# Progress Through Decay

## Some remarks on Outer Solar System RPS Needs

**Ralph D. Lorenz**
Johns Hopkins University
Applied Physics Laboratory,
Laurel, MD. USA
Ralph.lorenz@jhuapl.edu

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Key Points (1) : Solar vs RPS

**Energy = Data**. Beyond ~1AU science energy data transmission cost exceeds data acquisition cost (not just cameras, radars too). No amount of fancy electronics can beat that. Data return determines overall mission energy needs. Beware cubesats!

Radioisotope Power Systems (RPS) provide useful ‘waste’ heat, avoids expenditure of energy on heaters. This is very important for Titan in-situ missions (and enables Montgolfieres) but also important for other mission concepts.

Solar Watts and RPS Watts are not interchangeable. Solar must book-keep battery plus power for fault recovery, eclipses etc.

Solar power means shorter lifetime/higher orbit for Titan orbiters (drag).

Large arrays introduce ACS challenges (e.g. array flexing modes/instrument pointing stability ; vulnerability to small asymmetries in deployment, exposure to gravity gradient torques etc.)

**Bottom line : the devil is in the details !**

Key Points (2) : What Kind of RPS ?

Beginning of Mission (BOM) Power is **irrelevant**. Transit time beyond Jupiter >5 years : degradation of power converter is important (e.g. MMRTG is relatively poor in this respect) beyond decay of heat output of Pu fuel.

Waste heat is good, but you can have too much of a good thing : low conversion efficiency of thermoelectrics vs Stirling imposes a large burden of waste heat, requiring e.g. pumped fluid loops to reject heat from entry shell.

Rejected heat on in-situ missions will perturb environment. E.g. for low MMRTG efficiencies on Titan lander, need canted meteorology mast to avoid compromising wind measurement.

(Although, Titan Montgolfiere is enabled by abundant waste heat)

High specific power (likely unattainable by thermoelectrics) is enabling for Titan heavier-than-air vehicles.

Magellan

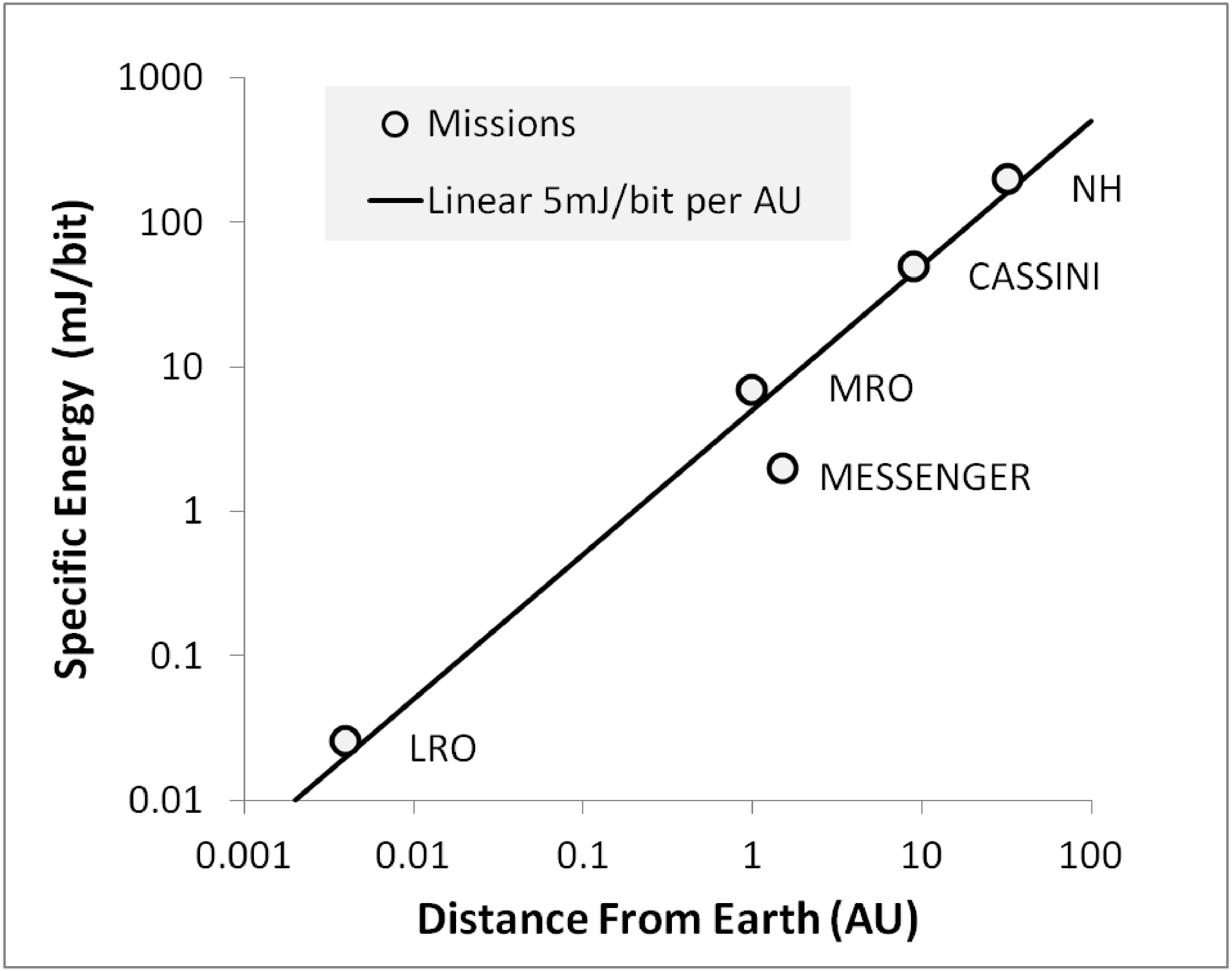
1100 W solar panels.  ~ 1 AU distance, warm conditions, High Gain

