpleTimeSeries in `<What>`
- STC Orbital Elements in `<WhereWhen>`
- More general external `<References>`
- Datatypes & rich strings for `<Params>`
- More expressive inferences in `<Why>`
- Benefit from vocabularies
- Ruggedized schema
What is VOEvent?

• “VOEvent defines the content & meaning of a standard information packet for representing, transmitting, publishing & archiving the discovery of a transient celestial event, with the implication that timely follow-up is being requested.”
What is VOEvent?

• “VOEvent defines the content & meaning of a standard information packet for representing, transmitting, publishing & archiving the discovery of a transient celestial event, with the implication that timely follow-up is being requested.”
Why VOEvent?

Messaging you need to know about

ASAS  ATEL
GCN  OGLE  IAUC
TALONS  SNEWS
CBAT  GMAN
AAVSO  EROS
NOVALERT  EWS
VSNET  AstroAlert
SN Neutrino Alert Net

VOEvent
VOEvent

- Who
- What
- Where
- When
- How
- Why
VOEvent

- **Who** – author’s provenance
- **What**
- **Where**
- **When**
- **How**
- **Why**
VOEvent

- Who – author’s provenance
- What – empirical measurements
- Where
- When
- How
- Why
VOEvent

- Who – author’s provenance
- What – empirical measurements
- Where – targeting in space
- When – constraints in time
- How
- Why

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VOEvent

• Who – author’s provenance
• What – empirical measurements
• WhereWhen – targeting in spacetime
• How
• Why
VOEvent

- **Who** – author’s provenance
- **What** – empirical measurements
- **WhereWhen** – targeting in spacetime
- **How** – instrumental signature
- **Why**
VOEvent

- **Who** – author’s provenance
- **What** – empirical measurements
- **WhereWhen** – targeting in spacetime
- **How** – instrumental signature
- **Why** – scientific characterization
VOEvent is XML

<Why importance=“1.0” expires=“1574-05-11T12:00:00”>
  <Inference probability=“1.0”>
    <Name>Tycho’s Stella Nova</Name>
    <Concept>stars.supernova.Ia</Concept>
  </Inference>
  <Inference probability=“1.0” relation=“associated”>
    <Name>3C 10</Name>
    <Concept>ISM.SNRemnant</Concept>
    <Description>Supernova remnant</Description>
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1 March 2011
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Semantics & ontologies
VOEvent is XML

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Engineering for empirical workflows
Follow-up with citations

<Citations>
   <EventIVORN cite="retraction">
      ivo://uraniborg.hven#572-11-11/0001
   </EventIVORN>
   <Description>Oops!</Description>
</Citations>
Follow-up with citations

• Use citations for:
  – Chaining follow-up observations
  – Retracting events
  – Splitting streams of events
  – Joining streams of events
• Use <references> for external content
For example...
Getting VOEvents

• Publish / subscribe

• Roy Williams and Bob Denny:

  http://skyalert.org

  http://voevent.dc3.com
Special Bonus Thing!

4. How to talk to humans about robots
A goal of this talk

Make sure the audience remembers the other 3 things
People like toys

People understand models
The Future Evolution of Alvin

• More complex behaviors
• Networks of telescopes
• Interface to WWT via Ascom
  – with Jonathan Fay
• Optics?
• Instrumentation?
• Instructions?
• Kits?
Summary

1. *What time is it?*
   UTC to be redefined != GMT

2. *How to talk to humans*
   Robotic telescopes funnel data to humans

3. *How to talk to other robots*
   Celestial transient alerts with VOEvent
For further information

1. What time is it?
   http://www.ucolick.org/~sla/leapsecs

2. How to talk to humans
   http://heasarc.gsfc.nasa.gov/fitsio/fpack

3. How to talk to other robots
   http://voevent.org
The final goal of this talk

Advertise IAU 285:

New Horizons in Time Domain Astronomy

September 19-23, 2011
Oxford, UK
Bye!