Acquires data with 400W radar at 806 kbps   (i.e. ~ 0.5 mJ/bit to obtain science data)

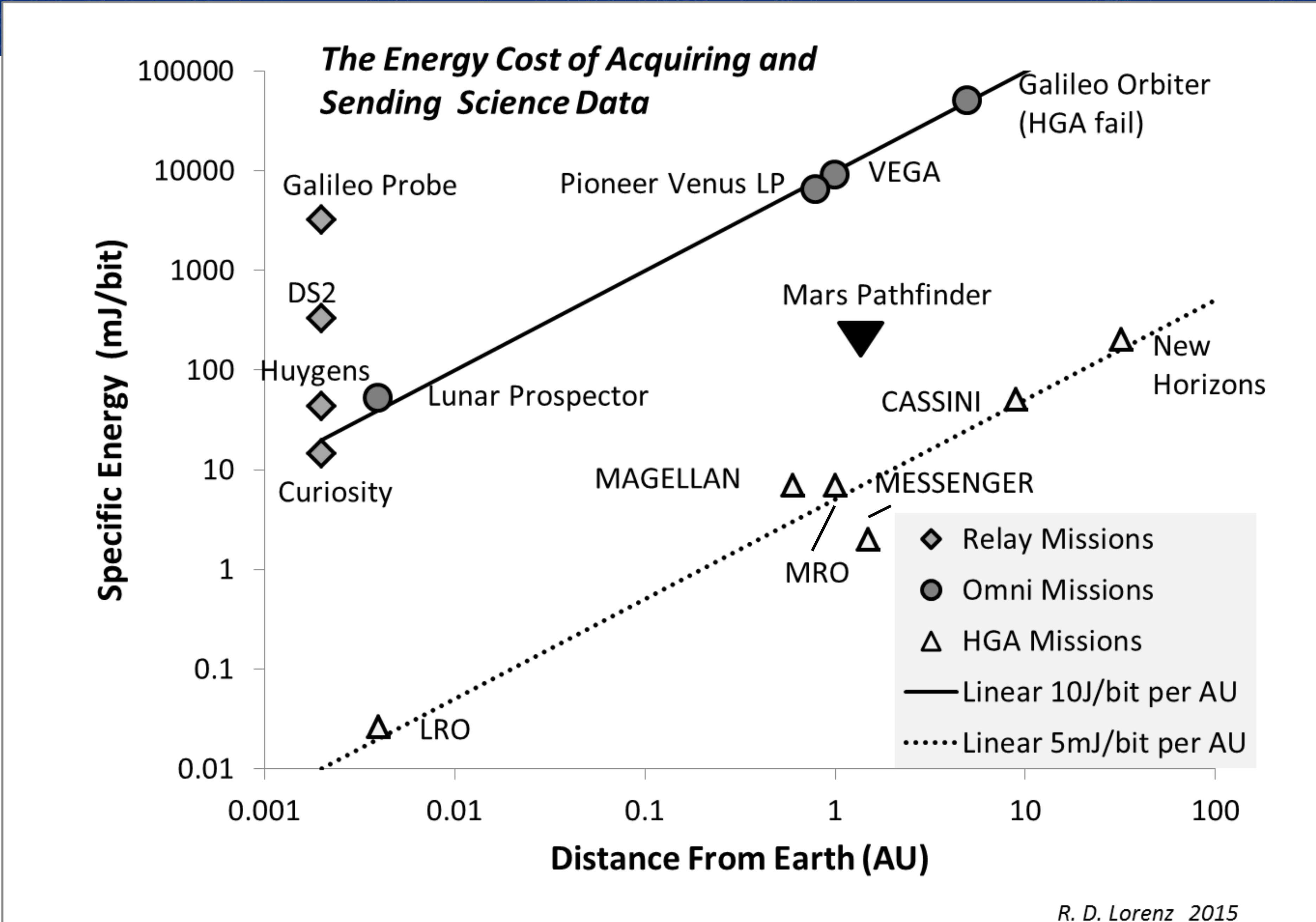
Transmits ~1.8 Gbit data to Earth at 268 kbps for ~2 hours per 3-hr orbit

Hence end-to-end demand is  12 MJ per 1.8 Gbit, or  7 mJ/bit

Even with a radar, the acquisition cost is a relatively small part of the total.




Spacecraft with High-Gain Antennas. Surprisingly linear dependence of specific energy with distance



The Energy Cost of Acquiring and Sending Science Data
Specific Energy (mJ/bit)
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Distance From Earth (AU)
Galileo Orbiter (HGA fail)
Galileo Probe
Pioneer Venus LP
VEGA
DS2
Mars Pathfinder
Huygens
Lunar Prospector
New Horizons
CASSINI
Curiosity
MAGELLAN
MESSENGER
MRO
LRO
Relay Missions
Omni Missions
HGA Missions
Linear 10J/bit per AU
Linear 5mJ/bit per AU
R. D. Lorenz 2015

# Conclusions

For most mission concepts, the overall energy/bit is dominated by telecom, captured empirically (and surprisingly well) by linear 10d J/bit for omni platforms, and 5d mJ/bit for HGA platforms, where d is the Earth-spacecraft distance (AU). Conversely, electrical energy limitations translate into data limitations.

This relationship may succinctly inform expectations regarding planetary 'cubesats' (limited in HGA size and energy) and serves as a guide to Radioisotope Power Systems needs

At Titan (10AU) energy for an HGA is 50 mJ/bit, 100 J/bit omni. MGA would be ~ geometric mean, or ~ 2J/bit, pretty close to end-to-end Titan mission studies (1 J/bit – Lorenz, J. Brit. Interplan. Soc., 2000)

Acquisition costs are generally tiny for remote sensing (~uJ/bit). Even for radars, costs are typically <mJ/bit

In-situ instruments for compositional analysis can be significant (~J/bit), although typically overall data volumes may be modest.

Energy Needs for Outer Solar System Missions – Quick and Dirty

New Horizons SSR 64 Gbit
Cassini Flybys ~ 3 Gbit each
Mars Express ~ 3 Gbit/day

So - spacecraft at Uranus (say) at 20 AU - HGA 5mJ/bit/AU = 0.1 J/bit
30 Cassini-like flybys of satellites, maybe 100 Gbit total.
So 10 GJ (1e10 J, 2.7 million W-hr). Spread over 2 years (6e7 s) means ~200 W (within a factor of 2 or so). Less power than this will mean less data !

Titan orbiter mapping - Titan is 83 million km$^2$. Near-IR Map at 50m/pixel means 3e10 pixels. Say 3 colors, 8 bit/pix, say compress by 4:1 = 6 bit/pix = 2e11 bits. At Titan HGA, ~0.05 J/bit, so again, total 10 GJ. Again, ~200W lets you do this in ~2 years.

Lower energy costs at Jupiter (x2) and higher solar flux at Jupiter ( another x4) mean missions at Saturn and beyond demand an order of magnitude more solar array area for a given data return !

Titan Orbiter – Drag Lifetime.
A Titan orbiter would be a strong candidate of NF-class mission. Could it be solar?

Solar Flux at Titan ~14 W/$m^2$. Say 50% efficiency (v. optimistic) then for 200W demand, need ~30$m^2$ of array*. For a 500kg vehicle that means ~16kg/$m^2$ ballistic coefficient (cf 100-1000 for typical spacecraft without arrays)

Roughly speaking , orbital lifetime of >1 year means <0.1km/day orbit contraction at start, thus atmospheric density of 1E-11 kg/$m^3$ (order of magnitude less than experienced for aerobraking), encountered at ~1300-1500km altitude. (Some science in dawn/dusk orbit, arrays edge-on? But not composition: phase angle!)

A more compact vehicle with RPS can orbit ~2 scale heights lower : better near-IR imaging, better radar, better magnetic fields, better gravity, more chemistry….

Large arrays (4x bigger at Saturn than Jupiter for same power, 8x bigger for same data..! ) present issues of gravity gradient torques ; possible asymmetries could cause solar radiation pressure torques. Flexing (jitter) issues (beam loading theory – deflection ~$L^4$)

**All these are issues that are *theoretically* tractable. But beware of claims of feasibility (cost/risk) unless they have been analyzed in detail !**

Exp Astron
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ORIGINAL ARTICLE

# AVIATR—Aerial Vehicle for In-situ and Airborne Titan Reconnaissance

## A Titan airplane mission concept

Jason W. Barnes · Lawrence Lemke · Rick Foch · Christopher P. McKay ·

Concept explored for Discovery-10

2 ASRGs – continuous flight, DTE

~115kg aircraft
Flight speed ~6 m/s

Original idea was fixed airframe : evolved for wings to make one fold from entry vehicle

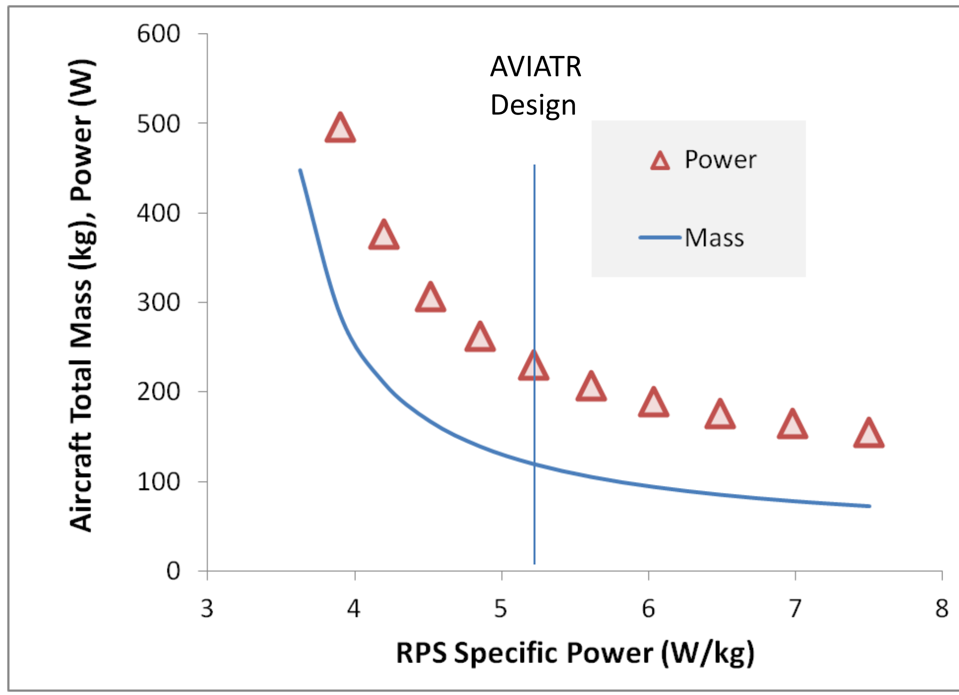
Simple Parametric Model anchored to AVIATR specs (assumes same flight speed)

$M = M_{payload} + M_{gubbins} + M_{power}$
$M_{payload}$ = 31 kg (includes HGA, IMU, autopilot etc.)
$M_{gubbins} \sim 1.0 * M_{power}$ (wings, harness, actuators, motor, etc.)
$M_{power} = P / S$, S is specific power in W/kg
Propulsive Power ~ 1.6 M (180 W to fly 115kg = 1.6 W/kg*) Add CDMS gives
P = 40 + 1.6 M (power to fly alone - payload and downlink not included!)

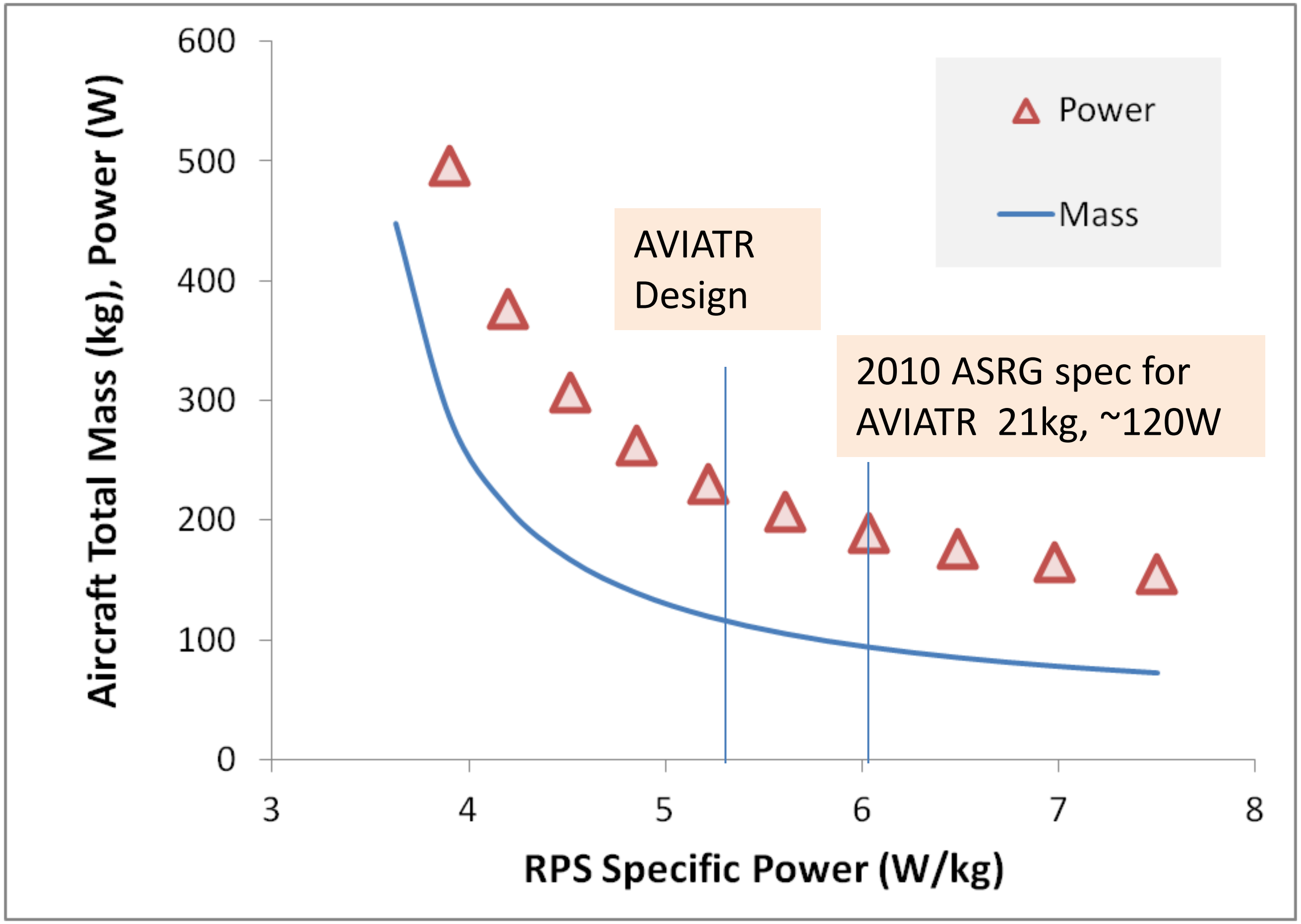
Then
$M = 31 + 2\, M_{power}$ and substituting
**$M = (31 + 80/S) / (1 – 3.2/S)$**

Singularity at S = 3.2 W/kg !

But practical designs require much better performance



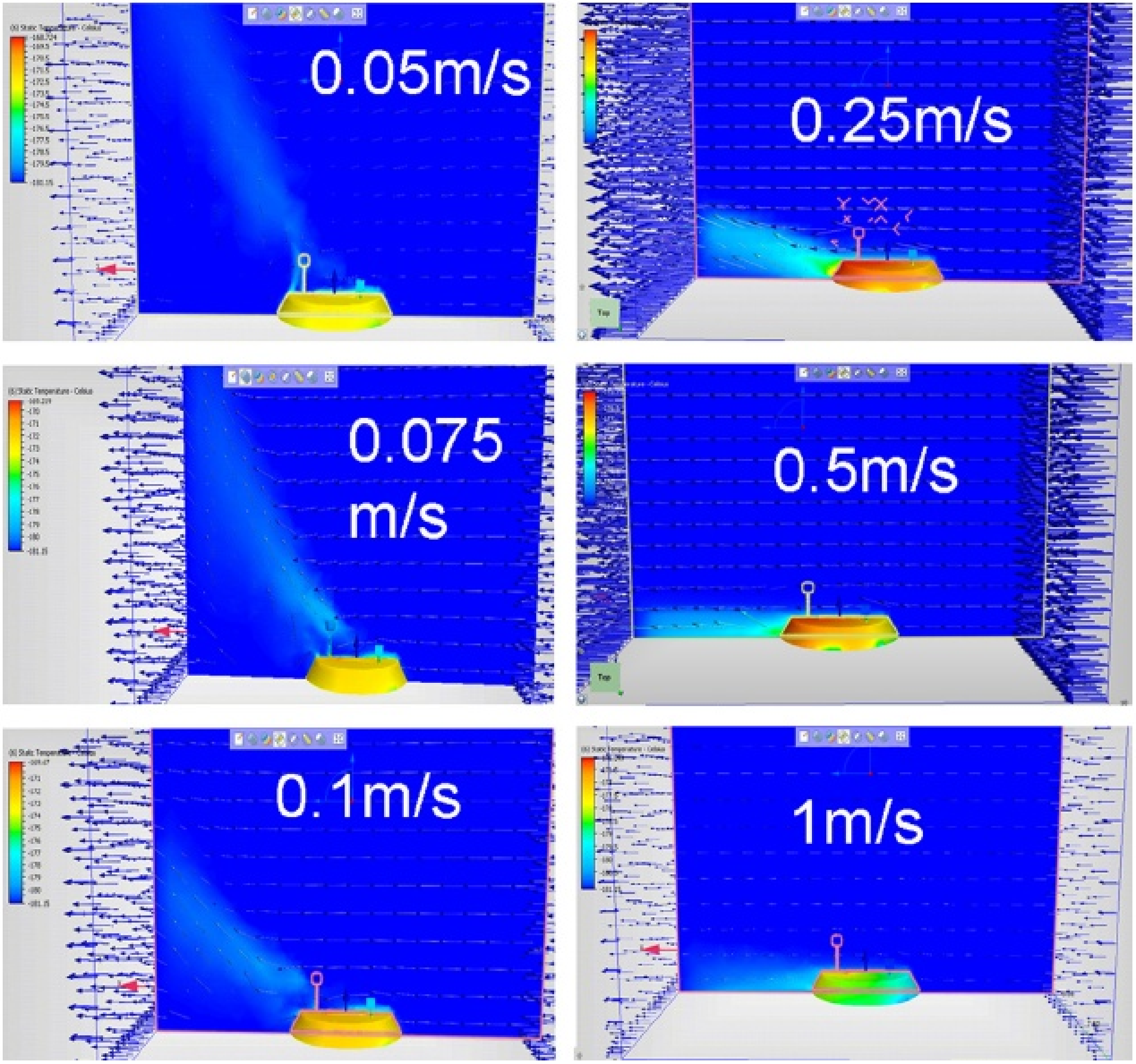

Reality check – empirical scaling, Lorenz, Journal of Aircraft, 2002 says $V \sim 11 m^{0.8} V^{0.9} (g/g_e)(\rho_e/\rho)$ - for 115 kg at 6.2 m/s is ~192W




**Specific Power is enabling for this mission ! Thermoelectrics have much lower performance by this metric : MMRTG performance (~2.8W/kg) at the time of the study is not even on this chart !**

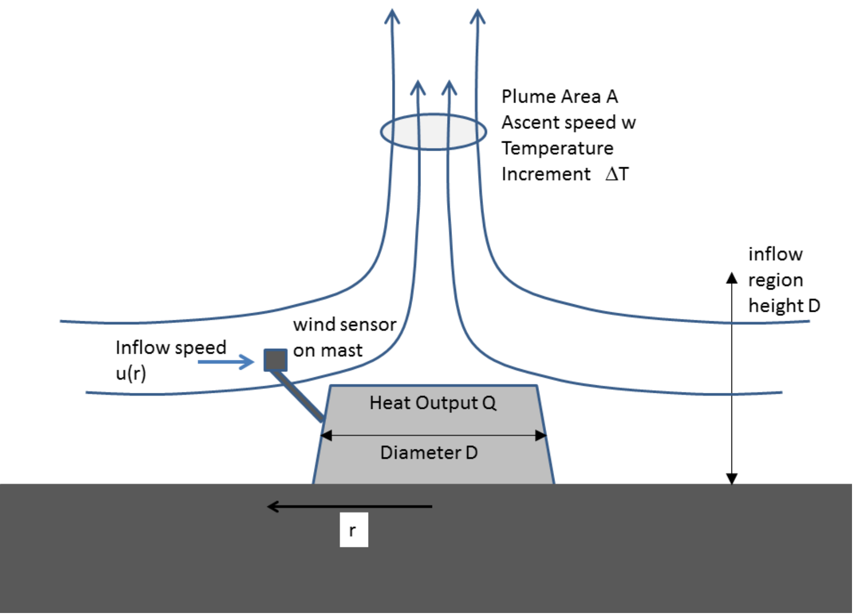
Analysis applies to vehicle with single folded wing and flight speed of 6 m/s. ‘Gossamer albatross’ low speed aircraft with low wing loading would have lower power demand, but likely (and rightly) perceived as large structural risk

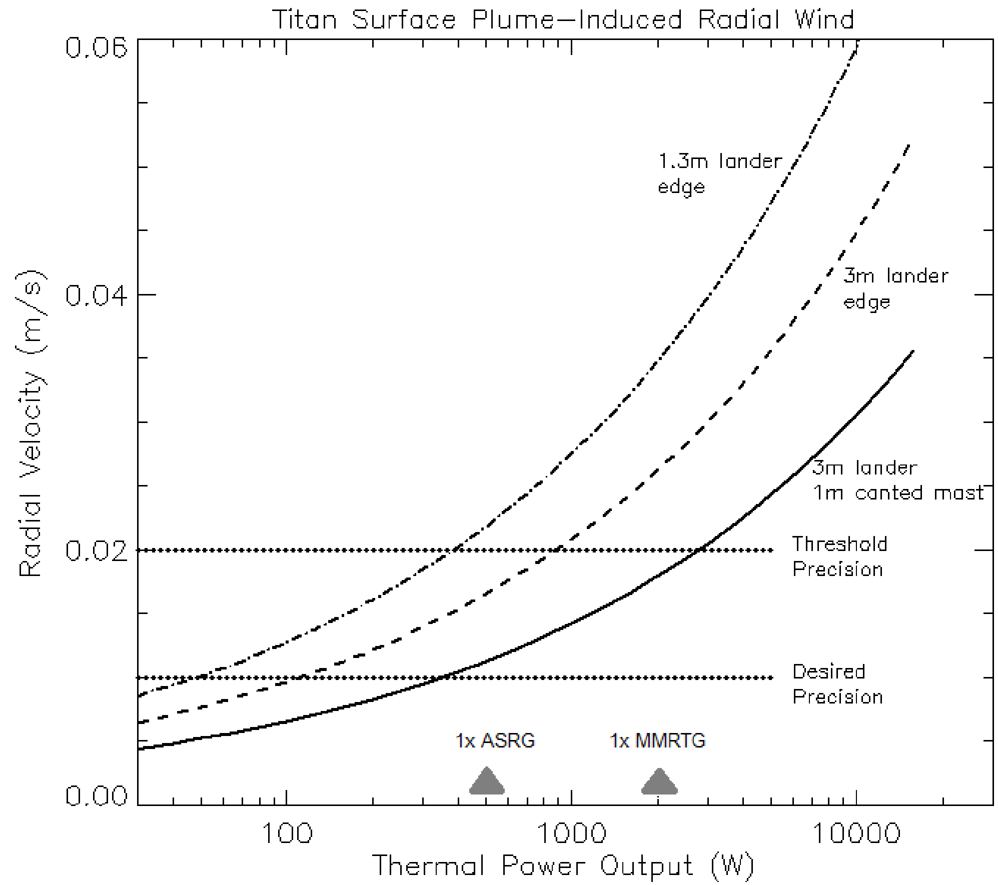
# APL CFD modeling of thermal plume for TiME (2x ASRG, $1kW_{th}$)




R.D. Lorenz, K.S. Sotzen / Planetary and Space Science 90 (2014) 81–89

Thermal plume leans over with increased windspeed – for 1kW heat output, a short (~1m) mast is adequate for winds >0.1m/s




Lander-induced thermal perturbations become more severe at higher heat loads/densities – even generate a local wind. Can be mitigated with canted meteorology mast (again, mitigations to non-preferred RPS options are possible, but are crippling in a cost-constrained mission scenario.)

Meteorology perturbations from RPS noted on Viking, and especially on Curiosity.

# Conclusions – Titan-Specific (1)

In-situ missions on or near Titan's surface are limited to a few hours in duration, or *must* use nuclear sources for power *and heat*: even with 100% conversion efficiency, solar or even solar/RHUs are not enough.

Montgolfiere balloon would work well with MMRTG-like thermoelectric source (2kW$_{th}$ ~ 100kg floated mass)

Airplane designs (AVIATR) require higher power-to-weight than anticipated capability of (any) thermoelectric converters.

# Conclusions (continued)

With ~5cm insulation, Huygens (1.3m, ~4m$^2$) was close to thermal balance on surface at ~400W$_{th}$. Some minor perturbations of surface environment noticed (~100W/m$^2$).

TiME capsule, about twice as large, designed to accommodate 2 ASRGs (1000W$_{th}$). Environment perturbations required detailed evaluation for science impact.

A thermoelectric mission with similar electrical power demands (~200W$_e$ - 4000W$_{th}$) would make a significant perturbation to local temperatures and even winds

In the Titan surface setting, a higher conversion efficiency system such as Stirling simplifies integration inside entry vehicle, and vastly reduces environment perturbation.

Some References (email me for (p)reprints)

Lorenz, R. D., Heat Rejection in the Titan Surface Environment : Impact on Science Investigations, AIAA Journal of Thermophysics and Heat Transfer, in press

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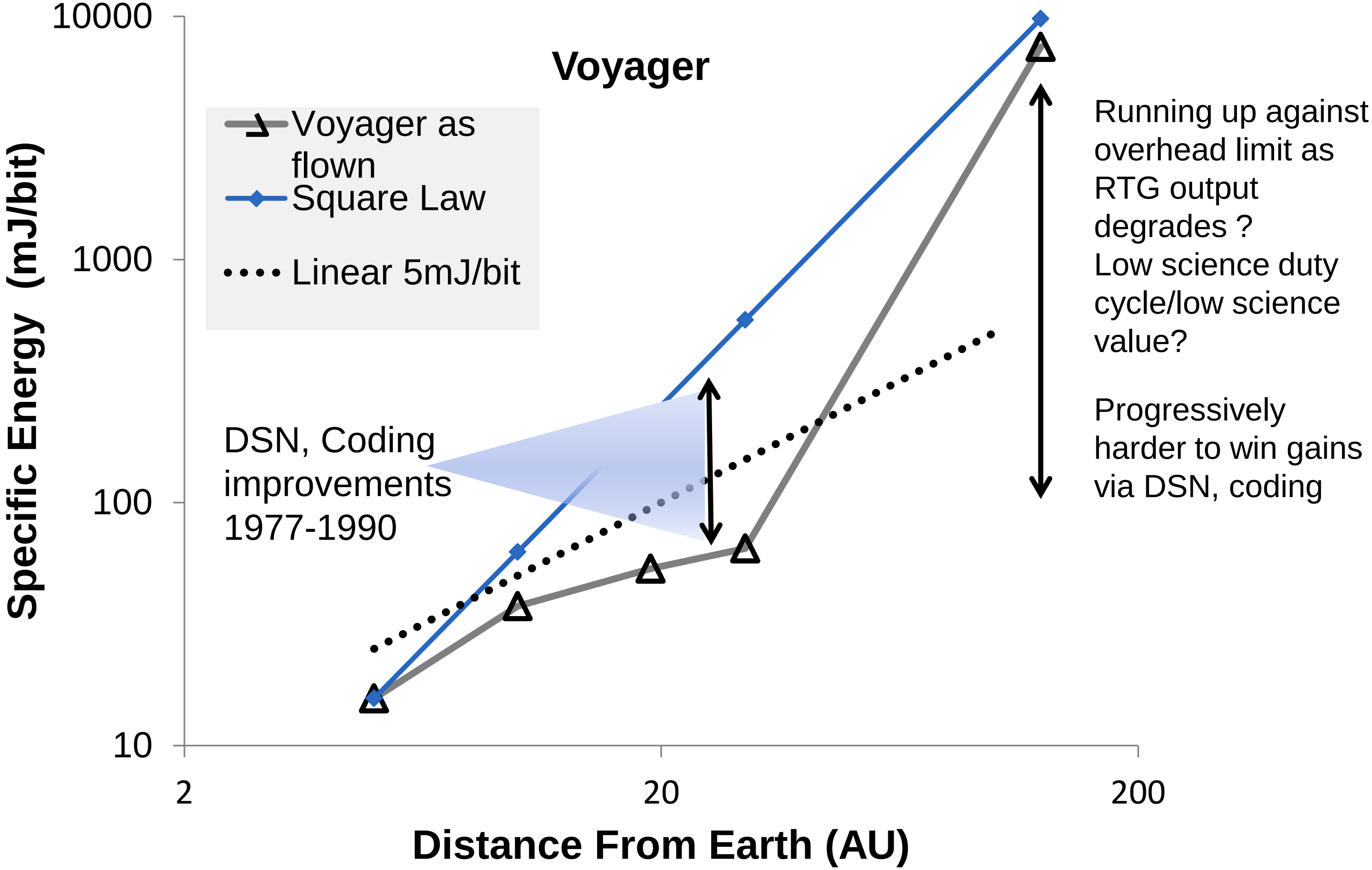
Voyager
Voyager as flown
Square Law
Linear 5mJ/bit
Specific Energy (mJ/bit)
10000
1000
100
10
2
20
200
Distance From Earth (AU)
DSN, Coding improvements 1977-1990
Running up against overhead limit as RTG output degrades ?
Low science duty cycle/low science value?
Progressively harder to win gains via DSN, coding